Ruggedness:
The blessing of bad geography in Africa

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Abstract: There is controversy about whether geography matters mainly because of its contemporaneous impact on economic outcomes or because of its interaction with historical events. Looking at terrain ruggedness, we are able to estimate the importance of these two channels. Because rugged terrain hinders trade and most productive activities, it has a negative direct effect on income. However, in Africa rugged terrain afforded protection to those being raided during the slave trades. Since the slave trades retarded subsequent economic development, in Africa ruggedness also has had a historical indirect positive effect on income. Studying all countries worldwide, we find that both effects are significant statistically and that for Africa the indirect positive effect dominates the direct negative effect. Looking within Africa, we provide evidence that the indirect effect operates through the slave trades. We also show that the slave trades, by encouraging population concentrations in rugged areas, have also amplified the negative direct impact of rugged terrain in Africa.

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

While it is commonly agreed that geography can have important consequences for economic outcomes, there is a growing debate over the channel of causality. Some authors stress a direct contemporaneous channel whereby geography directly affects economic outcomes today. For instance, Gallup and Sachs (2001) and Sachs and Malaney (2002) claim that a disease-prone environment has substantial negative consequences for current income levels because it reduces productivity, lowers the incentives to invest in human capital, draws scarce resources towards medical care, and discourages foreign investment and tourism.[1] Alternatively, other authors stress an indirect channel whereby geography indirectly affects economic outcomes today through its past interactions with key historical events. For instance, Acemoglu, Johnson, and Robinson (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 were high mortality discouraged Europeans from settling, colonizers implemented poor institutions which adversely affected subsequent economic development.[2] Generally, it is difficult to separate the two channels. First, because the physical environment is extremely persistent.[3] Second, because the geographical features on which the literature has focused are mostly specific to the areas that were subject to the historical events of interest. For instance, areas having a disease prone-environment today also had it in the past and tropical diseases do not have the potential to affect many areas not subject to colonization.[4]

In this paper we investigate one geographic characteristic, terrain ruggedness, for which we are able to estimate both the direct contemporaneous channel and the indirect historic channel. Rugged terrain has obvious negative direct impacts on current economic outcomes. 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,

[1] Other geographical characteristics that have been linked to economic outcomes through a direct contemporaneous channel include proximity to the coast, and the prevalence of desert or tropical climate (Kamarck, 1976, Mellinger, Sachs, and Gallup, 2000, Sachs, 2001, Rappaport and Sachs, 2003).

[2] Other papers that argue for connections between the physical environment and economic outcomes through historical interactions include Engerman and Sokoloff (1997, 2002), Sokoloff and Engerman (2000), Diamond (1997), and Acemoglu, Johnson, and Robinson (2002).

[3] An interesting exception is rainfall, which Miguel, Satyanath, and Sergenti (2004) use as an instrumental variable to investigate the effect of economic growth on the likelihood of civil conflict. Rainfall data has also been used to investigate the impact of income on witch killing in Tanzania (Miguel, 2005), of income on property crimes in 19th century Germany (Mehlum, Miguel, and Torvik, 2006*a*), and income on overseas remittances in the Philippines (Yang, 2006). Other studies focus on the direct link of rainfall on subsequence economic, social, and health outcomes (e.g., Maccini and Yang, 2006, Levine and Yang, 2006).

[4] Because of these difficulties, few studies attempt to quantify or directly test for the relative importance of the two channels. One notable exception is Easterly and Levine (2003), who employ tests of over-identifying restrictions in an instrumental variables framework. They conclude that measures of tropics, germs, and crops do not explain economic development beyond their ability to explain institutional development.

and Bhandari, 2002). As well, transportation over irregular terrain is slower and more costly.[5]

In Africa, in additional to this negative direct effect, ruggedness may also have had a positive indirect effect on economic outcomes, by allowing areas to escape from the slave trades and their negative consequences. For a period of nearly 500 years, from 1400 to 1900, Africa simultaneously experienced four slave trades (the trans-Atlantic, the trans-Saharan, the Red Sea, and the Indian Ocean slave trades). Over 18 million slaves were exported from Africa over this period, and even more died during raids and transport (total African population was roughly stable over this period at 50–70 million). There is ample historical evidence documenting the adverse long-term effects of Africa's slave trades.[6] Nunn (2006) examines the connection empirically. Combining historical shipping records and slave inventories reporting slave ethnicities, he constructs an estimate of the number of slaves taken from each country in Africa. He finds a robust negative relationship between the number of slaves taken and current income levels. The study also shows that, consistent with the historical evidence, the adverse effects of the slave trades arise because they weakened indigenous political structures and institutions, and promoted ethnic and political fragmentation.

Given the negative consequences of the slave trades, any feature that helped areas avoid the slave trades may have had beneficial long-term effects. One such key feature is terrain ruggedness. 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 during Africa's slave trades, caves for hiding, as well as 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] were able to use the military crests and, as far as the techniques of war at the time were concerned, were impregnable."[7] Because terrain ruggedness helped areas avoid the slave trades, and the slave trades retarded subsequent economic development, then one would expect a tendency for more rugged areas in Africa to have higher incomes today. This indirect benefit of ruggedness is opposite to the increased costs to cultivation, building, and trade imposed by ruggedness today.

After describing how we measure ruggedness in section 2 and introducing the econometric framework in section 3, in section 4 we investigate the relationship between ruggedness and income. Because Africa experiences both the direct and indirect effects of ruggedness, while the rest of the world experiences only the direct effect of ruggedness, we are able to identify the magnitude of both the direct and indirect effects of ruggedness on income. We find that both effects exist and are significant statistically. We also find that in all specifications the positive indirect effect for

[5]A 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.

[6]See for example Hawthorne (1999), Inikori (2000), Lovejoy (2000), and Klein (2003).

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

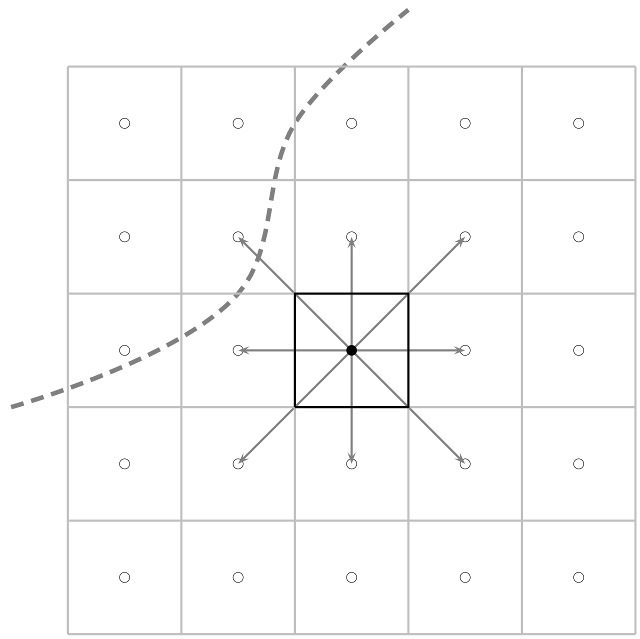

Figure 1. Schematic of the average uphill slope calculation used to measure ruggedness

Africa dominates the negative direct effect. The results are very robust. Then looking then within Africa, in section 5 we provide evidence that the indirect positive effect of ruggedness operates through the slave trades. Finally, in section 6 we explore the idea that, by encouraging population concentrations in rugged areas, the slave trades have also amplified the negative direct impact of rugged terrain in Africa.

2. Measuring terrain ruggedness

To facilitate the interpretation of our results, we now explain how we define and measure terrain ruggedness. Data sources for all other variables employed in the analysis are detailed in the appendix.

We measure terrain ruggedness for each country as the average uphill slope of the country's surface area. The purpose is to have a measure that captures the small-scale terrain irregularities, caverns, caves and cliff walls that afforded protection to those being raided during the slave trades. This is in contrast with the topography measures previously used by economists and political scientists, which are generally constructed to capture the presence of large-scale terrain irregularities, and mountains in particular.[8]

Our starting point is GTOPO30 (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 GTOPO30 are regularly spaced at 30-arc seconds (approximately 1 kilometre) across the entire surface of the Earth. Figure 1 represents a few 30 by 30 arc-second cells, with each cell centred on a point on this 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 absolute value of the difference in elevation between this point and the point on the Earth's surface 30 arc-seconds North of it (the hollow circle directly above it in the figure), and then divides this by the sea-level distance between the two points to obtain the uphill slope. The same calculation is performed for each of the eight major directions of the compass (North, Northeast, East, Southeast, South, Southwest, West, and Northwest), and the eight slopes obtained are then averaged to calculate the mean uphill slope for the 30 by 30 arc-second cell centred on the point. Finally, we average across all grid cells in the country not covered by water (taking into account the latitude-varying sea-level surface that corresponds to the 30 by 30 arc-second cell centred on each point) to obtain the average uphill slope of the country's land area.

