

Ruggedness: The blessing of bad geography in Africa

Nathan Nunn^{*‡}

Harvard University, NBER and BREAD

Diego Puga^{*§}

IMDEA Social Sciences Institute and CEPR

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ABSTRACT: We show that geography, through its impact on history, can have important effects on current economic development. The analysis focuses on the historic interaction between ruggedness and Africa's slave trades. Although rugged terrain hinders trade and most productive activities, negatively affecting income globally, within Africa rugged terrain afforded protection to those being raided during the slave trades. Since the slave trades retarded subsequent economic development, within Africa ruggedness has also had a historic indirect positive effect on income. Studying all countries worldwide, we estimate the differential effect of ruggedness on income for Africa. We show that the differential effect of ruggedness is statistically significant and economically meaningful, it is found in Africa only, it cannot be explained by other factors like Africa's unique geographic environment, and it is fully accounted for by the history of the slave trades.

Key words: terrain ruggedness, slave trades, Africa, geography, economic development

JEL classification: O11, O13, N50, N40

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[‡]Department of Economics, Harvard University, Littauer Center M-29, Cambridge, MA 02138 (e-mail: nunn@fas.harvard.edu).

[§]Madrid Institute for Advanced Studies (IMDEA) Social Sciences, Antiguo pabellón central del Hospital de Canto blanco, Carretera de Colmenar Viejo km. 14, 28049 Madrid, Spain (e-mail: diego.puga@imdea.org; website: <http://diegopuga.org>).

1. Introduction

Rugged terrain is tough to farm, costly to traverse, and often inhospitable to live in; yet in Africa, countries with a rugged landscape tend to perform better than flatter ones. This paper uncovers this paradox and explains it by reaching back more than two centuries — to the slave trades.

In Africa, between 1400 and 1900, four simultaneous slave trades, across the Atlantic, the Sahara Desert, the Red Sea and the Indian Ocean, led to the forced migration of over 18 million people, with many more dying in the process (Africa's total population was roughly stable over this period at 50–70 million). The economies they left behind were devastated: political institutions collapsed, and societies fragmented. For African people fleeing the slave trade, rugged terrain was a positive advantage. Enslavement generally took place through raids by one group on another, and hills, caves and cliff walls provided lookout posts and hiding places for those trying to escape. Today, however, the same geographical ruggedness is an economic handicap, making it expensive to transport goods, raising the cost of irrigating and farming the land, and simply making it more expensive to do business.

We use the historical importance of terrain ruggedness within Africa to inform the debate that has arisen about the importance of geography for economic development. While it is commonly agreed that geography can have important consequences for economic outcomes, there is a growing debate over the channel of causality. The traditional focus has been on direct contemporaneous effects of geography on economic outcomes (e.g. Kamarck, 1976, Mellinger, Sachs, and Gallup, 2000, Sachs, 2001, Gallup and Sachs, 2001, Sachs and Malaney, 2002, Rappaport and Sachs, 2003).¹ Recently, others have argued for a more nuanced effect of geography on economic outcomes, which works through past interactions with key historical events (Diamond, 1997, Engerman and Sokoloff, 1997, Sokoloff and Engerman, 2000, Acemoglu, Johnson, and Robinson, 2001, 2002, Engerman and Sokoloff, 2002). For instance, Acemoglu *et al.* (2001) argue that the importance of a disease-prone environment for current income levels lies in the effect that it had on potential settler mortality during colonization. In areas where high mortality discouraged Europeans from settling, colonizers implemented poor institutions which adversely affected subsequent economic development.

Generally, it is difficult to estimate the historic indirect effects of geography. The difficulty arises because locations are generally not only affected by the historic effect of a geographical characteristic, but also by any direct effects that may exist today. Since geographic features are constant over time, disentangling the two channels is difficult. Our analysis exploits the fact that the long-term, positive effect of ruggedness, through fending off slave-raiders, is concentrated in African countries, where the trades took place. Thus, we are able to identify the indirect historic effect of terrain ruggedness that works through the slave trade. We further test for this channel by using estimates, constructed by Nunn (2008), of the number of slaves taken from each country in

¹The geographical characteristics that have been linked to economic outcomes include a disease-prone environment, proximity to the coast, and the prevalence of desert or tropical climate.

Africa.²

We describe in section 2 how we measure terrain ruggedness (data sources for all other variables employed in the analysis are detailed in the appendix). Then, after introducing the econometric framework in section 3, we investigate the relationship between ruggedness and income in section 4. We find strong evidence for a differential positive effect of the ruggedness in Africa that is both robust and highly significant. Looking within Africa, in section 5 we provide evidence that the positive effect of ruggedness operates through the slave trades. We also estimate each of the coefficients for each of the channels implicit in the indirect effect of ruggedness. We find support for each of the underlying relationships: ruggedness negatively affects slave exports, and slave exports negatively affect the quality of domestic institutions, which is an important determinant of per capita income.

2. Terrain ruggedness

There are a variety of effects of ruggedness on income that are experienced by all regions of the world. The most well-established of these are the contemporary negative effects of ruggedness. Irregular terrain makes cultivation difficult. On steep slopes erosion becomes a potential hazard, and the control of water (e.g. irrigation) becomes much more difficult. According to the Food and Agriculture Organization (1993), when slopes are greater than 2 degrees, the benefits of cultivation often do not cover the necessary costs, and when slopes are greater than 6 degrees cultivation becomes impossible. In addition, because of the very high costs involved in earthwork, building costs are much greater when terrain is irregular (Rapaport and Snickars, 1999, Nogales, Archondo-Callao, and Bhandari, 2002). As well, transportation over irregular terrain is slower and more costly.³

Our hypothesis is that within Africa ruggedness had an additional historic effect resulting because of Africa's history of the slave trades. In Africa, we expect terrain ruggedness to also have beneficial effects by having helped areas avoid the negative long-term consequences of the slave trades. The most common method of enslavement was through raids and kidnapping by members of one ethnicity on another, or even between members of the same ethnicity (Northrup, 1978, Lovejoy, 2000). Rugged terrain afforded protection to those being raided. It provided caves for hiding and the ability to watch the lowlands and incoming paths. African historians have documented many examples of this. For instance, Bah (1976) describes how "[t]hroughout time, caverns, caves and cliff walls have served as places of refuge for people. [...] There are many examples of this defensive system in Africa. At Ebarak (south-eastern Senegal), there are still traces left of a tata wall near a cave in which the Bassaris, escaping from Fulani raids, hid." Writing about what is now Mali, Brasseur (1968) explains that "[h]idden in the uneven terrain, they [the Dogon]

²The figures are constructed by combining historical shipping records with slave inventories reporting slave ethnicities. Nunn finds that the slave trades had adverse effects on subsequent economic development because they weakened indigenous political structures and institutions, and promoted ethnic and political fragmentation.

³A recent study by Allen, Bourke, and Gibson (2005) highlights these negative effects of irregular terrain within Papua New Guinea. The authors show that steep terrain not only makes the production of cash crops very difficult, but it also makes it much more costly or even impossible to transport the crops to the markets. The end result is that the populations living in these parts of Papua New Guinea have lower incomes and poorer health.

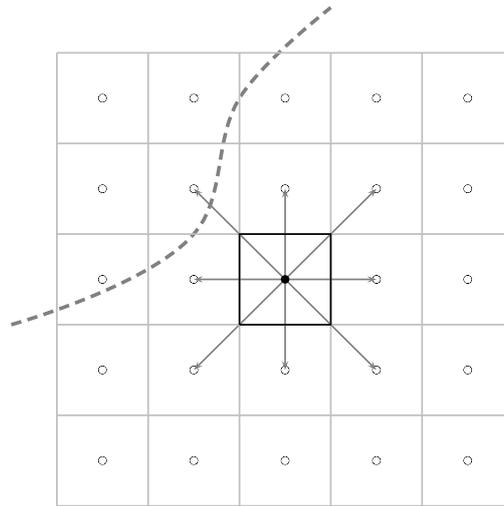


Figure 1: Schematic of the terrain ruggedness calculation

were able to use the military crests and, as far as the techniques of war at the time were concerned, were impregnable.”⁴

When measuring terrain ruggedness, our purpose is to have a measure that captures small-scale terrain irregularities, such as caverns, caves and cliff walls that afforded protection to those being raided during the slave trades. We do so by calculating the *terrain ruggedness index*, originally devised by Riley, DeGloria, and Elliot (1999) to quantify topographic heterogeneity in wildlife habitats providing concealment for preys and lookout posts. The main benefits of this measure are that it quantifies small-scale terrain irregularities and it was designed to capture precisely the type of topographic features we are interested in. Other measures that have been used by economists and political scientists are typically constructed to capture the presence of large-scale terrain irregularities, and mountains in particular.⁵ Nevertheless, we show below that the results are robust to the use of alternative measures of terrain ruggedness.

Our starting point is `GTPO30` (us Geological Survey, 1996), a global elevation data set developed through a collaborative international effort led by staff at the us Geological Survey’s Center for Earth Resources Observation and Science (EROS). Elevations in `GTPO30` are regularly spaced at 30-arc seconds across the entire surface of the Earth on a map using a geographic projection. The

⁴For additional evidence, see Marchesseau (1945), Podlewski (1961), Gleave and Prothero (1971), Bah (1985, 2003), Cordell (2003), and Kusimba (2004).

