Online Appendix 1. Estimating Travel Times

I estimate the time to travel from point A to point B. I control for the effects of time-cost components like the ruggedness of terrain, obstacles to straight-line travel and the possibility of travelling by canoe. The goal is to account for broad variations of transport cost across the continent.

Let H = the number of hours to travel through a square kilometer. The calculation uses the following framework:

$$H = F*SD*VF.$$

F = the "friction" of traveling through a square surface kilometer, measured in number of hours to travel a Euclidian distance of 1 kilometer. SD = adjustment for the actual distance traveled per Euclidian kilometer, taking into account the impact of the earths slope on the actual distance covered. VF = the average vertical factor, or the average impact of slope on hours of travel**.** The steeper the slope the longer it takes to travel a surface kilometer. Each square kilometer of the continent is assigned an average value of F, SD and VF.

Walking Rates (F_i).

Estimates of land cover come from the *Land Cover Map of Africa* developed by Mayaux, et al (2003) at the European Commission Joint Research Centre. Table A1 reclassifies the 27 FAO land cover types and reports the associated estimates of walking speeds, measured in hours per kilometer. Column (1) lists the 27 FAO classifications. Column (2) lists six re-classifications, aggregated by walking friction. (1) Rainforest is evergreen forest of thick canopy with vines and tangles. (2) Forest areas are woods of varying degrees of thickness, with spacing between trees for walking. (3) Mosaic forest is a patchwork of woody forest and clearings of either savanna or cropland. (4) Fields are open areas of grassland, shrub land or cropland with few trees. (5) Desert is barren land of dunes or rock. (6) Swamp/Mangrove is not walkable and requires a canoe.

The best available data on precolonial walking speeds come from Ivor Wilks (1975, pages 1-31). Wilks estimates the time to walk the Great Roads of Asante in the early 19th century. The Great Roads were public roads that radiated out from the capitol city of Kumasi. The eight Great Roads were maintained by the central government to extend the broadcast of its political power, to administer the affairs of state and to facilitate commerce. It is likely that these were among the best roads in precolonial sub-Saharan Africa. They traversed three of the five land cover classes for which we need data (forest, savanna and mosaic). In addition, the terrain in this region is relatively flat, minimizing contamination by variations in elevations, which will be added later.

I set travel time per day at 7 hours. According to Wilks, each of the Great Roads had a series of appointed "halting places." Each halting place was a seat of authority where banditry could be reported, lodging could be secured and provisions replenished. Wilks describes the travel time between each halting places as "equidistant," in the sense that they were separated by a conventional measure of a journey (in Twi language a "Kwansi," literally "part of the road"). Each journey (interpreted as a day's journey) was further divided into "watches" or "hours" or kwansimma (or little kwansin). A kwansin apparently consisted of seven kwansimma or seven travel hours. Two detailed travel itineraries from the early 1840s record the actual number of hours spent by travelers as they moved between halting places (Wilks 1975, page 9). One itinerary records an average travel time of 6.78 hours per day, the other an average travel time of 7.5 hours per day. Morton Stanley, during his trek across Africa in the late 1870s estimates 6-7 hours as a standard day's travel time (see below).

Many of the halting places along the Great Roads survive today as towns or villages. Wilks uses Ghana Ordnance Survey Maps to compute the approximate straight-line distances between halting places. These are straight-line distances, not the actual travel distances that account for road curvatures. Wilks reports separate frequency distributions for forest and savanna country:

> "The tendency to constancy in the length of a journey, shown in both forest and savanna regions, reflects the attempt of those concerned with the development of the great roads to evenly distribute the halting places along the route in so far as the nature of the terrain, and similar environmental factors, permitted (p. 30)."

Wilks is essentially arguing that the distances between halting places mark a standard expected day's travel in forested and savanna regions. By this method Wilks estimates an average day's journey to be 10 ½ miles per 7-hour day in the forest and 13.3 miles per 7-hour day in the savanna (p. 31). As a check, Wilks reports estimates that were recorded in the journals of Bowdich (1819) and Dupuis (1824), two British ambassadors resident in Asante in the early 19th century. Bowdich estimates an average linear distance of 10 miles per day in forest and 13.3 in savanna, almost exactly what Wilks estimates. Dupuis estimates a slightly higher average -- 12 miles per day in forest zones and 16 miles per day in savanna. I apply Wilks estimates. Table A1 reports the estimates in kilometers, converted at a rate of 1.6 kilometers per mile.

Mosaic land cover is a combination of forest and savanna or forest and cropland. It is an important land cover type in much of sub-Saharan Africa because over much of the continent the historic expansion of agriculture required the conversion of forest and jungle into arable land. For mosaic regions I take the mean of savanna and forest. This equals 11.9 miles per day.

For desert, I take the estimate of 27.5 km per 7 hour day = .233 hours per km. The estimate comes from Constant (2009). Constant walks across the Sahara desert and often comments on her pace. Some quotes include the following: "For the first time in the desert I will simply have to walk between twenty-five and thirty kilometres per day in order to keep to schedule (3438)." "He sets a fast stride and maintains it, for at least 30 kilometres over rough terrain. (4107)." "30 kilometres per day (4281)." "…plodding through prickles and over hills for twenty-five, thirty kilometres – then camp, eat, sleep…. Every day when I check our location and mark the kilometers on the map, I can see that we are covering good ground. (4870)." "I walk over 25 kilometres every day (4964)." "25 to 30 kilometres a day walking (6142)." Her guide said he did 50 per day, but he was riding camels and donkeys.