Considering the distribution of population across areas with different ruggedness

Measuring ruggedness as the mean uphill slope for each country treats all land in the country uniformly. Thus, it does not take into account that ruggedness will have a stronger negative contemporaneous impact on income in areas more densely populated today. In section 6 we use an alternative, population-weighted, measure of ruggedness and obtain identical qualitative results. We start from the same mean uphill slope for each 30 by 30 arc-second cell but, in averaging this for each country, we weight ruggedness in each 30 by 30 arc-second cell by the share of the country's population located in that 30 by 30 arc-second cell in 2000 according to the *LandScan* data set (Oak Ridge National Laboratory, 2001) (see the appendix for further details on the population data). We nevertheless use the land-weighted measure of ruggedness for our baseline estimates because it is fully exogenous. In addition, our estimation strategy requires using a common measure to estimate

[8] 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. The terrain ruggedness index used by Burchfield *et al.* (2006) to measure small-scale terrain irregularities was developed by Riley, DeGloria, and Elliot (1999) to characterize wildlife habitats. It is closely related to average uphill slope, but averages using the root mean square instead of the arithmetic mean, does not account for the fact that the diagonal distance between points on a regular geographic grid is greater than the horizontal and vertical distances, and that with geographic projections even the horizontal and vertical distances differ. Nevertheless, the correlation between our average uphill slope measure and the terrain ruggedness index of Riley *et al.* (1999) at the country level is above 0.99. Not surprisingly, using the Riley *et al.* (1999) index instead of average uphill slope for our analysis yields essentially identical results. Olken (1996) 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.

the direct contemporaneous and indirect historical effects of ruggedness, and it is not clear that introducing the current distribution of population is appropriate for the historical channel.

3. Econometric framework

We now develop our estimation strategy for investigating the relationship between ruggedness and income. As discussed, our starting point is that ruggedness has a direct negative effect on current income because it increases the costs of cultivation, building, and trade. This relationship can be written

$$y_i = \kappa_1 - \alpha r_i + \beta q_i + e_i \ , \tag{1}$$

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 an idiosyncratic error. We assume that e_i and all other error terms are independent and identically distributed and drawn from a normal distribution.

Historical studies and the empirical work of Nunn (2006) 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

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

where x_i is slave exports, κ_2 and γ are constants ($\gamma > 0$), and u_i is an idiosyncratic error.

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

$$x_i = \kappa_3 - \lambda r_i + v_i \ , \tag{3}$$

where κ_2 and λ are constants ($\lambda > 0$), and v_i is an idiosyncratic error.

Substituting (3) and (2) into (1) gives

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

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 non-African countries, the relationship between ruggedness and income only includes a negative direct effect $-\alpha$, but for African countries, in addition to the negative direct effect $-\alpha$, there is also a positive indirect effect $\beta\gamma\lambda$.

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

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

which is just more compact version of (4), using an indicator variable I_i^{Africa} that equals 1 if i is in Africa and 0 otherwise. In addition, we estimate a restricted version of the same equation that forces the ruggedness-income relationship to be the same for all countries.

$$y_i = \beta_4 + \beta_5 r_i + \varepsilon_i \; . \tag{6}$$

Our predictions about the relationships between ruggedness, the slave trades, and income yield the following hypotheses for the estimates of (5) and (6):

Hypothesis 1. $\beta_1 < 0$ (ruggedness has a direct negative effect on income).

Hypothesis 2. $\beta_2 > 0$ (in Africa ruggedness has an additional positive effect).

Hypothesis 3. $\beta_1 < \beta_5$ (not accounting for hypothesis 2 biases the direct effect towards zero).

The first hypothesis, captured by the sign of β_1, is that ruggedness has a direct negative effect on income. The second hypothesis, which is core to our paper, is that in Africa only, ruggedness has an additional positive effect on income. The third hypothesis compares the estimated direct effects of ruggedness in the unrestricted and restricted equations. We expect that, since β_5 absorbs both the direct and indirect effects of ruggedness, it will be an upwards biased estimate of $-\alpha$, whereas β_1 will be a consistent estimate of $-\alpha$. From this it follows that β_5 is greater than β_1. The following section tests whether the data supports these three hypotheses.

Equation (5) illustrates the relationship between income and ruggedness, leaving slave exports in the background. To bring slave exports to the foreground and check to what extent they can account for the differential effect of ruggedness in Africa, in section 5 we derive a different reduced-form equation. Consider again our three equations (1) to (3) that give the relationships between ruggedness, slave exports, and income. Previously, we substituted both (3) and (2) into (1) to obtain a reduced-form relationship between income and ruggedness only, given by (4). If we instead only substitute (2) into (1), we obtain a reduced-form relationship between income and both ruggedness and slave exports:

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

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

$$y_i = \beta_6 + \beta_7 r_i + \beta_8 r_i I_i^{\text{Africa}} + \beta_9 I_i^{\text{Africa}} + \beta_{10} x_i + \varepsilon_i \tag{7}$$

Estimating this reduced form allows us to test three additional hypotheses that are about ruggedness and slave exports:

Hypothesis 4. $\beta_{10} < 0$ (slave exports negatively affect income).

Hypothesis 5. $\beta_8 = 0$ (once slave exports are taken into account, the effect of ruggedness is no different in Africa).

Hypothesis 6. $\beta_7 < 0$ (once slave exports are taken into account, the effect of ruggedness is negative).

Hypothesis 4 is that slave exports are negatively related to current income. Hypothesis 5 provides a way of testing whether the slave trades can fully account for the positive indirect effect of ruggedness in 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. The last hypothesis is that once the indirect effect of ruggedness is taken into account by controlling for the slave trades, the direct effect of ruggedness can be correctly identified and should be negative.

4. The direct and indirect effects of ruggedness

As a first step in our empirical analysis, we now estimate the direct and indirect effects of ruggedness on income per person. Our baseline estimates of equations (5) and (6) 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 empirical confirmation for our hypotheses 1 and 2: ruggedness has a direct negative effect on income per person, but within Africa, there is an additional positive effect. The coefficient for ruggedness is negative and statistically significant (i.e., $\beta_1 < 0$ in equation (5)), while the coefficient for ruggedness interacted with an indicator variable for Africa is positive and statistically significant (i.e., $\beta_2 > 0$ in equation (5)). According to the estimated coefficients, within Africa the indirect positive effect swamps the direct negative effect. Adding up the negative direct effect (-0.078) and the positive indirect effect (0.156) yields a total effect of ruggedness on income in African countries of 0.078. Hence, overall, ruggedness has been a blessing for African countries.

In terms of magnitude, within Africa, a one standard deviation increase in ruggedness increases log real GDP per person by .26 standard deviations. This is the combination of a reduction of income per person by .26 standard deviations due to the negative direct effect and an increase by .51 standard deviations due to the positive indirect effect for Africa. Put differently, for a country at the mean African level of real income per person ($1,784), a one standard deviation increase in ruggedness relative to the African mean (an increase in average uphill slope from 2.69% to 5.74%) is estimated to raise income to $2,264, which is an increase of $481. This magnitude is quite substantial, especially given that we are considering one very specific geographic characteristic.

Next, in column (2), we repeat the estimation restricting the effect of ruggedness on income to be the same for African and non-African countries. Consistent with hypothesis 3 that the negative direct effect of ruggedness is biased upwards towards zero when the positive effect of ruggedness in Africa is not taken into account, the estimated coefficient of ruggedness in column (2) is greater than the coefficient in column (1) (i.e., β_5 in equation (6) is greater than β_1 in equation (5)).

