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A global strategy for road building

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The number and extent of roads will expand dramatically this century[1]. Globally, at least 25 million kilometres of new roads are anticipated by 2050; a 60% increase in the total length of roads over that in 2010. Nine-tenths of all road construction is expected to occur in developing nations[1], including many regions that sustain exceptional biodiversity and vital ecosystem services. Roads penetrating into wilderness or frontier areas are a major proximate driver of habitat loss and fragmentation, wildfires, overhunting and other environmental degradation, often with irreversible impacts on ecosystems[2–5]. Unfortunately, much road proliferation is chaotic or poorly planned[3,4,6], and the rate of expansion is so great that it often overwhelms the capacity of environmental planners and managers[2–7]. Here we present a global scheme for prioritizing road building. This large-scale zoning plan seeks to limit the environmental costs of road expansion while maximizing its benefits for human development, by helping to increase agricultural production, which is an urgent priority given that global food demand could double by mid-century[8,9]. Our analysis identifies areas with high environmental values where future road building should be avoided if possible, areas where strategic road improvements could promote agricultural development with relatively modest environmental costs, and 'conflict areas' where road building could have sizeable benefits for agriculture but with serious environmental damage. Our plan provides a template for proactively zoning and prioritizing roads during the most explosive era of road expansion in human history.

A multitude of factors is promoting rapid road expansion globally, including a quest for valuable resources such as timber, minerals, oil and arable land, and initiatives to increase regional trade, transportation and energy infrastructure[4,7]. Yet, while new roads can promote social and economic development[10,11], they also can open a Pandora's box of environmental problems[2–7]. This is especially the case in pristine or frontier regions, where new roads often dramatically increase land colonization, habitat disruption, and overexploitation of wildlife and natural resources[2–6]. It is broadly understood that the best strategy for maintaining the integrity of wilderness areas is by 'avoiding the first cut'—keeping them road-free[4]—because deforestation is highly contagious spatially[12] and because new roads tend to spawn networks of secondary and tertiary roads that greatly increase the extent of environmental damage[4]. Unfortunately, new roads are now penetrating into many of the world's last surviving wildernesses, including the Amazon[2,5,6,10], New Guinea[13], Siberia[14] and the Congo Basin[3,8,15].

However, some roads generate substantial social and economic benefits with only modest environmental costs. Particularly in developing nations, vast expanses of land have been settled but have low agricultural productivity because of poor access to fertilizers and modern farming technologies[11,16]. In such contexts, new roads—or road improvements such as paving—could increase access to agricultural supplies and markets, facilitating production increases and lowering post-harvest crop losses[13,17]. As such accessible areas tend to sustain more prosperous rural livelihoods, they may also act as 'magnets', attracting colonists away from environmentally vulnerable frontier areas, such as the margins of forests[17,18]. In this way, improving transportation in suitable areas could help to concentrate and improve agricultural production, raising farm yields[11,13] while potentially promoting land sparing for nature conservation[19].

Despite the pivotal role that roads have in human land-use, efforts to plan and zone roads are extremely inadequate. First, although roads increasingly dominate much of Earth's land surface (Fig. 1), many roads are unmapped, especially in developing nations; in the Brazilian Amazon, for example, the total length of unofficial or illegal roads is nearly triple that of official roads[20]. Second, environmental-impact assessments often place the burden of proof on road opponents[21,22], who rarely have sufficient information on rare species, biological resources and ecosystem services[23] needed to determine the actual environmental costs of roads. Third, many road assessments are limited in scope[4,22], focusing only on the direct effects of road building while ignoring its critical indirect effects, such as promoting deforestation, fires, poaching and land speculation. Finally, because there is no strategic, proactive system for zoning roads globally, road projects must be assessed with little information on their broader context (see the 2013 report on high-risk road development by the Conservation Strategy Fund; http://conservation-strategy.org/sites/default/files/field-file/CSFPolicyBrief_14_english_1.pdf). This increases the burden on road planners and evaluators, who are being swamped by the unprecedented pace of contemporary road expansion[2–7,11,15,20].

For these reasons, we devised a 'global roadmap' to identify areas in which roads or road improvements are likely to have major costs or benefits. The map has two components: an environmental-values layer that estimates the natural importance of ecosystems, and a road-benefits layer that estimates the potential for increased agricultural production, in part via new or improved roads. Combining these two layers allows us to identify areas where roads or road upgrades could have large potential benefits, areas where road building should be avoided wherever possible, and conflict areas where their potential costs and benefits are both sizeable.