⁵For example, Gerrard (2000) constructs a measure of the percentage of each country that is covered by mountains, which is used by Fearon and Laitin (2003), Collier and Hoeffler (2004) and others in studies of civil war and conflict. Ramcharan (2006) uses data from the Center for International Earth Science Information Network (2003) on the percentage of each country within different elevation ranges in an instrumental-variables analysis of how economic diversification affects financial diversification. An exception to the focus on large-scale terrain irregularities is the article by Burchfield, Overman, Puga, and Turner (2006), who construct measures of both small-scale and large-scale irregularities and show that they have opposite effects on the scatteredness of residential development in us metropolitan areas. Burchfield *et al.* (2006) measure small-scale terrain irregularities using the same terrain ruggedness index of Riley *et al.* (1999) that we use in this paper. Olken (2009) also uses small-scale terrain irregularities to compute a predicted measure of the signal strength of television transmissions to Indonesian villages in his study of the effects of television on social capital.

sea-level surface distance between two adjacent grid points on a meridian is half a nautical mile or, equivalently, 926 metres.

Figure 1 represents 30 by 30 arc-second cells, with each cell centred on a point from the ГТОР030 elevation grid. The ruggedness calculation takes a point on the Earth’s surface like the one marked by a solid circle in the centre of figure 1 and calculates the difference in elevation between this point and the point on the grid 30 arc-seconds North of it (the hollow circle directly above it in the figure). The calculation is performed for each of the eight major directions of the compass (North, Northeast, East, Southeast, South, Southwest, West, and Northwest). The terrain ruggedness index at the central point of figure 1 is given by the square root of the sum of the squared differences in elevation between the central point and the eight adjacent points. More formally, let $e_{r,c}$ denote elevation at the point located in row r and column c of a grid of elevation points. Then the terrain ruggedness index of Riley *et al.* (1999) at that point is calculated as $\sqrt{\sum_{i=r-1}^{r+1} \sum_{j=c-1}^{c+1} (e_{i,j} - e_{r,c})^2}$. We then average across all grid cells in the country not covered by water to obtain the average terrain ruggedness of the country’s land area. Since the sea-level surface that corresponds to a 30 by 30 arc-second cell varies in proportion to the cosine of its latitude, when calculating the average terrain ruggedness — or the average of any other variable — for each country, we weigh each cell by its latitude-varying sea-level surface.

The units for the terrain ruggedness index correspond to the units used to measure elevation differences. In our calculation, ruggedness is measured in hundreds of metres of elevation difference for grid points 30 arc-seconds (926 metres on a meridian) apart. Examples of countries with an average ruggedness that corresponds to nearly level terrain are Netherlands (terrain ruggedness 0.037) and Mauritania (0.115). Romania (1.267) and Zimbabwe (1.194) have mildly rugged terrain on average. Countries with terrain that is moderately rugged include Italy (2.458) and Djibouti (2.432). Highly rugged countries include Nepal (5.043) and Lesotho (6.202). Basic summary statistics for our ruggedness measure and correlations with other key variables are reported in an online appendix.

3. Econometric framework

We now develop our estimation strategy for investigating the relationship between ruggedness, the slave trade, and income. Our starting hypothesis is that ruggedness has an effect on current income that is the same for all parts of the world. This relationship can be written

$$y_i = \kappa_1 - \alpha r_i + \beta q_i + e_i, \quad (1)$$

where i indexes countries, y_i is income per capita, r_i is our measure of ruggedness, q_i is a measure of the efficiency or quality of the organization of society, κ_1 , α and β are constants ($\alpha > 0$ and $\beta > 0$), and e_i is a classical error term (i.e., we assume that e_i is independent and identically distributed, drawn from a normal distribution, with a conditional expectation of zero).

In equation (1), we assume that the common impact of ruggedness on income is negative. This is not important for the exposition. It simply anticipates our empirical findings of a negative common effect of ruggedness. In reality, an important part of $-\alpha$ is the effect of ruggedness on

income through increased costs of cultivation, building, and trade. However, $-\alpha$ may also contain persistent historic effects of ruggedness that are similar across regions. For example, rugged terrain may be correlated with historic deposits of precious minerals, which may have had long-term effects by impacting historic institutions (Dell, 2011).

Historical studies and the empirical work of Nunn (2008) have documented that Africa's slave trades adversely affected the political and social structures of societies. We capture this effect of Africa's slave trades with the following equation

$$q_i = \begin{cases} \kappa_2 - \gamma x_i + u_i & \text{if } i \text{ is in Africa,} \\ u_i & \text{otherwise,} \end{cases} \quad (2)$$

where x_i denotes slave exports, κ_2 and γ are constants ($\gamma > 0$), and u_i is a classical error term.

Historical accounts argue that the number of slaves taken from an area was reduced by the ruggedness of the terrain. This relationship is given by

$$x_i = \kappa_3 - \lambda r_i + v_i, \quad (3)$$

where κ_2 and λ are constants ($\lambda > 0$), and v_i is a classical error term.

Equations (1), (2) and (3) are the core relationships in our analysis. Our first approach is to combine all three by substituting equations (2) and (3) into (1), which gives

$$y_i = \begin{cases} \kappa_1 - \alpha r_i + \beta \gamma \lambda r_i + \kappa_4 + \zeta_i + \xi_i & \text{if } i \text{ is in Africa,} \\ \kappa_1 - \alpha r_i + \zeta_i & \text{otherwise,} \end{cases} \quad (4)$$

where $\kappa_4 \equiv \beta(\kappa_2 - \gamma \kappa_3)$, $\zeta_i \equiv e_i + \beta u_i$ and $\xi_i \equiv -\beta \gamma v_i$. Equation (4) summarizes the relationships between ruggedness, the slave trades, and current income. It illustrates the core hypothesis of the paper: that for African countries, there is an additional positive historic effect of ruggedness on income that works through the slave trades $\beta \gamma \lambda$.

Guided by equation (4), we estimate the following relationship between ruggedness and income:

$$y_i = \beta_0 + \beta_1 r_i + \beta_2 r_i I_i^{\text{Africa}} + \beta_3 I_i^{\text{Africa}} + \varepsilon_i, \quad (5)$$

where I_i^{Africa} is an indicator variable that equals 1 if i is in Africa and 0 otherwise.

Combining our predictions about the relationships between ruggedness, the slave trades, and income yields a first hypothesis, which is core to our paper:⁶

Hypothesis 1. $\beta_2 > 0$ (in Africa ruggedness has an additional positive effect on income).

We have assumed throughout that the conditional expectation of each of the error terms in equations (1)–(3) is equal to zero. In this case, estimating equation (5) provides a consistent estimate of the historic effect of ruggedness in Africa. In practice, our assumptions rely on there not being variables that belong in any of the structural equations (1)–(3), but are omitted from our reduced form estimating equation (5). More specifically, in order for an omitted variable to bias our coefficient of interest (β_2 in equation (5)), it must be the case that, either the relationship between

⁶We have implicitly assumed that β_2 is the same for all African countries. In section 4, we relax this assumption and allow the indirect effect of ruggedness to differ across the regions of Africa.

income and the omitted factor is different inside and outside of Africa, or that the relationship between the omitted factor and ruggedness is different inside and outside of Africa. For this reason, in our empirical analysis, we pay particular attention to identifying and including potentially omitted factors for which the relationship with either income or ruggedness is potentially different inside and outside of Africa.

Equation (5) illustrates the relationship between income and ruggedness, leaving slave exports in the background. Recall that we arrived at this equation by substituting both (3) and (2) into (1). In section 5 we bring slave exports to the foreground by instead only substituting (2) into (1) and estimating (3) separately. This gives us a relationship between income and both ruggedness (now only incorporating its common effect) and slave exports:

$$y_i = \begin{cases} \kappa_1 - \alpha r_i + \beta \kappa_2 - \beta \gamma x_i + \zeta_i & \text{if } i \text{ is in Africa,} \\ \kappa_1 - \alpha r_i + \zeta_i & \text{otherwise.} \end{cases} \quad (6)$$

We test this relationship and (3) by estimating the following equations (note that for all non-African countries slave exports are zero, $x_i = 0$):

$$y_i = \beta_6 + \beta_7 r_i + \beta_8 r_i I_i^{\text{Africa}} + \beta_9 I_i^{\text{Africa}} + \beta_{10} x_i + \epsilon_i, \quad (7)$$

$$x_i = \beta_{11} + \beta_{12} r_i + \epsilon_i. \quad (8)$$

Estimating (7) and (8) allows us to test four additional hypotheses:

Hypothesis 2. $\beta_{12} < 0$ (ruggedness negatively affects slave exports).

Hypothesis 3. $\beta_{10} < 0$ (slave exports negatively affect income).

Hypothesis 4. $\beta_8 = 0$ (once slave exports are taken into account, the effect of ruggedness is no different in Africa).

Hypothesis 5. $\beta_7 = -\alpha$ (once slave exports are taken into account, the coefficient on ruggedness provides a consistent estimate of the common effect of ruggedness).

Hypothesis 2 and 3 are that ruggedness deterred slave exports and that slave exports are negatively related to current income. Hypothesis 4 provides a way of testing whether the slave trades can fully account for the positive indirect effect of ruggedness within Africa. If the ruggedness-income relationship is different for Africa only because of the slave trades, then once we control for the effect of the slave trades on income, there should no longer be a differential effect of ruggedness for Africa. Hypothesis 5 states that taking into account the indirect effect of ruggedness by controlling for the slave trades, yields a consistent estimate of the common effect of ruggedness.