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 they may be driven, at least in part, by other geographical features correlated with ruggedness. Our primary interest is in the differential effect of ruggedness for Africa. In order for an omitted variable to bias this estimate, it must be the case that, either the relationship between income and the omitted factor is different within Africa

Table 1. The direct and indirect effects of ruggedness

	Dependent variable: Log real GDP per person 2000						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Ruggedness	-0.078 (0.036)**	0.003 (0.031)	-0.075 (0.037)**	-0.094 (0.036)***	-0.073 (0.029)**	-0.081 (0.031)***	-0.093 (0.031)***
Ruggedness $\cdot I^{\text{Africa}}$	0.156 (0.059)***		0.164 (0.059)***	0.164 (0.064)**	0.117 (0.053)**	0.163 (0.055)***	0.145 (0.060)**
I^{Africa}	-1.942 (0.220)***		-2.006 (0.221)***	-2.060 (0.325)***	-1.599 (0.300)***	-2.002 (0.247)***	-2.051 (0.387)***
Diamonds produced			0.055 (0.015)***				0.071 (0.022)***
Diamonds $\cdot I^{\text{Africa}}$			-0.043 (0.015)***				-0.057 (0.022)***
% Tropical climate				-0.007 (0.002)***			-0.010 (0.002)***
% Tropical climate $\cdot I^{\text{Africa}}$				0.004 (0.004)			0.008 (0.004)**
Distance to coast					-0.651 (0.190)***		-0.966 (0.184)***
Distance to coast $\cdot I^{\text{Africa}}$					-0.302 (0.428)		-0.243 (0.347)
% Desert						-0.005 (0.009)	-0.007 (0.007)
% Desert $\cdot I^{\text{Africa}}$						0.010 (0.014)	0.018 (0.012)
Constant	9.219 (0.143)***	8.506 (0.136)***	9.196 (0.147)***	9.511 (0.164)***	9.378 (0.141)***	9.241 (0.144)***	9.888 (0.153)***
Observations	170	170	170	170	170	170	170
R^2	0.356	0.000	0.375	0.404	0.419	0.358	0.540

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

and outside of Africa, or the relationship between the omitted factor and ruggedness is different within and outside of Africa.

A possible curse of mineral resources (Sachs and Warner, 2001, Mehlum, Moene, and Torvik, 2006*b*) could potentially affect our results for precisely this reason. 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.[9] To deal with potentially omitted differential effects such as this, we must add to our baseline specification of column (1) both the control variable (diamond production 1994–2000 normalized by land area in this case) and an interaction of the control variable with our Africa indicator variable to allow the effect of the control variable to differ for Africa. Column (3) shows that the effect of diamonds is positive and statistically significant in

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

general, but that for African countries there is a differential negative and statistically significant effect that nearly wipes out the general positive effect. Nevertheless, 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.[10]

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 this possibility, in column (4) we add to our baseline specification of column (1) 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 their 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.[11]

Given the arguments of Mellinger *et al.* (2000) and others that coastal access and soil quality are fundamental determinants of world income differences, in columns (5) and (6) we control respectively for the average distance to the nearest ice-free coast for each country (in thousands of kilometres) and for the percentage of each country's land that is desert. As before, we also include an interaction of each of these variables with the African indicator variable. Our results remain robust. Finally, in column (7) we include all these 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.

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, particularly, Lesotho and the Seychelles in Africa, and Switzerland, Nepal, Tajikistan, and Kyrgyzstan outside of Africa. Our first sensitivity check estimates our baseline specification after dropping these six observations, without and with our full set of control variables. Results are presented in columns (1) and (2) of table 2.[12]

[10]We have also tried including measures of other mineral resources, oil reserves and gold in particular, again together with an African interaction term but found no significant effects.

[11]If instead of looking at tropical diseases in general, we focus on malaria in particular by including an index of the stability of malaria transmission from Kiszewski, Mellinger, Spielman, Malaney, Sachs, and Sachs (2004) and the corresponding African interaction, our core results are also unchanged. The same is true if we include distance to the equator and the corresponding African interaction.

[12]In the scatter plot, one can also observe several small countries that have either unusually high or unusually low ruggedness. These observations are not particularly influential for our results, which remain qualitatively unchanged if we drop the 20 countries in our regressions with an area below 5,000 square kilometres (which is slightly above the area of Seychelles) or if we estimate a weighted least square regression using countries' areas as weights. A 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.

