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50 Years of Urbanization in Africa

Examining the Role of Climate Change

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Abstract

This paper documents a significant impact of climate variation on urbanization in Sub-Saharan Africa, primarily in more arid countries. By lowering farm incomes, reduced moisture availability encourages migration to nearby cities, while wetter conditions slow migration. The paper also provides evidence for rural-urban income links. In countries with a larger industrial base, reduced moisture shrinks the agricultural sector and raises total incomes in nearby cities. However, if local cities are entirely dependent on servicing agriculture so their fortunes move with those of agriculture, reduced moisture tends to reduce local urban incomes. Finally, the paper shows that climate 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 workforce. Overall, these findings imply a strong link between climate and urbanization in Africa.

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50 Years of Urbanization in Africa: The Role of Climate Change

J. Vernon Henderson, Adam Storeygard, and Uwe Deichmann

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 335 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 shows average moisture for different areas of Africa in the 1950s and 1960s, where moisture is measured by an index combining precipitation and potential evapotranspiration (which is itself a function of temperature). As explained later, a moisture level under 1 indicates that there is less rainfall available than would evaporate given prevailing temperature. This is a useful cut-off for defining 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 0.95 in Figure 1), increasing the vulnerability of these already vulnerable areas. This decline in moisture has surely affected agricultural productivity, and we show that declines in moisture push people to the urban sector in Africa.

In particular, we look at local, within-district urbanization for an unbalanced 50-year panel of 369 districts in 29 African countries. Typical intervals between censuses in the panel are 10-15 years. In arid countries, in our baseline specification, a one standard deviation increase in a district's annualized

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

moisture growth rate lowers the annualized growth rate of its urban share by about one sixth of the mean growth rate. Moreover, across the range of annualized growth in moisture, moving from the lowest to highest moisture growth rate (in a slightly trimmed sample) lowers the annualized growth in urban share by about 100% of the mean, a huge effect.

Having documented this population effect, we consider a critical related question: does this push raise urban incomes and stimulate development of the urban sector? The answer is theoretically ambiguous and depends on the initial state of the urban sector. 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 local city growth by drawing labor out of farming. However the decline in farming leads to decreased spending by farmers on local urban goods and services, potentially offsetting the first effect. The labor force effect dominates in this case, and total city income rises. If, however, cities only exist to serve agriculture with local services not traded across districts, then a decline in moisture has an ambiguous effect on city population because the two sectors are not in competition for labor for export activity. Since the export potential of the whole district decreases, total city income generally declines.

Empirically, using intensity of nighttime urban lights to reflect changes in income, we find that decreased moisture leads to an increase in total city income for towns likely to have an export manufacturing base. For the cities most likely to have an export base in arid countries, the elasticity of lights with respect to rainfall is -0.40. However, when cities are likely just to provide services to famers, reduced moisture has little effect on total city income.

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. 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. By 2006 to 2008, only 57-72% of the rural male labor force in these countries remained in agriculture.[2] Based on individual-level observations from the Demographic and Health Surveys (DHS), we show more systematically that increases in moisture increase the probability of working in agriculture. For women, a one standard deviation (levels) increase in moisture increases the probability of working in farm activities by about 0.03 from a mean of 0.44, a 7% increase, mostly through decreased probability of not working (-0.027). Increasing moisture across

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[2] 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.

its full range raises the probability of working on the farm by 0.18, a 40% increase. For men, for a one standard deviation increase in moisture, there is a similar (0.034) increase in probability of working on the farm but it comes at the expense of off-farm work (-0.0275). So, from a different perspective, if moisture declines, women are more likely to drop out of the rural labor force altogether, while men are likely to shift into non-farm activities[3]

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 today's gap in African GDP relative to other developing countries. We will review the large literature on possible future climate change in Africa by climatologists. 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 increased urbanization in Africa. Where towns have started to industrialize, overall urban incomes will likely grow, but 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

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[3] 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.

The key 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 an imprecise effect of rainfall after controlling for agricultural price indices. 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 in Africa to get 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 very informative and examine issues not covered in our approach, including movement across rural areas, between countries, and from rural area to cities (see Henry, Schoumaker, and Beauchemin 2004 on Burkina Faso) and temporary or circular movement (Parnell and Walawege 2011).[4] These studies typically interview rural residents about their migration history, thereby omitting permanent moves to cities, though the Demographic and Health Surveys may be useful for that purpose (Young, 2013). We limit our scope to net effects on urbanization within districts over significant 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

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[4] 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.

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 hyper-arid 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 inter-tropical 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, most recently in Kenya in 2013. Climate records indicate a warming trend over Africa during the 20th Century, continuing at a slightly faster pace in the first decade of the 21st Century, independently of ENSO impacts (Collins 2011; Nicholson et al. 2013).

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.[5] 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.[6] A significant literature on climate change

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[5] The report defines heat extremes as 3-sigma events with respect to the 1951-1980 local distribution.

[6] 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).

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).[7] 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 (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 help motivate some of the specifications we consider below.[8]

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

We model movement 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, 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. We will show that if, as we have modeled, cities have an exporting industrial sector in addition to a service sector trading with local agriculture, a decline in moisture will lead to increased urbanization and increased total city income.

3.1 The basic model

3.1.1 Urban sector

The 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

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[7] 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).

[8] 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).

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.[9] Final output of manufactures is tradable nationally or internationally at fixed prices to the city. Given these two sectors, the wage rate per unit labor in the city is

$$w = p_s b = cL_m^{\varepsilon} \qquad (1)$$

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

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. In a standard version of the urban model in Duranton and Puga (2004), 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.[10]

City effective total labor supply after 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

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[9] 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 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}.

[10] 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:

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

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 $y = w(1-tN_U)$.

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

$$p_a f(N_A, R), \quad f_1 < 0,\ f_2 > 0\ . \tag{4}$$

The farm 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.

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

$$p_a f(N_A, R) - p_s b(1 - tN_U) = 0 \tag{5}$$
$$N_U = N - N_A \tag{6}$$

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

$$bL_s = N\ D(p_a f(N_A, R),\ p_a,\ p_s) \tag{7}$$

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_A / 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) after substituting in (6), and (5). 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

$$\frac{dp_s}{p_s} = \varepsilon \frac{dL_m}{L_m} \tag{8a}$$
$$\frac{dL_s}{L_s} = \eta_y \frac{f_1}{f} dN_A + \eta_y \frac{f_2}{f} dR + \eta_{p_s} \frac{dp_s}{p_s}, \quad \eta_{p_s} < 0 \tag{8b}$$
$$dL_s + dL_m = -[1 - 2t(N - N_A)]dN_A \tag{8c}$$
$$\frac{f_1}{f} dN_A + \frac{f_2}{f} dR - \frac{dp_s}{p_s} - \frac{t}{1 - t(N - N_A)} dN_A = 0 \tag{8d}$$

Combining (8a-c) to remove dL_m and dL_s into (8a) we get

$$\frac{dp_s}{p_s} = -\varepsilon\ [1+\varepsilon\frac{L_s}{L_m}\eta_{p_s}]^{-1}\left(\left[\frac{1-2t(\mathrm{N}-\mathrm{N}_A)+L_s\eta_y\frac{f_1}{f}}{L_m}\right]dN_A + \frac{L_s}{L_m}\eta_y\frac{f_2}{f}dR\right) \qquad (9)$$

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

$$\frac{dN_A}{dR} = -\frac{f_2}{f}\ \frac{L_m+\varepsilon L_s(\eta_y+\eta_{p_s})}{Z} \qquad (10)$$

$$Z \equiv \frac{f_1}{f}[L_m+\varepsilon L_s(\eta_y+\eta_{p_s})] - \frac{t}{1-t(N-N_A)}(L_m+\varepsilon L_s\eta_{p_s}) + \varepsilon[1-2t(N-N_A)]$$

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_A, and therefore that the expression in (8d) divided by dN_A is negative when $dR = 0$. This reduces to

$$Z(L_m+\varepsilon L_s\eta_{p_s})^{-1} < 0. \qquad (11)$$

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 $L_m / L_s > \varepsilon$. Given the literature believes ε < 0.08 for example, then 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 $Z < 0$, $dN_A / dR > 0$ 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 $f_2 \to 0$, so does the response. The role of f_2 / f is critical 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

$y(N-N_A) = p_a f(N_A, R)\ (N-N_A)$. Thus

$$\frac{dy(N-N_A)}{dR} = p_a f_2 Z^{-1}[1-t(N-N_A)]^{-1} * M \qquad (12)$$

where

$$M \equiv [L_m+\varepsilon L_s(\eta_y+\eta_{p_s})][1-2t(N-N_A)] + t(N-N_A)\varepsilon L_s\eta_y + (N-N_A)\varepsilon[1-2t(N-N_A)][1-t(N-N_A)]$$

Under the current assumption that $(L_m + \varepsilon L_s \eta_{p_s})$ > 0, $Z < 0$. If we further require that city earned incomes ($[1-2t(N-N_A)]$) be positive, M must be positive. Given *Z* is negative, $dy(N-N_A)/dR$ is negative.