We created the environmental-values layer (Fig. 2a) by integrating global data sets on three classes of parameters: biodiversity (number of threatened terrestrial-vertebrate species, estimated number of plant species per ecoregion); key wilderness habitats (G200 terrestrial ecoregions, important bird areas and endemic bird areas, biodiversity hotspots, frontier forests, high-biodiversity wilderness areas); and carbon storage and climate-regulation services of the local ecosystem (see Methods and Supplementary Figs 1–11). Values for each class were equally weighted, rescaled (range: 0–1) and then averaged to produce the environmental-values layer. Regions that scored highly on this layer include wet and humid tropical and subtropical forests, Mediterranean ecosystems, wildlife-rich savanna woodlands in South America and Africa, many islands, certain mountain ranges, and some higher-latitude forests, among others.

The road-benefits layer (Fig. 2b) identifies areas where new roads or road improvements could potentially help to improve agricultural production. Like the environmental-values layer, it is a relative index (range: 0–1). In general terms, areas that score highly on this layer have been largely converted to agriculture (and thus have little native vegetation remaining), are relatively low-yielding despite having soils and climates

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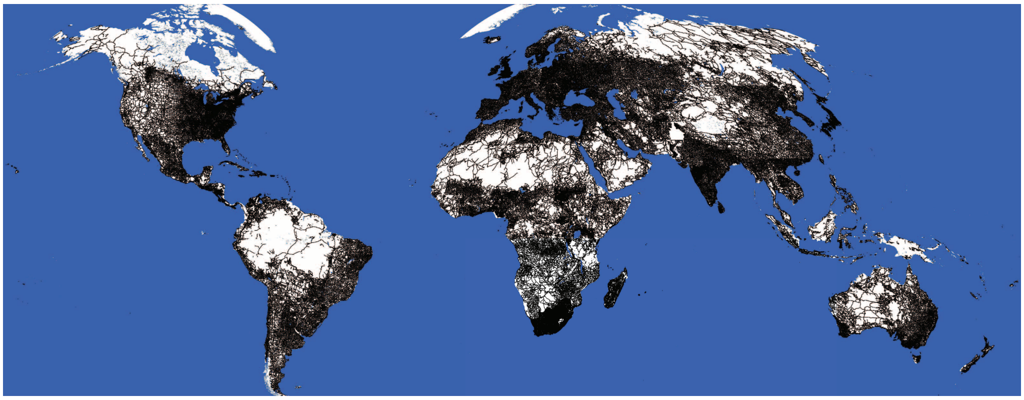

Figure 1 | The distribution of major roads globally. Roads are indicated in black; white areas lack mapped roads. The quality of road maps varies greatly among nations, with many smaller and unofficial roads remaining unmapped. We generated this map using data from the integrated gROADS database (http://sedac.ciesin.columbia.edu/data/set/groads-global-roads-open-access-v1 accessed 7 June 2014); Center for International Earth Science Information Network - CIESIN - Columbia University, and Information Technology Outreach Services - ITOS - University of Georgia. 2013. Global Roads Open Access Data Set, Version 1 (gROADSv1). Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). http://dx.doi.org/10.7927/H4VD6WCT.

broadly suitable for agriculture, are not so distant from urban markets that crop-transportation costs would be prohibitive even with new or improved roads, and are expected to see large future increases in agricultural production to meet projected food or export demands (see Methods and Supplementary Figs 12–16 for details of how these data sets were integrated). All continents have regions that score highly, including parts of south Asia, east and southeast Asia, West and East Africa, central Eurasia, west-central North America, Central America and Mexico, and the Atlantic region of South America.

We classified each of the environmental-values (Fig. 2a) and road-benefits (Fig. 2b) layers into deciles and then cross-tabulated them to generate 100 unique colour combinations (see Supplementary Information for details). In this scheme, green-shaded areas are where road building would have relatively high environmental costs and only modest potential benefits for agriculture. Red-shaded areas are the opposite, with high potential to increase agricultural production and lower scores on the environmental-values axis. Black and dark-shaded areas are ‘conflict zones’ with high values on both axes, whereas white and light-shaded areas are lower priorities for both environment and agriculture.

