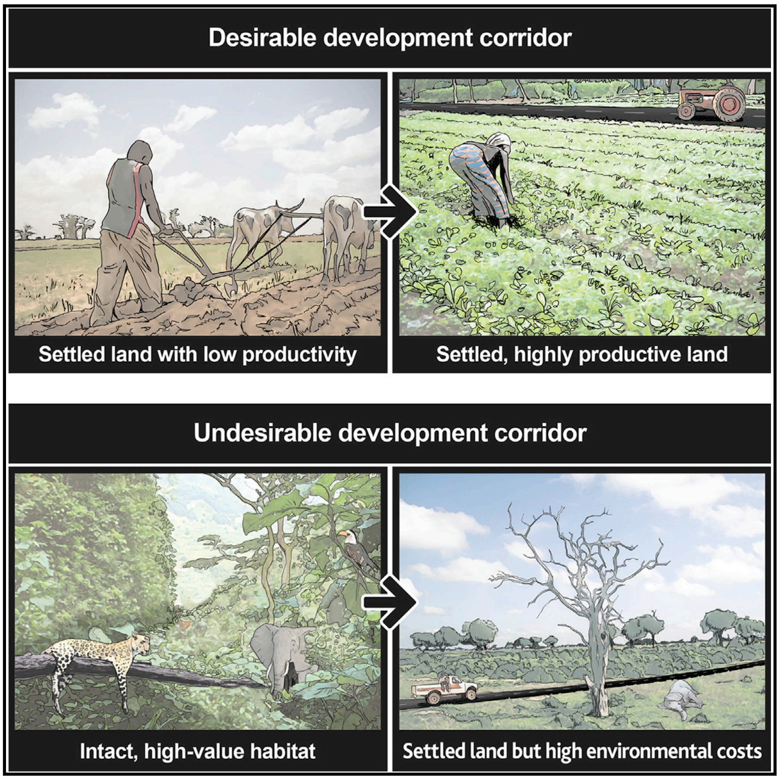
Report

Current Biology

Estimating the Environmental Costs of Africa's Massive "Development Corridors"

Graphical Abstract



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In Brief

Laurance et al. assess the potential environmental costs of 33 planned or progressing "development corridors" in Africa. If completed, the corridors would total over 53,000 km in length and are likely to imperil many African ecosystems. New corridors in equatorial forests and savanna woodlands are projected to have the greatest environmental costs.

Highlights

- Massive new "development corridors" will crisscross the African continent
- The corridors would open up sparsely populated regions to major development pressures
- Environmental costs would most likely be greatest in equatorial forests and savannas
- Some corridors have only limited prospects for increasing agricultural production

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Estimating the Environmental Costs of Africa's Massive ''Development Corridors''

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SUMMARY

In sub-Saharan Africa, dozens of major ''development corridors'' have been proposed or are being created to increase agricultural production [1–4], mineral exports [5–7], and economic integration. The corridors involve large-scale expansion of infrastructure such as roads, railroads, pipelines, and port facilities and will open up extensive areas of land to new environmental pressures [1, 4, 8]. We assessed the potential environmental impacts of 33 planned or existing corridors that, if completed, would total over 53,000 km in length and crisscross much of the African continent. We mapped each corridor and estimated human occupancy (using the distribution of persistent night-lights) and environmental values (endangered and endemic vertebrates, plant diversity, critical habitats, carbon storage, and climate-regulation services) inside a 50-km-wide band overlaid onto each corridor. We also assessed the potential for each corridor to facilitate increases in agricultural production. The corridors varied considerably in their environmental values, and many were only sparsely populated. Because of marginal soils or climates, some corridors appear to have only modest agricultural potential. Collectively, the corridors would bisect over 400 existing protected areas and could degrade a further ~1,800 by promoting habitat disruption near or inside the reserves. We conclude that many of the development corridors will promote serious and largely irreversible environmental changes and should proceed only if rigorous mitigation and protection measures can be employed. Some planned corridors with high environmental values and limited agricultural benefits should possibly be cancelled altogether.

RESULTS

Assessing the Development Corridors

We evaluated the development corridors using the framework for a ''global road-mapping strategy'' that aims to maximize the agricultural benefits of new or improved transportation projects while minimizing their environmental costs [8, 9]. This strategy involves limiting road expansion within relatively intact ecosystems with high environmental values while focusing road building in arable, already-settled lands where sizeable gaps exist between current and potential farm yields.

Improving agricultural yields and food security is a frequently invoked justification for the African development corridors [1–4], given the continent's rapidly growing human population, which is projected to increase nearly 4-fold this century [10]. Africa has large expanses of arable, settled land where farm yields are far less than optimal [11]. In these areas, new or upgraded roads could potentially help to raise yields by improving access to urban markets and promoting rural investments and better farming methods [1, 8]. With increasing agricultural productivity and rising profits, such areas might also act as ''magnets'' for colonists, drawing them away from vulnerable frontier areas and helping to promote land sparing for nature conservation [12, 13].

Spatial Scale of Corridors

We identified 33 unique development corridors (Figure 1), of which ten are active, nine are proposed for upgrading, and 14 are planned (Table 1). We separately classified different segments of a given corridor if they differed in being (1) already active, (2) slated for or undergoing major upgrading, or (3) planned for the future (Supplemental Experimental Procedures).

According to our analyses, the 33 corridors will total 53,226 km in length if completed in their entirety. Individual corridors would range in length from 363 km to 4,825 km, with a median length of 1,262 km (Table 1). Seven of the 33 corridors are spatially dominated by forests, three by desert shrubland habitats, and the remainder by savanna woodlands (Table 1).

Human Occupancy

To generate standardized comparisons, we overlaid a 50-km-wide band onto each corridor, centered on the road and/or railroad at the core of the corridor. We used satellite data to estimate relative human occupancy within the corridor-band based on the spatial distribution of persistent night-lights, using an ~1-km^2 pixel size. We employed a very low night-light threshold sufficient for detecting even dispersed, electrified rural settlements, although this would not reveal settlements entirely lacking night-lights (Supplemental Experimental Procedures).

We found two striking results. First, the corridors differed greatly in their apparent human occupancy, with the incidence