For rainforest, I use the average daily estimate of .88 hours per km found in Henry Morton Stanley (1891):

> "The next day left the track and struck through the huge towering forest and jungle with undergrowth by compass....Naturally penetrating a trackless wild

> for the first time the march was at a funeral pace, in some places at the rate of 400 yards an hour (.366 km per hr. or 2.73 hours per km), in other more open portions that is of less undergrowth, we could travel at a rate of half, three quarters, and even a mile per hour (.625 hours per km) – so that from 6:30 AM to 11 AM when we halted for lunch and rest, and from 12:30 PM to 3 o'clock or 4 PM and from 6 to 7 hours per day, we could make a march of about 5 miles (.880 hours per km) (p. 98)."

For Mangrove, swamp and waterbodies with no water current I use the estimate of 2.9 mph (.216 hours per km) found in Smith (1970, p. 523), who reports average rowing speeds in the lagoons along the Lower Guinea coast in the early 19th century.[1] 3.0 mph is the average observed times for modern-day canoe and kayak travel.

Table A1 converts all estimates into hours per kilometer using 1.6 kilometers per mile and 7 hours per day.

Headload.

Transport times have to account for the impact of any headload being carried. Ergonomic tests conducted by the U. S. Army Department concluded that carrying load by head is more efficient than carrying load by arms because arms rely on small muscle groups that tend to tire quickly. S. J. Legg (1985) reports:

> "In the head-carriage method, the stress is born by the vertebral column and the legs. The limiting factor in carrying heavy loads on the head is not energy cost but rather the mechanical load tolerated by the musculature. Movement of the body as a whole is restricted, but the method is very suitable for repeated short distance carries (p. 199)."

Stanley (1878, vol. I, p. 82) describes how he used this principle to allocate the 18,000 pounds of his caravan load among his 300 porters:

> "… each man's load was given to him according as we judge to his power of bearing burthen. To the man of strong sturdy make, with a large development of muscle, the cloth bail of 60 pounds was given, …; to the short compactly formed man, the bead sack of 50 pounds weight; to the light use of 18 or 20 years old, the box of 40 pounds,... (p. 81-2)"

Pandolf, Givoni and Goldman (1977) use the following equation to predict the energy expenditure of carrying various headloads:

$$M = 1.5W + 2.0(W+L)\,(L/W)^2 + n(W=L)\,(1.5V^2 + 0.35VG)$$

M = metabolic rate in watts; W = porters' weight in kg; L = load carried; V = speed of walking in meters per second; G = grade in %; and n = terrain ruggedness. According to this equation, a 190 pound man (77 kg) carrying a 60-pound head-load (27.2 kg) at a rate of .329 hours per km

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[1] My estimate excludes the 1.1 mph quote because that quote is for travelling upstream from Kuramo to Ikorodu where "a canoe meets the strong currents caused by the outflow of the Ogun and other rivers into the lagoon (p. 523)."

would burn 23.4% more watts of energy than a 190 pound man carrying nothing. A 170 pound porter carrying 50 pounds would burn an additional 21%, and a 150 pound man carrying 40 pounds would burn an additional 23%. Additions are less at slower walking rates. Through jungle (.88 hours per km) the additions are between 16.2% and 20.0%. The additional energy would need to be replenished with food and rest. In addition, "movement of the body as a whole is restricted," which should reduce walking speed. I add a load factor of 20% to the walking rates to account for load-related effects on speed and headload.

Henry Morton Stanley's Travel Log as a Check.

As a check on the walking rate reported in Table A1, Table A2 reports rates collected from the published logs of Henry Morton Stanley's multi-year expedition through Africa between 1874 and 1876 (1879, Vol II, pp. 516-550). Stanley was the first European to march inland from Zanj on the east coast of Africa westward up to Lake Victoria in the Highlands, southward down the Great Rift Valley, westward again through a portion of jungle in the Congo Basin, before floating down the Congo River to Isangila Falls and from there overland to the Atlantic Ocean. At the end of vol. II of the book that documents this expedition Stanley published a travel log that records "dates," "name of country," "name of station, village, or camp," "distance between (miles)," and "remarks." I found 355 entries in these logs for which distance and date are reported.

Table A2 reports the average travel times by water and land for what Stanley calls "Wanderings" or sections of his trek across Africa. Columns (1) and (3) report the hours per kilometer assuming 7 hour days. Not all dates in the log are sequential. The hourly travel rates reported in column (1) include non-marching days used for rest and re-provisioning. Care is taken to exclude off-days used for other purposes (like the side trip to visit the Emperor of Uganda). Column (2) reports the number of observations used in these calculations. Column (3) reports average travel times that do not include rest days. It includes only observations with consecutive dates, and so cannot include a day of rest. These are the observations that are most comparable to the estimates in Table A1, the major exception being they include the impact of slope. Column (5) reproduces the Wilks estimates that match the dominant land cover type of each of Stanley's wanderings.

Wilk's estimates of travel times are comparable to Stanley's observed travel times. The slight differences reflect the fact that Stanley's elevations were more varied than those found along the Great Roads of Asante. Stanley traveled over mountain passes, up to the highland lakes region and down into the surrounding valleys before reaching the Congo River.[2] Stanley also took longer to travel by water. Lake Victoria and Lake Tanganyika are bodies of relatively still water, so their rates should be similar to the ones observed in the lagoons off the Lower Guinea coast. Stanley's vessel was called Lady Alice, constructed in Europe, dismantled into parts, transported to the African coast and carried overland to the lakes and rivers in the interior. Pictures show it to be significantly wider and heavier than the average African canoe. Stanley repeatedly refers to the swiftness of the African canoes he encountered on the Congo River and to the elegance of their construction. Also, while circumnavigating Lake Victoria and Lake Tanganyika, Stanley

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[2] The last two entries have only 4 observations.

was interested in exploring and documenting as many bays, inlets and rivers as possible, which slowed progress.