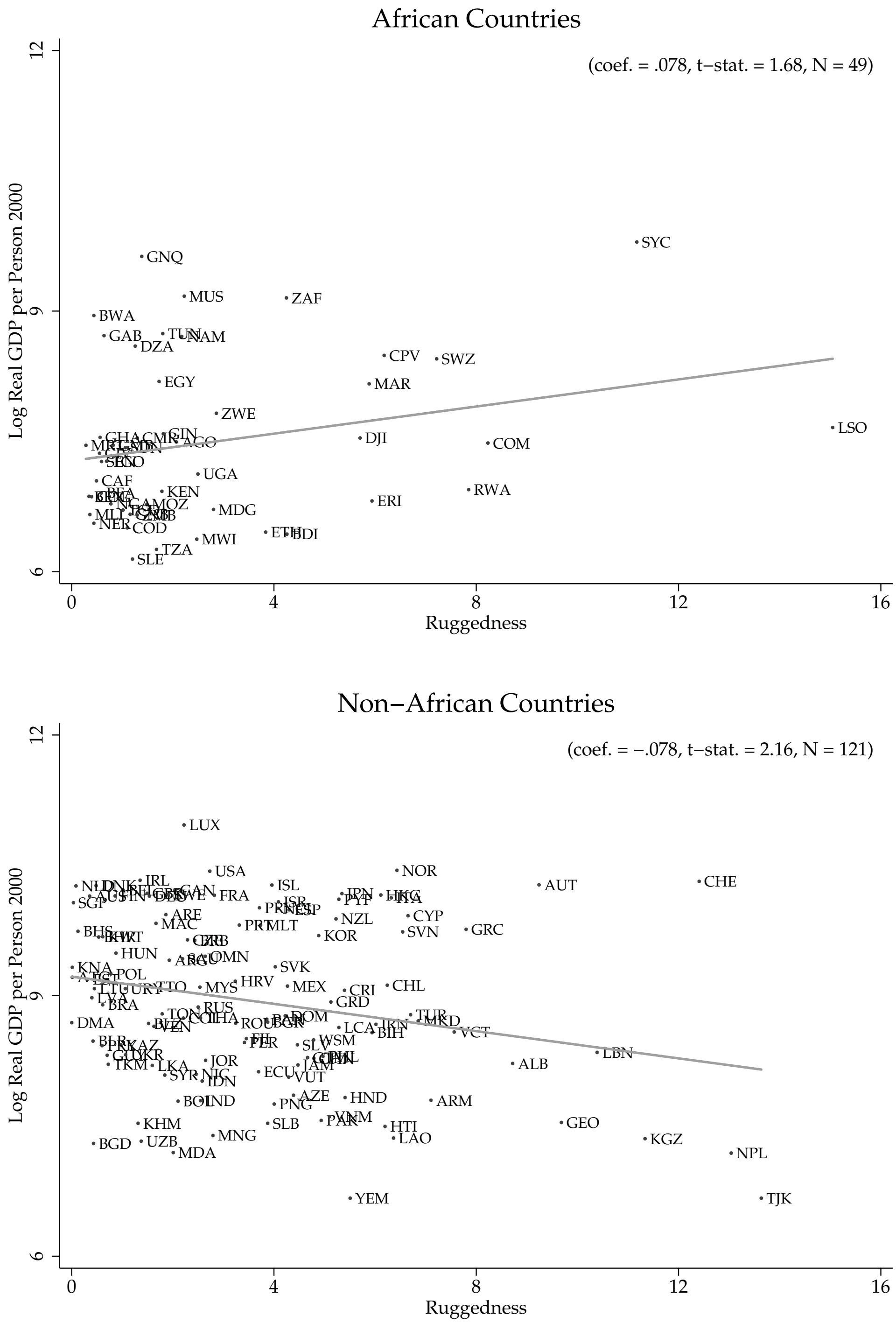

Figure 2. Income and ruggedness among African and non-African countries

Table 2. Robustness with respect to influential observations

	Dependent variable: Log real GDP per person 2000							
	Omit if Ruggedness > 11		Omit if $\lvert \text{DFBETA} \rvert > 2/\sqrt{N}$		Using ln(Ruggedness)		Box-Cox Trans. of Ruggedness	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Ruggedness	-0.057 (0.037)	-0.103 (0.035)***	-0.085 (0.033)**	-0.115 (0.027)***	-0.132 (0.059)**	-0.164 (0.050)***	-0.151 (0.064)**	-0.183 (0.055)***
Ruggedness $\cdot I^{\text{Africa}}$	0.113 (0.062)*	0.105 (0.050)**	0.183 (0.061)***	0.154 (0.052)***	0.359 (0.136)***	0.361 (0.152)**	0.332 (0.116)***	0.323 (0.127)**
I^{Africa}	-1.851 (0.222)***	-1.797 (0.315)***	-2.028 (0.212)***	-2.039 (0.303)***	-1.661 (0.158)***	-1.872 (0.318)***	-1.767 (0.171)***	-1.959 (0.344)***
Diamonds produced		0.069 (0.021)***		0.067 (0.021)***		0.074 (0.026)***		0.068 (0.025)***
Diamonds $\cdot I^{\text{Africa}}$		-0.058 (0.021)***		-0.054 (0.021)***		-0.060 (0.026)**		-0.054 (0.025)**
% Tropical climate		-0.010 (0.002)***		-0.009 (0.002)***		-0.010 (0.002)***		-0.010 (0.002)***
% Tropical climate $\cdot I^{\text{Africa}}$		0.005 (0.003)		0.007 (0.004)*		0.009 (0.004)**		0.008 (0.004)**
Distance to coast		-0.957 (0.225)***		-0.933 (0.182)***		-0.984 (0.202)***		-0.990 (0.192)***
Distance to coast $\cdot I^{\text{Africa}}$		-0.216 (0.372)		-0.363 (0.378)		-0.195 (0.346)		-0.194 (0.345)
% Desert		-0.007 (0.007)		-0.007 (0.007)		-0.004 (0.006)		-0.005 (0.007)
% Desert $\cdot I^{\text{Africa}}$		0.012 (0.010)		0.030 (0.018)*		0.019 (0.012)		0.019 (0.012)
Constant	9.158 (0.142)***	9.908 (0.170)***	9.228 (0.137)***	9.922 (0.149)***	9.038 (0.090)***	9.672 (0.124)***	9.121 (0.103)***	9.775 (0.130)***
Observations	164	164	162	163	170	170	170	170
R^2	0.376	0.552	0.389	0.564	0.346	0.531	0.353	0.538

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

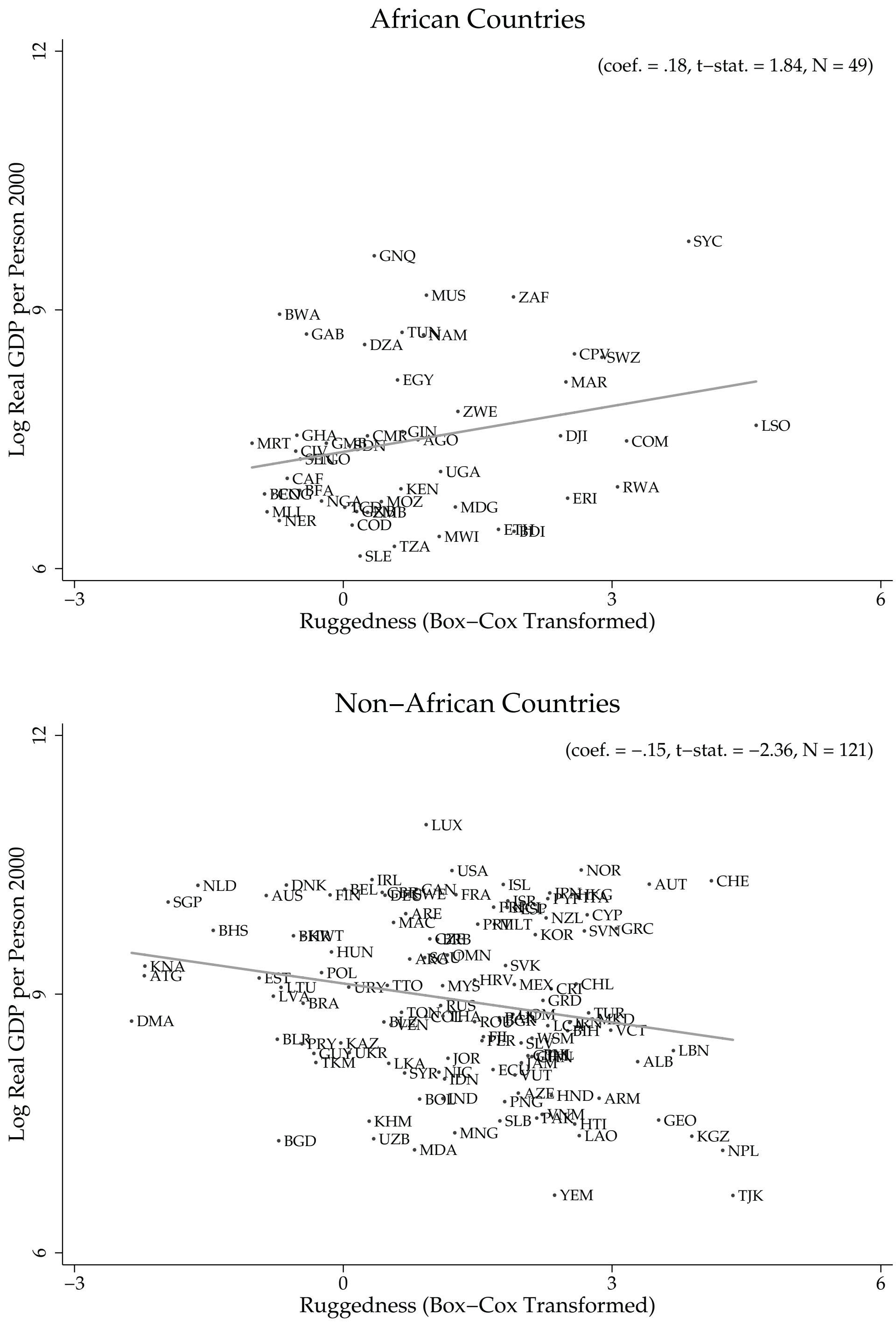

Figure 3. Income and ruggedness (Box-Cox transformed) among African and non-African countries

We next adopt a more systematic approach to deal with influential observations, and remove influential observations using each observation's DFBETA, 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. Following Belsley, Kuh, and Welsch (1980), we omit all observations for which $|\text{DFBETA}_i| > 2/\sqrt{N}$, where N is the number of observations, in our case 170.[13] Results are presented in columns (3) and (4) of table 2.

In all four of the regressions with omitted observations, the ruggedness coefficient remains negative and, except in column (1), statistically significant. The ruggedness interaction remains positive and statistically significant, confirming that there exists a differential effect of ruggedness for 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 columns (5) and (6), 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 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 columns (7) and (8). The estimates confirm the impression given by the figures. There is a positive and significant differential effect of ruggedness within Africa.

Is the effect of ruggedness also different for other areas?

An obvious objection to the above results is that we have only allowed the effect of ruggedness on economic outcomes to differ for African countries. To check whether other continents of the world also experience a differential impact of ruggedness, we add to our baseline specification indicator variables for other continents as well as interactions between ruggedness and these indicator variables. Estimates are reported in table 3. The first column reports our baseline estimates for comparison. Column (2) includes indicator variables for Europe, North America, South America, and Oceania (the omitted continent is Asia), and allows the effect of ruggedness to differ for each continent. Overall, there is no evidence of differential effects for continents other than Africa. The one exception is Europe, which is estimated to have a positive differential ruggedness effect. However, this is driven by just one country, Switzerland. When we omit Switzerland in column

Table 3. Considering differential effects for other areas

	Dependent variable: Log real GDP per person 2000			
	Baseline	Additional continents	Omit Switzerland	Geographic interactions
	(1)	(2)	(3)	(4)
Ruggedness	-0.078 (0.036)**	-0.097 (0.040)**	-0.097 (0.040)**	-0.110 (0.040)***
Ruggedness $\cdot I^{\text{Africa}}$	0.156 (0.059)***	0.175 (0.062)***	0.175 (0.062)***	0.132 (0.052)**
I^{Africa}	-1.942 (0.220)***	-1.632 (0.295)***	-1.632 (0.295)***	-1.742 (0.219)***
Ruggedness $\cdot I^{\text{Europe}}$		0.111 (0.062)*	0.083 (0.073)	
I^{Europe}		0.604 (0.319)*	0.670 (0.331)**	
Ruggedness $\cdot I^{\text{North America}}$		-0.065 (0.067)	-0.065 (0.067)	
$I^{\text{North America}}$		0.559 (0.336)*	0.559 (0.336)*	
Ruggedness $\cdot I^{\text{South America}}$		0.122 (0.081)	0.122 (0.081)	
$I^{\text{South America}}$		-0.330 (0.312)	-0.330 (0.312)	
Ruggedness $\cdot I^{\text{Oceania}}$		0.042 (0.196)	0.042 (0.196)	
I^{Oceania}		0.351 (0.762)	0.351 (0.762)	
Ruggedness · % Tropical cl.				0.001 (0.001)
% Tropical climate				-0.008 (0.003)***
Ruggedness · % Desert				0.000 (0.007)
% Desert				-0.011 (0.009)
Constant	9.219 (0.143)***	8.909 (0.240)***	8.909 (0.240)***	9.590 (0.172)***
Observations	170	170	169	170
R^2	0.356	0.464	0.459	0.411

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

(3), even the differential effect for Europe disappears.