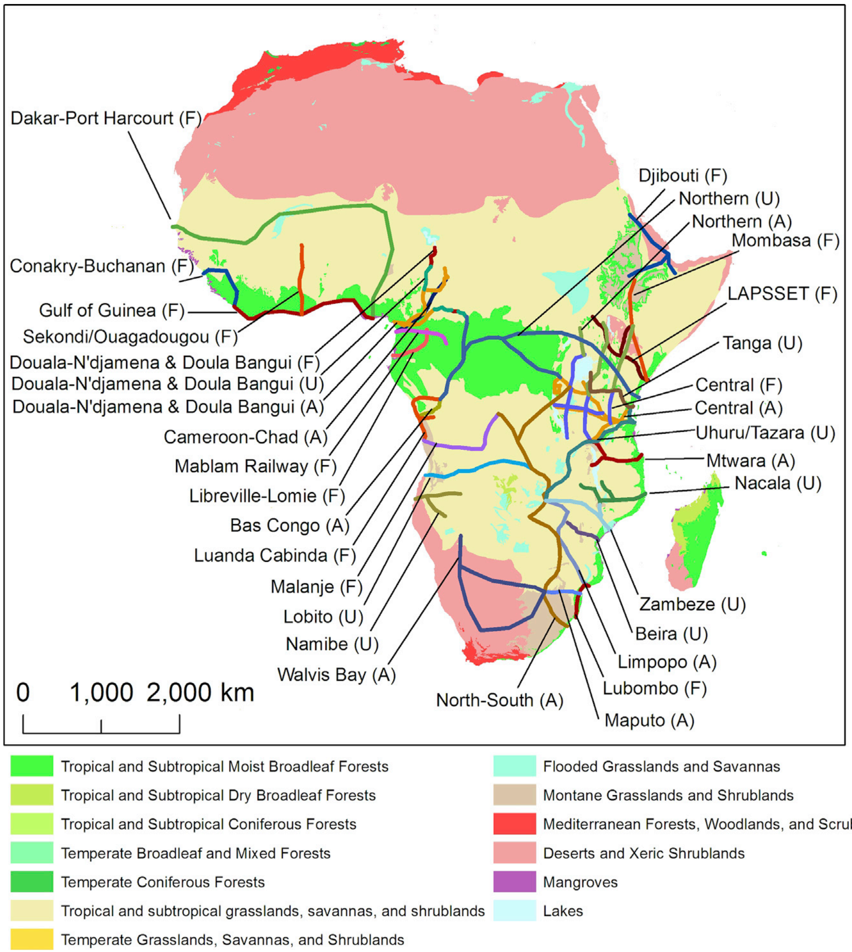

Figure 1. Development Corridors in Sub-Saharan Africa

Nearby or overlapping corridors are distinguished by different colors. The current status of each corridor is indicated in parentheses (A, already active; F, planned for the future; U, upgrade planned or underway).

of detectable night-lights varying from 0.7% to 45.7% of the total area of each corridor band (Table 1). These occupancy values did not differ significantly among forested, savanna woodland, and desert shrubland biomes ($F_{2,30}$ = 2.76, p = 0.08; one-way ANOVA). Second, most corridors were only sparsely populated, with only eight having >10% of their pixels with night-lights and just two having >30% of their pixels with night-lights. These results were robust to the size of the sampling unit used and differing spatial patterns of human settlement (Supplemental Experimental Procedures).

Environmental Values

We estimated a composite index of environmental values for each corridor band based on a previously integrated dataset [8] on threatened vertebrate species, vascular-plant diversity, key wildlife habitats and wilderness values, and the carbon storage and local climate-stabilizing capacity of native vegetation, generated for Earth's entire ice-free land surface (Supplemental Experimental Procedures). Index values for each 1-km^2 pixel were averaged across each corridor band (0, lowest value globally; 1, highest value globally).

The 33 corridors had widely varying environmental values (Table 1). Values differed significantly among biomes ($F_{2,30}$ = 13.17, p = 0.0001; one-way ANOVA), with those dominated by forests ($\bar{X}$ ± SD = 0.41 ± 0.09) being higher (p < 0.001; Tukey's tests) on average than those dominated by savanna woodlands (0.25 ± 0.07) or desert shrublands (0.19 ± 0.06).

Conservation Priority

We reasoned that corridors that combined both high environmental values and low human occupancy should be regarded as having the highest overall conservation priority, and vice versa. Environmental and human-occupancy values were not significantly correlated (r = 0.069, p = 0.70; Pearson correlation with arsine-squareroot-transformed occupancy data). To combine the two metrics into a single index, we rescaled values for each from 0 (lowest priority) to 1 (highest priority) and then averaged them for each corridor.

Conservation-priority values differed significantly among biome types ($F_{2,30}$ = 6.77, p = 0.0037; one-way ANOVA), with forests (0.75 ± 0.19) and savanna woodlands (0.62 ± 0.10) having higher values on average (p < 0.01 and p < 0.05, respectively; Tukey's tests) than desert shrublands (0.40 ± 0.18). Exceptionally high (>0.75) conservation values were evident for equatorial corridors in densely forested areas of the greater Congo Basin (M'Balam Railway, Libreville-Lomie, and Northern Upgrade) and West Africa (Conakry-Buchanan), as well as some equatorial savanna woodland areas (Uhuru-Tazara and Mtwara) in East Africa (Table 1; Figure 1). On average, there was no significant difference (t = 0.49, degrees of freedom [df] = 31, p = 0.63; two-sample t test) in conservation-priority values between the 14 planned corridors (0.65 ± 0.17) and the 19 corridors that exist or are currently being upgraded (0.62 ± 0.16).

Protected Areas

The 33 corridors would have major impacts on existing protected areas (Figure 2; Supplemental Experimental Procedures). Using spatial data from the World Database on Protected Areas (http://www.protectedplanet.net), we found that the roads and/or railroads at the heart of the corridors would bisect a total of 408 protected areas while cutting through a total of 5,742 km of protected habitat (Table 1). Among the affected protected areas, 29 would be intersected by two or more corridor systems.

If one includes the 50-km-wide band overlaying each corridor, then 2,168 protected areas would fall at least partially within one corridor band. Of these, 675 would be overlapped by two or

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Table 1. Attributes of 33 Development Corridors in Sub-Saharan Africa, Ranked from Their Highest to Lowest Estimated Conservation Priority