4. The differential effect of ruggedness in Africa

As a first step in our empirical analysis, we now estimate the common effect of ruggedness on income per person and its differential effect for Africa. Our baseline estimates of equation (5) are given in table 1. Looking first at column (1), when we estimate equation (5) by regressing income per person on ruggedness while allowing for a differential effect in African countries, we find that

Table 1: The differential effect of ruggedness in Africa

	Dependent variable: Log real GDP per person 2000					
	(1)	(2)	(3)	(4)	(5)	(6)
Ruggedness	-0.203 (0.093)**	-0.196 (0.094)**	-0.203 (0.094)**	-0.243 (0.092)**	-0.193 (0.081)**	-0.231 (0.077)**
Ruggedness · I^{Africa}	0.393 (0.144)**	0.404 (0.146)**	0.406 (0.138)**	0.414 (0.157)**	0.302 (0.130)**	0.321 (0.127)**
I^{Africa}	-1.948 (0.220)**	-2.014 (0.222)**	-1.707 (0.325)**	-2.066 (0.324)**	-1.615 (0.295)**	-1.562 (0.415)**
Diamonds		0.017 (0.012)				0.028 (0.010)**
Diamonds · I^{Africa}		-0.014 (0.012)				-0.026 (0.011)**
% Fertile soil			0.000 (0.003)			-0.002 (0.003)
% Fertile soil · I^{Africa}			-0.008 (0.006)			-0.009 (0.007)
% Tropical climate				-0.007 (0.002)**		-0.009 (0.002)**
% Tropical climate · I^{Africa}				0.004 (0.004)		0.006 (0.004)
Distance to coast					-0.657 (0.177)**	-1.039 (0.193)**
Distance to coast · I^{Africa}					-0.291 (0.360)	-0.194 (0.386)
Constant	9.223 (0.143)**	9.204 (0.148)**	9.221 (0.200)**	9.514 (0.164)**	9.388 (0.134)**	9.959 (0.195)**
Observations	170	170	170	170	170	170
R^2	0.357	0.367	0.363	0.405	0.421	0.537

Notes: Coefficients are reported with robust standard errors in brackets. ***, **, and * indicate significance at the 1, 5, and 10 percent levels.

the coefficient for ruggedness is negative and statistically significant (i.e., $\beta_1 < 0$ in equation (5)). This indicates a negative common effect of ruggedness for the world as a whole. This is consistent with ruggedness negatively affecting income by increasing the costs of trade, construction and agriculture. While we cannot rule out the existence of some positive common consequences of ruggedness, we find that the net common effect is negative.

The coefficient estimate for ruggedness interacted with an indicator variable for Africa is positive and statistically significant (i.e., $\beta_2 > 0$ in equation (5)). This differential effect for Africa is consistent with hypothesis 1. Within Africa, there is an additional positive effect of ruggedness on income.

Robustness with respect to omitted geographical variables

When interpreting our core results regarding the relationship between ruggedness and current economic outcomes, a possible source of concern is that the estimated differential effect of ruggedness within Africa may be driven, at least in part, by other geographical features. However, for an omitted variable to bias our estimated differential effect, it is not enough that the omitted variable is correlated with income and ruggedness. It must be the case that, either the relationship between

the omitted factor and income is different within and outside of Africa, or the relationship between the omitted factor and ruggedness is different within and outside of Africa. Thus, to deal with potentially omitted differential effects, we include in our baseline specification of column (1) both the control variable and an interaction of the control variable with our Africa indicator variable. By doing this we allow the effect of the control variable to differ for Africa.

A potentially confounding factor, which may have differential effects within and outside of Africa, is the curse of mineral resources (Sachs and Warner, 2001, Mehlum, Moene, and Torvik, 2006). If diamond deposits are correlated with ruggedness, and diamond production increases income outside of Africa, but decreases income within Africa because of poor institutions, then this could potentially bias the estimated differential effect of ruggedness.⁷ Column (2) adds to our baseline specification of column (1) a control variable measuring carats of gem-quality diamonds extracted per square kilometre 1958–2000 (see the appendix for details of how this and other geographical controls are constructed), as well as an interaction of this control with the Africa indicator variable. We find weak evidence that the effect of diamonds is positive in general, but that for African countries there is a differential negative effect that nearly wipes out the general positive effect (however, neither effect is statistically significant unless we include other controls as in column (6)). The inclusion of this control variable and its interaction with the Africa indicator variable does not alter our results regarding the relationship between ruggedness and current economic outcomes. We have also tried controlling for other mineral resources, such as oil reserves and gold (together with an African interaction term). The results are unaffected by the inclusion of these additional controls.

It is also possible that in general rugged areas have worse soil quality, but within Africa rugged areas have better soil quality. For example, the Rift Valley region of Africa is rugged but has very fertile soil. To control for this possibility, we construct a measure of the percentage of fertile soil in each country. This is defined as soil that is not subject to severe constraints for growing rain-fed crops in terms of either soil fertility, depth, chemical and drainage properties, or moisture storage capacity, and is based on the FAO/UNESCO Digital Soil Map of the World. In column (3), we add the measure of soil fertility and its interaction with the Africa indicator variable to our baseline specification. The results show that the differential effect of ruggedness remains robust to controlling for soil quality.

A related argument can be made about tropical diseases. If rugged areas are less prone to tropical diseases within Africa but not in the rest of the world, then this could potentially bias the estimated differential effect of ruggedness. To check for this possibility, in column (4) we add to our baseline specification a variable measuring the percentage of each country that has any of the four tropical climates in the Köppen-Geiger climate classification, as well as an interaction of this variable with the Africa indicator variable. We see that there is a statistically significant negative relationship between tropical climate and income, but that the effect is no different for African countries. Our core results are, once again, unchanged.

We recognize that alternative proxies for tropical diseases are also possible. For example, one

⁷See Mehlum *et al.* (2006) and Robinson, Torvik, and Verdier (2006) for theory and empirical evidence supporting such a differential effect of resource endowments.

can focus specifically on malaria and include an index of the stability of malaria transmission from Kiszewski, Mellinger, Spielman, Malaney, Sachs, and Sachs (2004) and the corresponding African interaction. When we do this our core results remain unchanged. The same is also true if we control for the distance to the equator and the corresponding African interaction.

Motivated by the arguments of Rappaport and Sachs (2003) and others that coastal access is a fundamental determinant of income differences, in column (5) we control for the average distance (measured in thousands of kilometres) to the nearest ice-free coast for each country. As before, we also include an interaction of the distance variable with the African indicator variable. Our results remain robust. Finally, in column (6) we include all of the geographic controls and their corresponding interaction terms. We find again that our baseline results from column (1) are robust to controlling for other geographic characteristics that could have a differential effect in Africa.⁸

Robustness with respect to alternative income and ruggedness measures

We next consider a number of sensitivity checks to ensure that the findings documented to this point are in fact robust. First, one can think of many alternative measures of ruggedness. We have chosen to use a well-established measure of terrain ruggedness that was developed by Riley *et al.* (1999) to quantify topographic heterogeneity that creates hiding places and outlook posts in wildlife habitats. The first robustness check that we perform is to ensure that our results hold using other measures of ruggedness. The first alternative measure we consider is the average absolute value of the slope of the terrain. Thus, using the same GTOPO30 elevation data, we calculate the average uphill slope of the country's surface area.⁹ Our second alternative measure is the average standard deviation of elevation within the same eight-cell neighbourhood. The third measure is motivated by the possibility that what matters is having a large enough amount of sufficiently rugged terrain nearby, even if some portions of the country are fairly flat. To capture this logic, we calculate the percentage of a country's land area that is highly rugged.¹⁰ All of these measures treat land uniformly when averaging over cells to construct country averages. Thus, they do not capture the possibility that ruggedness may be more important (and thus should be given more weight) in areas that are more densely populated today. Therefore, our final alternative measure is a population-weighted measure of ruggedness. We start by calculating the ruggedness of each 30 by 30 arc-second cell but, in averaging this for each country, we weight ruggedness in each cell by the share of the country's population located in that cell.¹¹

The second robustness check that we perform is a test of whether our results are robust when

⁸Of independent interest is the relationship between ruggedness and our set of control variables. We do not find a significant relationship between ruggedness and either diamond production, soil fertility, or distance from the coast. We do find a negative relationship between ruggedness and the fraction of a country that has a tropical climate. As well, we do not find Africa to be significantly more or less rugged than the rest of the world.

⁹For every point on the 30 arc-seconds grid, we calculate the absolute value of the slope between the point and the eight adjacent points. The absolute values of the eight slopes are then averaged to calculate the mean uphill slope for each 30 by 30 arc-second cell. We then average across all grid cells in a country not covered by water to obtain the average uphill slope of the country's land area. Again, our calculations take into account the latitude-varying sea-level surface that corresponds to the 30 by 30 arc-second cell centred on each point.

¹⁰We use a threshold set at 240 metres for the terrain ruggedness index calculated on the 30 arc-seconds grid, below which Riley *et al.*, 1999 classify terrain as being 'level' to 'intermediately rugged'.

¹¹The population data are for 2000 and are from the *LandScan* data set (Oak Ridge National Laboratory, 2001).

Table 2: Robustness with respect to influential observations

	Dependent variable: Log real GDP per person 2000				
	Omit 10 most rugged	Omit 10 smallest	Omit if $ DFBETA > 2/\sqrt{N}$	Using ln(Ruggedness)	Box-Cox Trans. of Ruggedness
	(1)	(2)	(3)	(4)	(5)
Ruggedness	-0.202 (0.083)**	-0.221 (0.083)***	-0.261 (0.068)***	-0.171 (0.051)***	-0.249 (0.075)***
Ruggedness · I^{Africa}	0.286 (0.133)**	0.188 (0.099)*	0.223 (0.116)*	0.234 (0.119)**	0.333 (0.142)**
I^{Africa}	-1.448 (0.454)***	-1.465 (0.405)***	-1.510 (0.406)***	-1.083 (0.394)***	-1.139 (0.391)***
All controls	Yes	Yes	Yes	Yes	Yes
Observations	160	160	164	170	170
R^2	0.520	0.545	0.564	0.527	0.533

Notes: Coefficients are reported with robust standard errors in brackets. ***, **, and * indicate significance at the 1, 5, and 10 percent levels. All regressions include a constant and our full set of control variables: Diamonds, Diamonds · I^{Africa} , % Fertile soil, % Fertile soil · I^{Africa} , % Tropical climate, % Tropical climate · I^{Africa} , Distance to coast, and Distance to coast · I^{Africa} . Coefficients and standard errors for the control variable are reported in an online appendix.

we consider income from other time periods. When looking at time periods earlier than 2000, we turn to data from Maddison (2007), which has much better historic coverage than the World Bank.¹² We find that our results are robust using income from any year between 1950 and 2000, or for average annual income between 1950 and 2000.