On top of this scheme we overlaid polygons for 177,857 protected areas (Supplementary Fig. 17) globally, using available data from the World Database on Protected Areas (http://www.wdpa.org). Protected areas

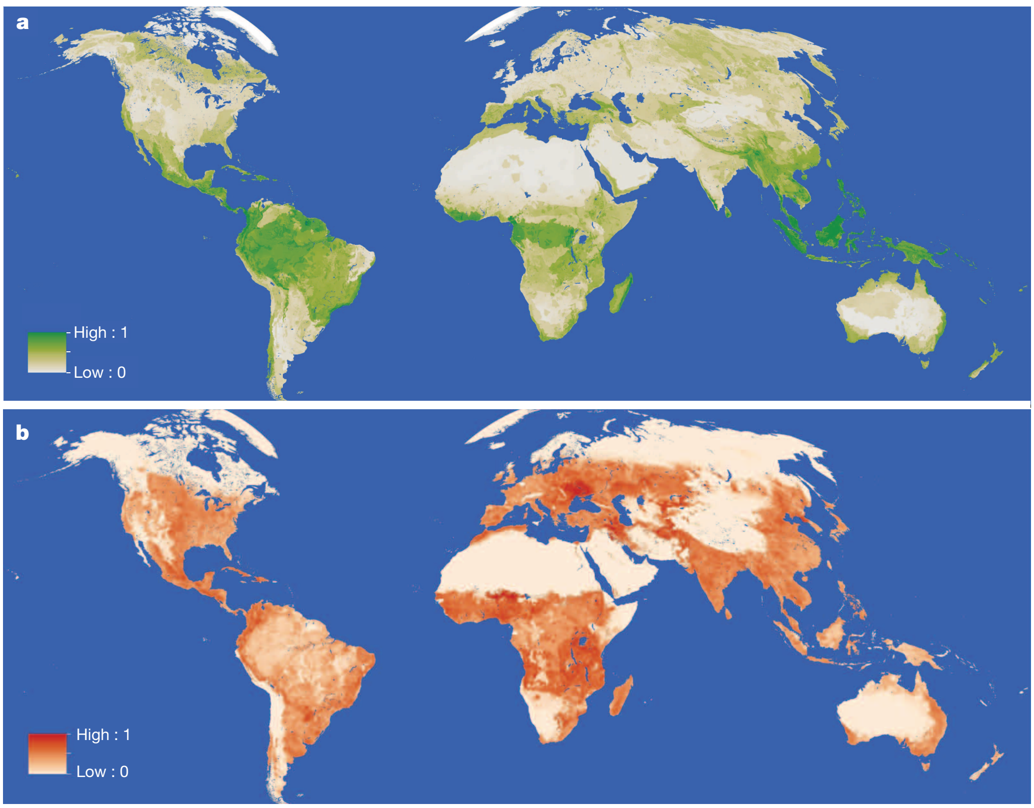

Figure 2 | The environmental-values and road-benefits layers. a, b, The environmental-values layer (**a**) integrates data on terrestrial biodiversity, key habitats, wilderness, and environmental services. The road-benefits layer (**b**) shows areas broadly suitable for agricultural intensification, where new roads or road improvements could potentially promote increased production. See Supplementary Information for data sources.