A final possible source of concern is that perhaps 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 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 34.3% of land in Africa compared with 19.2% 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 desert, rugged areas are less arid. If deserts are particularly prevalent in Africa (they cover 12.9% of land in Africa compared with 3.4% 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 desert. We consider these possibilities in column (4) of table 3. There, we add to our baseline estimation variables measuring the percentage of each country with tropical climates and the percentage of each country covered by desert (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). The coefficients of interest measuring the direct effect of ruggedness and the differential effect for Africa change little and remain statistically significant.[14]

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

Having established a robust differential impact of ruggedness within Africa, we now examine whether Africa's slave trades can account for this differential effect. We do this in two steps. First, we show that there were fewer slaves exported from more rugged areas, even after we control for initial population density and other potential geographic determinants of slave exports. This involves estimating equation (3) from section 3. Second, we estimate equation (7) from section 3 to show that slave exports can fully account for the differential effect of ruggedness in Africa.

We use data from Nunn (2006) on the number of slaves exported from each country in Africa between 1400 and 1900 during Africa's four slave trades. We normalize total slave exports by the land area of each country. Because the variable is extremely skewed to the left and some countries have zero slave exports, we take the natural logarithm of one plus the measure, i.e. $\ln(1 + \text{slave exports/area})$.

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

[14] One could also think that certain countries, because of inferior access to technology or poor governance, are worse equipped to mitigate the direct contemporaneous effect of ruggedness. However, note that this would work *against* estimating a positive differential effect of ruggedness in 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.

Table 4. Ruggedness as a deterrent of slave exports

	Dependent variable: Log slave exports per area 1400–1900				
	(1)	(2)	(3)	(4)	(5)
Ruggedness	-0.603 (0.123)***	-0.566 (0.132)***	-0.561 (0.154)***	-0.504 (0.159)***	-0.500 (0.184)***
Log population density 1500		0.359 (0.223)			0.322 (0.253)
% Desert			-0.001 (0.023)		0.006 (0.025)
% Tropical climate			0.020 (0.010)**		0.012 (0.011)
Distance to coast			-0.369 (1.211)		-1.201 (1.468)
Distance to slave markets, Atlantic trade				-0.474 (0.279)*	-0.423 (0.357)
Distance to slave markets, Indian trade				-0.572 (0.187)***	-0.502 (0.176)***
Distance to slave markets, Red Sea trade				0.519 (0.550)	0.365 (0.645)
Distance to slave markets, Saharan trade				-1.219 (0.549)**	-0.993 (0.502)**
Constant	5.509 (0.528)***	2.838 (1.647)*	4.533 (1.110)***	15.252 (4.268)***	11.642 (6.299)*
Observations	49	49	49	49	49
R^2	0.332	0.374	0.407	0.438	0.512

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

Column (1) in table 4 reports the unconditional relationship between slave exports and ruggedness for all 49 African countries included in our previous estimations. It shows that there is a negative and statistically significant relationship between ruggedness and slave exports, and that ruggedness alone explains about one third of the variation in slave exports. In the remaining columns of the table we include additional variables to address several potential concerns regarding the relationship between ruggedness and slave exports. First, it is possible that the reason fewer slaves were taken from countries with higher average uphill slope is that there were fewer people living in more rugged areas, not because rugged terrain provided protection. To allow for this possibility, in column (2) we control for population density in 1500. We see that the negative relationship between ruggedness and slave exports is robust, suggesting that the relationship is not working through lower initial population density in rugged areas. Next, to check whether ruggedness is proxying for other geographical characteristics that could have affected slave exports, in column (3) we control for the proportion of countries' land area that has tropical climates, the proportion that is desert, and the average distance to the coast. The negative relationship between slave exports and ruggedness remains robust to these controls. The last set

Table 5. Controlling for slave exports, the differential effect of ruggedness for Africa vanishes

	Dependent variable: Log real GDP per person 2000			
	(1)	(2)	(3)	(4)
Ruggedness	-0.078 (0.036)**	-0.078 (0.036)**	-0.093 (0.031)***	-0.093 (0.031)***
Ruggedness $\cdot I^{\text{Africa}}$	0.156 (0.059)***	0.042 (0.064)	0.145 (0.060)**	0.033 (0.060)
I^{Africa}	-1.942 (0.220)***	-0.898 (0.342)***	-2.051 (0.387)***	-1.116 (0.392)***
Log slave exports per 1000 km^2		-0.189 (0.042)***		-0.184 (0.034)***
Diamonds produced			0.071 (0.022)***	0.071 (0.022)***
Diamonds $\cdot I^{\text{Africa}}$			-0.057 (0.022)***	-0.063 (0.022)***
% Tropical climate			-0.010 (0.002)***	-0.010 (0.002)***
% Tropical climate $\cdot I^{\text{Africa}}$			0.008 (0.004)**	0.010 (0.004)***
Distance to coast			-0.966 (0.184)***	-0.966 (0.185)***
Distance to coast $\cdot I^{\text{Africa}}$			-0.243 (0.347)	-0.279 (0.309)
% Desert			-0.007 (0.007)	-0.007 (0.007)
% Desert $\cdot I^{\text{Africa}}$			0.018 (0.012)	0.015 (0.010)
Constant	9.219 (0.143)***	9.219 (0.143)***	9.888 (0.153)***	9.888 (0.153)***
Observations	170	170	170	170
R^2	0.356	0.407	0.540	0.581

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

of controls that we introduce are the distance from each country to the closest slave market in each of the four slave trades (in thousands of kilometres). These distances were shown by Nunn (2006) to be important determinants of slave exports. Again, the ruggedness coefficient remains negative and significant when these distances are controlled for. In the final column of the table we include all control variables simultaneously. The significant negative relationship between slave exports and ruggedness remains. Overall, the results of table 4 confirm the historical accounts suggesting that irregular terrain was an effective means of avoiding the slave trades.

Having shown that ruggedness has a differential effect in Africa and that ruggedness deterred slave exports, we now check to what extent slave exports can account for Africa's differential effect. We do this by estimating equation (7) from section 3, with results reported in table 5. Column (1) reproduces, for comparison, our estimates of equation (5), which does not control for slave exports. In columns (2), we estimate equation (7), which is identical to equation (5), except that slave exports are also included in the estimating equation. Columns (3) and (4) report the same estimations as (1) and (2) respectively with the same controls used in section 4. With or without the full set of controls, when slave exports are controlled for, the estimated differential effect of ruggedness within Africa disappears. The estimated coefficient is essentially zero, and is no longer statistically significant. This confirms hypothesis 5, and provides support for the explanation that the differential effect of ruggedness arises because of the slave trades. The estimates also support hypotheses 4 and 6. Slave exports have had a negative and statistically significant effect on economic outcomes, and once slave exports are accounted for, the estimated direct effect of ruggedness on income is negative and statistically significant.

6. The distribution of population relative to rugged areas

We have shown that the data support our hypothesis that, within Africa, rugged terrain has had an indirect benefit on current economic outcomes because inhabitants of rugged areas were better able to protect themselves from the slave trades and avoid their long-run negative consequences. In this section, we also show that this benefit may have come at a cost, since it has meant that African populations are now more concentrated in rugged areas relative to populations in other parts of the world.

Migration towards rugged areas in response to the slave trades

In parts of Africa threatened by the slave trades, populations in more rugged areas tended to increase relative to populations in less rugged areas. This is because in rugged areas people were better able to defend against the depopulating effects of the slave trades, and also because population tended to migrate to more rugged areas escaping from slave raids (see Cordell, 2003). If these relocations were permanent, then populations today will be more concentrated in rugged areas, which we have seen adversely affects income.