We re-estimate our baseline estimating equation with the full set of controls (i.e., the specification in column (6) in table 1), using all the different combination of the income and ruggedness measures. We find that the estimated positive differential effect of ruggedness is very robust. In all regressions, we find that the differential effect of ruggedness within Africa is positive and statistically significant.¹³

Robustness with respect to influential observations

Next, we check whether the results from table 1 are driven by some particularly influential outliers. Figure 2 shows a scatter plot of income per person against ruggedness for African countries (top panel) and non-African countries (bottom panel). In these plots of the raw data, one observes a positive relationship for African countries and a negative relationship for non-African countries. However, a number of observations appear as clear outliers in terms of their ruggedness. Our first

¹²In 2000, Maddison only has data for 159 countries, compared to 170 for the World Bank. But once one starts to move back in time, Maddison's coverage is much better than the World Bank's. For example, prior to 1980 the World Bank does not have data on real per capita PPP-adjusted GDP. Maddison has data for 137 countries as far back as back to 1950.

¹³For brevity, we do not report the results here. See the online appendix for the complete results.

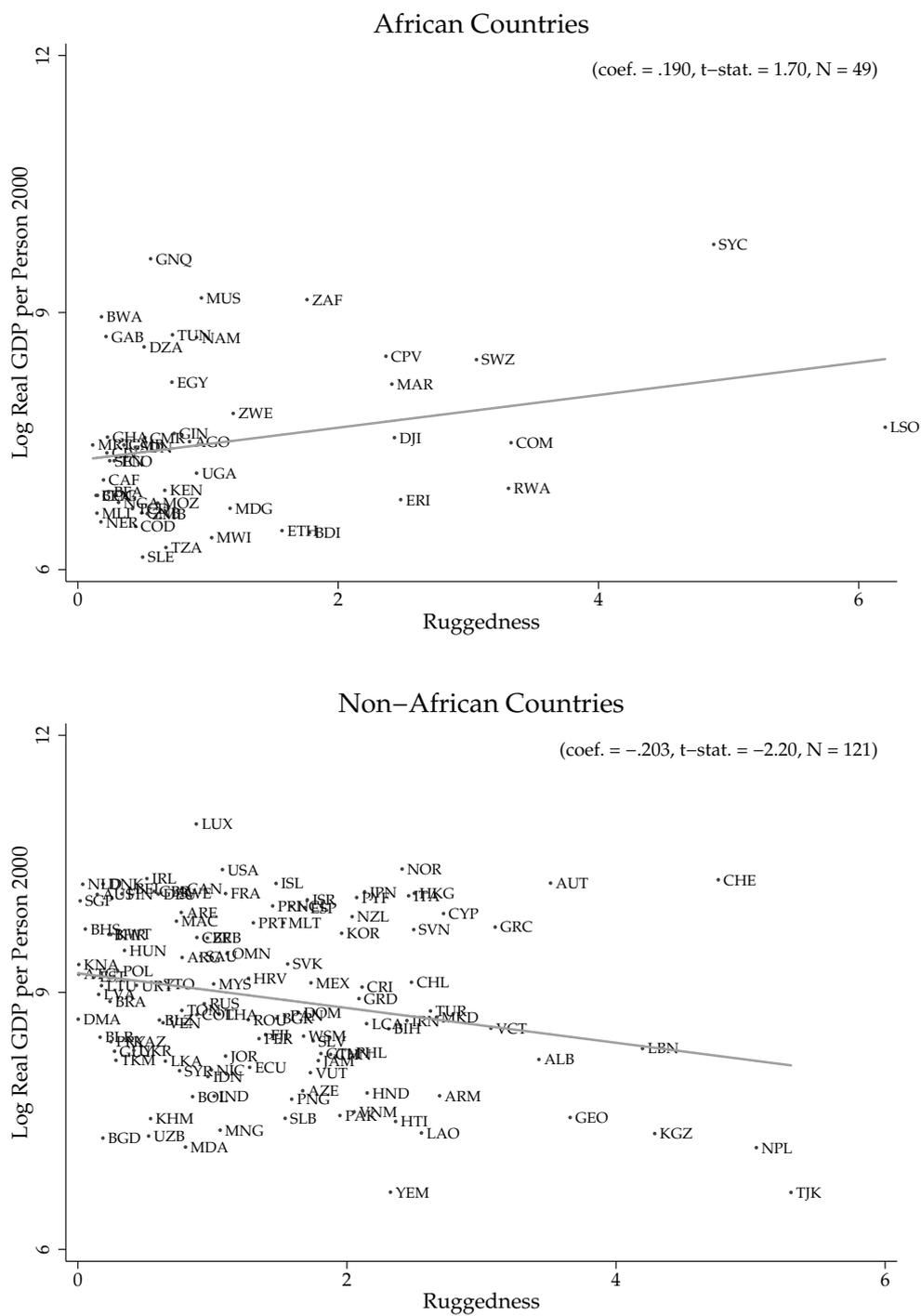


Figure 2: Income and ruggedness among African and non- African countries

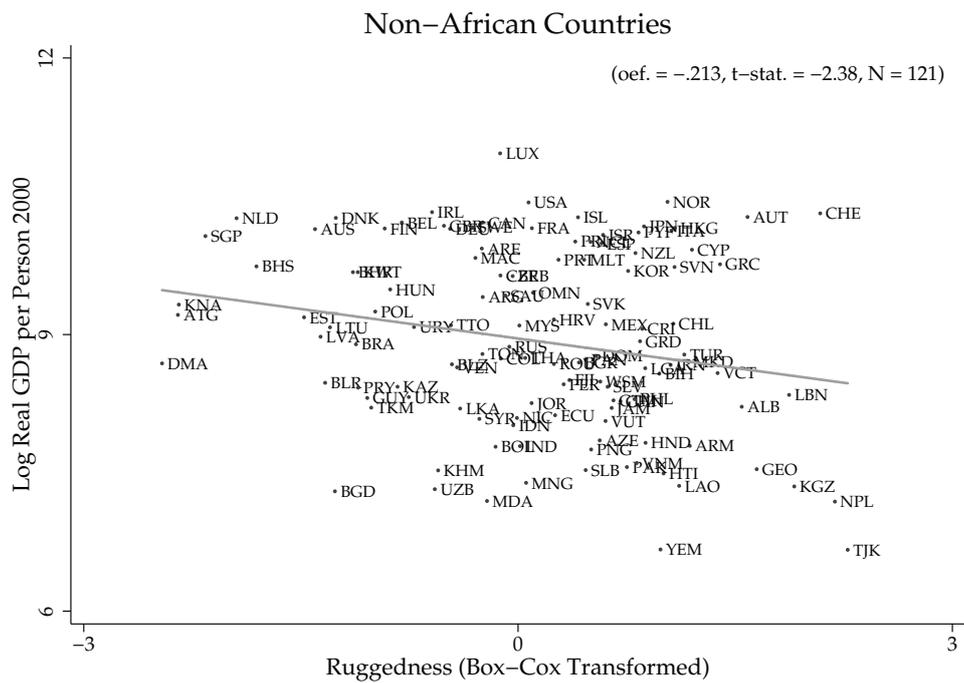
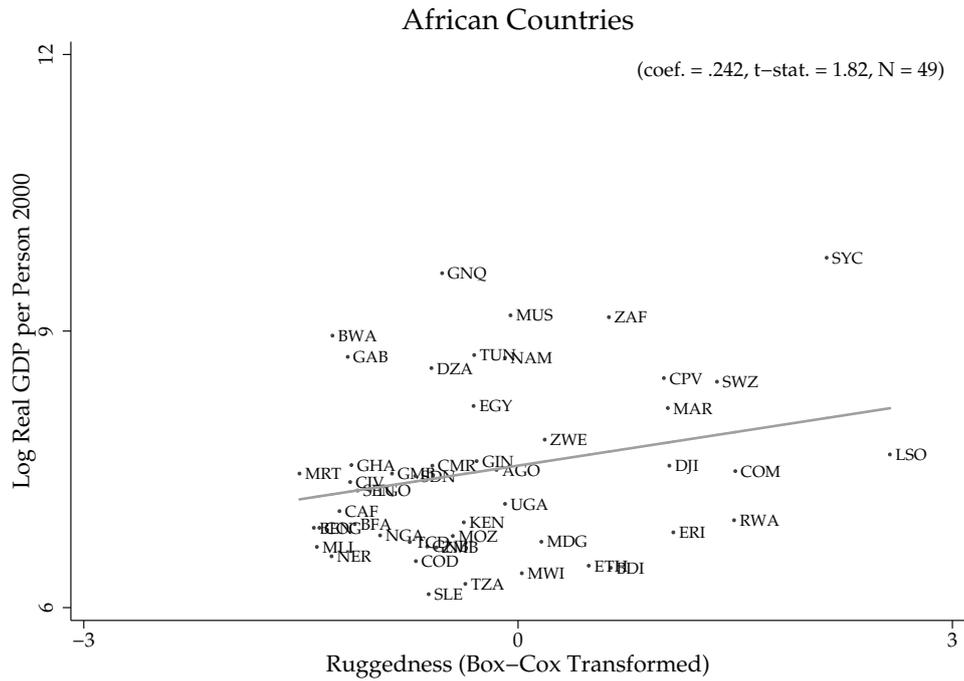


Figure 3: Income and ruggedness (Box-Cox transformed) among African and non-African countries

sensitivity check estimates our baseline specification, with our full set of control variables, after dropping the ten most rugged countries. The results are presented in column (1) of table 2.