Canoe Travel (F_j)

Rivers attract traders. They serve as natural highways across the landscape. Compared to overland transportation, rivers have advantages and disadvantages. They are not available everywhere and they often do not flow in the direction one might want. On the plus side, water reduces friction and facilitates the transformation of human energy into velocity. The buoyancy of water, when manipulated by a paddler in an appropriately constructed vessel, can transport comparable weight faster than an overland porter. Roberts (1987, pp. 73-74) discusses the relative carrying capacities of the two technologies in the 19th century Middle Niger Valley. A 20-30 ton freight canoe could transport as much produce as a caravan of 1000 porters (.025 tons per porter). Stanley (1878, vol. I, p. 64) used 300 porters to carry 8 tons of bulk, which is a comparable carrying capacity for porters (.026 tons per perter). Ideally, we would like estimates of transport costs per ton-mile of river transport. Roberts (1987, p. 62) reports that "[a] colonial officer in 1892 estimated that it cost six times more to move a quantity of goods by caravan than by canoe…," but we have no way of evaluating such claims or conducting an analysis for the entire continent.

We do know, however, that canoe transport required additional capital investment. The quality and size of canoes was dictated by the availability of trees and the returns to trade. Canoes were dug out of trees by hand using iron axes and adze-like tools. As early as 1506, Fernandes writes about "huge canoes carrying 120 warriors" on the Sierra Leone River (Smith 1970, p. 518). As early as 1682 Barbot describes canoes along the Gold Coast being 70 feet long and 7-8 feet wide (Smith 1970 , p. 518). Around the Niger Bend in the late 18th century, Mungo Park (2000) observed a canoe composed of two log sections attached end-to-end (unlike a catamaran) that ferried four horses and several men across the river (p. 293). By the end of the 19th century Murdock's Ethnographic Atlas records guilds of specialized boat-makers along the Niger River and on the western shore of Lake Victoria. Stanley (1879, p. 392) depicts sketches of the variety of canoes he observed during his trek across Africa in the 1870s. War and trade spurred developments in the technology (Smith 1970).

There may also have been additional labor cost when transporting slaves by canoe. On land, slaves destined for sale often doubled as porters, but in canoes paddlers were often recruited from reliable workers in a village who required remuneration of some kind. There were also small additional costs for transporting slaves on land. Land caravans may have required a few more guards because there were more opportunities for captives to escape; slaves as porters required more food than slaves as canoe passengers; and women and children might slow the march on land.

These costs, however, are negligible compared to the cost of a canoe and its crew. Since canoes are lumpy inputs there is the possibility of economies of scale in the canoe technology. According to Roberts (1987, 73-74) this was not the case in the Middle Niger Valley. A common canoe of 6-10 ton capacity was often manned by two crew members and a captain. A large 20-30 ton freight canoe was often manned by a crew of 16-18 plus 2 mates and a captain. Henry Morton Stanley describes war canoes on the Congo River as large as 85 and 90 feet in length "with two rows of upstanding paddles, 40 men on a side... (1879, Vol II, p. 270)." The ratios of canoe tonnage or canoe size relative to crew size does not suggest appreciable economies of scale.

Economies of scale did exist in the size of caravans, on land and water, to protect from attack when travelling through hostile territory. States sometimes provided public goods on water similar to the halting place along the Great Roads of Asante. Mountains divide and river unite, the saying goes. Roberts discusses how the King of Segu in the late 18th century spaced villages 15 km apart along the Niger River in order to regularize and protect trade. The growth of Segu plantations and their grain production spurred the development (Roberts 1987, pp. 71-72). Smaller merchants who could not tie up capital in canoes could rent passage as individuals or groups (pp. 73-74). Harms (1987, chapters 2 and 3) discusses similarly-spaced trading towns and sharing arrangements along the lower Congo River. Here the advantage may be with river transport because it may have been cheaper to protect waterways than to maintain and protect roads. In addition, canoes did double-duty. When not in use for trade they could be used to dispatch troops, blockade enemies and wage war (Smith 1970, pp. 525-532).

These are all interesting and important economic considerations, but in a global sense, they pale in comparison to the differences in speed by land and by water. The major advantage of river transportation was speed, the combination of rowing tonnage on flowing water. Not all rivers were navigable at all times. Some were shallow streams that could not support a canoe full of people and trade goods. Some rivers dried up during the drier seasons. Some rivers flowed faster than others, some were wider than others, and some were deeper than others.

All of these features of rivers find expression in the hydrological identity for river velocity:

$$\text{Velocity (meters/sec)} = \text{Discharge rate } (\text{m}^3/\text{sec}) \,/\, \text{Cross-sectional area } (\text{m}^2).$$

Velocity is the rate of flow measured in meters per second. It is a function of the rate at which the river system discharges its volume of water, divided by the cross-section (width x depth) of the riverbed through which the water is discharged. The Global Runoff Data Centre (GRDC 2009) maintains a GIS dataset that contains volumetric discharge rates for 687 major river systems around the world. Based on the concept that a river basin covers all land that drains to the point of lowest elevation, the estimation procedure starts at river outlets (pour points) that coincide with either a confluence with a river, a mouth into an ocean or an endorheic sink (like Lake Chad). The basins above the pour points are mapped using the flow direction data in the HYDRO1k Elevation Derivative Database. The procedure identifies 405 river basins and 687 river networks around the world.

The GRDC dataset also contains data on average river discharge rate. Discharge rates measure the volume of water discharged per second from the basin. The GRDC dataset contains discharge rates recorded at 3,843 gauging stations between 1961 and 1990. The dataset splits river polylines into equidistant 0.25-length units. The WaterGAP 2.1 program is used to assign a discharge rate to each river segment. The spatial resolution is 0.5 degree.