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.*

We could also look at changes in per capita incomes explicitly, although the direction should be obvious. [11] However, 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. 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]

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). We exposit this case assuming the local manufacturing sector exists, but the situation is analogous in the case where there is no manufacturing at all and the service sector technology (per worker output) is given by $bL_s^{\varepsilon_s}, \varepsilon_s \geq 0$. In the new situation where $(L_m + \varepsilon L_s \eta_{p_s})$ < 0, stability requires $Z > 0$. Now the sign of dN_A/dR in eq. (10) is ambiguous. As a simple example, if $\eta_y + \eta_{p_s} = 0$, then dN_A/dR < 0. In that case, as $L_m \to 0$, $dN_A/dR \to 0$. When $L_m = 0$, the sign of dN_A/dR depends entirely on the sign of $\eta_y + \eta_{p_s}$. There, if $\eta_y + \eta_{p_s} = 0$, there is no effect of rainfall on the rural-urban population allocation, because migration effects only

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[11] For completeness, we also note the expression for the change in city per capita income:

$$\frac{dy}{dR} = p_a f_2 Z^{-1}\{-(L_m + \varepsilon L_s \eta_{p_s})\frac{t}{1-t(N-N_A)} + \varepsilon[1-2t(N-N_A)]\}.$$

In the current situation, given $Z < 0$, $L_m + \varepsilon L_s \eta_{p_s}$ > 0, and the definition of *Z*, dy/dR > 0.

[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

$$\frac{d(N_U y p_s^{\sigma_s} C)}{dR} = p_s^{-\sigma_s} C N_U y \frac{f_2}{f} Z^{-1}\left[(1-\alpha)\varepsilon[1-2t(N-N_A)] + \frac{[1-2t(N-N_A)](L_m + \varepsilon\eta_{p_s} L_s) + [1-(1+\sigma_s)t(N-N_A)]\varepsilon\eta_y L}{[1-t(N-N_A)](N-N_A)}\right].$$

If $Z < 0$ this expression is negative.

come through changes in demand for services (and the effect on demand for services of reduced price is exactly offset by the effect on demand of reduced per person income). Ambiguity arises in the general case in (10), if $\eta_y + \eta_{p_s} < 0$.

Total urban income from (12) is more consistently increased by rainfall. Given $Z > 0$, if $\eta_y + \eta_{p_s} \geq 0$, we can unambiguously show that $dy(N - N_A)/dR > 0$. Increased rainfall raises local farm productivity and all local incomes.[13] With city population modestly affected, total city incomes must rise. However, if $\eta_y << |\eta_{p_s}|$, so that city population declines a lot, we cannot rule out the possibility that urban incomes 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, 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 effect of moisture changes on local city incomes depending on whether manufacturing has a noticeable local presence will inform the empirical work in Section 6.

Whether a city has manufacturing is of course endogenous. The 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 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.[14]

4. Data on urbanization and climate

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.[15] 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

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[13] See the expression for changes in per capita income in fn. 11 above.

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

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

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 are dropped because of data problems with urban or district definitions.[16] We limit the panel sample to intercensal periods (*L*) of less than 20 years, so Liberia is included in long difference specifications only, because its two available censuses were 34 years apart. We have information from 2 to 5 censuses between 1960 and 2010 for each remaining country (Figure 3 and the Data Appendix). Kenya is effectively 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 panel estimation are outlined 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 it is more developed, province maps were redrawn post-Apartheid, and pre-Apartheid migration restrictions make it a special case.

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 viewed as 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 estimated monthly PET from 1950 to 2010 using the

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[16] 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.

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).[17]

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.[18]

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 these intercensal periods of different lengths. We also estimate a long difference formulation. The base specification is

$$u_{ijt} = \alpha_{jt} + \beta w_{ijt,smooth} + \beta_0 X_{ij} + \beta_1 X'_{ij} w_{ijt,smooth} + \varepsilon_{ijt} \tag{13}$$

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;

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

$w_{ijt,smooth} = \left[lnW_{ij,t,smooth3} - lnW_{ij,t-L_J,smooth3}\right]/L_{jt}$;

$W_{ij,smooth3}$ is average moisture from $t - 2$ to t;

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

X_{ij} are time invariant controls, including initial levels of variables.

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

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

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.

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

In (13), growth in urbanization is a function of growth in moisture, where the growth specification removes the effect of time-invariant district characteristics (distance to markets, soil quality and the like) on urbanization *levels*. Of course, some of these factors (X'_{ij}) such as aridity and the likelihood that local towns have a manufacturing base may also affect 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 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 the 1965 and 1980 censuses 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 shown below.

Our theoretical model suggests that the effect of moisture growth on local urbanization will depend on two factors. First is how arid the area is and thus how dependent agriculture is on rainfall variation (the magnitude of f_2 / f in equation 10). We expect a smaller response to changes in climate in the more humid parts of Africa where, potentially, $f_2 \rightarrow 0$. We therefore run regressions distinguishing effects for countries located in arid regions, by adding an interaction between moisture growth and a dummy for a country being moist. We set the moisture threshold as country average value exceeding 1.0 for 1950-1969.

The second factor is whether a district's cities have an industrial sector producing goods for export to national or international markets. In this section we focus more on the arid versus moist country division, whereas in Section 6 the industrial distinction will be critical. There are no relevant district-level data on industry, so we try two strategies to designate industrial cities. First, we use a threshold of agriculture's share of national GDP net of resource rents. Besides the fact that we are using a national measure to proxy for local conditions, this division is problematic for three inter-related reasons. First, our panel extends up to 42 years for any one country; and a country's industrial share and likelihood of cities having manufacturing changes over time. Second, we do not have the relevant sector GDP data at even the country level for most countries until the mid-1980s, so we use values from the middle of the period (a 1986-88 average) rather than the beginning.[19] Finally, our preferred 30% cut-off limits power by defining too few "industrial" countries, representing only 15% of our sample, so we set the cut-off at 40% in this section. This implies that 52% of our sample is industrial. The second proxy for industrial activity is log distance to the coast. In Africa, high land transport costs mean that this is a good predictor of whether a city will have industries that export to national or international markets.

In addition to the panel formulation, we look at long differences. These average 29 years, and may capture responses to climate change on an inter-generational time scale. Intuitively, the initial period represents the climate experience of a family's older generation and the last period the experience of the younger generation.

5.2 Identification

Our chief identification concerns are omitted variables and whether there is sufficient within-country variation in the data. In Figure 5a, the growth in moisture variable has more density to the left of zero, consistent with drying; and it has a large spread of positive and negative values. However, Figure 5b shows that spread does shrink 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. We thus control for distance to the coast and initial urbanization, which might represent a variety of factors. For example, initial urbanization might be correlated with both growth in urbanization (e.g., mean reversion) and growth in moisture (by chance or via an Urban Heat Island or Urban Dry Island effect). Figure 6 shows a modest positive correlation (significant at the 10% level) for arid countries, which are our focus. Because initial urbanization also introduces endogeneity by construction, we report results with and without controls. As they have limited effect, we keep them for most specifications.

In Section 5.4, we consider heterogeneity based on several additional factors. In particular, moisture availability could interact with soil quality, especially the soil's ability to retain water and a measure of favorable soil pH constructed from Ramankutty et al. (2002). Acidic soils (with a low pH) and alkaline soils (with a high pH) tend to be less fertile. 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. We also consider a broad measure of irrigation

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[19] 1990-1992 for Tanzania because of missing data.

infrastructure, basically measuring whether a district has more than the sample median of land area with any evidence of ever having had irrigation (Siebert et al 2007). Irrigation can help farmers cope with rainfall deficits, but as mentioned earlier, the vast majority of African farmland is not irrigated. Besides the overall change in moisture between census years, the variability of conditions within and between years could also affect farmers' decisions to migrate. High variability could be important in encouraging exit from the rural sector because of higher uncertainty. Noise in climate trends could delay migration responses because signals are noisy. We therefore experiment with measures of rainfall uncertainty and noisiness. Finally, when rainfall is normally spread evenly over the year, as opposed to being highly concentrated in 1 or 2 months, as is typical in monsoon climates, this may accentuate or mute the effects of overall changes in moisture. To measure this degree of "inequality" in rainfall across the year, we use a Gini measure, where the Lorenz curve is the accumulation of annual rainfall across months of the year (using data for 1950-69) ranked from lowest to highest rainfall and the Gini, as usual, is the degree of deviation from the 45 degree line, which corresponds to equal rainfall in every month.

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 low poorly measured 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 0.3% from the top and bottom of the distribution of growth in urban share and in moisture, a total of 8 observations for the whole sample. The reported arid sample in Table 1 is trimmed. We report the impact of trimming in footnotes.