In the scatter plot, one can also observe that small countries (based on land area) tend to have either unusually high (e.g., Seychelles, identified in the figure by its ISO 3166-1 code SYC) or unusually low ruggedness (e.g., Saint Kitts and Nevis, KNA). Given this, we perform a second robustness check where the ten smallest countries are omitted from the sample. The estimates are reported in column (2) of table 2.¹⁴

We next adopt a more systematic approach to deal with influential observations, and remove influential observations using each observation's $DFBETA_i$, which is a measure of the difference in the estimated coefficient for the ruggedness interaction (scaled by the standard error) when the observation is included and when it is excluded from the sample. Following Belsley, Kuh, and Welsch (1980), we omit all observations for which $|DFBETA_i| > 2/\sqrt{N}$, where N is the number of observations, in our case 170.¹⁵ Results are presented in column (3) of table 2.

In all three of the regressions with omitted observations, the ruggedness coefficient remains negative and statistically significant, and the ruggedness interaction remains positive and statistically significant, confirming the existence of a differential effect of ruggedness within Africa.

The reason why, in figure 2, a small number of observations appear as particularly influential is because the ruggedness measure is skewed to the left, leaving a small number of observations with large values. We remedy this in two ways. First, we take the natural log of ruggedness and use this in the estimating equations. This draws in the outlying observations in the regression. The estimates of interest, reported in column (4), remain robust to this transformation. However, looking at the natural log of ruggedness variable, one finds that the measure is no longer left skewed, but it is now right skewed, with a small number of influential observations taking on very small values. Because of this, we pursue a second strategy where we perform a zero-skewness Box-Cox power transformation on the ruggedness variable to obtain a measure with zero skewness. The relationships between income and the zero-skewness ruggedness measure are shown in figure 3. It is evident that the income-ruggedness relationships using the zero-skewness measure do not feature influential, outlying observations. In addition, a different relationship within Africa and outside of Africa is still apparent in the scatter plots of the data. Estimates using the zero-skewness measure are reported in column (5). The estimates confirm the impression given by the figures. There is a positive and significant differential effect of ruggedness within Africa.

Do other African characteristics or colonial rule explain the differential effect of ruggedness?

A final possible source of concern is that the differential effect of ruggedness for Africa is not really an African effect. Perhaps it arises because the effect of ruggedness on income differs for areas with some geographic characteristic that happens to be particularly prevalent in Africa. For

¹⁴A related concern is that our results may be driven by "atypical" African countries, such as island countries or North African countries. Our results are also robust to omitting these "atypical" African countries from the sample.

¹⁵Using other measures and rules for the omission of influential observations, such as $DFITS$, Cook's distance or Welsch distance, provide very similar results.

Table 3: Considering differential effects of ruggedness by characteristics prevalent in Africa

	Dependent variable: Log real GDP per person 2000				
	(1)	(2)	(3)	(4)	(5)
Ruggedness	-0.259 (0.101)**	-0.322 (0.160)**	-0.374 (0.161)**	-0.386 (0.176)**	-0.543 (0.179)**
Ruggedness · I^{Africa}	0.357 (0.130)**	0.400 (0.155)**	0.360 (0.140)**	0.399 (0.203)**	0.435 (0.135)**
I^{Africa}	-1.814 (0.213)**	-1.977 (0.223)**	-1.818 (0.218)**	-1.740 (0.337)**	-1.994 (0.216)**
Ruggedness · % Tropical cl.	0.001 (0.002)		0.001 (0.002)	0.002 (0.002)	0.002 (0.002)
Ruggedness · % Tropical cl. % Tropical climate	Yes	No	Yes	Yes	Yes
Ruggedness · % Fertile soil % Fertile soil	No	Yes	Yes	Yes	Yes
Ruggedness · Colonizer FEs Colonizer FEs	No	No	No	Yes	No
Ruggedness · Legal Origin FEs Legal Origin FEs	No	No	No	No	Yes
Observations	170	170	170	170	170
R^2	0.404	0.363	0.408	0.430	0.559

Notes: Coefficients are reported with robust standard errors in brackets. ***, **, and * indicate significance at the 1, 5, and 10 percent levels.

instance, it could be that in countries where a large fraction of the territory experiences tropical climates, rugged areas are cooler, dryer, or even less prone to tropical diseases. If tropical climates are particularly prevalent in Africa (they characterize 34.0% of land in Africa compared with 19.3% of the rest of the world excluding Antarctica), perhaps the interaction between ruggedness and the Africa indicator is proxying for an interaction between ruggedness and tropical climates. Similarly, it could be that in countries where a large fraction of the territory is covered by dry unfertile soil, like desert, rugged areas are less arid. If areas with poor soil are particularly prevalent in Africa (fertile soil comprises 22.5% of the land in Africa compared with 25.3% in the rest of the world excluding Antarctica), perhaps the interaction between ruggedness and the Africa indicator is proxying for an interaction between ruggedness and poor soil quality.

We consider these possibilities in columns (1)–(3) of table 3, where we add to our baseline estimating equation variables measuring the percentage of each country with tropical climates and the percentage of each country with fertile soil (these can be seen as playing the same role as the Africa indicator), as well as interactions between ruggedness and these two variables (these can be seen as playing the same role as the interaction between ruggedness and the Africa indicator).¹⁶ In columns (1) and (2) we include each of the two sets of controls one at a time, and in column (3) we include them together. The coefficients of interest, measuring the common effect of ruggedness

¹⁶The results are also robust if we use a measure of the proportion of a country's land that is desert, rather than the proportion with fertile soil.

and the differential effect for Africa, change little and remain statistically significant.¹⁷

We next consider the possibility that our Africa indicator variable may be picking up the prevalence of colonial rule. In areas that were colonized, rugged terrain may have provided a way to defend against colonial rule. Since a greater proportion of countries in Africa, relative to the rest of the world, experienced colonial rule (within Africa 89.5% of the countries were colonized, while outside of Africa this figure is 44.1%), the differential effect of ruggedness in Africa may be biased by a differential effect of ruggedness in countries that were colonized.

We control for this possibility in columns (4) and (5) of table 3. In column (4), we include five indicator variables for the identity of a country's colonizer, with the omitted category being for countries that were not colonized.¹⁸ We also include the set of colonizer indicator variables interacted with ruggedness. The differential effect of ruggedness remains positive and statistically significant.

Numerous studies have shown that differences in the legal origin of the colonizing powers is an important determinant of a variety of country characteristics, including financial development, labour market regulations, contract enforcement, and economic growth (La Porta, Lopez-de-Silanes, and Shleifer, 2008). Given the particular strong impact of colonial rule that works through legal origin, we also control directly for each country's legal origin, by including four legal origin indicator variables and their interactions ruggedness. The four indicators are for French, German, Scandinavian, and Socialist legal origins, with the omitted category being British legal origin. The positive differential effect of ruggedness remains when accounting for differences in countries' legal origins.

Differential effects of ruggedness across regions within Africa

One concern with the results presented to this point is that we only allow the effect of ruggedness on economic outcomes to differ for African countries. We have also checked whether one also finds a positive and statistically significant differential effect of ruggedness within other parts of the world. Treating other continents in the exact same manner that we have treated Africa in equation (5) (including a continent indicator and an indicator interacted with ruggedness), we find that for no other continent is there a positive and statistically significant differential effect of ruggedness. In other words, the positive differential effect of ruggedness is *unique to Africa*, and is not found in North America, South America, Europe, Asia, or Oceania.

Having determined that the differential effect of ruggedness is specific to the African continent, we examine whether the strength of the effect differs across the regions within Africa in a manner that is consistent with the known history of the slave trades. Our argument is that ruggedness

¹⁷One could also think that certain countries, because of inferior access to technology or poor governance, are worse equipped to mitigate the common negative effects of ruggedness. However, note that this would work *against* estimating a positive differential effect of ruggedness within Africa, since access to technology and governance are likely to be worse on average in Africa. A further concern is that the tropical climate measure is potentially endogenous to ruggedness, since some areas may not be classified as tropical if they are rugged. A preferable measure would quantify how tropical a climate would be if it were not rugged. Using a country's distance from the equator as a proxy for this measure yields very similar results.

¹⁸The five categories for the identity of the colonizer are: British, Portuguese, French, Spanish, and other European.