Andreadis, et al (2013) estimate river width and depth using well-established geomorphic relationships between discharge rates and drainage areas (p. 7164).[3] Their estimates of river width are evaluated using LANSAT satellite imagery data. I convert the estimates of river velocity into hours per kilometer to make them comparable to the walking rates. The estimated mean for the continent of Africa is 0.44 hours per km (a velocity of 2.3 kilometers per hour). The standard deviation is 0.11. 68.2 percent of the river segments flow at an estimated rate between 0.55 hours per km (1.82 km per hour) and 0.33 hours per kilometer (3.0 km/hr.). The fastest river segment takes 0.15 hours to cover a km (6.6 km/hr.) The slowest is 0.95 hours per km (1.05 km/hr.). Segments are removed if they contain a major waterfall and rapids.[4] This forces traders to portage through these cells along the river.

The 1961-90 readings on discharge rates appear to be applicable to the precolonial era. When Nohara et al (2006) extend climate change models back to 1900, the rapid economic growth scenario produces little change in mean precipitation and river discharge, although the variance among the individual models is very large. Alsan (2015, online appendix) reports paleoclimatic data that show no change in African temperature between 1500 and 1900. Fenske and Kala (2015, online appendix) reports observed temperatures for Benguela and Whydah between 1725 and 1875 that show no trend. Nohara et al (2006, p. 1081) do show that the WEM (weighted ensemble mean) statistic for climate change models shows more variance around the equator than elsewhere. There is certainly direct evidence of southward expansion of the Sahara desert. Timbuktu was a great medieval city situated at the bend of the Niger River. The city is now well within the desert. The calculations presented here do not account for localized changes in river discharge and land-cover.

The Vertical Factor (VF)

The estimates of river velocity already capture the effect of slope, which is gradual along the run-off. Discontinuous sections like waterfalls and rapids have been removed using available maps, forcing travelers to portage along the river through these sections. The estimated walking rates are different. They assume a flat surface. The calculation must therefore take into account the fact that it is more difficult to walk uphill than downhill or along a flat surface. It is not reasonable to expect traders to scale cliffs, steep mountains or canyons walls, so a limit must be imposed.

The vertical factor for walking deals with these issues. It is derived from Waldo Tobler's (1993) Hiking Function, a function commonly used to account for the impact of slope on walking velocity.

$$V = 6e^{-3.5|s+.05|}$$

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[3] For a review of this literature and a discussion of similar but alternative algorithms for calculating river width, see Dai Yamazaki, Fiachra O'Loughlin, Mark A. Trigg, Zachary F. Miller, Tamlin M. Pavelsky, & Paul D. Bates, (2014).

[4] The project consulted online maps for the Congo River Basin, East Africa Rivers, the Niger River system, South Africa Rivers and Sudan River Rapids. The project also consulted maps and descriptions in four books. See Livingstone (1857), Hamilton (2005), Harwood (2013) and Coppinger and Williams (1994).

"V" is the walking velocity (measured in km per hour) and "s" is the slope of the terrain. On flat terrain, V(s) equals approximately 5 km per hour. At a slope of 50 degrees the predicted walking rate is virtually zero. At 30 degrees it is 0.5 km per hour. On the downside, the drop in velocity is approximately .5 km per hour less at each absolute slope value, so at a slope of -30% the walking velocity drops to approximately 1km per hour instead of 0.5.

The vertical factor (VF) enters the calculation of H as a multiplicative factor that is applied to F*SD. Since V(0) = 5, the vertical factor is normalized as VF = V(s)/5. Also, the vertical factor and F*SD must be in the same units. The Tobler V is measured in km per hour while F*SD is measured in hours per km. The final vertical factor used in the calculation is 5/V(s), where dV/ds < 0. A 30% up slope generates a vertical factor of 5/.5 = 10, estimating that it takes ten times as long to walk up a 30 degree slope as it does to walk on a flat surface.

A maximum slope can be imposed beyond which the Vertical Factor is infinity. Imposing a maximum is like imposing the assumption that walkers find a way around cliffs and steep mountains. For reference, a 6% slope is the maximum allowed for an interstate highway in the United States. Safe building access ramps are between 7-15 percent. Stair slopes are between 30-35 percent. The steepest gradient in San Francisco is on Filbert Street at 31.5 percent. According to the Guinness Book of World Records, Baldwin Street in New Zealand is the world's steepest residential street, a 350 meters street with a section of 35% slope. In our estimate, the VF captures changes in average altitude between two square-kilometer cells. Setting a maximum of, say, 30 percent assumes that a trading caravan facing a kilometer-long path as steep as a staircase will find an alternate way around. It is not unreasonable to assume that trader will avoid kilometer-long slopes steeper than a steep building access ramp (15%), especially if the porters in the trading party are carrying loads. Low maximum slopes are synonymous to assuming that travelers used local knowledge to find the easiest local paths forward.[5]

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[5] The ArcGIS Cost Path algorithm retains in memory a table of transition costs for all directions leading from a cell, not just the least cost direction. Imposing a maximum vertical factor forces the calculation to "backtrack" and find a path that is not blocked by the maximum vertical factor.

Travel-Time (F_{ij})

I use these data to estimate travel times in precolonial Africa. I calculate an H for each .452 square kilometer of the African continent.[6] The data projection is Africa Equidistant Conic, which is a secant projection with standard parallels at approximately 20 and -23 latitudes. It is the appropriate projection for calculating distances in Sub-Saharan Africa because it straddles the equator. Cell sizes are set to the cell size of the Digital Elevation Model.

First, a cost raster F_i is calculated that measures the time to walk across cells. The vertical factor (VF) is applied to F_i. If a cell in F_i contains a river then the value of the cell is set to zero. This prevents double counting when the river velocities in raster F_j are added to form $F_{ij} = F_i + F_j$. ArcGIS generates SD and estimates an H. H is a raster of the quickest way to get to the closest of a set of destinations. Destinations could be the coast or a slave port or a pre-1500 urban center. Figures 1 and 2 display the resulting estimates of average travel times per society to the nearest slave port assuming a maximum vertical factor of 20% (displayed in Figure A1) and a minimum river velocity of .27 hours per kilometer (Displayed in Figure A2).[7] Travel time per society is the weighted average of all cells contained within the society's borders. Adjustable parameters are F_i (land frictions), minimum Fj (river velocity) and max VF (% slope).