5.3 Base specification results

Table 2 presents basic panel results for the growth rate in urban share as a function of the growth rate of moisture between censuses. Column 1 shows that there is no effect on average. In columns 2-4 we allow the base effect for arid countries to be isolated from the effect for moist countries. Columns 3 and 4 introduce controls, first alone and then also interacted with the moist country dummy. The most notable and robust result is a large negative effect that is limited to arid countries. In columns 3 and 4 (with little difference between them), a one standard deviation increase in moisture growth in arid countries (0.016 from Table 1) leads to an increase in the annual growth of urbanization of 0.005, which is about a sixth of the arid-country mean. Across the range of growth rates in the trimmed arid sample, the effect is about 100% of the mean. Controls have little impact.[20]

The offsetting positive effect of moisture growth in moist countries compared to arid ones is large (0.521 in column 4), but statistically weaker. This suggests a more non-linear approach where growth in moisture in already very moist places could have negative effects in agriculture. We tried dividing moist countries into those with medium moisture (1.0-1.1) and those with higher moisture (over 1.1), with the latter being a very heterogeneous group. If we raise the second cutoff even to 1.2, only 8% of the sample is left in the very moist group. In column 5, we report the results with the second cutoff at 1.1, but, even with that, the results are quite suggestive. Starting (with fewer controls) from a base of -0.317 for arid countries, medium moist countries add an insignificant 0.261, while very moist countries add a significant 0.765. This is consistent with adverse effects of increased rainfall in already moist areas, but we don't pursue the issue further for three reasons. First, as shown in column 6, Kenya drives the whole effect. Second, the number of very high moisture areas (e.g., well over 1.40 and not Kenya) is too limited for inference. Third, as we will see in a number of specifications to follow, the positive effect for higher moisture countries is more muted.

Whether urban areas are likely to have an exporting industry plays an important role in our model. Table 3 explores heterogeneity based on our two proxies for this. In columns 1 and 2, we interact our high national agricultural share dummy with the moist country dummy, the change in moisture, and their interaction. Compared to columns 3 and 4 of Table 2, there is little impact of distinguishing moisture effects for more agricultural countries.

In Table 3 columns 3-5, we replace the agricultural share dummy with log distance to the coast. The results have limited precision but are consistent with our model. In columns 3-5, in arid countries, districts near the coast have very large negative effects of increased moisture on urbanization. These effects at the coast where cities are highly likely to have export bases are 3-4 times those found in Table 2. This negative effect decreases with distance from the coast as cities are more likely to be agricultural service centers. In column 3, this interactive term capturing how moisture effects weaken as we move away from the coast is substantial, but only significant at the 10% level. In column 4, the introduction of several controls reduces the effect only slightly but renders it insignificant. In column 5 we limit the sample to coastal countries where the primate city is on the coast. It is these countries where distance to coast best represents access to national and international markets. Results are similar to those in

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[20] Controls do however have an effect in the untrimmed sample. There, without controls, the base (i.e. arid countries) moisture growth coefficient (s.e.) is -0.446 (0.162) while with controls it drops to -0.275 (0.129). Trimming removes most of this gap.

column 3. The point estimates suggest that moisture growth effects on urbanization peter out at about the mean plus one standard deviation of distance from the coast.

In Table 4 columns 1-4, we vary the smoothing period in the column 4 formulation of Table 2. We chose to smooth across 3 years a priori. It turns out to produce the largest effect across smoothing periods of 2 to 5 years, and a more precisely estimated one than longer smoothing periods. In columns 5 and 6, we consider growth in rainfall and growth in temperature separately. The rainfall results mirror the moisture results, while temperature effects are insignificant, suggesting that in this context most of the relevant variation in moisture is driven by rainfall variation.

In Tables 2-4 we defined moist and arid areas at the country level. Identification came from within-country variation in moisture growth, allowing for differential effects between two sets of countries. We could alternatively define arid and moist areas at the district level. While this is more intuitive, in the presence of country-year fixed effects, identification requires variation in the arid/moist status of districts within countries. In practice, little such variation exists: in 11 of 17 arid countries all districts are arid, and in 2 more, 2 or fewer districts are non-arid. So in Table 5, columns 1 and 2, we interact moisture changes with initial district-level moisture as a *continuous* variable. Results are consistent with those in Table 2. Column 2 (with controls) implies that an arid district with initial moisture of 0.5 has a moisture growth elasticity of -0.15, although coefficient estimates have limited precision.

Finally, in the last column of Table 5 we report a long difference specification, restricting to a sample of 264 districts in 23 countries with censuses at least 18 years apart, and again trimming 0.3% from the top and bottom of the sample. Given the longer time frame, we smooth across 0-10 years before the census.[21] Point estimates are similar to the panel, but standard errors are large.

5.4 Other dimensions of heterogeneity

As noted above, the effect we find could be influenced by several other factors related to farming conditions. We focus on three for which we have relevant data: the soil's ability to retain water, favorable soil pH, and irrigation potential. None of these measures shows any evidence of even remotely significant or large effects, entered alone or interacted with growth in moisture.

We also considered three other climate measures related to variability within and across years. First is the Gini of rainfall across months within the year. Moisture effects might be lower when rainfall is concentrated in 1-2 months (in an endogenous growing season) than when it is more evenly spread throughout the year. Second, more noise around the annualized growth rate measure mutes the signal

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[21] Using 0-9 or 0-11 gives similar results.

and may retard migration responses to moisture changes. We measure noise by the standard error of prediction. Based on the annualized growth rate, $w_{ijt,smooth}$, calculated as shown in 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: $SEP_{ijt} = \sqrt{\sum_{s=t-L_j}^{t} (\hat{W}_{ijs,\text{smooth}3} - W_{ijs,\text{smooth}3})^2 / (L_j - 2)}$. Finally, changes in climate variability, as well as changes in climate, may increase uncertainty and encourage migration on their own. We took the standard deviation for the 10 years before the end census period (*t*) and for 10 years before the beginning census period (*t-L*) and differenced to get the change in variability (we also tried 17 year periods). Neither two interactive effects with moisture growth, the Gini and SEP_{ijt} , nor the change in standard deviation on its own produced consistent or significant effects.[22]

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 has developed some sort of 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 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.

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[22] High ethnolinguistic fractionalization at the national level might limit migration responses across space, but we found no significant effects, perhaps because it is highly correlated with the moist country dummy. We also considered road accessibility measures, but these are highly endogenous and only available for recent years.

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.[23] 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 lit area. Summary statistics are in Annex 2.

Our specification is

$$\ln\left(light_{ict}+1\right)=\sum_{j=0}^{k}\beta_j \ln rain_{ic,t-j}+\sum_{j=0}^{k}\gamma_j \ln(rain_{ic,t-j})*X_i+\phi_i+\lambda_t+\alpha_c t_c+\varepsilon_{ict} \qquad (14)$$

where

$light_{ict}$ is light DN summed over all pixels in city i, country c, in year t;

$rain_{ict}$ is average rainfall in millimeters per day within 30 km of city i, current or lagged;

X_i are country-level indicators for moisture level and agricultural share, as well as city-level indicators;

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

$\alpha_c t_c$ is a city-specific linear time trend;

ε_{ict} is an error term, clustered at the city level to capture city-specific serial correlation.

Equation (14) is an annual panel specification for cities. To identify rainfall effects on lights, we control for time-invariant city conditions, time effects (to account for annual differences in sensor settings across and within satellites), and city-specific linear growth trends. The idea 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

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

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. We can thus define a better proxy for whether cities are industrial: the national agriculture share in GDP data for 1989-1991. We can use a lower threshold of 30% of GDP in agriculture, and still define more industrialized countries so that they contain 25% of this larger sample.[24] We also again try to proxy the likelihood of a city having industry by its distance to the coast. We use the same moist/arid cutoff of 1.0 as in Section 5. Here, as suggested by the theory, we will find that the impact of rainfall in the current year and in some cases the previous year has a very different impact on the city income proxy depending on a city's likely dependence on agriculture, and also on whether the country is arid or moist as in Section 5.

Our main results are in Table 6. Column 1 shows a zero average effect, while column 2 highlights the differential between towns that are more and less likely to have an industrial base. In column 3, the elasticity of city lights with respect to rainfall is -0.163 for the base case of an arid country where cities are more likely to have industry. Applying the lights-GDP elasticity of about 0.3 from Henderson, Storeygard and Weil (2012), this implies a rainfall-city product elasticity of about -0.05 for more industrialized countries. If agricultural productivity increases with increased rainfall, local city industry suffers in the competition for the local district labor force and lights decrease. In arid countries where cities and towns are more likely to just serve local agriculture, there is a positive net elasticity, again as predicted by theory, but it is much smaller in absolute value, and only significantly different from zero in column 2 (p=0.038), not column 3 (p=0.11). The net effects for moist countries are not precisely estimated and the distinction here is not as important as in the previous section. Point estimates suggest that the effect in moist countries where cities are more likely to have industry is zero.

In column 4, distance to the coast replaces national agricultural share as a proxy for city manufacturing potential. The results are very strong. In arid countries, for cities on the coast and hence most likely to be engaged in export activity, the elasticity of light with respect to rainfall is now -0.40. The elasticity declines with distance from the coast (with very significant effects), reaching zero at about the sample mean log distance to the coast (12.5, or log of approximately 270,000 meters). Net coefficients for moist countries are again insignificant.