								Bisected by Road and/or Railroad		Overlapped by 50-km-wide Corridor Band		
Corridor Name	Status	Type	Length (km)	Environ. Value[a]	Human Occupancy[b]	Conservation Priority[c]	Agricult. Potential[a]	No. PAs[d]	Length (km)	No. PAs[d]	Affected Area (km^2)	Major Biome[e]
M'Balam Railway	future	road/rail	715	0.53	0.7	0.989	0.36	19	438.9	38	19,180	forest
Libreville-Lomie	future	road/rail	636	0.54	4.2	0.961	0.38	2	40.9	22	4,999	forest
Northern	upgrade	road/rail	4,825	0.40	2.9	0.820	0.59	40	545.3	247	29,865	forest
Uhuru/Tazara	upgrade	road/rail	1,902	0.38	1.4	0.815	0.70	29	301.7	252	15,503	savanna
Conakry-Buchanan	future	rail/pipeline	803	0.36	2.0	0.786	0.64	6	50.9	23	2,498	forest
Mtwara	active	road/rail	1,054	0.33	1.8	0.755	0.68	8	120.6	147	4,729	savanna
Douala-N'djamena and Douala- Bangui	active	road/rail	1,857	0.33	1.9	0.754	0.53	6	75.5	21	3,942	savanna
Tanga	upgrade	road/rail	922	0.33	4.2	0.728	0.71	17	140.3	190	11,981	savanna
Central	active	road/rail	3,379	0.32	3.3	0.727	0.70	42	824.5	235	41,170	savanna
Central	future	road/rail	2,820	0.31	2.4	0.726	0.68	50	1141.1	359	56,891	savanna
Lobito	upgrade	road/rail	1,419	0.29	3.5	0.692	0.65	2	6.4	16	1,700	savanna
Cameroon-Chad	active	rail/pipeline	951	0.29	3.8	0.688	0.50	7	58.7	9	2,065	forest
Mombasa Corridor	future	road/rail	1,325	0.27	2.6	0.679	0.49	4	229.7	18	13,291	savanna
Nacala	upgrade	road/rail	1,291	0.27	4.1	0.662	0.64	3	47.2	37	2,324	savanna
Northern	active	road/rail	2,221	0.24	2.8	0.644	0.58	28	326.3	211	17,203	savanna
Malanje	future	road/rail	1,262	0.24	3.1	0.640	0.66	0	0	1	64	savanna
Zambeze	upgrade	road/rail	1,148	0.20	1.5	0.614	0.55	4	146.4	54	8,722	savanna
LAPSSET	future	rail/pipeline	1,617	0.19	0.8	0.611	0.46	30	327.2	132	15,481	savanna
Namibe	upgrade	road/rail	945	0.23	4.8	0.610	0.68	0	0	2	1,307	savanna
Sekondi/Ouagadougou	future	road/rail	899	0.30	12.3	0.605	0.54	14	213.8	81	8,597	savanna
Djibouti	future	road/rail	1,571	0.22	4.4	0.603	0.48	4	134.5	10	6,752	desert
Lubombo	future	road/rail	499	0.36	18.7	0.600	0.53	5	22.6	30	2,340	forest
North-South	active	road/rail	4,441	0.28	12.0	0.586	0.61	34	315	252	18,591.3	savanna
Douala-N'djamena and Douala- Bangui	upgrade	road/rail	698	0.16	1.5	0.570	0.52	1	3.1	6	2,133	savanna
Douala-N'djamena and Douala- Bangui	future	road/rail	363	0.11	1.2	0.516	0.51	4	3.5	6	2,205	savanna
Luanda Cabinda	future	rail/pipeline	1,089	0.23	13.3	0.516	0.65	5	71.9	9	1,933	savanna
Limpopo	active	road/rail	1,424	0.16	6.4	0.515	0.54	20	336.5	77	18,764	savanna
Beira	upgrade	road/rail	479	0.24	14.5	0.514	0.58	0	0	3	325	savanna
Bas Congo	active	road/rail	415	0.20	14.6	0.468	0.67	0	0	8	871	savanna
Walvis Bay Corridors	active	road/rail	3,454	0.10	8.4	0.426	0.47	14	422.5	86	17,326	desert

(*Continued on next page*)

Table 1. *Continued*

								Bisected by Road and/or Railroad		Overlapped by 50-km-wide Corridor Band		
Corridor Name	Status	Type	Length (km)	Environ. Value[a]	Human Occupancy[b]	Conservation Priority[c]	Agricult. Potential[a]	No. PAs[d]	Length (km)	No. PAs[d]	Affected Area (km^2)	Major Biome[e]
Dakar-Port Harcourt	future	road/rail	4,349	0.09	8.4	0.415	0.56	20	280.0	114	18,888	savanna
Gulf of Guinea	future	road/rail	1,995	0.37	37.1	0.407	0.56	14	213.7	79	11,072	forest
Maputo	active	road/rail	458	0.24	45.7	0.167	0.46	5	6.4	68	1,206	desert

See also Figures S1–S4.

[a] Relative to all terrestrial ecosystems globally (0–1 scale), as estimated by [8].

[b] Percentage of all 1-km^2 cells within each polygon with persistent night-lights.

[c] Scaled from 0–1, with 1 indicating the highest relative conservation priority.

[d] Protected areas (PAs) mapped in the World Database on Protected Areas (http://www.protectedplanet.net).

[e] "Forest," tropical and subtropical broadleaf forests, mangroves, temperate broadleaf and mixed forests, coniferous forests, and boreal forests; "savanna," grasslands, savannas, shrublands, and woodlands at varying latitudes; "desert," deserts and xeric shrublands, montane grasslands and shrublands, and tundra.

more bands (Table 1). An estimated 276,236 km^2 of protected-area habitat would fall within at least one corridor band.

Among the 33 corridors, corridor length was the only significant predictor of the magnitude of impacts on protected areas. Longer corridors altered a significantly greater number, intersected length, and amount of habitat ($F_{1,30}$>16.4, p $\leq$ 0.0003) of protected areas, whereas biome type was not significant ($F_{1,30} \leq 2.9$, p $\geq$ 0.11) in any case (analysis of covariance with log-transformed values).

Potential Agricultural Benefits

The estimated potential for transportation improvements to increase agricultural production [8] varied considerably among the corridors (Table 1; Supplemental Experimental Procedures). Mean values varied among biome types ($F_{2,30}$ = 6.22, p = 0.0055; one-way ANOVA), being significantly (p < 0.05) higher in savanna woodlands ($\overline{X}$ ± SD = 0.60 ± 0.07) than in forests (0.51 ± 0.10) or desert shrublands (0.47 ± 0.01).

Notably, the 14 planned corridors had lower agricultural potential (*t* = 2.03, df = 31, p = 0.05; two-sample t test) on average (0.53 ± 0.10) than did the 19 corridors that already exist or are being upgraded (0.60 ± 0.08) (Table 1). This might arise because a larger fraction of the planned corridors occur in forested areas (36%), which have lower agricultural potential than do those in savanna woodlands, compared to the corridors that exist or are being upgraded (11%).

Finally, the agricultural-potential index was not significantly correlated with the environmental-value (*r* = −0.011, p = 0.63), human-occupancy (*r* = −0.129, p = 0.47), or overall conservation-value (*r* = 0.025, p = 0.89) metrics (Pearson correlations, n = 33). This suggests, optimistically, that there may be only limited direct tradeoffs between the environmental costs and potential agricultural benefits of the 33 corridors (Figure 3).

DISCUSSION

Explosive Change

It is possible that, in recorded history, no continent has ever changed as rapidly as is presently occurring in Africa. For instance, the extractive-industries boom in Africa is notable not so much for its direct effects—which will be substantial [5, 14]—but for the powerful economic impetus it is providing for new roads and railways needed for extracting high-volume minerals such as iron and coal [1, 5]. Development corridors promoted by Africa's mineral boom are also seen as prime locations to expand and intensify agriculture [1–4]. Will these corridors focus and improve agriculture in already-settled areas, thereby sparing other lands for nature conservation, or will they simply increase the scale and pace of environmental degradation?