There are a number of reasons why past population movements may persist. If there are benefits to agglomeration, then relocation requires a coordinated effort, which may be difficult. As well, many forms of capital, such as wells, buildings, and streets, are very difficult or even impossible

Table 6. Within Africa: the determinants of living in rugged areas

	Dependent variable: Correlation between population density and ruggedness	
	(1)	(2)
Std. dev. ruggedness	-0.013 (0.003)***	-0.012 (0.002)***
Log slave exports per 1000 km^2	-0.002 (0.002)	-0.001 (0.002)
Log slave exports per 1000 km^2 · Std. dev. ruggedness	0.002 (0.001)***	0.002 (0.001)**
Diamonds produced		0.000 (0.000)***
% Tropical climate		0.000 (0.000)
Distance to coast		0.004 (0.009)
% Desert		0.000 (0.000)
Constant	0.021 (0.011)**	0.008 (0.016)
Observations	49	49
R^2	0.606	0.630

Notes: The dependent variable is the correlation coefficient between ruggedness and population density across all 30 arc-second by 30 arc-second cells within the country. Coefficients are reported with robust standard errors in brackets. ***, **, and * indicate significance at the 1, 5, and 10 percent levels.

to move. Finally, culture and religious beliefs that incorporate the rugged landscape may impede relocation. For example, the Dogon, who inhabit the cliffs of the Badiagara escarpment in Mali, place great spiritual significance on the caves located on the cliffs. They believe that spirits inhabit the cliffs, and they also bury their dead there (Olson, 1996).

We now test whether there is evidence that these historically documented population movements persist until today. We do this by constructing a measure of whether people in a country tend to live in the more or less rugged parts of the country. Consider again figure 1, which shows the construction of average ruggedness for each 30 arc-second by 30 arc-second cell within a country. Combining these ruggedness data with data from Oak Ridge National Laboratory (2001) on the total ambient population in each cell of the same grid, we calculate the correlation coefficient between population density and terrain ruggedness in each country using 30 by 30 arc-second cells as units (see the appendix for further details). Not surprisingly, we find that for most countries (138 of 170), the correlation coefficient is negative, indicating that populations tend to concentrate in the less rugged parts of the country.

Using our population-ruggedness correlation measure, we first examine whether there is evidence that within Africa the combination of the threat of slave raids with the availability of areas with varying ruggedness created past population movements that have persisted until today. In

Table 7. Controlling for the distribution of population relative to rugged areas

	Dependent variable: Log real GDP per person 2000					
	(1)	(2)	(3)	(4)	(5)	(6)
Ruggedness	-0.078 (0.036)**	-0.093 (0.031)***	-0.122 (0.038)***	-0.125 (0.034)***		
Ruggedness $\cdot I^{\text{Africa}}$	0.156 (0.059)***	0.145 (0.060)**	0.193 (0.082)**	0.157 (0.072)**	0.182 (0.060)***	0.169 (0.064)***
Corr(Pop. dens., Ruggedness)			-3.645 (0.938)***	-2.718 (1.019)***		
Corr(Pop. dens., Ruggedness) $\cdot I^{\text{Africa}}$			2.922 (6.321)	0.793 (5.599)		
Ruggedness (pop. weighted)					-0.182 (0.073)**	-0.200 (0.074)***
I^{Africa}	-1.942 (0.220)***	-2.051 (0.387)***	-1.877 (0.216)***	-1.947 (0.359)***	-1.865 (0.217)***	-1.993 (0.374)***
Diamonds produced		0.071 (0.022)***		0.074 (0.021)***		0.077 (0.024)***
Diamonds $\cdot I^{\text{Africa}}$		-0.057 (0.022)***		-0.060 (0.021)***		-0.064 (0.024)***
% Tropical climate		-0.010 (0.002)***		-0.009 (0.002)***		-0.009 (0.002)***
% Tropical climate $\cdot I^{\text{Africa}}$		0.008 (0.004)**		0.007 (0.004)*		0.007 (0.004)*
Distance to coast		-0.966 (0.184)***		-0.889 (0.187)***		-1.051 (0.197)***
Distance to coast $\cdot I^{\text{Africa}}$		-0.243 (0.347)		-0.307 (0.359)		-0.027 (0.370)
% Desert		-0.007 (0.007)		-0.005 (0.007)		-0.004 (0.006)
% Desert $\cdot I^{\text{Africa}}$		0.018 (0.012)		0.017 (0.012)		0.014 (0.010)
Constant	9.219 (0.143)***	9.888 (0.153)***	9.164 (0.140)***	9.810 (0.154)***	9.244 (0.144)***	9.878 (0.162)***
Observations	170	170	170	170	170	170
R^2	0.356	0.540	0.388	0.558	0.358	0.538

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

particular, we estimate the following equation:

$$\text{Corr(Pop. dens, Ruggedness)} = \eta_0 + \eta_1 \sigma_i^r + \eta_2 x_i + \eta_3 x_i \cdot \sigma_i^r + \varepsilon_i \ , \qquad (8)$$

where Corr(Pop. dens, Ruggedness) is our ruggedness-population density correlation measure, σ_i^r is the standard deviation of ruggedness within each country, and as before x_i denotes slave exports.

This specification captures the effect that the threat of capture during the slave trades had on population movements. We take our measure of slave exports x_i as a proxy for how exposed a country was to the slave trades. If a country is threatened by the slave trades, then this may cause migration to more rugged areas. However, this will only be feasible if more rugged areas are available to migrate to. Therefore, the movement will depend not only on the threat from the slave trades x_i, but also on the variation in terrain ruggedness within the country σ_i^r. The importance of the interaction between the threat from the slave trades and varying ruggedness for population patterns is captured by the coefficient η_3 that multiplies $x_i \cdot \sigma_i^r$ in the estimating equation. Because slave exports are expected to have a greater effect on migration when there are more differences in terrain ruggedness within a country, we expect $\eta_3 > 0$. At the extreme, if the whole country is equally rugged ($\sigma_i^r = 0$), then there is no benefit to moving to another part of the country in response to the threat of capture. In this case, the relationship between population concentration and slave exports in (8) is given by η_2 only, and therefore we expect $\eta_2 = 0$.

The estimates of equation (8) are reported in column (1) of table 6. As expected, the estimated coefficient for slave exports alone η_2 is not significantly different from zero, but the estimated coefficient for slave exports interacted with the standard deviation of ruggedness η_3 is positive and statistically significant. In column (2) we also control for our set of country geographic characteristics. The results remain robust to this. Overall, the estimates suggest that when populations within African countries were threatened by the slave trades *and* differences in ruggedness existed, then less rugged areas lost population relative to more rugged areas. This concentration of the population in the more rugged parts of the country persists today.

Controlling for the distribution of population relative to rugged areas

This evidence that the slave trades caused persistent movements to more rugged areas suggests an additional effect of ruggedness within Africa. Although ruggedness provided protection against the slave trades, this protection came at a cost. Populations became permanently more concentrated in rugged areas. An implication of this is that our estimate of the indirect effect of ruggedness so far (the estimated coefficient for the interaction between ruggedness and the African indicator variable) has captured both the long-run benefit from ruggedness as a deterrent of slave exports, as well as the long-run cost from having population persistently more concentrated in rugged areas in response to the threat of the slave trades. We now try to isolate the benefit from ruggedness as a deterrent of slave exports, by controlling for concentration of population in more rugged areas. We do this through two complementary strategies.

First, we include the ruggedness-population correlation measure in estimating equation (5), while allowing the effect this variable to differ within Africa and outside of Africa. The results are reported in column (3) and (4) of table 7 (where column (4) incorporates the same controls used in section 4). Columns (1) and (2) reproduce our baseline estimates of table 1 for comparison. Consistent with our expectations, when one controls for the current population concentration, the estimated indirect effect of ruggedness (i.e., the coefficient for ruggedness $\cdot I^{\text{Africa}}$) increases. In other words, the slave trades have not only created a positive indirect effect of ruggedness on income in Africa, but by encouraging population concentrations in rugged areas, they have also amplified the negative direct impact of ruggedness in Africa. However, the differences between estimates in columns (1) and (2) and between the estimates of columns (3) and (4) are not large, which suggests that the indirect benefits of ruggedness by deterring slave exports in Africa are much greater than the costs that arise from past migrations to more rugged areas.

Second, rather than using a separate measure to control for a country's concentration of its populations in rugged areas, an alternative strategy is to construct a ruggedness measure that weights mean uphill slope by population rather than by land area.[15] This allows the contemporaneous impact of ruggedness on income to work locally in proportion to population density, so that ruggedness matters more in densely populated areas and not at all in uninhabited areas. The estimates using this alternative ruggedness measure are reported in columns (5) and (6).[16] The direct effect remains negative and significant and the differential effect in Africa remains positive, larger in magnitude than the direct effect, and statistically significant. Once again, comparison with columns (1) and (2) shows that, once we account for the current population concentration across areas with different ruggedness, the estimated indirect effect of ruggedness increases.