In column 5 of Table 6 we look for lagged effects. For the base case of arid countries where cities are likely to have some industry, there is a significant negative lagged effect of rainfall on city incomes,

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[24] 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%.

about half as large as the contemporaneous effect. Point estimates suggest that this lagged negative effect of increased rainfall on city lights in the base case is again offset in moist countries and those where cities are less likely to have an industrial base, but these effects are statistically weak. Longer lags are not precisely estimated.

In Table 7, we consider two other forms of heterogeneity. First, we consider 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 do not actually expect differential effects. In columns 1 and 2, we interact rainfall with an indicator for whether the nearest power plant to a city is hydro or not. This has little effect. In columns 3 and 4, we interact rainfall with an indicator for cities with an estimated initial population over 50,000. We expect these to be especially likely to have an industrial base. The base effect is stronger for these cities, but precision is poor.

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 stop working 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. We note we looked only at responses in the rural sector. Our data do not provide industry information to analyze shifts between services and manufacturing in the urban sector (which in themselves may be second order effects) nor do they provide relevant migration information.

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 (Annex 3). 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 Annex 4. Sample size is 100,788 men and 312,769 women aged 15-49.[25]

While the majority of males and females do report working (paid or unpaid), the percentages are only 82% and 67% respectively for our sample. We do not 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.[26]

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 vs. 44%) 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% for women.

Since all DHS 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 not survey the exact same clusters, and the number of clusters typically increases 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, work in agriculture, and work in non-agricultural occupation. Agricultural work is the reference occupation, so covariate effects on it are a residual (since marginal effects must sum to zero across the three choices). The general specification is

$$y_{icjt} = \alpha x_{icjt} + \beta \overline{W}_{cj,(t-1,t-3)} + d_{jt} + f_c + e_{icjt} \qquad (15)$$

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[25] Reducing the sample to the 25-49 age group to include only respondents who have completed all possible education does not change results.

[26] 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.

where

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

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

$\bar{W}_{cj,(t-1,t-3)}$ is average moisture over the three previous years;

f_c is a supercluster (or province) fixed effect;

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

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

We control for predetermined individual characteristics age and education in x_{icjt}, and run 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 yet to have an effect at survey time, we use years *t-3* to *t-1*. We cluster standard errors by supercluster, noting that 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 super-cluster 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.[27]

7.2 Results

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[27] 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).

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 the home 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. The 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 district 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. Reestimating 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

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. These effects are confined to arid countries, not surprisingly.

As our model predicts, decreased moisture increases total city income in countries where these cities are likely to have manufacturing, and therefore be able to absorb workers leaving the farm into the urban labor force. Again as theory predicts, in contexts 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, 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. With global climate change, support for agricultural adaptation and for more effective urban management is therefore an even more urgent priority.

References

Alderman, H., Hoddinott, J., & Kinsey, B. (2006). Long term consequences of early childhood malnutrition. *Oxford Economic Papers*, 58(3), 450-474.

Auffhammer, M., Hsiang, S. M., Schlenker, W., & Sobel, A. (2011). Global climate models and climate data: a user guide for economists. Working Paper 19087. National Bureau of Economic Research, Cambridge, MA.

Barrios, S., Bertinelli, L., & Strobl, E. (2006). Climatic change and rural–urban migration: The case of sub-Saharan Africa. *Journal of Urban Economics*, 60(3), 357-371.

Barrios, S., Bertinelli, L., & Strobl, E. (2010). Trends in rainfall and economic growth in Africa: A neglected cause of the African growth tragedy. *The Review of Economics and Statistics*, 92(2), 350-366.

Bruce, J.W. 1998. Country Profiles of Land Tenure: Africa, (1996). University of Wisconsin Land Tenure Center Research Paper 130.

Brückner, M. (2012). Economic growth, size of the agricultural sector, and urbanization in Africa. *Journal of Urban Economics*, 71(1), 26-36.

Brückner, M., & Ciccone, A. (2011). Rain and the democratic window of opportunity. *Econometrica*, 79(3), 923-947.

Burke, M. B., Miguel, E., Satyanath, S., Dykema, J. A., & Lobell, D. B. (2009). Warming increases the risk of civil war in Africa. *Proceedings of the National Academy of Sciences*, 106(49), 20670-20674.

Burke, M., Dykema, J., Lobell, D., Miguel, E., & Satyanath, S. (2012). Incorporating Climate Uncertainty into Estimates of Climate Change Impacts. NBER Working Paper 17092.

Calzadilla, A., Zhu, T., Rehdanz, K., Tol, R. S., & Ringler, C. (2013). Economy wide impacts of climate change on agriculture in Sub-Saharan Africa. *Ecological Economics*, 93, 150-165.

Collier, P., Conway, G., & Venables, T. (2008). Climate change and Africa. *Oxford Review of Economic Policy*, 24(2), 337-353.

Collins, J. M. (2011). Temperature variability over Africa. *Journal of Climate*, 24(14), 3649-3666.

Conway, G. (2009). The science of climate change in Africa: impacts and adaptation. Grantham Institute for Climate Change Discussion Paper.

Cooper, P.J.M., Stern, R.D., Noguer, M. & Gathenya, J.M. (2013). Climate Change Adaptation Strategies in Sub-Saharan Africa: Foundations for the Future. In Singh, B.R. (ed.), *Climate change – Realities, impacts over ice cap, sea level and risks*, Intech, http://dx.doi.org/10.5772/55133.

Deschênes, O., & Greenstone, M. (2007). The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather. *The American Economic Review*, 354-385.

Deschênes, O., Greenstone, M., & Guryan, J. (2009). Climate change and birth weight. *The American Economic Review*, 99(2), 211-217.

Duranton, G., & Puga, D. (2004). Micro-foundations of urban agglomeration economies. In J. Vernon Henderson and Jacques-François Thisse (eds), *Handbook of regional and urban economics*, 4, 2063-2117.

Elvidge, C. D., Baugh, K. E., Kihn, E. A., Kroehl, H. W., & Davis, E. R. (1997). Mapping city lights with nighttime data from the DMSP Operational Linescan System. *Photogrammetric Engineering and Remote Sensing*, 63(6), 727-734.

Elvidge, Christopher D., Daniel Ziskin, Kimberly E. Baugh, Benjamin T. Tuttle, Tilottama Ghosh, Dee W. Pack, Edward H. Erwin, and Mikhail Zhizhin 2009. "A Fifteen Year Record of Global Natural Gas Flaring Derived from Satellite Data." Energies, 2: 595-622.

Fay, M., and Opal, C. (2000). Urbanization without growth: a not-so-uncommon phenomenon. World Bank Policy Research Working Paper 2412.

Galor, O., Moav, O. and Vollrath, D. (2009). Inequality in Land Ownership, the Emergence of Human Capital Promoting Institutions, and the Great Divergence. *Review of Economic Studies* 76(1): 143-179.

Gollin, D., Jedwab, R. & Vollrath, D. (2013). Urbanization with and without Industrialization, mimeo.

Hassan, R., & Nhemachena, C. (2008). Determinants of African farmers' strategies for adapting to climate change: Multinomial choice analysis. *African Journal of Agricultural and Resource Economics*, 2(1), 83-104.

Henderson, J. V., Roberts, M., & Storeygard, A. (2013). Is Urbanization in Sub-Saharan Africa Different? World Bank Policy Research Working Paper 6481.

Henderson, J.V., Storeygard, A., & Weil, D. N. (2011). A Bright Idea for measuring economic growth. *The American Economic Review*, 101(3), 194-199.

Henderson, J.V., Storeygard, A., & Weil, D. N. (2012). Measuring economic growth from outer space. *The American Economic Review*, 102(2), 994-1028.

Henry, S., Schoumaker, B., & Beauchemin, C. (2004). The Impact of Rainfall on the First Out-Migration: A Multi-level Event-History Analysis in Burkina Faso. *Population & Environment*, 25(5), 423-460.

Hsiang, S. M., Meng, K. C., & Cane, M. A. (2011). Civil conflicts are associated with the global climate. *Nature*, 476(7361), 438-441.

Jedwab, R. (2011). Why Is African Urbanization Different? Evidence from Resource Exports in Ghana and Ivory Coast. Unpublished, Paris School of Economics.

Jónsson, G. (2010). The environmental factor in migration dynamics: a review of African case studies. Working Paper 21, International Migration Institute, Oxford University.

Knox, J., Hess, T., Daccache, A., & Wheeler, T. (2012). Climate change impacts on crop productivity in Africa and South Asia. *Environmental Research Letters*, 7(3), 034032.

Kurukulasuriya, P., Mendelsohn, R., Hassan, R., Benhin, J., Deressa, T., Diop, M., & Dinar, A. (2006). Will African agriculture survive climate change? *The World Bank Economic Review*, 20(3), 367-388.

Kurukulasuriya, P., & Mendelsohn, R. (2008). A Ricardian analysis of the impact of climate change on African cropland. *African Journal of Agricultural and Resource Economics*, 2(1).