Our analyses suggest that different development corridors in Africa are likely to have highly variable agricultural benefits and environmental costs. Many corridors are likely to attract large-scale immigration, including legal and illegal miners, commercial agricultural interests, and colonists seeking newly accessible farming or grazing areas [1, 5]. Our comparisons suggest that (1) the vicinities of most (>75%) corridors are currently only sparsely populated; (2) the proposed corridors will be most numerous and extensive in the vast Guinea and Miombo savanna woodlands but will also have sizeable impacts on

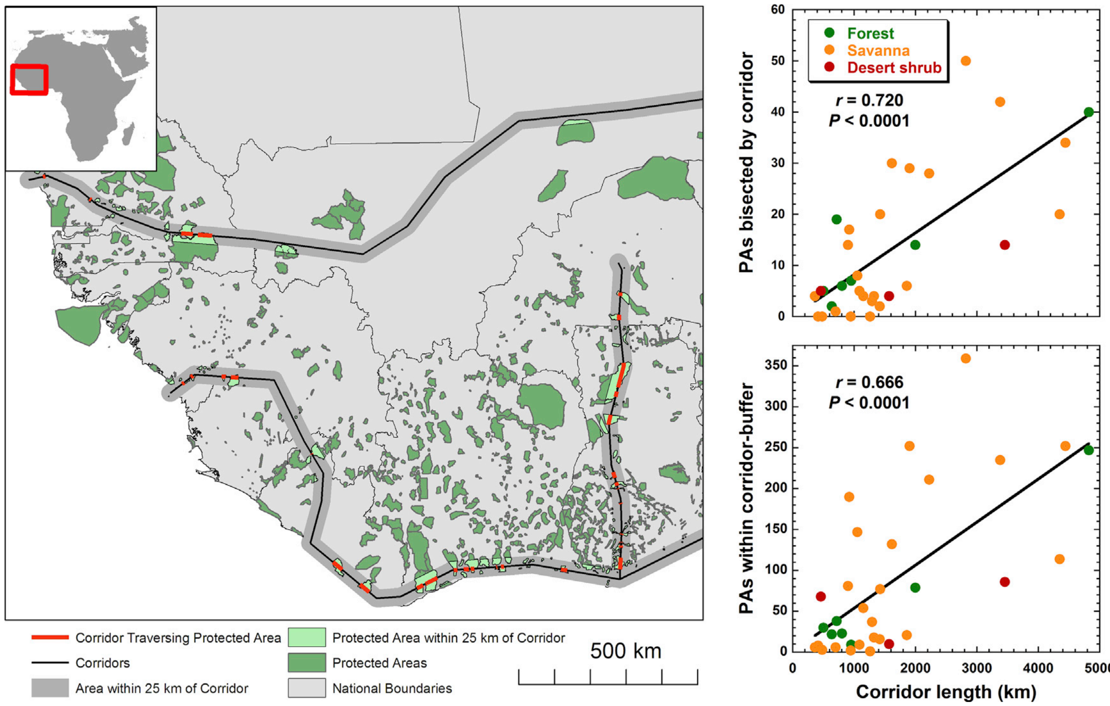

Figure 2. Effects of 33 Development Corridors on Protected Areas in Sub-Saharan Africa

Left: West African protected areas bisected by a corridor road or railroad (red lines) or overlapped by a 50-km-wide band centered on the road or railroad (pale green). Right: For each corridor, the number of protected areas bisected by the road or railroad (above) or overlapped at least partially by the 50-km-wide band (below), as a function of corridor length.

tropical forests and some desert shrublands; (3) the environmental and conservation values of affected habitats will be especially high for forests and savanna woodlands in equatorial regions; (4) the corridors (especially longer corridors) will impact on many protected areas, either by bisecting them (over 400 designated protected areas) or by increasing land-use pressures around reserves and hunting and encroachment inside reserves [15]; (5) the potential for the corridors to generate agricultural benefits is generally greater in savanna woodlands than in dense forests or desert shrublands; (6) the 14 corridors that are currently being planned (Table 1; Figure 3) are likely to yield relatively low agricultural benefits; and (7) there is little association between the potential agricultural benefits and estimated conservation value of each corridor (Figure 3).

Development corridors are seen in many quarters as desirable for Africa, particularly given the continent's escalating population [10], generally underperforming agriculture [11], and growing food-security concerns [1–4, 16]. For such reasons, the corridors are likely to be the focus of near-term investment and development assistance. Our findings suggest that a carefully selected subset of the existing and proposed corridors could generate sizeable agricultural benefits while having limited environmental costs. Based on our analysis, the 33 corridors appear to be divisible into three broad categories (Figure 3): (1) five "promising" corridors with relatively low conservation values and a large potential to benefit agriculture; (2) 22 "marginal" corridors, evenly divided between those with either high conservation values and high potential agricultural benefits or low agricultural benefits and low conservation values; and (3) six "inadvisable" corridors with high conservation values and low potential agricultural benefits.

We assert that corridors in the "marginal" and especially the "inadvisable" categories (Figure 3) should be implemented only with a clear focus on limiting their environmental impacts via stringent land-use zoning, improved law enforcement, and other mitigation and offset strategies [5, 16, 17]. The high environmental costs and modest agricultural benefits of some corridors could provide a rationale for curtailing or cancelling them. Notably, three of the inadvisable corridors (M'Balam Railway, Libreville-Lomie, and Mombasa Corridor) and ten of the marginal corridors (Conakry-Buchanan, Central-Future, Melanje, LAPSSET, Sekondi/Ouagadougou, Djibouti, Lubombo, Douala-N'djamena and Douala-Bangui-Future, Dakar-Port Harcourt, and Gulf of Guinea) are still in the planning stages (Table 1). On average, these planned corridors have significantly lower agricultural potential than do those that already exist or are currently being upgraded (Table 1). This suggests that at least some of the planned corridors are poorly justified from a food-security perspective.

Further Considerations

At least three additional factors are relevant to cost-benefit analyses for the 33 development corridors. First, a number of the corridors are being promoted by plans for large-scale mining projects [1, 5–7], which can yield considerable (although not necessarily socially equitable) financial benefits. This clearly will be a consideration for affected governments, investors, and other corridor proponents. The second is the physical length

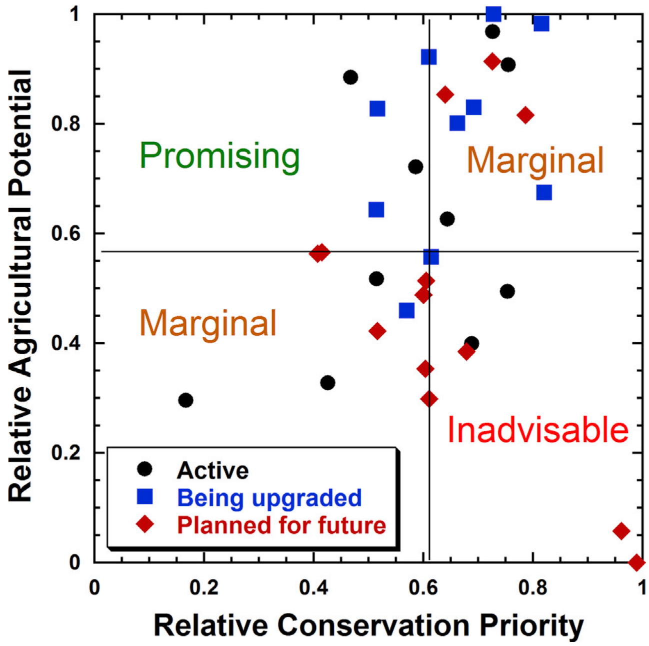

Figure 3. Categorization of 33 African Development Corridors by Estimates of Their Relative Conservation Priority and Potential to Yield Agricultural Benefits

Both axes were rescaled from 0–1 to facilitate comparisons. Dark lines indicate median values on each axis. There is no significant relationship between the two variables ($r = 0.025$, $p = 0.89$; Pearson correlation).

of the corridor, because longer corridors impact larger areas of habitat and promote the degradation of more protected areas relative to shorter corridors. The impact of an individual corridor on protected areas is approximately linearly proportional to its length (Figure 2; Table 1).