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[6] These layers should all be in the same projection. I use WGS_1984_Equidistant_Conic.

[7] Slave ports are taken from the Transatlantic Slave Trade Database. They include all mainland slave ports on the West coast of Africa that exported more than 4,000 slaves between 1600 and 1865. On the East African coast the ports included all mainland slave ports plus Zanzibar, which was a major island port in the Indian Ocean trade that was just off the coast. The lower limit on river velocity was set to be at least as fast as walking. The .27 cut-off was set early in the project to equal Dupuis' estimate of 16 miles per 7-hour day for walking across savanna, to avoid the scene of walkers moving faster than canoes. This is also comparable to the .255 hours per kilometer for walking across desert. The cut-off was not chosen or recalibrated to improve analytical results.

Table A1. Hours to Walk a Kilometer, by 28 FAO Land Cover Classifications

FAO Land Cover Class	Reclassification	Hours per km	
		No load	With load
Closed evergreen low land forest	Rain Forest	0.880	1.06
Degraded evergreen low land forest	Rain Forest	0.880	1.06
Sub montane forest (900 to 1500 m)	forest	0.417	0.500
Montane forest (greater than 1500 m)	forest	0.417	0.500
Swamp forest	Water	0.216	0.216
Mangrove	Water	0.216	0.216
Mosaic forest/cropland	Mosaic forest	0.368	0.442
Mosaic forest/savanna	Mosaic forest	0.368	0.442
Close deciduous forest	forest	0.417	0.500
Deciduous woodland	forest	0.417	0.500
Deciduous shrubland with sparse trees	field	0.329	0.395
Open deciduous shrubland	field	0.329	0.395
Closed grassland	field	0.329	0.395
Open grassland with sparse shrubs	field	0.329	0.395
Open grassland	field	0.329	0.395
Sparse grassland	field	0.329	0.395
Swamp bushland and grassland	water	0.216	0.216
Cropland (greater than 50%)	field	0.329	0.395
Cropland with open the woody vegetation	field	0.329	0.395
Irrigated cropland's	field	0.329	0.395
Tree crops	field	0.329	0.395
Sandy desert with dunes	desert	0.255	0.306
Stony desert	desert	0.255	0.306
Bare rock	desert	0.255	0.306
Salt hard pans	desert	0.255	0.306
Water bodies	water	0.216	0.216
Cities	Field	0.329	0.395

Sources: Estimates of hours per kilometer comes from Wilks (1975, pp. 1-31), Constance (2009), Smith (1970, p. 523), and Stanley (1891, p. 98). Headload factors are based on a formula found in Pandolf, Givoni and Goldman (1977). See the online Appendix 1 for a complete discussion.

Table A2. Henry Morton Stanley's Logs

	Observed From Stanley's Logs				Estimates (with and without load)
	Avg. for all days		Avg. for travel days		Avg for travel days
Stanley's Wanderings	hrs./km	Obs.	hrs./km	Obs.	hrs./km
	(1)	(2)	(3)	(4)	(5)
Overland to Lake Victoria	0.591	50	0.42	26	.329, .395
Circumnavigation of Lake Victoria	0.282	53	0.240	47	0.216
Overland in Uganda	1.281	17	0.425	8	.329, .395
Overland from Nyanza Muta-Nzige to Ujiji	0.694	102	0.422	62	0.329, .395
Circumnavigation of Lake Tanganyika	0.295	64	0.245	58	.216
Overland to Lualaba River near Nyangwe	0.695	40	0.417	26	.368, .442
Congo River to Isangila Falls (minus cateracts)	0.380	21	0.265	4	.216
Overland from Isangila Falls to Atlantic Ocean	0.703	7	0.841	4	.88, 1.06

Notes: Columns (1) and (3) report the hours per kilometer assuming 7 hour days. Column (1) includes non-marching days used for rest and re-provisioning. Column (3) reports average travel times that do not include rest days (only observations with consecutive dates). Column (5) reproduces the estimates from Table A1 that match the dominant land cover type of each of Stanley's wanderings.

Source: Stanley (1878, pp. 516-561).

Figure A1. Hours to walk 100 kilometers.

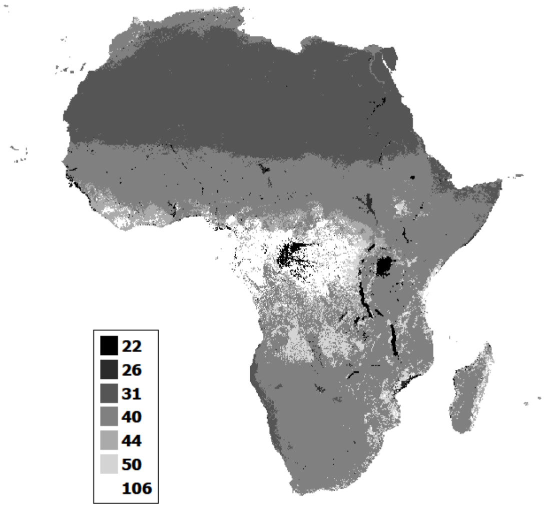
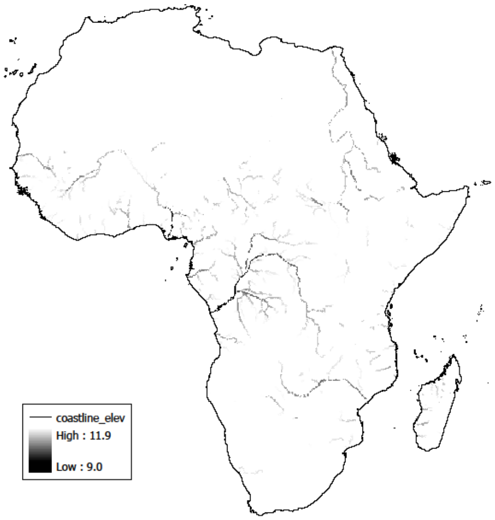


Figure A2. Hours to row 100 kilometers



Online Appendix 2. Heterogeneity

Heterogeneity by political centralization and descent. Next, the model is used to investigate the possibility that exposure to capture influenced African slavery through its impact on political hierarchy and patrilineal descent. These variables had a significant impact on the probability of observing slavery, but the variables could be endogenous to catchment. Fage, for example, suggests that the slave trade could have encouraged the spread of slavery through the spread of political centralization. Controlling for the final level of political centralization does not preclude this possibility. The same applies to patrilineal descent, if catchment discouraged patriliny.