Lobell, D. B., Burke, M. B., Tebaldi, C., Mastrandrea, M. D., Falcon, W. P., & Naylor, R. L. (2008). Prioritizing climate change adaptation needs for food security in 2030. *Science*, 319(5863), 607-610.

Maccini, S., & Yang, D. (2009). Under the Weather: Health, Schooling, and Economic Consequences of Early-Life Rainfall. *American Economic Review*, 99(3), 1006-1026.

Marchiori, L., Maystadt, J. F., & Schumacher, I. (2012). The impact of weather anomalies on migration in sub-Saharan Africa. *Journal of Environmental Economics and Management*, 63(3), 355-374.

Marchiori, L., Maystadt, J. F., & Schumacher, I. (2013). Is environmentally-induced income variability a driver of migration? A macroeconomic perspective. Working paper.

McGranahan, G., Mitlin, D., Satterthwaite, D., Tacoli, C., & Turok, I. (2009). Africa's urban transition and the role of regional collaboration. International Institute for Environmental Development, London.

Mendelsohn, R., Nordhaus, W. D., & Shaw, D. (1994). The impact of global warming on agriculture: a Ricardian analysis. *The American Economic Review*, 84(4): 753-771.

Munshi, K. (2003). Networks in the modern economy: Mexican migrants in the US labor market. *The Quarterly Journal of Economics*, 118(2), 549-599.

Naudé, W. (2010). The determinants of migration from Sub-Saharan African countries. *Journal of African Economies*, 19(3), 330-356.

Nicholson, S. E., Nash, D. J., Chase, B. M., Grab, S. W., Shanahan, T. M., Verschuren, D., Asrat, A., Lezine, A.M. & Umer, M. (2013). Temperature variability over Africa during the last 2000 years. *The Holocene*, 23(8), 1085-1094.

Novella, Nicholas and Wassila Thiaw (2012). Africa Rainfall Climatology Version 2. Washington: National Oceanic and Atmospheric Administration.

Okafor, R., Adeleke, I., & Oparac, A. (2007). An appraisal of the conduct and provisional results of the Nigerian Population and Housing Census of 2006. *Proceedings of American Statistical Association: Survey Research Methods Section*. 2199-2205. https://www.amstat.org/sections/srms/Proceedings/y2007/Files/JSM2007-000561.pdf.

O'Loughlin, J., Witmer, F. D., Linke, A. M., Laing, A., Gettelman, A., & Dudhia, J. (2012). Climate variability and conflict risk in East Africa, 1990–2009. *Proceedings of the National Academy of Sciences*, 109(45), 18344-18349.

Parnell, S., & Walawege, R. (2011). Sub-Saharan African urbanisation and global environmental change. *Global Environmental Change*, 21, S12-S20.

Piguet, E. (2010). Linking climate change, environmental degradation, and migration: a methodological overview. *Wiley Interdisciplinary Reviews: Climate Change*, 1(4), 517-524.

Ramankutty, N, J. A. Foley, J. Norman and K. McSweeney. (2002). The global distribution of cultivable lands: current patterns and sensitivity to possible climate change. *Global Ecology and Biogeography*, 11(5): 377–392.

Roudier, P., Sultan, B., Quirion, P., & Berg, A. (2011). The impact of future climate change on West African crop yields: What does the recent literature say? *Global Environmental Change*, 21(3), 1073-1083.

Schlenker, W., Hanemann, W. M., & Fisher, A. C. (2006). The impact of global warming on US agriculture: an econometric analysis of optimal growing conditions. *Review of Economics and Statistics*, 88(1), 113-125.

Schlenker, W., & Lobell, D. B. (2010). Robust negative impacts of climate change on African agriculture. *Environmental Research Letters*, 5(1), 014010.

Shah, M., & Steinberg, B. M. (2013). Drought of Opportunities: Contemporaneous and Long Term Impacts of Rainfall Shocks on Human Capital (No. w19140). National Bureau of Economic Research.

Siebert, Stefan, Petra Döll, Sebastian Feick, Jippe Hoogeveen and Karen Frenken (2007) Global Map of Irrigation Areas version 4.0.1. Johann Wolfgang Goethe University, Frankfurt am Main, Germany / Food and Agriculture Organization of the United Nations, Rome, Italy.

Thornthwaite, C. W. (1948) An Approach toward a Rational Classification of Climate. *Geographical Review*, 38(1), 55-94 (January).

Thornton, P. K., Jones, P. G., Ericksen, P. J., & Challinor, A. J. (2011). Agriculture and food systems in sub-Saharan Africa in a 4 C+ world. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 369(1934), 117-136.

Thornton, P. K., Jones, P. G., Owiyo, T., Kruska, R. L., Herrero, M., V. Orindi, V. & A. Omolo, (2008). Climate change and poverty in Africa: Mapping hotspots of vulnerability. *African Journal of Agricultural and Resource Economics*, 2(1), 24-44.

UNEP (1992), *World Atlas of Desertification*, United Nations Environment Programme, Nairobi.

Vizy, E. K., Cook, K. H., Crétat, J., & Neupane, N. (2013). Projections of a wetter Sahel in the 21st century from global and regional models. *Journal of Climate*, 26(13): 4664-4687.

Vrieling, A., de Beurs, K. M., & Brown, M. E. (2011). Variability of African farming systems from phenological analysis of NDVI time series. *Climatic change*, 109(3-4), 455-477.

Vrieling, A., de Leeuw, J., & Said, M. Y. (2013). Length of Growing Period over Africa: Variability and Trends from 30 Years of NDVI Time Series. *Remote Sensing*, 5(2), 982-1000.

Willmott, C. J. & Matsuura, K. (2012). Terrestrial air temperature: 1900–2010 gridded monthly time series. Version 3.01. Center for Climatic Research, Dep. Of Geography, University of Delaware, Newark. http://climate.geog.udel.edu/~climate.

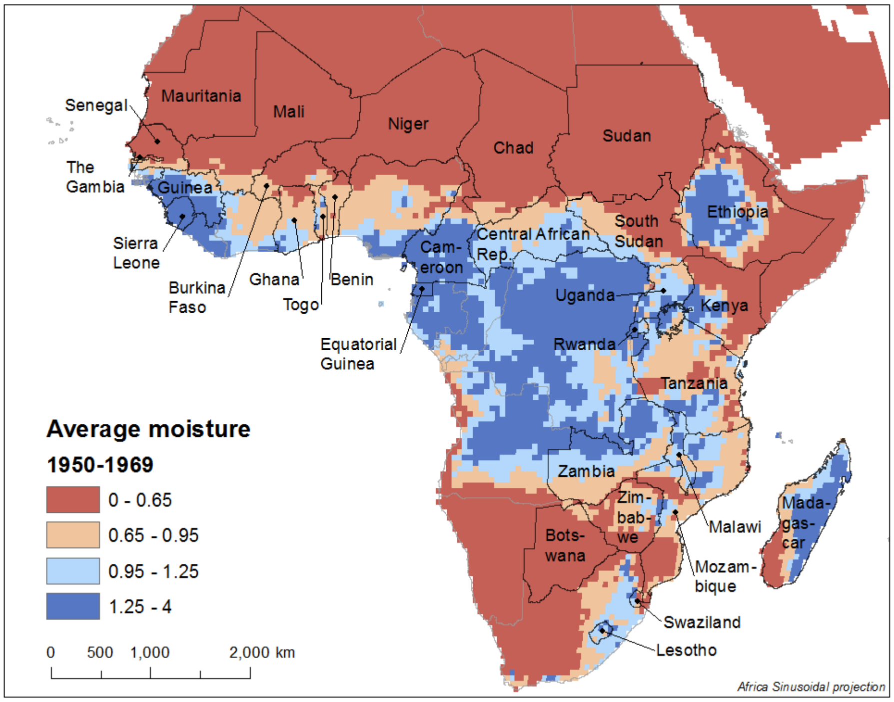
Willmott, C. J., Rowe, C. M., & Mintz, Y. (1985). Climatology of the terrestrial seasonal water cycle. *Journal of Climatology*, 5(6), 589-606.

World Bank (2013), Turn down the heat. Climate extremes, regional impacts and the case for resilience, A report for the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analytics, Washington, D.C.

You, L., Ringler, C., Nelson, G., Wood-Sichra, U., Robertson, R., Wood, S., & Sun, Y. (2010). What is the irrigation potential for Africa? Discussion Paper No. 993. International Food Policy Research Institute (IFPRI), Washington, D.C.

Young, A. (2013). Inequality, the Urban-Rural Gap, and Migration. *The Quarterly Journal of Economics* 128 (November 2013): 1727-1785.

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



Note: Map boundaries reflect the situation as of June 2014. During the time period covered by this study several borders changed. See Annex 1 for details on the time periods used for each country.