7. Conclusions

This paper contributes to the ongoing controversy about whether geography matters mainly because of its direct contemporaneous impact on economic outcomes or because of its interaction with historical events. The issue is not just a matter of intellectual curiosity. It is very important for development policies, and has been the source of much recent debate. Researchers such as Jeffrey Sachs (2005) and others, who believe that geography matters primarily through a direct contemporaneous channel, argue that foreign aid and investment are needed to overcome the adverse geographic environments of poor countries. According to this view, with enough foreign aid the adverse effects of geography can be mitigated and alleviated, allowing the world's poorest countries to develop. Arguing against the effectiveness of foreign aid are those such as William Easterly (2006*a*,*b*, 2007), who believe that the importance of geography lies in its influence on past

[15] As detailed in section 2, to construct this population-weighted ruggedness measure, we start from the same mean uphill slope for each 30 by 30 arc-second cell as in our standard ruggedness measure but, in averaging this for each country, we weight ruggedness in each 30 by 30 arc-second cell by the share of the country's population located in that 30 by 30 arc-second cell in 2000.

[16] The specifications in columns (5) and (6) are identical to those in columns (1) and (2) respectively, with our standard ruggedness measure replaced by population-weighted ruggedness. The measure of ruggedness interacted with the African indicator variable in columns (5) and (6) is still our standard ruggedness variable, since there is no reason why the strength of the historical channel through which ruggedness affects income should be proportional to current population densities. Nevertheless, interacting population-weighted ruggedness instead of area-weighted ruggedness with the African indicator variable does not affect our qualitative results. As noted earlier, we have chosen to use area-weighted ruggedness up until this last section because it is truly exogenous (whereas the distribution of population is potentially related to various economic, cultural, and institutional factors) and in order to use a common measure to estimate the direct contemporaneous and indirect historical effects of ruggedness.

events, which have shaped the evolution of societies.[17] It is felt that the reason for underdevelopment has more to do with poor domestic governance, dysfunctional institutions, or poor economic policies, all of which have deep historical roots. According to this view, aid rather than being a panacea for underdevelopment, is largely ineffective and can even exacerbate poor governance, hampering economic development.[18]

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 separately identify the direct contemporaneous channel and the indirect historic channel. We find a direct negative effect of ruggedness on income, which is consistent with irregular terrain making agriculture, building, and transportation more costly. 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. This differential effect of ruggedness is confined to Africa, is not due to geographic features that are particularly prominent in this continent, and can be fully accounted for by the slave trades.

On the whole, the results point to the importance of both a direct and an indirect channel through which ruggedness affects income. In terms of relative magnitudes, within Africa, the positive indirect effect of ruggedness swamps the direct negative effect. In this case, geography matters more through its indirect effect on past events, than it does through it current direct effect on income. However, these results are specific to terrain ruggedness and do not imply that the indirect historic channel dominates the direct contemporaneous channel in other contexts.

Finally, our paper also suggests that the direct and indirect channels can interact in interesting ways. The combination of the threat of slave raids with the availability of areas with varying ruggedness has resulted in a concentration of population in particularly rugged areas that has persisted until today. In doing so, in addition to creating an indirect benefit of ruggedness in Africa, the slave trades have also amplified the negative direct and contemporaneous impact of ruggedness in Africa.

References

Acemoglu, Daron, Simon Johnson, and James A. Robinson. 2001. The colonial origins of comparative development: An empirical investigation. *American Economic Review* 91(5):1369–1401.

Acemoglu, Daron, Simon Johnson, and James A. Robinson. 2002. Reversal of fortune: Geography and institutions in the making of the modern world income distribution. *Quarterly Journal of Economics* 117(4):1231–1294.

Allen, Bryant, R. Michael Bourke, and John Gibson. 2005. Poor rural places in Papua New Guinea. *Asia Pacific Viewpoint* 46(2):201–217.

[17] See in particular Easterly and Levine (2003).

[18] See Djankov, Montalvo, and Reynal-Querol (2005) for recent evidence on this "curse of aid".

Bah, Thierno Mouctar. 1976. The impact of wars on housing in pre-colonial black Africa. *African Environment* 76(3):3–18.

Bah, Thierno Mouctar. 1985. *Architecture Militaire Traditionalle et Poliorcétique dans le Soudan Occidental*. Yaondé, Cameroon: Editions CLE.

Bah, Thierno Mouctar. 2003. Slave-raiding and defensive systems south of lake Chad from the sixteenth to the nineteenth century. In Sylviane A. Diouf (ed.) *Fighting the Slave Trade: West African Strategies*. Athens, OH: Ohio University Press, 15–49.

Belsley, David A., Edwin Kuh, and Roy E. Welsch. 1980. *Regression Diagnostics: Identifying Influential Data and Sources of Collinearity*. New York, NY: John Wiley & Sons.

Brasseur, Georges. 1968. *Les Établissements Humains au Mali*. Dakar, Senegal: Mémoires de l'IFAN.

Burchfield, Marcy, Henry G. Overman, Diego Puga, and Matthew A. Turner. 2006. Causes of sprawl: A portrait from space. *Quarterly Journal of Economics* 121(2):587–633.

Center for International Earth Science Information Network. 2003. *National Aggregates of Geospatial Data Collection: Population, Landscape, and Climate Estimates (PLACE)*. New York, NY: Center for International Earth Science Information Network (CIESIN), Columbia University.

Collier, Paul and Anke Hoeffler. 2004. Greed and grievance in civil war. *Oxford Economic Papers* 56(4):563–595.

Collins Bartholomew. 2005. *Collins Bartholomew World Premium*. Glasgow, UK: Collins Bartholomew.

Cordell, Dennis D. 2003. The myth of inevitability and invincibility: Resistance to slavers and the slave trade in Central Africa, 1850–1910. In Sylviane A. Diouf (ed.) *Fighting the Slave Trade: West African Strategies*. Athens, OH: Ohio University Press, 31–49.

Diamond, Jared. 1997. *Guns, Germs, and Steel*. New York, NY: W. W. Norton & Company.

Djankov, Simeon, Jose G. Montalvo, and Marta Reynal-Querol. 2005. The curse of aid. Working Paper 870, Universitat Pompeu Fabra.

Easterly, William. 2006*a*. *The White Man's Burden: Why the West's Efforts to Aid the Rest Have Done so Much Ill and so Little Good*. New York, NY: Penguin Press.

Easterly, William. 2006*b*. Reliving the 1950s: The big push, poverty traps, and takeoffs in economic development. *Journal of Economic Growth* 11(4):289–318.

Easterly, William. 2007. Was development assistance a mistake? *American Economic Review Papers and Proceedings* 97(2):forthcoming.

Easterly, William and Ross Levine. 2003. Tropics, germs, and crops: The role of endowments in economic development. *Journal of Monetary Economics* 50(1):3–39.

Engerman, Stanley L. and Kenneth L. Sokoloff. 1997. Factor endowments, institutions, and differential paths of growth among New World economies: A view from economic historians of the United States. In Stephen Harber (ed.) *How Latin America Fell Behind*. Stanford: Stanford University Press, 260–304.

Engerman, Stanley L. and Kenneth L. Sokoloff. 2002. Factor endowments, inequality, and paths of development among new world economies. Working Paper 9259, National Bureau of Economic Research.

Fearon, James D. and David Laitin. 2003. Ethnicity, insurgency, and civil war. *American Political Science Review* 97(1):75–90.

Food and Agriculture Organization. 1993. *Guidelines for Land-Use Planning*. Rome: Food and Agriculture Organization of the United Nations.

Gallup, John Luke and Jeffrey D. Sachs. 2001. The economic burden of malaria. *American Journal of Tropical Medicine and Hygiene* 64(1-2):85–96.

Gerrard, A. J. W. 2000. What is a mountain? Processed, The World Bank Development Research Group.

Gleave, M. B. and R. M. Prothero. 1971. Population density and 'slave raiding' – A comment. *Journal of African History* 12(2):319–324.

Hawthorne, Walter. 1999. The production of slaves where there was no state: The Guinea-Bissau region, 1450–1815. *Slavery & Abolition* 20(2):97–124.

Inikori, Joseph E. 2000. Africa and the trans-Atlantic slave trade. In Toyin Falola (ed.) *Africa Volume I: African History Before 1885*. Durham, NC: Carolina Academic Press, 389–412.

Kamarck, Andrew M. 1976. *The Tropics and Economic Development*. Baltimore, MD: John Hopkins University Press.

Kiszewski, Anthony, Andrew Mellinger, Andrew Spielman, Pia Malaney, Sonia Ehrlich Sachs, and Jeffrey Sachs. 2004. A global index of the stability of malaria transmission. *American Journal of Tropical Medicine and Hygiene* 70(5):486–498.