Table B1, therefore, reports the results of running the catchment model on the probability of observing political hierarchy and patrilineal descent. The estimated coefficients reveal no evidence that catchment encouraged the building of political hierarchy or influenced patrilineal descent, so these can be considered exogenous covariates. The pattern across hierarchies suggests that catchment may have *reduced* the probability of building political hierarchies beyond petty chiefdoms, but the last column shows that this was not the case. The estimated coefficient on political centralization is negative but statistically insignificant.

Figure 5, therefore, graphs the predicted impact of catchment by the levels of political hierarchy and patrilineal descent, all else equal. Panel (a) graphs the predicted probabilities of slavery for each of the four levels of political hierarchy. Large chiefdoms and states were likely to be slave societies regardless of the number of inhabitants captured and exported. The major effect of catchment was concentrated among politically decentralized societies. While exposure did not influence the probability of being a village or a petty chiefdom, it did increase the probability that a village or petty chiefdom would adopt slavery as one of its institutions.

Panel (b), therefore, graphs the difference between decentralized and centralized societies, all else equal. At low levels of catchment decentralized societies are approximately 20 percent less-likely to be slave than are centralized societies. At high levels of catchment the predicted difference is approximately 10 percent.[8] Panel (c) shows the same pattern by descent. At low levels of catchment patrilineal societies are predicted to be approximately 20 percent less likely to be slave. At high levels of catchment the predicted difference is approximately 10 percent. These graphs show how political decentralization and patrilineal descent constrained the transition to slavery, as Miellassaux argues, but also how exposure to catchment incentivized these types of societies to overcome those constraints.

Heterogeneity by century and coast. The relationship between international slave trading and African slavery has a long, complex and nuanced history, so one should not expect one model to fit all regions and times. Italian city-states, Arab caliphates and European kingdoms all used conquest and trade to obtain treasure, land and slaves. Muslim and Christian armies fought "just" wars that justified the enslavement of non-believers. Roman and Islamic law contained well-

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[8] The larger standard errors at the higher levels of slave exports reflect the smaller number of observations and cells, and the smaller differences in probabilities across categories. Confidence intervals are tighter around the mean of -8.39.

developed civil codes regulating the legal status of slaves (Patterson, 1982). The southern frontier of this Mediterranean system was sub-Saharan Africa.

The first panel of Table B2 reports results of the catchment model applied to the east and west coasts separately, and for the 16th through 19th centuries. In West Africa, exposure to catchment in the early centuries is a better predictor of African slavery than exposure in later centuries. On the east coast, although there is a decline in the coefficient, it is not monotonic or as pronounced as the decline on the west coast. In either case, the impact of catchment on African slavery is not confined to one coast or the other, although the histories and the resulting slave systems may have been different.

The second panel applies the catchment model to *changes* in exposure across the centuries and shows the same pattern. On the west coast, increases in exposure in the early centuries is a better predictor than increases in the later centuries, again suggesting that longevity in exposure helps explain the eventual adoption of slavery along the west coast of Africa. Some West African societies with long exposure experienced a reduction in catchment following British abolition of its slave trade in 1807. The last row of panel (b), therefore, compares changes before and after 1800, which maintains the monotonic decline in the West African coefficients over time. There is no decline in the coefficient for the east coast.

These results are broadly consistent with the different coastal histories. While African trade in the Indian Ocean dates from the Middle Ages (Subrahmanyam (2019; Horton and Middleton 1988, pp. 72-87), according to Lovejoy (1983, 226-251) the major transformation in East African slavery dates from the late 18th and early 19th centuries, with the expansion of European, Omani and Swahili slave plantations on the mainland and its islands. Kilwa expanded as a slave exporting port in the 1780s under French encouragement to supply the sugar plantations of the Mascarene Islands and Madagascar. Mombasa also developed plantations during the late 18th century, and by the early 19th century clove plantations expanded on Pemba and Zanzibar where slaves were used to clear the land and work the fields. On Zanzibar, clove exports increased from 140 tons in 1839 to 2100 tons in 1849 and 3100 tons in 1859 (Martin 1991, p. 451). The plantation sector spread to the mainland opposite Zanzibar, especially along an 110 km stretch of coast from Mtwapa to Mambrui, but included other places as far north as the Banadir coast and as far south as Mozambique (Lovejoy 1983, p. 230). Arab merchants reached the inland commercial center of Tabora, half way between the coast and Lake Tanganyika in the 1830s. By the 1870s, Muslims, including Arabs, Swahili and converts among the inland Nyamwezi and Yao, dominated a vast network of trade routes that stretched beyond the highland lake country into the Congo basin, establishing a network of inland slave plantations to supply the caravan trade (the inland route that David Livingstone and later Morton Stanley followed).