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

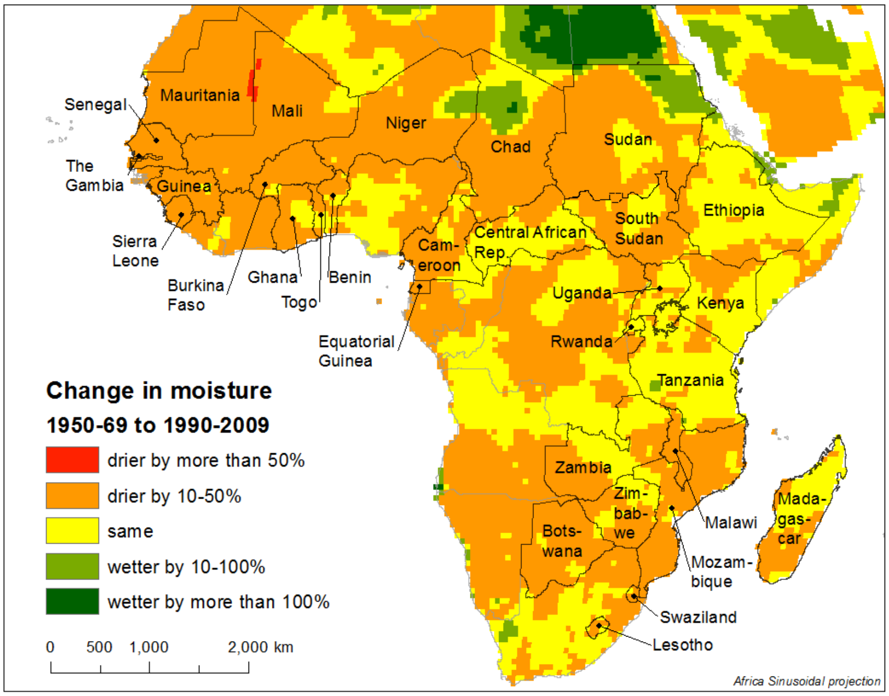
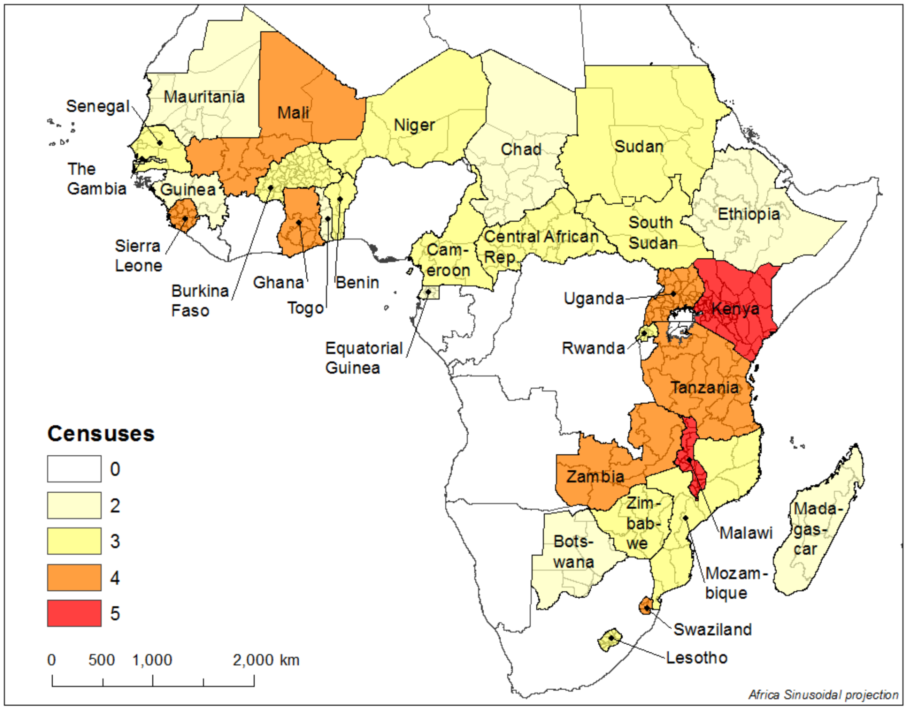


Figure 3. Census data sample



Note: Map boundaries reflect the situation as of June 2014. During the time period covered by this study several borders changed. See Annex 1 for details on the time periods used for each country.

Figure 4. Variability in climate change in Africa

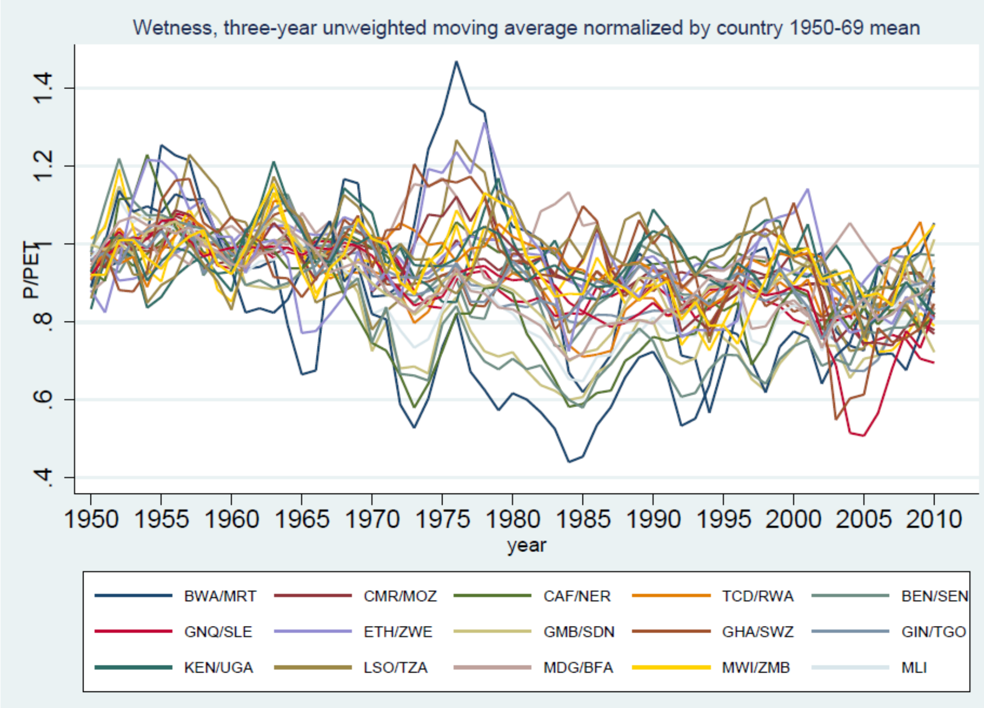
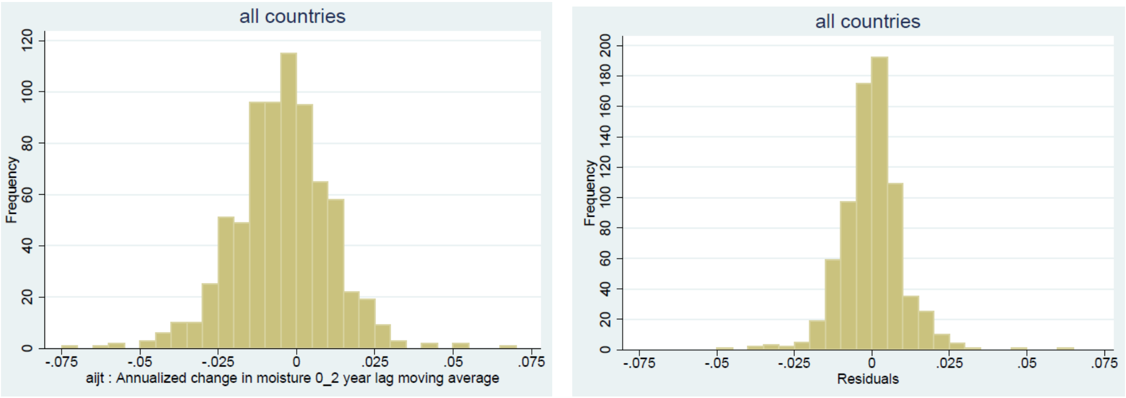