Finally, in terms of their environmental costs, one can make a strong case for limiting the geographic spread of new corridors, especially into sparsely populated areas and those in environmentally important regions. Habitat disruption tends to spread contagiously around roads and other transportation infrastructure [13, 18], with the first colonists arriving in an area typically causing more habitat degradation per capita than do those who arrive later [13]. To facilitate commercial agriculture, the best locations for new or improved roads are within a few hours of urban areas, to limit transportation costs and shipping-related crop spoilage [8]. In the coming decades, cities, which provide major markets for commercial farmers, are projected to grow very rapidly in parts of Africa [19]. Hence, consolidating and geographically focusing the development corridors within populated areas or those projected to grow rapidly would be highly desirable from an environmental perspective [20], rather than having them penetrate remote hinterlands or crisscross large expanses of the African continent. That some projected urban-growth areas overlap strongly with critical biodiversity hotspots, such as the Eastern Afromontane region and Guinean forests of West Africa [19], underscores the urgent need for strategic land-use planning and zoning in sub-Saharan Africa.

Our conclusions should be qualified by two caveats. First, the size of the 50-km-wide band that we used to estimate the landscape-scale impacts of new roads or railroads is arbitrary—a plausible value that allowed us to make standardized comparisons among the different development corridors. Halo effects from human activities around roads and other transportation infrastructure can range from ~10 km wide (for Amazon deforestation [21]) to ~80 km wide or more (for Amazonian fires [22] and hunting-related declines of African forest elephants [23]). Furthermore, major paved roads often spawn networks of secondary and tertiary roads that can greatly increase the spatial scale of habitat disruption [24]. For instance, the first paved highway in the Brazilian Amazon, completed in the early 1970s, has today evolved into an ~400-km-wide slash of forest destruction across the eastern Amazon basin [13]. Hence, our conclusions, particularly regarding the potential for the development corridors to degrade current protected areas (Figure 2; Table 1), could be conservative. This is an alarming prospect, given that protected areas already fail adequately to conserve the diverse range of African ecosystems [25, 26] and wildlife [27–29].

Second, our analysis focuses on the largest and most ambitious slate of projects in Africa—the massive development corridors—but it is not all encompassing. Africa is, for example, also experiencing rapid expansion of energy infrastructure, such as complexes of major hydroelectric dams, construction roads, and power lines in the Congo Basin [30]. Like the development corridors, some of these projects will have far-reaching impacts on African ecosystems.

Conclusions

African environments are being altered at an explosive pace. A key priority in the coming decades will be increasing agricultural production and efficiency to improve food security and alleviate poverty for Africa's rapidly growing population [31] while harnessing the unprecedented scale of foreign investments focusing on land [32] and natural-resource [5–7, 33–35] exploitation. The success or failure of these efforts will be influenced heavily by Africa's development corridors, which will strongly affect future patterns of mining, land occupation, agriculture, and associated development pressures. Our analysis suggests that, as currently planned, a number of the development corridors would yield only limited agricultural benefits while severely degrading African ecosystems and wildlife. Concerted efforts are needed to reduce and mitigate these impacts.

SUPPLEMENTAL INFORMATION

Supplemental Information includes Supplemental Experimental Procedures and four figures and can be found with this article online at http://dx.doi.org/10.1016/j.cub.2015.10.046.

AUTHOR CONTRIBUTIONS

W.F.L. coordinated the study and wrote the manuscript. S.S. conducted the spatial analyses. L.W. and J.A.S. collected data on African development corridors.