International trade off the west coast of Africa was limited or nonexistent before the middle of the 15th century when the lateen sail enabled Portuguese caravels to sail down the west coast. There is evidence of pre-existing coastwise trade along the lagoons of the Lower Guinea Coast between the Kingdom of Benin and the Akan of the Gold Coast, but no international trade into the Atlantic. Then came the discovery and settling of the Americas, the decimation of American populations and the transplantation of slave codes across the Atlantic. By the mid-17th century, an old and sporadic Atlantic trade in slaves had become the central commodity of trade. The real price of slave exports on the west African coast rose by 500% in the 18th century (Richardson, 1991; Eltis and Richardson, 2004). Slave exports increased by 1000% (Eltis, 2009). After the British abolished its trade in 1807, Atlantic slave merchants expanded to the east coast of Africa to avoid detection by British patrols.

Table B1. IV Probit Estimates of Exposure to Capture on Political Hierarchy and Patrilineal Descent

	Villages	Petty Chiefdoms	Large Chiefdoms	States	Politically Centralized	Patrilineal Descent
	(1)	(2)	(3)	(4)	(5)	(6)
ln (Slave Exports per km)	0.012	0.043	-0.035	-0.031	-0.056	-0.018
	(0.046)	(0.031)	(0.026)	(0.047)	(0.036)	(0.030)
Institutional Controls	Yes	Yes	Yes	Yes	Yes	Yes
Environmental Controls	Yes	Yes	Yes	Yes	Yes	Yes
Regional Controls	Yes	Yes	Yes	Yes	Yes	Yes
First Stage F Statistic	15.86	15.86	15.86	15.86	15.86	13.01
Cragg-Donald F Statistic	69.57	69.57	69.57	69.57	69.57	70.94
Kleibergen-Paap Wald F Statistic	20.25	20.25	20.25	20.25	20.25	20.9
Observations	379	379	379	379	379	376

Notes: Dependent variable is the presence of slavery, V70, from Murdock's Ethnographic Atlas. Robust standard errors in parentheses clustered by ethno-linguistic affiliation. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Coefficient estimates obtained from instrumental variable probits using the Maximum Likelihood Method. First-stage F statistics come from the instrumental variable probit using the Newey Two-Step Method. Cragg-Donald and Kleibergen-Paap Wald F-statistics obtained from linear instrumental variable estimation.

Sources: Slave exports come from Nunn and Wantchenkon (2011). Institution categorical variables come from Murdock's Ethnographic Atlas: Institutional controls include Political Hierarchies (V33) or Patrilineal Descent (V43). The Centralized category includes Large Chiefdoms and States. Environmental controls include Tsetse Fly Suitability from Alsan (2015) and Agricultural Suitability Index from Michalopoulos and Papailoannou (2013). Region controls of North, South, East, West and Central come from Michalopoulos and Papailoannou (2013). Date of observation comes from Murdock's Ethnographic Atlas (V102). Data on Ethno-Linguistic Affiliation are taken from Alsan (2015). See the online Appendix 1 for construction of the Travel Time variables.

Table B2. IV Probit Estimate of Exposure to Capture, by Century and Coast
(Dep. Var. = African Slavery)

	West Coast					East Coast				
	Coef.	Obs.	First Stage F-statistics			Coef.	Obs.	First Stage F-statistics		
			2-step	C-D	K-W			2-step	C-D	K-P
(a) Slave Exports										
16th Century	0.332**	211	2.83	13.27	2.65	0.200***	104	7.42	28.59	22.14
	(0.151)					(0.070)				
17th Century	0.251***	211	2.85	13.39	4.36	0.221***	104	7.36	28.06	22.18
	(0.088)					(0.077)				
18th Century	0.176***	211	3.28	12.73	11.5	0.193***	104	7.21	24.52	18.32
	(0.038)					(0.071)				
19th Century	0.127***	211	10.89	62.67	29.2	0.178***	104	8.69	30.19	24.69
	(0.038)					(0.067)				
(b) Δ Slave Exports										
(17th - 16th) Centuries	0.260***	202	2.91	15.16	5.42	---	---	---	---	---
	(0.089)									
(18th - 17th) Centuries	0.165***	203	3.33	12.52	11.1	0.209***	104	7.16	28.73	18.17
	(0.047)					(0.077)				
(19th - 18th) Centuries	0.190***	176	8.01	46.35	21.3	0.185**	102	7.99	26.55	22.94
	(0.060)					(0.078)				
(18th + 19th) - (16th 17th)	0.110**	208	9.39	51.39	30	0.183***	104	8.39	25.91	20.33
	(0.048)					(0.070)				

Notes: Dependent variable is the presence of slavery, V70, from Murdock's Ethnographic Atlas. Robust standard errors are in parentheses clustered by ethno-linguistic affiliation. *** p<0.01, ** p<0.05, * p<0.1. Coefficient estimates obtained from instrumental variable probits using the Maximum Likelihood Method. First-stage F statistics come from the instrumental variable probit using the Newey Two-Step Method (2-Step). Cragg-Donald (C-D) and Kleibergen-Paap (K-P) Wald F-statistics obtained from linear instrumental variable estimation.

Sources: Slave exports come from Nunn and Wantchenkon (2011). Institution categorical variables come from Murdock's Ethnographic Atlas. Controls include Political Hierarchies (V33), Patrilineal Descent (V43), Tsetse Fly Suitability from Alsan (2015), Agricultural Suitability Index from Michalopoulos and Papailoannou (2013) and date of observation from (V102). Data on Ethno-Linguistic Affiliation are taken from Alsan (2015). Regions come from Michalopoulos and Papailoannou (2013). West Africa includes the North, West and Central regions. East Africa includes the East and South regions. See the online Appendix 1 for construction of the Travel Time variables.