Figure 5. Spread of Dependent Variable


a. Raw data

b. Factoring out country fixed effects

Figure 6. Initial urbanization and moisture growth: arid countries

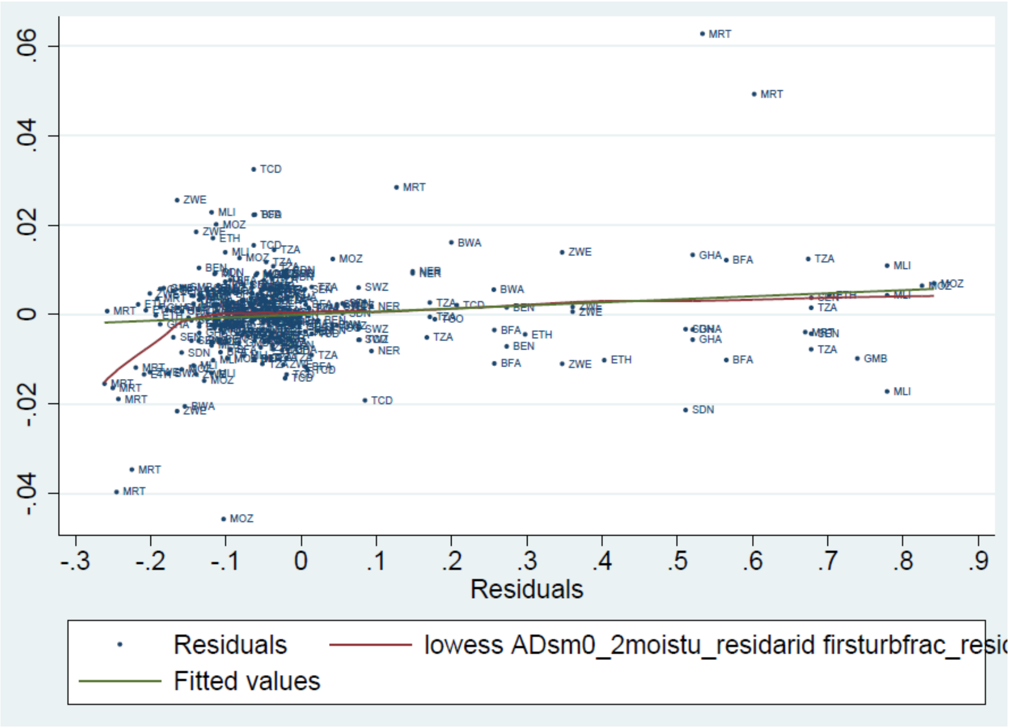
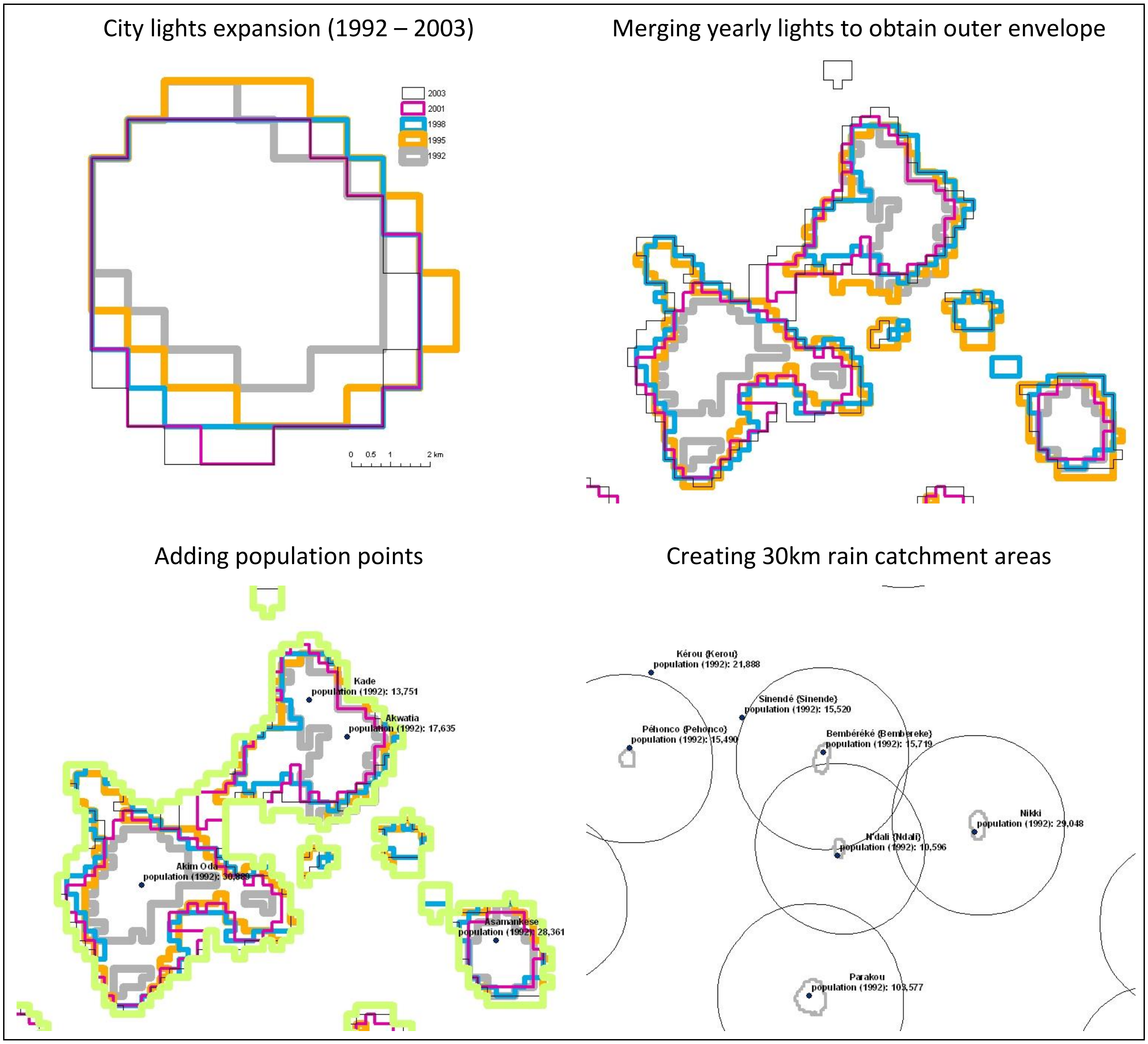


Figure 7: Spatial data integration to obtain city level lights and rain catchment data



City lights expansion (1992 – 2003)

Merging yearly lights to obtain outer envelope

Adding population points

Creating 30km rain catchment areas

Table 1. Summary statistics: Urban share growth

	full (N=741)				arid trim (N=293)			
	mean	sd	min	max	mean	sd	min	max
Annual moisture growth	-0.0045	0.015	-0.072	0.067	-0.0013	0.015	-0.047	0.052
district avg. moist. 1950-69	0.974	0.45	0.031	2.29	0.654	0.301	0.031	1.29
Annual growth: urban share	0.031	0.047	-0.162	0.305	0.027	0.034	-0.126	0.165
Initial urban share	0.142	0.212	0	1	0.179	0.224	0	1
ln(distance to coast)	5.963	1.218	0	7.476	5.693	1.334	0	7.419
area (square kilometers)	33411	63293	53.2	503510	60150	88744	53.2	503510

Table 2. Annualized growth in urban share: Base results

	(1)	(2)	(3)	(4)	(5)	(6)
Δmoisture	0.166	-0.311**	-0.291**	-0.293**	-0.291**	-0.290**
	[0.175]	[0.136]	[0.129]	[0.127]	[0.129]	[0.129]
D_moist_country*Δmoisture		0.741**	0.588**	0.521*		
		[0.289]	[0.281]	[0.288]		
D_med_moist_country*Δmoisture					0.261	0.262
					[0.468]	[0.469]
D_high_moist_country*Δmoisture					0.702**	0.387
					[0.327]	[0.496]
D_Kenya*Δmoisture						0.539
						[0.611]
Initial urban share			-0.0519***	-0.0428***	-0.0521***	-0.0522***
			[0.00542]	[0.00736]	[0.00542]	[0.00546]
ln(distance to coast)			0.00145	0.000353	0.00124	0.000839
			[0.00171]	[0.00223]	[0.00173]	[0.00176]
D moist_country*initial urban share				-0.0167		
				[0.0113]		
D_ moist_country*ln(distance to coast)				0.00331		
				[0.00374]		
R^2	0.318	0.322	0.377	0.380	0.378	0.379

Sample is 733 observations for 366 districts. All specifications include country*year fixed effects. Robust standard errors, clustered by district, are in brackets. ***p<0.01; ** p<0.05; * p< 0.10.

Table 3. Annualized growth in urban share: Heterogeneity by city type

	(1)	(2)	(3)	(4)	(5)
Δmoisture	-0.274	-0.285*	-1.363**	-1.098*	-1.475**
	[0.173]	[0.171]	[0.614]	[0.566]	[0.659]
D_moist_country*Δmoisture	0.717*	0.616	1.602**	0.369	
	[0.367]	[0.397]	[0.806]	[0.965]	
D_high_ag_country*Δmoisture	-0.0503	-0.0702			
	[0.243]	[0.242]			
D_moist_c*D_high_ag*Δmoisture	-0.275	-0.154			
	[0.570]	[0.587]			
Δmoisture*ln(distance to coast)			0.180*	0.135	0.201*
			[0.101]	[0.0938]	[0.118]
D_moist_c * Δmoist.*ln(dist. coast)			-0.171	0.0241	
			[0.136]	[0.161]	
ln(distance to coast)	0.000908	-0.00299	0.00193	0.000901	0.000351
	[0.00177]	[0.00300]	[0.00182]	[0.00218]	[0.00326]
R^2	0.378	0.383	0.378	0.382	0.609
Controls	yes	yes	yes	yes	yes
Country type dummies*controls	no	yes	no	yes	n.a.
Observations	733	733	733	733	154
Districts	366	366	366	366	76

All specifications include country*year fixed effects. Controls are initial fraction urban and ln(distance to coast). In column 2, all controls are also interacted with both the D_moist and D_high_ag variables. All specifications include country*year fixed effects. Robust standard errors, clustered by district, are in brackets. ***p<0.01; ** p<0.05; * p< 0.10.