Table 4: Differential effects of ruggedness across regions within Africa

	Dependent variable: Log real GDP per person 2000				
	(1)	(2)	(3)	(4)	(5)
Ruggedness	-0.203 (0.093)**	-0.203 (0.093)**	-0.203 (0.093)**	-0.203 (0.093)**	-0.203 (0.093)**
Ruggedness · I^{Africa}	0.312 (0.159)**	0.408 (0.161)**	0.409 (0.147)***	0.406 (0.147)***	0.448 (0.179)**
I^{Africa}	-1.735 (0.291)**	-1.844 (0.229)***	-2.008 (0.230)***	-2.046 (0.222)***	-2.054 (0.232)***
Ruggedness · $I^{\text{West Africa}}$	0.532 (0.154)***				
$I^{\text{West Africa}}$	-0.635 (0.283)**				
Ruggedness · $I^{\text{East Africa}}$		0.162 (0.274)			
$I^{\text{East Africa}}$		-0.760 (0.532)			
Ruggedness · $I^{\text{Central Africa}}$			0.575 (1.197)		
$I^{\text{Central Africa}}$			0.020 (0.597)		
Ruggedness · $I^{\text{North Africa}}$				-0.404 (0.131)***	
$I^{\text{North Africa}}$				1.465 (0.241)***	
Ruggedness · $I^{\text{South Africa}}$					-0.200 (0.195)
$I^{\text{South Africa}}$					0.592 (0.519)
Constant	9.223 (0.144)***	9.223 (0.144)***	9.223 (0.144)***	9.223 (0.144)***	9.223 (0.144)***
Observations	170	170	170	170	170
R^2	0.367	0.368	0.359	0.375	0.363

Notes: Coefficients are reported with robust standard errors in brackets. ***, **, and * indicate significance at the 1, 5, and 10 percent levels.

has a differential positive effect within Africa because no other continent was subject to the slave trades that devastated Africa between 1400 and 1900. However, the exposure to the slave trades was not uniform across the continent. West Africa was the region most severely impacted by the slave trades, whereas North Africa was barely touched.¹⁹ Thus, the logic of our core argument suggests that ruggedness should have a more beneficial effect within West Africa, where the threat of being enslaved was greatest, but within North Africa, where slave capture was nearly absent, the effect should be much smaller, and not very different from that in the rest of the world. To check this, we examine the five regions of Africa defined by Bratton and van de Walle (1997): West Africa, Central Africa, North Africa, South Africa, and East Africa. We construct an indicator variable for each region and then individually include each indicator variable and its interaction

¹⁹The correlation between our measure of slave exports, described in detail in the next section, and a West Africa indicator variable is 0.53 and is statistically significant. The correlation between slave exports and a North Africa indicator variable is -0.30 and is also statistically significant. For all other African regions, the correlation between slave exports and a region indicator variable is not statistically different from zero.

with ruggedness in equation (5). The estimates are reported in table 4. The results show that for West Africa and North Africa there is a statistically different effect of ruggedness relative to the average for all of Africa. Within West Africa, the positive effect of ruggedness is significantly larger. This is consistent with the positive effect of ruggedness working through the slave trades, and with West Africa being the region most severely impacted by the slave trades. In North Africa, where slave capture was almost completely absent, there is no positive effect of ruggedness.²⁰ The results also show that the other three regions lie between these two extremes. For these regions, the positive differential effect of ruggedness is not statistically different from that for Africa as a whole.

Our finding that, across regions within Africa, the magnitudes of the differential effects of the ruggedness aligns closely with the intensity of the slave trades provides suggestive evidence that the differential effect of ruggedness within Africa is intimately linked to the slave trades. In the following sections, we examine this directly, and provide additional evidence that this is in fact the case.

5. Do slave exports account for Africa's differential effect?

We now examine whether the slave trades can account for the differential effect of ruggedness within Africa. Our first step is to check for direct evidence that ruggedness provided protection against slave raiding. We do this using data from Nunn (2008) on the number of slaves taken from each country between 1400 and 1900 during Africa's four slave trades. The figures are constructed by combining historical shipping records with slave inventories reporting slave ethnicities (see the appendix and Nunn, 2008, for details). Because the variable is very skewed to the left and some countries have zero slave exports, we take the natural logarithm of one plus the measure, i.e. $\ln(1 + \text{slave exports}/\text{area})$. Using these data, we estimate equation (8) from section 3. Results are reported in columns (5)–(7) of table 5.

Column (5) of table 5 reports the unconditional relationship between ruggedness and slave exports among the 49 African countries in our sample. The estimate shows that there is a negative and statistically significant relationship between ruggedness and slave exports, and that ruggedness alone explains almost 30% of the variation in slave exports. This confirms hypothesis 2 (i.e., $\beta_{12} < 0$ in equation (8)). In columns (6) and (7), we include additional variables to address several potential concerns regarding the relationship between ruggedness and slave exports. We first include our baseline set of control variables. Among the four controls, the fraction of fertile soil is the only covariate that is statistically significant. The positive coefficient likely reflects the fact that soil fertility was an important determinant of having a dense and sedentary initial population, which led to more slaves being captured. In column (7), we include additional controls for other factors that may be important determinants of slave exports. We control directly for log population density in 1400. This is a particularly important characteristic, since it is possible that the reason fewer slaves were taken from countries with greater terrain ruggedness is that there were fewer

²⁰This is calculated by adding the coefficient of the North Africa interaction to the coefficient of the Africa interaction. This gives: $0.406 + -0.404 = -0.002$.

people living in more rugged areas, and not just because rugged terrain provided protection. The variable has a positive and statistically significant coefficient. Since Nunn (2008) shows that slave exports are decreasing in the distance from each country to the closest final destination in each of the four slave trades, we also include the sailing distance from each country's coast to the closest final destination for the trans-Atlantic and Indian Ocean slave trades and the overland distance to the closest final destination for the trans-Saharan and Red Sea slave trades (measured in thousands of kilometres). For the trans-Atlantic and Indian Ocean slave trades, in addition to the voyage by ship, slaves captured inland would have to be brought to the coast. Our distance to coast variable accounts for this.²¹ The ruggedness coefficient remains negative and significant at the 1% level even after controlling for these additional factors.

Having established that rugged terrain deterred slave exports, we now turn to showing that slave exports are negatively related to current economic outcomes and that this fully accounts for the differential effect of ruggedness within Africa. In column (1) of table 5, we estimate equation (7) from section 3. This is identical to equation (5) (for which we reported estimates in column (1) of table 1), except that slave exports are also included in the estimating equation. Column (3) reports the same estimation as column (1) except that we also include our baseline set of control variables from table 1 in the estimating equation. With or without the full set of controls, when slave exports are controlled for, the differential effect of ruggedness within Africa disappears. The estimated coefficient on ruggedness $\cdot I^{\text{Africa}}$ is close to zero, and is no longer statistically significant. This confirms hypothesis 4 (i.e., $\beta_8 = 0$ in equation (7)), and provides support for the explanation that the differential effect of ruggedness arises because of the slave trades.

In columns (2) and (4), we re-estimate the specifications of, respectively, columns (1) and (3), leaving out the interaction between ruggedness and the Africa indicator variable. The estimates confirm hypothesis 3, which states that current economic outcomes in Africa are worse in places more affected by the slave trades (i.e., $\beta_{10} < 0$ in equation (7)). We can also see in columns (2) and (4) that the common effect of ruggedness, once slave exports are accounted for, is negative and very close to the magnitudes from columns (1) and (6) of table 1. This confirms hypothesis 5, which states that β_7 in equation (7) provides a consistent estimate of the common effect of ruggedness on income for the world as a whole.²²

The estimates from table 5 can be used to calculate an alternative estimate of the indirect historic effect of ruggedness on income. The coefficients for slave export intensity from columns (1) and (3) provide estimates of the effect of slave exports on income, i.e., $\beta\gamma$ from equation (6). The coefficients for ruggedness from columns (5)–(7) provide estimates of λ from equation (1). Therefore, the product of the two coefficients provides an alternative estimate of the indirect historic effect of

²¹It is possible that land sufficiently distant from the coast was not exposed to the slave trades, and that therefore a measure that places greater emphasis on the amount of land below a threshold distance from the coast is a more precise determinant. If we use the percentage of a country's land area that is more than 100 kilometres from the coast instead of the distance to the nearest coast, the results are qualitatively identical.

²²If we estimate equation (7) without controlling for slave exports, then we estimate a small negative coefficient for ruggedness that is not significantly different from zero (coefficient -0.067 with standard error 0.082). This is as expected. The negative common effect of ruggedness is biased upwards (i.e., towards zero), since the positive effect of ruggedness within Africa is not being taken into account.

Table 5: The impact and determinants of slave exports

	Dep. variable: Log real GDP per person 2000				Dep. variable: Slave export intensity		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Slave export intensity	-0.203 (0.037)***	-0.222 (0.035)***	-0.206 (0.036)***	-0.214 (0.034)***			
Ruggedness	-0.203 (0.093)**	-0.169 (0.077)**	-0.231 (0.077)***	-0.220 (0.066)***	-1.330 (0.262)***	-1.326 (0.274)***	-0.989 (0.358)***
Ruggedness · I^{Africa}	0.124 (0.152)		0.047 (0.143)				
I^{Africa}	-0.819 (0.317)***	-0.591 (0.222)***	-0.825 (0.356)**	-0.728 (0.354)**			
Diamonds			0.028 (0.010)***	0.028 (0.010)***		-0.005 (0.006)	-0.001 (0.005)
Diamonds · I^{Africa}			-0.027 (0.010)**	-0.027 (0.010)***			
% Fertile soil			-0.002 (0.003)	-0.002 (0.003)		0.042 (0.015)***	0.031 (0.019)
% Fertile soil · I^{Africa}			0.000 (0.006)	0.001 (0.006)			
% Tropical climate			-0.009 (0.002)***	-0.009 (0.002)***		0.013 (0.009)	0.003 (0.010)
% Tropical climate · I^{Africa}			0.009 (0.003)***	0.008 (0.003)***			
Distance to coast			-1.039 (0.194)***	-1.039 (0.194)***		0.154 (1.174)	-1.939 (1.694)
Distance to coast · I^{Africa}			-0.162 (0.321)	-0.191 (0.343)			
Log pop. density 1400							0.326 (0.179)*
Dist. Saharan slave market							-1.670 (0.914)*
Dist. Atlantic slave market							-0.973 (0.480)**
Dist. Red Sea slave market							-0.082 (0.635)
Dist. Indian slave market							-0.925 (0.486)*
Constant	9.223 (0.144)***	9.175 (0.127)***	9.959 (0.195)***	9.943 (0.195)***	5.572 (0.503)***	3.575 (1.251)***	22.359 (10.008)**
Observations	170	170	170	170	49	49	49
R^2	0.418	0.415	0.586	0.585	0.289	0.448	0.587

Notes: Coefficients are reported with robust standard errors in brackets. ***, **, and * indicate significance at the 1, 5, and 10 percent levels.

ruggedness $\beta\gamma\lambda$. Because this is a direct estimate of the effect of ruggedness that works through the slave trades, it is potentially more precise than our reduced form estimate (i.e., β_2 from equation (5)), which is based solely on the differential effect of ruggedness within Africa.