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REFERENCES

1. Weng, L., Boedhihartono, A.K., Dirks, P., Dixon, J., Lubis, M.I., and Sayer, J.A. (2013). Mineral industries, growth corridors and agricultural development in Africa. Glob. Food Secur. *2*, 195–202.
2. Anon. (2011) The hopeful continent: Africa rising. The Economist, December 3, 2011. http://www.economist.com/node/21541015.
3. Delgado, C., Hopkins, J., Kelly, V., Hazell, P., McKenna, A., Gruhn, P., Hojjati, B., Sil, J., and Courbois, C. (1998). Agricultural Growth Linkages in Sub-Saharan Africa (International Food Policy Research Institute).
4. African Agricultural Development Company (2013). Developing sustainable agriculture in Africa. http://www.agdevco.com/about_us.php.
5. Edwards, D.P., Sloan, S., Weng, L., Sayer, J., Dirks, P., and Laurance, W.F. (2014). Mining and the African environment. Conserv. Lett. *7*, 302–311.
6. Taylor, C.D., Schulz, K.J., Doebrich, J.L., Orris, G.J., Denning, P.D., and Kirschbaum, M.J. (2009). Geology and nonfuel mineral deposits of Africa and the Middle East. U.S. Geological Survey Open-File Report 2005–1294-E. http://pubs.usgs.gov/of/2005/1294/e/index.htm.
7. Zhang, H., and Wilkes, A. (2010). Trends in Chinese Trade and Investment in Africa's Mining Sector (Chinese Academy of Land Resources and Economy).
8. Laurance, W.F., Clements, G.R., Sloan, S., O'Connell, C.S., Mueller, N.D., Goosem, M., Venter, O., Edwards, D.P., Phalan, B., Balmford, A., et al. (2014). A global strategy for road building. Nature *513*, 229–232.
9. Laurance, W.F., and Balmford, A. (2013). Land use: A global map for road building. Nature *495*, 308–309.
10. United Nations (2015). World Population Prospects: The 2015 Revision (U.N. Population Division).
11. Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., and Foley, J.A. (2012). Closing yield gaps through nutrient and water management. Nature *490*, 254–257.
12. Rudel, T.K. (2005). Tropical Forests: Regional Paths of Destruction and Regeneration in the Late Twentieth Century (Columbia University Press).
13. Laurance, W.F., Goosem, M., and Laurance, S.G. (2009). Impacts of roads and linear clearings on tropical forests. Trends Ecol. Evol. *24*, 659–669.
14. Durán, A.P., Rauch, J., and Gaston, K.J. (2013). Global spatial coincidence between protected areas and metal mining activities. Biol. Conserv. *160*, 272–278.
15. Laurance, W.F., Useche, D.C., Rendeiro, J., Kalka, M., Bradshaw, C.J.A., Sloan, S.P., Laurance, S.G., Campbell, M., Abernethy, K., Alvarez, P., et al. (2012). Averting biodiversity collapse in tropical forest protected areas. Nature *489*, 290–294.
16. Laurance, W.F., Sayer, J., and Cassman, K.G. (2014). Agricultural expansion and its impacts on tropical nature. Trends Ecol. Evol. *29*, 107–116.
17. Laurance, W.F., Peletier-Jellema, A., Geenen, B., Koster, H., Verweij, P., Van Dijck, P., Lovejoy, T.E., Schleicher, J., and Van Kuijk, M. (2015). Reducing the global environmental impacts of rapid infrastructure expansion. Curr. Biol. *25*, R259–R262.
18. Boakes, E.H., Mace, G.M., McGowan, P.J.K., and Fuller, R.A. (2010). Extreme contagion in global habitat clearance. Proc. Biol. Sci. *277*, 1081–1085.
19. Seto, K.C., Güneralp, B., and Hutyra, L.R. (2012). Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proc. Natl. Acad. Sci. USA *109*, 16083–16088.
20. Rhodes, J.R., Lunney, D., Callaghan, J., and McAlpine, C.A. (2014). A few large roads or many small ones? How to accommodate growth in vehicle numbers to minimise impacts on wildlife. PLoS ONE *9*, e91093.
21. Barber, C.P., Cochrane, M.A., Souza, C.M., Jr., and Laurance, W.F. (2014). Roads, deforestation, and the mitigating effect of protected areas in the Amazon. Biol. Conserv. *177*, 203–209.
22. Adeney, J.M., Christensen, N.L., and Pimm, S.L. (2009). Reserves protect against deforestation fires in the Amazon. PLoS ONE *4*, e5014.
23. Blake, S., Strindberg, S., Boudjan, P., Makombo, C., Bila-Isia, I., Ilambu, O., Grossmann, F., Bene-Bene, L., de Semboli, B., Mbenzo, V., et al. (2007). Forest elephant crisis in the Congo Basin. PLoS Biol. *5*, e111.
24. Fearnside, P.M., and de Alencastro Graça, P.M. (2006). BR-319: Brazil's Manaus-Porto Velho highway and the potential impact of linking the arc of deforestation to central amazonia. Environ. Manage. *38*, 705–716.
25. Rodrigues, A.S.L., Andelman, S.J., Bakarr, M.I., Boitani, L., Brooks, T.M., Cowling, R.M., Fishpool, L.D.C., Da Fonseca, G.A.B., Gaston, K.J., Hoffmann, M., et al. (2004). Effectiveness of the global protected area network in representing species diversity. Nature *428*, 640–643.
26. Butchart, S.M., Clarke, M., Smith, R.J., Sykes, R.E., Scharlemann, J.P.W., Harfoot, M., Buchanan, G.M., Angulo, A., Balmford, A., Bretzky, B., et al. (2015). Shortfalls and solutions for meeting national and global conservation area targets. Conserv. Lett. *8*, 329–337.
27. Riggo, J., Jacobson, A., Dollar, L., Bayer, H., Becker, M., Dickman, A., Funston, P., Groom, R., Henschel, P., de Iongh, H., et al. (2013). The size of savannah Africa: a lion's (*Panthera leo*) view. Biodivers. Conserv. *22*, 17–35.
28. Blake, S., Deem, S.L., Strindberg, S., Maisels, F., Momont, L., Isia, I.-B., Douglas-Hamilton, I., Karesh, W.B., and Kock, M.D. (2008). Roadless wilderness area determines forest elephant movements in the Congo Basin. PLoS ONE *3*, e3546.
29. Dobson, A.P., Borner, M., Sinclair, A.R.E., Hudson, P.J., Anderson, T.M., Bigurube, G., Davenport, T.B.B., Deutsch, J., Durant, S.M., Estes, R.D., et al. (2010). Road will ruin Serengeti. Nature *467*, 272–273.
30. Pearce, F. (2013). Will huge new hydro projects bring power to Africa's people? Yale Environment 360, May 30, 2013. http://e360.yale.edu/feature/will_huge_new_hydro_projects_bring_power_to_africas_people/2656/.
31. Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., et al. (2011). Solutions for a cultivated planet. Nature *478*, 337–342.
32. Cotula, L., Vermeulen, S., Leonard, R., and Keeley, J. (2009). Land grab or development opportunity? Agricultural investment and international land deals in Africa (IIED/FAO/IFAD). http://www.ifad.org/pub/land/land_grab.pdf.
33. Laurance, W.F. (2014). Africa's ecosystems imperiled by mining frenzy. The Ecologist, June 24, 2014. http://www.theecologist.org/News/news_analysis/2449005/africas_ecosystems_imperilled_by_mining_frenzy.html.
34. Caro, T, Dobson, A., Marshall, A.J., and Peres, C.A. (2014). Compromise solutions between conservation and road building in the tropics. Curr. Biol. *24*, R722–R725.
35. Searchinger, T.D., Estes, L., Thornton, P.K., Beringer, T., Notenbaert, A., Rubenstein, D., Heinlich, R., Licker, R., and Herrero, M. (2015). High carbon and biodiversity costs from converting Africa's wet savannahs to cropland. Nature Clim. Change *5*, 481–486.

Current Biology
Supplemental Information

Estimating the Environmental Costs of Africa's Massive "Development Corridors"

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Supplemental Information

Supplemental Experimental Procedures

Spatial Scale of Development Corridors

To identify the 33 corridors, we used data from Weng et al. [S1] augmented with additional data collected by Lingfei Weng as part of her doctoral thesis [S2]. These data were collected from a wide range of sources (summarized in [S2]), including online information, technical reports, and personal interviews in Africa. Weng et al. [S1] originally mapped 29 African development corridors classed as having an operational, in-construction, or planned status in whole or in part. On this basis we defined 33 corridors of unique name and status (Table 1), spanning 38 countries in sub-Saharan Africa.

Spatial data on the corridors and their attributes were analyzed using ArcGIS (http://www.esri.com/software/arcgis/arcinfo). Each corridor was classified by its spatially most prevalent biome type, using three broad biome categories: (1) forest (tropical and subtropical broadleaf forests, mangroves, temperate broadleaf and mixed forests, coniferous forests, boreal forests); (2) savanna or savanna-woodland (grasslands, savannas, shrublands, and woodlands at varying latitudes) and (3) desert-shrubland (deserts and xeric shrublands, montane grasslands and shrublands, tundra). To generate this classification, biome data (http://sedac.ciesin.columbia.edu/data/collection/nagdc/maps/gallery/search?facets=region:africa) were overland onto the 50 km-wide band centered on each corridor or corridor segment.

Human Occupancy

We estimated human occupancy within each corridor as the percentage of pixels within its 50 km-wide band that showed evidence of persistent nightlights. Only persistent lights were considered to minimize ephemeral light sources such as wildfires in the analysis. Nightlight data came from the OLS-DMSP satellite in 2010 [S3]. This sensor records luminosity on a 64-point scale using a pixel size of ~1 km resolution. We defined any pixel with nightlight values of ≥1 as being occupied. We used this low threshold because many undeveloped or rural areas may have only limited illumination. Prior analyses by Sloan et al. [S4] suggest that a threshold of ≥1 would detect even dim, dispersed electrified rural settlements and infrastructure, although structures that lack any persistent nightlights would not be detectable.

We assessed the sensitivity of our estimates of human occupancy to the clustering (or uneven distribution) of nightlights within the corridors. We did so because one might expect human impacts to differ between two corridors with identical human populations if one had its lights strongly clumped (such as in a few cities) whereas the other had its lights dispersed much more evenly (suggesting a more widespread rural population, and generally greater human impact). To test for this potentially confounding factor, we compared estimates of nightlight incidence for each corridor using two dramatically different sample areas, 1 km^2 (1 x 1 km) versus 500 km^2 (10 x 50 km), as illustrated for corridors in West Africa (Fig. S1). If differences in spatial pattern were important, then the two differing sample areas should yield quite different nightlight estimates.