Table 4. Growth in urban share: smoothing and rainfall vs temperature

	(1)	(2)	(3)	(4)	(5)
Δmoisture	-0.210**	-0.293**	-0.193	-0.131	
	[0.107]	[0.127]	[0.134]	[0.154]	
D_moist_country*Δmoisture	0.323	0.521*	0.343	0.254	
	[0.297]	[0.288]	[0.355]	[0.385]	
Δrainfall					-0.333**
					[0.143]
Δtemperature					-0.397
					[1.617]
D_moist_country*Δrainfall					0.482
					[0.329]
D_moist_country*Δtemperature					-2.759
					[2.581]
R^2	0.379	0.380	0.379	0.378	0.384
Smoothing	0-1	0-2	0-3	0-4	0-2

Sample is 733 observations for 366 districts. All specifications include country*year fixed effects and initial fraction urban and ln(distance to coast), both interacted with a dummy for moist countries. Robust standard errors, clustered by district, are in brackets. ***p<0.01; ** p<0.05; * p< 0.10.

Table 5. Growth in moisture: other specifications

	(1) **Panel**	(2) **Panel**	(3) **LD**
Δmoisture	-0.348	-0.364*	-0.381
	[0.217]	[0.207]	[0.427]
D_moist_country*Δmoisture			1.171
			[1.359]
District mean moisture 1950-69	0.0203***	0.0187***	
	[0.00550]	[0.00501]	
District mean moisture 50-69*Δ moisture	0.475*	0.434*	
	[0.261]	[0.253]	
R^2	0.333	0.390	0.496
Controls	no	yes	yes
D_moist*controls	no	n.a.	yes
moisture smoothing periods	0-2	0-2	0-10

Panel sample is 733 for 366 districts; LD sample is 260 districts. All specifications include country*year fixed effects. Controls are initial fraction urban and ln(distance to coast). Robust standard errors, clustered by district, are in brackets. ***p<0.01; ** p<0.05; * p< 0.10.

Table 6. Urban night lights and immediate hinterland climate

	(1)	(2)	(3)	(4)	(5)
ln(rain) (30 km radius)	-0.00338	-0.131***	-0.163***	-0.398***	-0.121***
	[0.0246]	[0.0340]	[0.0289]	[0.111]	[0.0270]
D_ag_country*ln(rain)		0.199***	0.216***		0.192***
		[0.0466]	[0.0429]		[0.0425]
D_moist_country*ln(rain)			0.145	0.412	0.0490
			[0.118]	[0.334]	[0.115]
D_moist_country*D_ag_country*ln(rain)			-0.0772		-0.0319
			[0.152]		[0.145]
ln(distance to coast)*ln(rain)				0.0311***	
				[0.00992]	
D_moist*ln(distance to coast)* ln(rain)				-0.0278	
				[0.0301]	
ln(rain) lag 1					-0.0694***
					[0.0230]
D_ag_country*ln(rain) lag 1					0.0547
					[0.0397]
D_moist_country*ln(rain) lag 1					0.118
					[0.0737]
D_moist_count*D_ag_count*ln(rain) lag 1					0.107
					[0.125]
Observations	19,685	19,685	19,685	19464	18,527
Cities	1,158	1,158	1,158	1,145	1,158
R^2	0.459	0.460	0.460	0.460	0.451

All specifications include city and year fixed effects and linear city-specific time trends. Robust standard errors, clustered by city, are in brackets. *** p<0.01, ** p<0.05, * p<0.1.

Table 7. Urban night lights and climate: hydro source and city size specifications

	(1)	(2)	(3)	(4)
ln(rain) (30 km radius)	-0.126***	-0.146***	-0.140***	-0.152***
	[0.0294]	[0.0241]	[0.0351]	[0.0307]
D_ag_country*ln(rain)	0.233***	0.221***	0.235***	0.227***
	[0.0622]	[0.0620]	[0.0527]	[0.0504]
D_moist_country*ln(rain)		0.106		0.0606
		[0.106]		[0.129]
D_moist_country*D_ag_country*ln(rain)		0.0603		0.0248
		[0.195]		[0.172]
ln(rain)*D_city_near_hydropower	0.0926	-0.0942		
	[0.168]	[0.101]		
D_ag_country*ln(rain)*D_city_near_hydropower	-0.185	-0.000451		
	[0.182]	[0.123]		
D_moist_country*ln(rain)*D_city_near_hydropower		0.181		
		[0.266]		
D_moist_country*D_ag_country*ln(rain)*D_city_near_hydro		-0.152		
		[0.346]		
ln(rain)*D_city_pop >50,000			0.0632	-0.0996
			[0.118]	[0.0605]
D_ag_country*ln(rain)*D_city_pop >50,000			-0.184	0.00839
			[0.130]	[0.0820]
D_moist_country*ln(rain)*D_city_pop >50,000				0.401
				[0.303]
D_moist_country*D_ag_country*ln(rain)*D_city_pop >50,000				-0.541
				[0.348]
Observations	15,622	15,622	19,685	19,685
R^2	0.464	0.464	0.460	0.460
Cities	919	919	1,158	1,158

All specifications include city and year fixed effects and linear city-specific time trends. Robust standard errors, clustered by city, are in brackets. *** 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	0.0015.7E-4***	-0.0003.1E-4***	-2.6E-40.000***	6.5E-4***	-3.2E-4***	-3.3E-4***
	([0.0001.2E-5)]	([0.0001.1E-5)]	([1.1E-50.000)]	[1.5E-5]	[1.2E-5]	[1.4E-5]
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	8.8E-4***	5.7E-4***	-3.1E-4***	7.2E-4***	-5.5E-4***	-1.7E-4***
	[1.6E-5]	[1.8E-5]	[1.8E-5]	[1.5E-5]	[2.1E-5]	[2.2E-5]
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

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.

Annex 1 Urbanization country sample

Country	# units	Year 0	Year 1	Year 2	Year 3	Year 4	Cen-suses	mis-sing*	panel units	LD units	LD end	LD note	LD mis-sing*
Benin	6	1979	1992	2002			3		12	6	2002		
Burkina Faso	12	1985	1996	2006			3		24	12	2006		
Botswana	8	1991	2001				2		8				
C. Afr. Rep.	16	1975	1988	2003			3		32	16	2003		
Cameroon	7	1976	1987	2005			3		14	7	2005		
Eq. Guinea	6	1983	1994				2		6				
Ethiopia	11	1994	2007				2		11				
Ghana	7	1960	1970	1984	2000		4		21	7	2000		
Guinea	4	1983	1996				2		4				
Gambia	7	1993	2003				2		7				
Kenya	39	1969	1979	1989			3	8	70	31	1989		8
Kenya (2)	40	1999	2009				2		40				
Lesotho	10	1986	1996	2006			3		20	10	2006		
Madagascar	6	1975	1993				2		6	6	1993		
Mali	8	1976	1987	1998	2009		4		24	8	2009		
Mozambique	11	1980	1997	2007			3	1	21	10	2007		1
Mauritania	13	1977	1988				2		13				
Malawi	23	1966	1977	1987	1998	2008	5		92	23	2008		
Niger	7	1977	1988	2001			3		14	7	2001		
Rwanda	9	1978	1991	2002			3		18	9	2002		
Sudan	9	1973	1983	1993			3		18	9	1993		
Senegal	8	1976	1988	2002			3		16	8	2002		
Sierra Leone	4	1963	1974	1985	2004		4		12	4	2004		
Swaziland	4	1966	1976	1986	1997		4		12	4	1997		
Chad	14	1993	2009				2		14	10	2009	LD from 1964	4
Togo	5	1970	1981				2		5	5	2010	LD to 2010	
Tanzania	21	1967	1978	1988	2002		4	1	62	20	2002		1
Uganda	38	1969	1980	1991	2002		4	8	106	32	2002		6
Zambia	8	1969	1980	1990	2000		4	1	23	7	2000		1
Zimbabwe	8	1982	1992	2002			3		16	8	2002		
Liberia										6	2008	LD 1974-2008	
Total	369		30 countries				89	19	741	265	24	countries	21

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

Annex 2: Summary statistics for lights data

	count	mean	sd	min	max
ln(rain) 30 km	19685	0.701	0.687	-8.589	2.469
%GDP (net of res. rents) in agriculture (1989-91)	18359	37.23	15.37	3.19	68.63
Population > 50k in 1992	19685	0.249	0.432	0	1
Dummy: closest power plant is hydro	15622	0.482	0.5	0	1
Dummy: %GDP in agriculture > 30%	19685	0.738	0.44	0	1
Δln(rain) 30 km	18527	0.011	0.333	-4.996	6.022
Δln(lights+1)	18527	0.096	1.033	-8.401	8.58

Annex 3: 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), 2003, 2008	
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), 2005-2006, 2010-2011	

Annex 4. 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	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	0.01	0.098	0	1
Age	28.362	9.847	15	49	28.624	9.61	15	49
Avg. moisture	0.874	0.48	0.022	3.491	0.881	0.489	0.022	3.491