Online Appendix 3. Some Historical Examples of Transformation

The following are some examples of the kinds of social transformations picked up by the econometric analysis. Whatley and Gillezeau (2011a) develop a model where the initial spatial distribution of resources and endowments generates a spatial distribution of state capacity and political centralization. In the slave trade era, centralized states choose between taxing a peasantry, conquering nearby villages or raiding villages for slaves. Conquest has the higher fixed cost associated with occupying, protecting and taxing peasants. As slave prices rise, slaving becomes the more attractive option and conquest stalls. Villages can form alliances in defense, but if the cost of alliance is high (say, due to ethnic differences), or if village elders are protected from capture, then villages can become catchment zones. Since international slave prices net of transport cost increase as one approaches the coast, regional geopolitical histories are driven by politically centralized inland societies raiding towards the coast. The model captures the general geopolitical history of the Guinea Coast during the 18th century expansion of the trans-Atlantic slave trade, and the emergence of centralized interior slave-raiding states like Asante (Wilks 1975), Dahomey (Law 1989), Futa Djallon (Lovejoy 2016), Oyo (Law 1977) and the Sokoto Caliphate (Lovejoy 2005).

In response, decentralized societies followed a variety of strategies to protect themselves, ranging from building walls, moving further away, forming coalitions and changing crop patterns (Diouf 2003). The decentralized patrilineal Balanta, for example, responded by moving into large, tightly-packed villages for protection. In our dataset, Balanta slave exports were 5.6 per km, in the upper tail of the distribution and with exports beginning as early as the 16th century. According to Hawthorne (2001):

> "As armies and roving bands of slave raiders struck at decentralized coastal populations, upland areas became very vulnerable to attack. Hence, from the end of the sixteenth century or start of the seventeenth century Balanta began to abandon difficult-to-defend locations, which favored yam production, for isolated lowlands which favored paddy rice (p. 14)."

Intensive rice cultivation, however, required iron tools, and in search of goods to exchange for imported iron the Balanta themselves became involved in the slave trade, and as a consequence slavery.

> "…sometime before the mid-fifteenth century arrival of Europeans, paddy-rice farming techniques were developed on coastal Guinea by Mande speakers. However, it was only after coastal populations began to bear the brunt of the slave raids that fed an expanding Atlantic economy and Europeans began to supply the Guinea-Bissau region with iron that Balanta began to cultivate large quantities of rice… (Hawthorns 2001, p. 21)"

Since they were patrilineal in descent, "[w]omen and boys could be absorbed as slaves, but not males beyond the age of initiation (Hawthorne, 1999; Klein, 2001)." As for political transformation,

> "As the distance between households diminished, Balanta refashioned their stateless social and political structures to foster broader, village-wide identities. Through those structures, the heads of households, b'lante b'ndang, organized large bodies of laborers to exploit the environment effectively (Hawthorne 2001, p. 19)."[9]

Where warfare and raiding had limited success, a trade diaspora could exploit intra-societal conflict and mobilized inside agents to do their bidding. The most important of these were the Luso-African traders of the upper Guinea coast (Green 2012), the Aro in the Bight of Biafra (Northrup 1978; Nwokeji 2010), the Maraka in the Senegambia region (Jobson 1932; Roberts 1987), the Bobangi in the Congo River basin (Harms 1981) and the Swahili along the east coast (Horton and Middleton 1988, Sheriff 2010). The Aro, like many of these trade diasporas, did not raid for slaves but incorporated slaves to facilitate trade and to protect those who wanted protection (having access to imported weapons). They bought and sold slaves, and provided the trade goods to exchange for them.

The Bobangi were an ethnic group that controlled an identifiable homeland, so they show up in the *Ethnographic Atlas*. They came to dominate a large stretch of the Congo River above Pool Malebo (formerly Stanley Pool) in one of the largest river systems in the world. In our dataset, the Bobangi (recorded as Bangi) were not victims of the slave trade, but all of the societies around them were, like the Teke, Sanga, Ngala and Sakata. The Bobangi controlled commerce on the massive Congo River by controlling the flow of imported guns. Skirmishes and internal conflicts within and between traditional fishing villages produced captives that the Bobangi bought and sold (Harms, 1981). By 1877, when Morton Stanley reaches this section of the Congo River from the east he encounters guns on the Congo river for the very first time and wonders why traders so involved in international trade could be so belligerent and unwelcoming (Stanley 1878, p. 297-302).

A third example comes from the Bambara of the Middle Niger Valley in the 18th century, which exhibits a full-blown transformation. According to Roberts (1980, 1987) traditional Bambara kinship economy was based on cereal agriculture augmented by hunting. Age sets institutionalized the intergenerational transfers of surplus. Membership was open to all children of the same age regardless of clan and often regardless of ethnic origin. The bachelor age set was the site of the most intense intergenerational conflict. Young men, wanting access to wives, were most conscious of the restrictions on marriage and access to eldership.[10] Around the beginning of the 18th century, Mamari Kulubali led his bachelor group through a series of altercations with elders. The elders eventually ostracized him from the community, but the sanction backfired as Mamari was able to convince many of the bachelors to follow him. After some initial successes through raids and battles, slaves and other young people joined Mamari in what amounted to the

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[9] On the technology of paddy rice production among the coastal mangroves, the demand for iron tools, and the resulting iron-slave cycle, see Hawthorne (2003).

[10] Over time and through negotiated compromise, the bachelor age group gained an independent administrative structure. They elected their own leaders who controlled recalcitrant members through judicial sanctions. They also provided public labor for widows, the sick, and other family units that lacked sufficient manpower, in exchange for which they received compensations that they taxed and consumed collectively (Roberts 1980. P. 404).

transformation of an agricultural age set into an offensive and militarized unit capable of reproducing itself.

The resulting Segu Bambara state apparatus was dependent upon warfare and produced little if any food, instead producing slaves and professional warriors who disdained agricultural production. Fulbe herdsmen, dependent upon Segu for protection, sent tribute in the form of cattle and slaves. Some slaves were recruited into the military, others were sold to Maraka merchants or sent directly to Kangaba or Jenne in exchange for horses, firearms, flints, sulfur, cloth and other luxury consumption goods. Maraka cities paid substantial taxes to the Segu Bambara state for protection, behind which they coordinated a slave plantation sector geared to the commercial production of cotton and cereals.

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