Consider the estimates with our baseline set of control variables, reported in columns (4) and (6) of table 5. They give $\widehat{\beta\gamma} = -0.206$ and $\hat{\lambda} = -1.326$. Therefore, $\widehat{\beta\gamma\lambda} = -0.206 \times -1.326 = 0.273$. We can compare this estimate to our reduced-form estimate reported in column (6) of table 1, which is 0.321. The indirect effect of ruggedness working through slave exports is almost identical to the reduced-form differential effect of ruggedness within Africa estimated in section 4. This provides

reassuring confirmation that the reduced form differential effect of ruggedness within Africa is in fact being driven by the historic effect of ruggedness working through Africa’s slave trades.

Economic magnitude of the effects

To this point we have been focusing on the statistical significance of our estimated coefficients, ignoring the magnitude of their effects. Using the estimates from table 5, we now undertake a number of counterfactual calculations to show that the economic magnitudes of the indirect historic impact of ruggedness, working through the slave trades, is substantial.

We first consider the estimated magnitude of the impact of the slave trades on income. For context, consider a hypothetical African country with the mean level of slave exports and mean log real GDP per person among African countries. According to the estimates from column (3) of table 5, if this country was instead completely untouched by the slave trades, then its per capita income would increase by \$2,365, from \$1,784 to \$4,149.²³

We next consider the magnitude of the historic benefit of ruggedness, which occurs through reduced slave exports. Consider the benefit of a one standard deviation increase in ruggedness from the average of 1.110 to 2.389. According to the estimates from column (6) of table 5, this reduces slave exports by $1.326 \times 1.279 = 1.70$, which is a 0.54 standard deviation decline in slave export intensity. This in turn increases log real GDP per person by \$747, from the average \$1,784 to \$2,531, which is a 0.37 standard deviation increase in log income per person.²⁴

These effects are substantial, particularly given that we are considering the historic impact of one very specific geographic characteristic — terrain ruggedness — working through one historic event — the slave trades.

The effect of slave exports on income through rule of law

We have so far estimated the indirect effect of ruggedness on income, $\beta\gamma\lambda$, in two ways. First, by estimating the reduced-form relationship between income and ruggedness from equation (4) to obtain the combined differential effect of ruggedness within Africa $\widehat{\beta\gamma\lambda}$. Second, by estimating separately the effect of ruggedness on slave exports from equation (1) to obtain $\hat{\lambda}$ and the effect of slave exports on income of equation (6) to obtain $\widehat{\beta\gamma}$. A third alternative is to estimate the three equations (1)–(3) separately to obtain $\hat{\lambda}$, $\hat{\beta}$, and $\hat{\gamma}$ independently. One problem with this third alternative is that it is difficult to obtain an appropriate measure for q_i , which summarizes the different aspects of the organization of societies that are negatively affected by the slave trades. As a partial step in this direction, we use the “rule of law” variable from the World Bank’s *Worldwide*

²³This is calculated from: $\ln y' = \ln 1,784 - 0.206 \times (-4.09)$, where 4.09 is the mean slave export intensity measure among African countries, -0.206 is the estimated impact of slave exports on income (from column (3) of table 5), and y' denotes the counterfactual income, had the slave trades not occurred in the hypothetical country. Solving for y' gives \$4,149.

²⁴This is calculated from: $\ln y' = \ln 1,784 - 0.206 \times (-1.326 \times 1.279)$, where 1.279 is the standard deviation of ruggedness among African countries, -1.326 is the estimated impact of ruggedness on slave exports (from column (6) of table 5), and -0.206 is the estimated impact of slave exports on income (from column (3) of table 5). Solving for y' gives \$2,531.

Table 6: The effect of slave exports on income through rule of law

	Dep. variable: Log real GDP per person 2000		Dep. variable: Rule of law		
	(1)	(2)	(3)	(4)	(5)
Rule of law 1996-2000	0.871 (0.044)***	0.813 (0.059)***			
Ruggedness	-0.034 (0.041)	-0.051 (0.039)		-0.147 (0.067)**	-0.156 (0.049)***
I^{Africa}	-0.699 (0.131)***	-0.109 (0.352)	-0.509 (0.188)**	-0.885 (0.306)***	-0.935 (0.344)***
Slave export intensity			-0.086 (0.031)***	-0.098 (0.034)***	-0.100 (0.033)***
Diamonds		0.009 (0.014)		0.028 (0.009)***	0.019 (0.008)**
Diamonds $\cdot I^{\text{Africa}}$		-0.009 (0.015)		-0.026 (0.009)***	-0.017 (0.008)**
% Fertile soil		0.000 (0.002)		-0.002 (0.003)	0.003 (0.003)
% Fertile soil $\cdot I^{\text{Africa}}$		-0.015 (0.006)**		0.011 (0.005)**	0.006 (0.005)
% Tropical climate		-0.002 (0.001)		-0.010 (0.002)***	-0.011 (0.002)***
% Tropical climate $\cdot I^{\text{Africa}}$		0.003 (0.003)		0.004 (0.003)	0.006 (0.003)**
Distance to coast		-0.221 (0.174)		-0.984 (0.189)***	-0.427 (0.162)***
Distance to coast $\cdot I^{\text{Africa}}$		-0.576 (0.347)*		0.233 (0.296)	-0.340 (0.270)
$I^{\text{French civil law}}$					-0.528 (0.157)***
$I^{\text{French civil law}} \cdot I^{\text{Africa}}$					0.463 (0.230)**
$I^{\text{Socialist law}}$					-1.183 (0.192)***
$I^{\text{German civil law}}$					0.640 (0.331)*
$I^{\text{Scandinavian law}}$					0.774 (0.209)***
Constant	8.783 (0.076)***	8.922 (0.159)***	0.218 (0.087)**	1.113 (0.198)***	1.244 (0.226)***
Observations	169	169	169	169	169
R^2	0.746	0.776	0.191	0.449	0.644

Notes: Coefficients are reported with robust standard errors in brackets. ***, **, and * indicate significance at the 1, 5, and 10 percent levels.

Governance Indicators database (Kaufmann, Kraay, and Mastruzzi, 2008). Estimates of equations (1) and (2) using this variable are reported in table 6.

The first two columns of the table report estimates of equation (1), which captures the effects of institutional quality, as proxied by the rule of law, on real per capita income in 2000. In column (1), we control for the Africa indicator variable only, and in column (2) we also control for our standard set of control variables and their interactions with the Africa indicator variable. The estimates show a strong negative, and statistically significant, relationship between the rule of law and per capita income. This result confirms the findings from a number of previous studies that stress the

importance of governance and domestic institutions for long-term economic development (e.g., Acemoglu *et al.*, 2001).

Columns (3)–(5) of table 6 report estimates of equation (2), which models the relationship between slave exports and the quality of the organization of societies. The estimates of column (3) control for the Africa indicator variable only. We include the Africa indicator to ensure that our estimated effect of slave exports on institutional quality is not estimated from the difference between Africa and the rest of the world. Because slave exports are zero for all countries outside of Africa, and because we always control for an Africa fixed effect, the estimated coefficient for slave exports is estimated from the relationship between slave exports and institutional quality within Africa only. In columns (4) and (5), we include additional control variables. We first include our baseline set of control variables and their interactions with the Africa indicator variable. Then, in column (5), we also add our legal origin fixed effects and their interactions with the Africa indicator variable.²⁵ The estimates provide strong support for the slave trade adversely affecting domestic institutions today. The coefficient for slave exports is negative and statistically significant.

Combining the estimated coefficients $\hat{\lambda} = -1.326$ from column (6) of table 5, $\hat{\beta} = 0.813$ from column (2) of table 6, and $\hat{\gamma} = -0.065$ from column (4) of table 6 yields $\hat{\lambda} \times \hat{\beta} \times \hat{\gamma} = 0.070$. Like the reduced-form estimate from column (6) of table 1, the indirect effect of ruggedness is found to be positive. However, the magnitude from the structural estimates is just under one fourth of the magnitude implied by the reduced-form estimate. This occurs because our structural estimates implicitly assume that the only effect of slave exports on income is through the rule of law. Any effect of the slave trade on per capita income that does not occur through our measured rule of law will not be captured when we estimate β and γ individually. This is not true however, for our estimate of the relationship between slave exports and income, $\widehat{\beta\gamma} = -0.206$. The relationship between slave exports and income implied by the individual estimates of β and γ is $\hat{\beta} \times \hat{\gamma} = 0.813 \times -0.065 = -0.053$. The difference between the two estimated magnitudes is consistent with the slave trade affecting income through channels other than the rule of law. Exploring such channels is the subject of ongoing research. For instance, the recent results of Nunn and Wantchekon (2008), which show that the slave trades had a negative effect on levels of trust 100 year after the end of the trade, provide evidence that the slave trades likely affect current income levels through a variety of additional channels other than the rule of law.²⁶

²⁵Because our regression includes an Africa indicator variable, a full set of legal origin indicator variables, and interactions between them, non-African British common law countries constitute the omitted baseline category. Therefore, the differential effect (relative to this baseline) of the other legal origins for non-African countries is given by the coefficients of the legal origin indicator variables, while the differential effect of the other legal origins for African countries is given by the interaction of the legal origin indicators with the Africa indicator variable. Because African countries are only of either British or French legal origin, and none are of Socialist, German, or Scandinavian legal origin, indicators variables for these later three groups interacted with the Africa indicator variable are dropped from the regression.