Klein, Martin. 2003. Defensive strategies: Wasulu, Masina, and the slave trade. In Sylviane A. Diouf (ed.) *Fighting the Slave Trade: West African Strategies*. Athens, OH: Ohio University Press, 62–78.

Kottek, Markus, Jürgen Grieser, Christoph Beck, Bruno Rudolf, and Franz Rubel. 2006. World map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift* 15(3):259–263.

Kusimba, Chapurukha M. 2004. Archaeology of slavery in East Africa. *African Archaeological Review* 21(2):59–88.

Levine, David I. and Dean Yang. 2006. A note on the impact of local rainfall on rice output in Indonesian districts. Processed, University of California, Berkeley.

Lovejoy, Paul E. 2000. *Transformations in Slavery: A History of Slavery in Africa*. Second edition. Cambridge, UK: Cambridge University Press.

Maccini, Sharon and Dean Yang. 2006. Under the weather: Health, schooling, and socioeconomic consequences of early-life rainfall. Processed, University of Michigan.

Marchesseau, G. 1945. Quelques éléments d'ethnographie sur les Mofu du massif de Durum. *Bulletin de la Société d'Etudes Camerounaises* 10(1):7–54.

McEvedy, Colin and Richard Jones. 1978. *Atlas of World Population History*. Harmondsworth: Penguin Books.

Mehlum, Halvor, Edward Miguel, and Ragnar Torvik. 2006*a*. Poverty and crime in 19th century Germany. *Journal of Urban Economics* 59(3):370–388.

Mehlum, Halvor, Karl Moene, and Ragnar Torvik. 2006*b*. Institutions and the resource curse. *Economic Journal* 116(508):1–20.

Mellinger, Andrew, Jeffrey D. Sachs, and John Gallup. 2000. Climate, coastal proximity, and development. In Gordon L. Clark, Maryann P. Feldman, and Meric S. Gertler (eds.) *Oxford Handbook of Economic Geography*. Oxford, UK: Oxford University Press, 169–194.

Miguel, Edward. 2005. Poverty and witch killing. *Review of Economic Studies* 72(4):1153–1172.

Miguel, Edward, Shanker Satyanath, and Ernest Sergenti. 2004. Economic shocks and civil conflict: An instrumental variables approach. *Journal of Political Economy* 112(4):725–753.

Nogales, Alberto, Rodrigo Archondo-Callao, and Anil Bhandari. 2002. *Road Cost Knowledge System*. Washington, DC: World Bank.

Northrup, David. 1978. *Trade Without Rulers: Pre-Colonial Economic Development in South-Eastern Nigeria*. Oxford, UK: Claredon Press.

Nunn, Nathan. 2006. The long-term effects of Africa's slave trades. Processed, University of British Columbia.

Oak Ridge National Laboratory. 2001. *LandScan Global Population Database 2000*. Oak Ridge, TN: Oak Ridge National Laboratory.

Olken, Benjamin A. 1996. Do television and radio destroy social capital? Evidence from Indonesian villages. Processed, Harvard University.

Olson, James S. 1996. *The Peoples of Africa: An Ethnohistorical Dictionary*. London: Greenwood Press.

Podlewski, André Michel. 1961. Etude démographique de trois ethnies païennes du Nord-Cameroun: Matakam, Kapsiki, Goudé. *Recherches et Etudes Camerounaises* 4:1–70.

Ramcharan, Rodney. 2006. Does economic diversification lead to financial development? Evidence from topography. Working Paper 06/35, International Monetary Fund.

Rapaport, Eric and Folke Snickars. 1999. GIS-based road location in Sweden: A case study to minimize environmental damage, building costs and travel time. In John Stillwell, Stan Geertman, and Stan Openshaw (eds.) *Geographical Information and Planning*. New York, NY: Springer, 135–153.

Rappaport, Jordan and Jeffrey D. Sachs. 2003. The United States as a coastal nation. *Journal of Economic Growth* 8(1):5–46.

Riley, Shawn J., Stephen D. DeGloria, and Robert Elliot. 1999. A terrain ruggedness index that quantifies topographic heterogeneity. *Intermountain Journal of Sciences* 5(1–4):23–27.

Robinson, James A., Ragnar Torvik, and Thierry Verdier. 2006. Political foundations of the resource curse. *Journal of Development Economics* 79(2):447–468.

Sachs, Jeffrey. 2001. The geography of poverty and wealth. *Scientific American* March:70–75.

Sachs, Jeffrey. 2005. *The End of Poverty*. New York, NY: Penguin Press.

Sachs, Jeffrey and Pia Malaney. 2002. The economic and social burden of malaria. *Nature* 415(6872):680–685.

Sachs, Jeffrey D. and Andrew M. Warner. 2001. The curse of natural resources. *European Economic Review* 45(4–6):827–838.

Sokoloff, Kenneth L. and Stanley L. Engerman. 2000. History lessons: Institutions, factor endowments, and paths of development in the New world. *Journal of Economic Perspectives* 14(3):217–232.

United Nations. 2007. *United Nations Common Database*. New York, NY: United Nations Statistics Division.

US Geological Survey. 1996. GTOPO30. Sioux Falls, SD: United States Geological Survey Center for Earth Resources Observation and Science (EROS).

US Geological Survey. 2002. *Mineral Commodity Summaries 2002*. Reston, VA: United States Government Printing Office.

US National Imagery and Mapping Agency. 2000. *Vector Map (VMAP) Level 0/Digital Chart of the World*. Fifth edition. Fairfax, VA: United States National Imagery and Mapping Agency.

World Bank. 2006. *World Development Indicators*. Washington, DC: World Bank.

Yang, Dean. 2006. Are remittances insurance? Evidence from rainfall shocks in the Philippines. Processed, University of Michigan.

Data appendix

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).

Country boundaries

We assign geographical 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. When calculating the percentage of each country's land surface area with certain characteristics, we exclude areas covered by inland water area features contained in the same edition of the *Digital Chart of the World*.

Land area

The land area data are from United Nations (2007), except for Macau and Hong Kong where it is taken from the Encyclopædia Britannica.

Diamond production

Data on diamond production for 1994–2000 are obtained from the US Geological Survey's *Mineral Commodity Summaries* 1996–2002 (e.g., US Geological Survey, 2002). The variable is measured as the production of gemstones measured in thousands of carats of gem diamond per square kilometre of land area.

Proportion 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, Kottek, Grieser, Beck, Rudolf, and Rubel (2006) classify each cell on a 30 arc-minute grid covering the entire 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 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 computed 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 averaged this distance across all points in each country not covered by inland water features.

Proportion of each country covered by desert

The percentage of the land surface area of each country covered by sandy desert, dunes, rocky or lava flows, was calculated on the basis of the desert layer of the *Collins Bartholomew World Premium* digital map data (Collins Bartholomew, 2005) and the country boundaries described above.

Slave exports

Estimates of the total slave exported between 1400 and 1900 in Africa's four slave trades are from Nunn (2006). 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 log of one plus slave exports normalized by land area. See Nunn (2006) for more information on the nature of the data, including why it is appropriate to use the natural log of slave exports.

Correlation between population density and terrain ruggedness

The correlation between population density and terrain ruggedness in each country is calculated using 30 by 30 arc-second cells as units. A local ruggedness measure for each cell is calculated by averaging the slopes between the cell and the eight neighbouring cells, as previously discussed and depicted in figure 1. Population density for each cell is calculated by dividing the estimate of the population normally present in the cell contained in the *LandScan* data set (Oak Ridge National Laboratory, 2001) by the land surface area of the cell. The *LandScan* data set comprises worldwide population estimates on the same 30 by 30 arc-seconds latitude/longitude grid as the GTOPO30 data set that we use to calculate ruggedness. To construct the estimate of ambient population for each grid cell in *LandScan*, census counts (at sub-national level) are apportioned to cells based on likelihood coefficients that depend on nighttime lights, land cover data, and various geographic characteristics. We then calculate the pairwise correlation between population density and terrain ruggedness at the level of 30 by 30 arc-second cells for each country.

Population density in 1500

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 1500 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 1500, we take the natural logarithm of one plus the raw measure, i.e. $\ln(1 + \text{population}/\text{area})$.

Distance to export markets

Four variables measuring the distance from each country to the closest slave market in each of Africa's four slave trades are taken from Nunn (2006). 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 slave market for that 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 slave market for that slave trade. All distance variables are in thousands of kilometres.