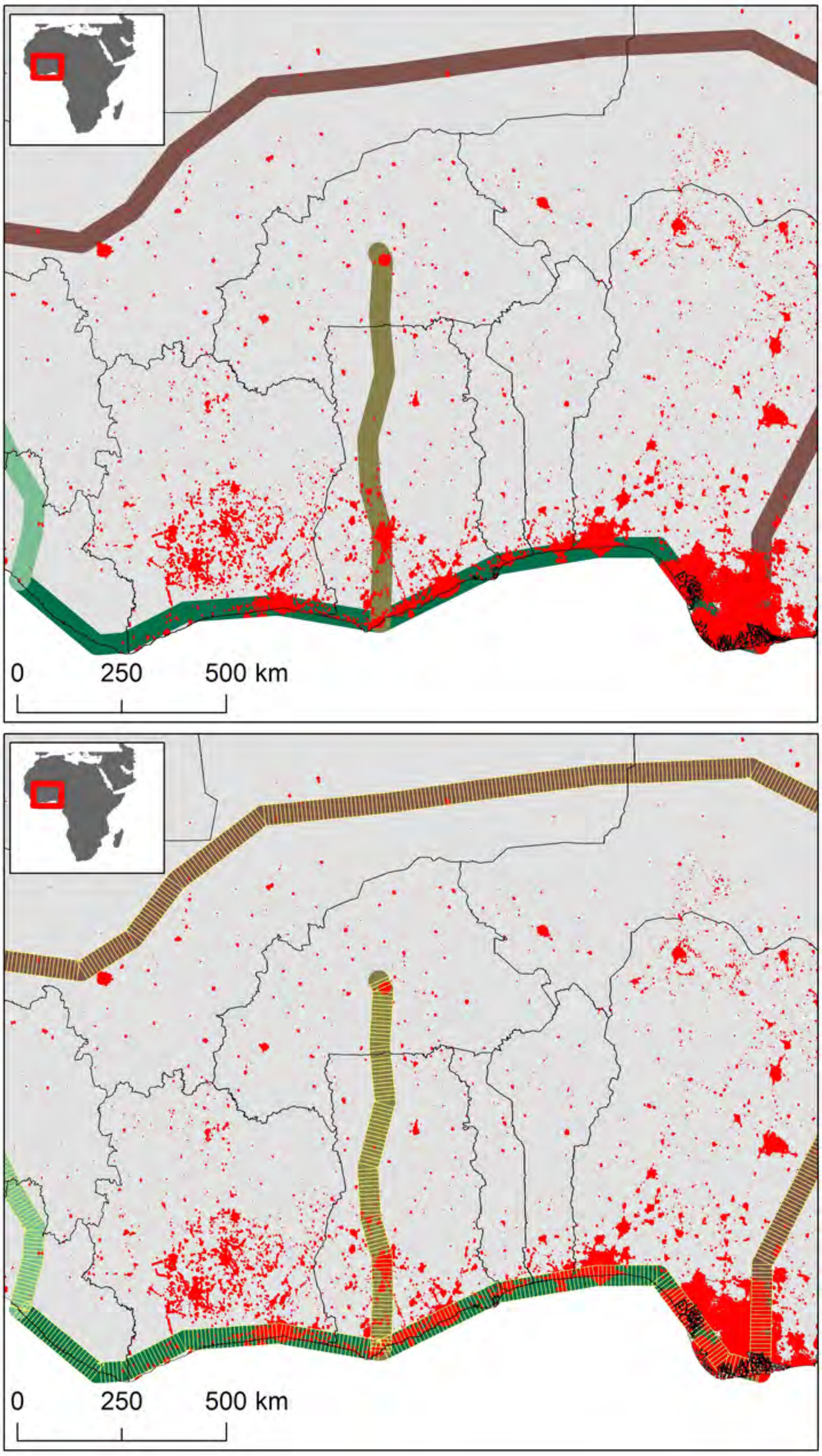

Fig. S1. Comparison of small (above) and large (below) sample areas for estimating nightlight incidence in West African development corridors. Nightlights are shown in red. This figure relates to Table 1.

When nightlight estimates were generated for each corridor using these two different sample areas, the values were very comparable (Fig. S2). For each method, percentage-nightlight data were adjusted using angular (arcsine-squareroot) transformations, as is appropriate for proportional data. The strong, linear relationship between nightlight frequencies generated using the two sampling areas suggests that any differences in the spatial pattern of nightlights among corridors was not an important confounding factor. Hence, our analysis provided a reasonably robust measure of nightlight incidence for each corridor.

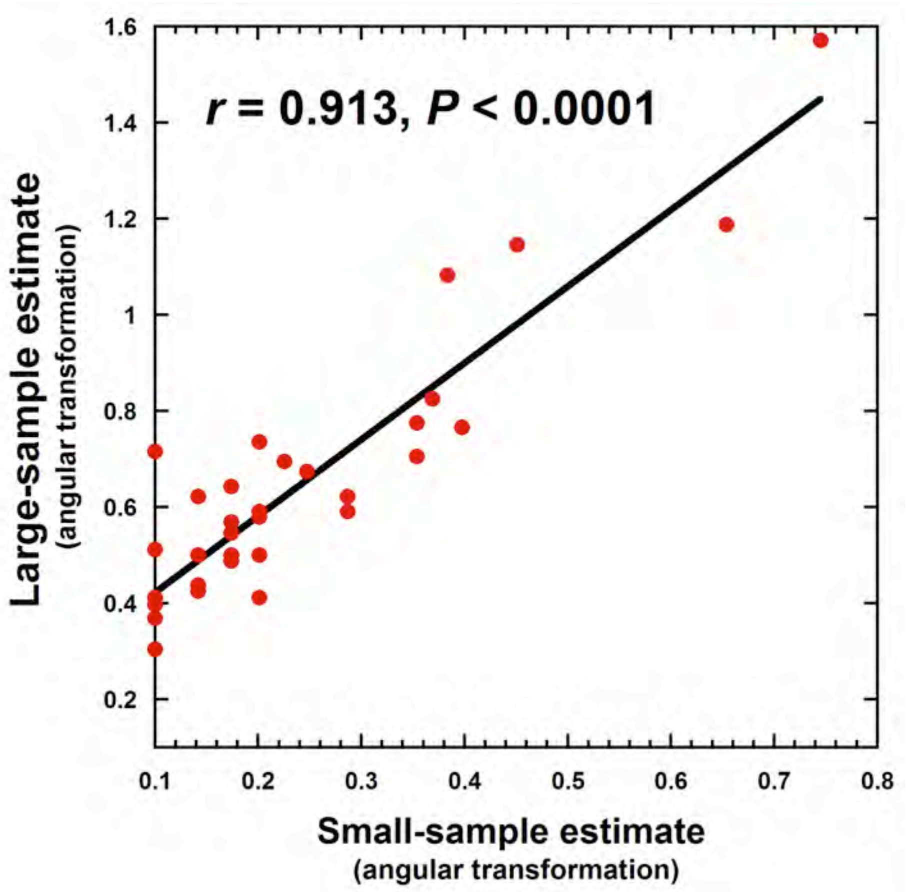

Fig. S2. Comparison of nightlight-frequency estimates for 33 African development corridors using small (1 km^2) and large (500 km^2) samples. This figure relates to Table 1.