²⁶An additional channel through which the slave trades can negatively affect income today is ethnic conflict. Slaves were almost exclusively captured by other Africans (Koelle, 1854, Nunn and Wantchekon, 2008). This triggered conflicts between neighbouring ethnicities, which may still persist today (e.g., Azevedo, 1982, Inikori, 2000, Hubbell, 2001). Identifying this channel empirically is difficult, because it is possible that the seeds of ethnic conflict were planted before the slave trades and we do not have data on ethnic conflict prior to the slave trades. However, we note that our results are robust to controlling for years of violent civil conflict 1975–1999, using data from Fearon and Laitin (2003).

6. Conclusions

The study provides evidence showing that geography can have important effects on income through its interaction with historical events. By focusing on a dimension of geography, terrain ruggedness, which varies throughout the world and on a historical event, the slaves trades over the period 1400-1900, which is geographically confined to Africa, we are able to estimate the indirect historic effect of ruggedness on income. For the world as a whole, we find a negative relationship between ruggedness on income. We also find that rugged terrain had an additional effect in Africa during the 15th to 19th centuries: it afforded protection to those being raided during Africa's slave trades. By allowing areas to escape from the detrimental effects that the slave trades had on subsequent economic development, ruggedness also creates long-run benefits in Africa through an indirect historic channel. We show that this differential effect of ruggedness is found in Africa only, it cannot be explained by Africa's unique geographic environment, and it is fully accounted for by Africa's the slave trades. On the whole, the results provides one example of the importance of geography through historic channels.

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Data appendix

Data availability

All the data necessary to reproduce the results of this paper are available from <http://diegopuga.org/data/rugged/>.

Country boundaries

We assign geographic features to countries using digital boundary data based on the fifth edition of the *Digital Chart of the World* (us National Imagery and Mapping Agency, 2000), which we have updated to reflect 2000 country boundaries using information from the International Organization for Standardization ISO 3166 Maintenance Agency and other sources. We exclude areas covered by inland water area features contained in the same edition of the *Digital Chart of the World*. When calculating the percentage of each country's land surface area with certain characteristics or the average value of a variable for a country, we perform all calculations on a 30 arc-second geographic grid, correcting for the fact that the actual land area covered by a 30 arc-second cell varies with latitude.

Land area

The land area data are from the Food and Agriculture Organization (2008), except for Macau and Hong Kong where it is taken from the Encyclopædia Britannica.

Income per person

We measure average country-level income by the natural logarithm of real gross domestic product per person in 2000. The data are from the World Bank *World Development Indicators* (World Bank, 2006). Units are 2006 international dollars, with purchasing power parity conversions performed using the Elteto-Koves-Szulc method.

To check the robustness of our results to the use of income data from other time periods and from an alternative source, in the text we refer to results using the natural logarithm of real gross domestic product per person in 1950 and in 2000, and its annual average from 1950–2000, with data from Angus Maddison (Maddison, 2007, updated October 2008). Units are 1990 international dollars, with purchasing power parity conversions performed using the Geary-Khamis method.

Gem-quality diamond extraction

Data on carats of gem-quality diamond extracted by each country between 1958–2000 are obtained from the 1959–2004 editions of the *Mineral Yearbook*, published first by the us Bureau of Mines (us Bureau of Mines, 1960–1996) and then by the us Geological Survey (us Geological Survey,

1997–2007). We use the most recent data for each country-year in Volume I (Metals and Minerals), completed with data from Volume III (Area Reports: International) of the 1997–2000 editions. For countries that have split or changed boundaries, we assign diamond extraction on the basis of mine location with respect to current boundaries. The variable is then normalized by land area to obtain carats of gem-quality diamond per square kilometre.

Percentage of each country with fertile soil

On the basis of the FAO/UNESCO Digital Soil Map of the World and linked soil association composition table and climatic data compiled by the Climate Research Unit of the University of East Anglia, Fischer, van Velthuisen, Shah, and Nachtergaele (2002) identify whether each cell on a 5-minute grid covering almost the entire land area of the Earth is subject to various constraints for growing rain-fed crops. Based on plates 20 (soil moisture storage capacity constraints), 21 (soil depth constraints), 22 (soil fertility constraints), 23 (soil drainage constraints), 24 (soil texture constraints), and 25 (soil chemical constraints) in Fischer *et al.* (2002) and the country boundaries described above, we calculate the percentage of the land surface area of each country that has fertile soil (defined as soil that is not subject to severe constraints for growing rain-fed crops in terms of either soil fertility, depth, chemical and drainage properties, or moisture storage capacity). Cape Verde, French Polynesia, Mauritius and Seychelles are not covered by the Fischer *et al.* (2002) data, so for these countries we use instead the percentage of their land surface area that is classified by the Food and Agriculture Organization (2008) as arable land or permanent crop land.

Percentage of each country with tropical climate

Using detailed temperature and precipitation data from the Climatic Research Unit of the University of East Anglia and the Global Precipitation Climatology Centre of the German Weather Service, Kottke, Grieser, Beck, Rudolf, and Rubel (2006) classify each cell on a 30 arc-minute grid covering the entire land area of the Earth into one of 31 climates in the widely-used Köppen-Geiger climate classification. Based on these data and the country boundaries described above, we calculate the percentage of the land surface area of each country that has any of the four Köppen-Geiger tropical climates.

Average distance to the nearest ice-free coast

To calculate the average distance to the closest ice-free coast in each country, we first compute the distance to the nearest ice-free coast for every point in the country in equi-rectangular projection with standard parallels at 30 degrees, on the basis of sea and sea ice area features contained in the fifth edition of the *Digital Chart of the World* (us National Imagery and Mapping Agency, 2000) and the country boundaries described above. We then average this distance across all land in each country not covered by inland water features. Units are thousands of kilometres.

European colonial origin indicators

European colonial origin indicators are based on Teorell and Hadenius (2007). They distinguish between British, French, Portuguese, Spanish, and other European (Dutch, Belgian and Italian) colonial origin for countries colonized since 1700. For countries under several colonial powers, the last one is counted provided that it lasted for 10 years or longer. Since Teorell and Hadenius (2007) exclude the British settler colonies (the United States, Canada, Australia, Israel and New Zealand), we code these as having a British colonial origin. We complete their data using the same rule to determine the European colonial origin of French Polynesia (French), Hong Kong (British), Macau (Portuguese), New Caledonia (French), Nauru (British), Philippines (Spanish), Puerto Rico (Spanish), and Papua New Guinea (British).

Legal origin indicators

Legal origin indicators (common law, French civil law, German civil law, Scandinavian law, and Socialist law) are from La Porta, Lopez-de-Silanes, Shleifer, and Vishny (1999). Some of our regressions include French Polynesia, absent from their data, which we have coded as French civil law.

African region indicators

Region indicators for Sub-Saharan Africa (East Africa, Central Africa, West Africa, and South Africa) are from Bratton and van de Walle (1997). We assign African countries North of the Saharan desert, which were not classified by Bratton and van de Walle (1997), to the region of North Africa.

Slave exports

Estimates of the number of slaves exported between 1400 and 1900 in Africa's four slave trades are from Nunn (2008). The data are constructed by combining shipping data with data from various historic documents reporting the ethnicities of slaves shipped from Africa. Combining the two sources, Nunn is able to construct an estimate of the number of slaves shipped from each country in Africa between 1400 and 1900 during Africa's four slave trades. We normalize the export figures by a country's land surface area, computed as explained above. Because some country's have zero slave exports, we take the natural logarithm of one plus the number of slaves exported per thousand square kilometres. See Nunn (2008) for more information on the nature of the data, including why it is appropriate to use the natural logarithm of slave exports.

Quality of governance

To measure the quality of governance in each country, we use the composite variable "rule of law" from version VII of the World Bank's *Worldwide Governance Indicators* database (Kaufmann *et al.*, 2008). It consists of "perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence" (Kaufmann *et al.*, 2008, p. 7).

Distance to export markets

Four variables measuring the distance from each country to the closest final destination slave market in each of Africa's four slave trades are taken from Nunn (2008). For the trans-Atlantic and Indian Ocean slave trades, the measure is the sailing distance from the point on the coast that is closest to the country's centroid to the closest final export destination for slave trade. For the trans-Saharan and Red Sea slave trades, the measure is the great-circle overland distance from the country's centroid to the closest final export destination for that slave trade. Units are thousands of kilometres.

Population density in 1400

The data are constructed using historic population estimates from McEvedy and Jones (1978). For countries grouped with others in McEvedy and Jones (1978), we allocate population to countries in the group according to the distribution of population in 1950, obtained from United Nations (2007). We normalize total population in 1400 by the land area of each country, calculated as described above. Because the variable is extremely skewed to the left and because the territory covered by some countries today had zero population density in 1400, we take the natural logarithm of one plus population density (measured in people per square kilometre).