Environmental Values

We estimated a composite index of natural values for the 50 km-wide band overlaying each corridor based on a previously-derived dataset [S5] on threatened vertebrate species, vascular-plant diversity, key wildlife habitats and wilderness values, and the carbon storage and local climate-stabilizing capacity of native vegetation, generated for Earth's entire ice-free land surface. This spatial dataset was designed to capture relevant natural values that could be impacted directly or indirectly by human activities. We generated this composite index because parameters describing biodiversity and environmental services have complex global distributions and thus cannot be captured by any single data source. Details of this analysis, including all spatial datasets used, are readily available online (http://global-roadmap.org).

The resulting data coverage (Fig. S3) provides an integrated, spatially explicit index of natural values. Index values for each 1-km^2 pixel were averaged across each corridor-band

(0=lowest value globally, 1=highest value globally) to provide a single, overall value for each corridor.

Fig. S3. Composite index of natural values for the African continent (from [S5]). Darker-green areas have higher overall natural values. This figure relates to Table 1.

Potential Agricultural Benefits

This data layer (generated previously in [S5]) identifies areas where new transportation infrastructure (or infrastructure improvements such as road paving) could potentially facilitate increases in agricultural production and yields (Fig. S4). The index places a higher weighting on areas that have already been substantially converted to farming or grazing (and hence where most native vegetation has already been removed), that are edaphically and climatically suitable for agriculture, that have large yield gaps, that could be readily accessible to urban markets with suitable road or transportation improvements, and that occur in nations projected to have large increases in agricultural production in the future [S5]. For areas that score highly on the agricultural-benefits layer, transportation improvements are likely to be a necessary but not sufficient condition to increase agricultural production. Additional factors, such as appropriate agricultural practices and adequate inputs of fertilizers and irrigation, would also typically be needed. Details of the analysis, including all spatial datasets used, are readily available online (http://global-roadmap.org).

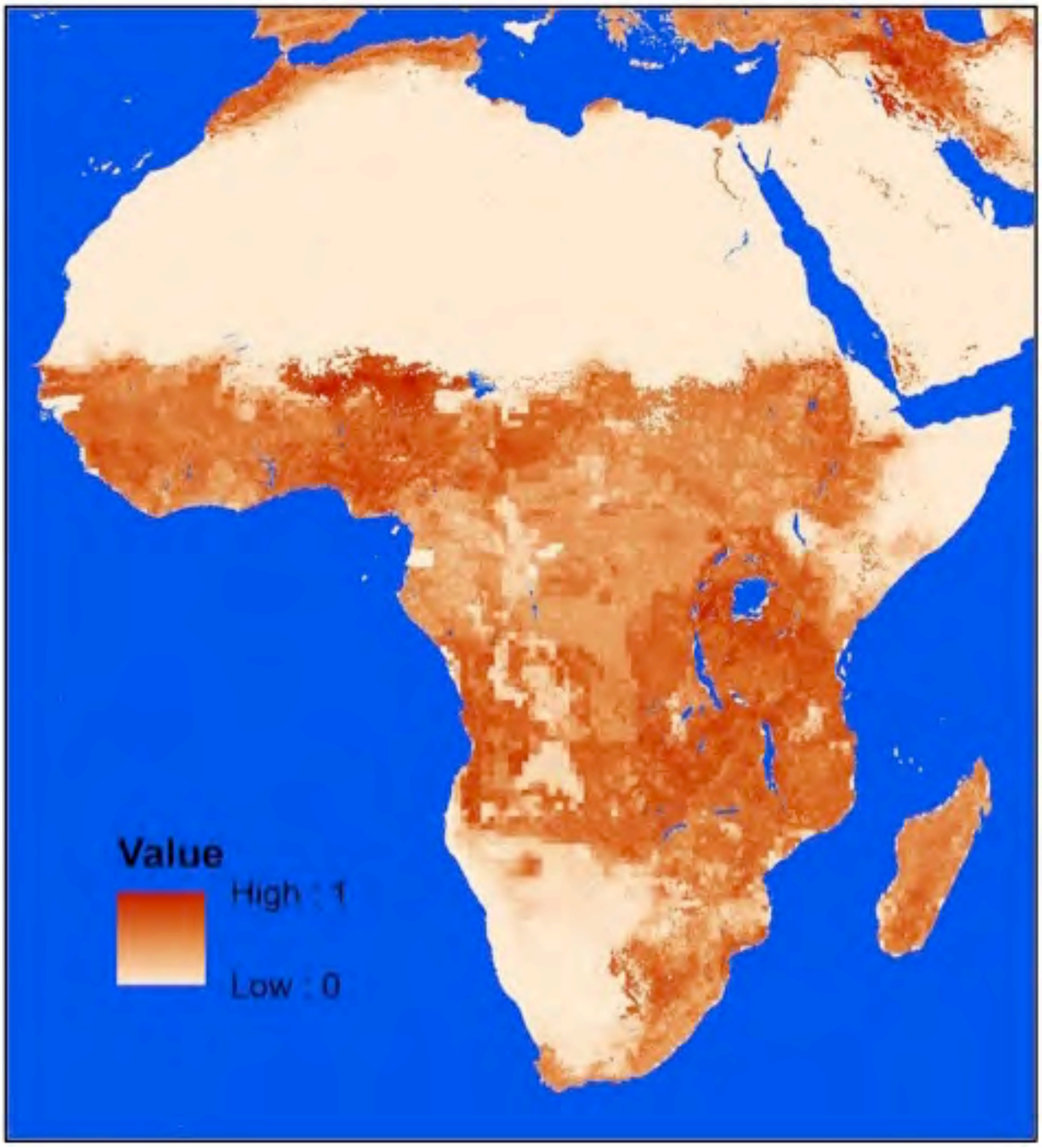

Fig. S4. A composite index showing areas where transportation improvements are likely to facilitate higher agricultural yields and production (from [S5]). Darker-red areas have higher values. This figure relates to Table 1.

Protected Areas

Spatial data on protected areas came from the World Database on Protected Areas (http://www.protectedplanet.net/). The WDPA is the most comprehensive database globally on terrestrial and marine protected areas, and was used to obtain shapefiles and attribute data for African protected areas. Like all such global databases, it is a work in progress, and includes a limited number of errors of omission or misclassification.

SUPPLEMENTAL REFERENCES

S1. Weng, L., Boedhihartono, A.K., Dirks, P., Dixon, J., Lubis, M.I., Sayer, J.A. (2013). Mineral industries, growth corridors and agricultural development in Africa. Glob. Food Secur. *2*, 195-202.

S2. Weng, L. (2015). Foreign Investments in African Extractive Industries: a Focus on China-Africa with Case Studies in Cameroon. Ph.D. thesis (Cairns, Australia: James Cook University).

S3. NOAA (2010). DMPS-OLS Nighttime Lights Time Series Imagery (Washington, D.C.: National Oceanic and Atmospheric Administration) (http://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html; accessed 15 April 2013).

S4. Sloan, S., Jenkins, C.N., Joppa, L.N., Gaveau, D.L.A., Laurance, W.F. (2014). Remaining natural vegetation in the global biodiversity hotspots. Biol. Conserv. *117*, 12-24.

S5. Laurance, W.F., Clements, G.R., Sloan, S., O'Connell, C., Mueller, N.D., Goosem, M., Venter, O., Edwards, D.P., Phalan, B., Balmford, A., et al. (2014). A global strategy for road building. Nature *513*, 229-232.