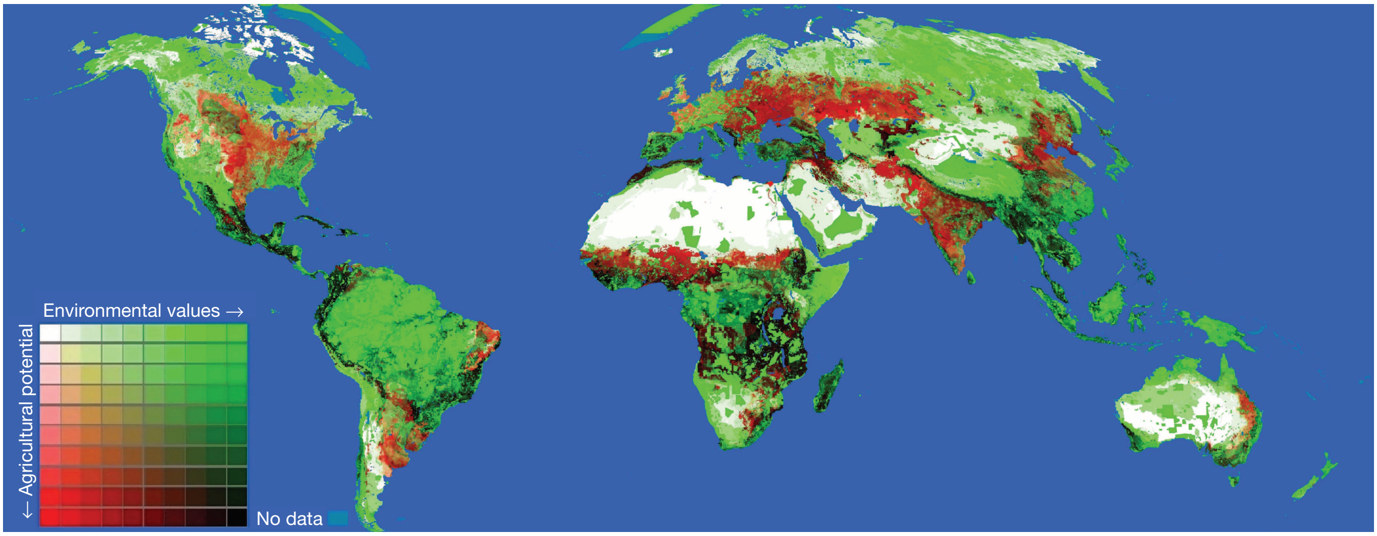

Figure 3 | A global roadmap. Shown are priority road-free areas (green shades), priority agricultural areas (red shades), conflict areas (dark shades), and lower-priority areas (light shades). Values of the environmental-values and road-benefits layers are each divided into deciles, yielding 100 unique colour combinations. See Supplementary Information for details and data sources.

were zoned fully green because we judged that they should be free of new roads wherever possible, given that roads can facilitate illegal activities such as poaching, encroachment, and vehicle-related road-kill of wildlife[2–4] that are contrary to the goals of protected-area management[24,25].

The resulting global roadmap (Fig. 3) attempts to portray key relative risks and rewards of road building for each 1-km^2 pixel on Earth's land surface. In broad terms, our map illustrates the enormous potential for environmental loss and degradation as a result of contemporary road expansion (Table 1 and Supplementary Fig. 18). Roads are currently proliferating or planned in many areas categorized as having high environmental values but only modest agricultural potential, such as the Amazon Basin, parts of the Asia-Pacific region, and higher-latitude forests in the Northern Hemisphere.

The roadmap also reveals extensive conflict areas (Fig. 3), where environmental and agricultural values are both high, particularly in Sub-Saharan Africa, Madagascar, Central America, the Mediterranean, southeast and south-central Asia, the Andes, and the Atlantic region of South America. Conflict zones often occur in regions with rapid population growth, high species endemism, or both. In total, 1.97 billion hectares (16.5% of global land area) fall into conflict areas (Table 1). Land-use pressures in such regions are mounting rapidly; it has been estimated that, unless current agricultural yields markedly improve, approximately 1 billion hectares of additional farming and grazing land will be needed by 2050 to meet projected food demands[9], with extensive additional lands converted for production of biofuels[26].

However, our road-planning scheme also suggests that many areas could be targeted for agricultural production increases with relatively modest environmental costs. Such areas include expanses of the Indian subcontinent, central Eurasia, the Irano-Anatolian region, and African Sahel, among others (Fig. 3). In total, 1.46 billion hectares of land (12.3% of global land area) is zoned red (Table 1), suggesting that there is considerable potential on every continent to increase agricultural production, by raising yields on existing farming and grazing land.

Although improved roads or other transportation can facilitate agricultural yield increases[11,13,17,18], additional measures—such as investments in improved farming methods, fertilizers and, where appropriate, irrigation—will also be essential. A particular challenge will be devising strategies to help developing nations with exceptional environmental values, such as Madagascar and Indonesia (Fig. 2a), to meet pressing economic and food-production needs while limiting the environmental costs of rapid road development. For such nations, international payments for ecosystem services, ecotourism, and sustainable harvesting of native production forests could potentially help to balance economic and environmental priorities[27]. A further priority when planning road and agricultural investments is to consider how factors such as inter-annual weather variability or projected future climate change could impact on crop yields[28].

The global roadmap we created underscores the potential benefits and need for strategic road planning, but actual road planning will be undertaken at smaller national or regional scales. For this, we created more detailed maps that show finer-scale features (for example, Extended Data Fig. 1). These maps and their components are freely available (http://global-roadmap.org) and can be combined with additional data, such as more detailed information on topography, soils, existing croplands and local road networks, to facilitate road planning.

Integrating local information is important because the drivers and environmental impacts of road construction will vary in different contexts. For example, in arable, largely road-free areas of East Africa (Fig. 4a), new roads driven by a burgeoning mining boom[11,29] could provoke major land-use changes and habitat loss. Yet expanding roads from timber and mining operations could also have large impacts in Siberia (Fig. 4b), even

Table 1 | Percentages of seven geographical regions that fall into four broad categories on the global roadmap

Zone	Africa	Asia	Australia	Europe	North and Central America	South America	Oceania	Global
Conserve	29.03	45.69	34.21	26.44	47.39	66.28	95.29	46.31
Agriculture	7.93	12.44	3.63	32.92	11.35	6.83	0.23	12.29
Conflict	24.75	14.87	7.01	9.10	8.70	15.74	0.58	16.54
Low-tension	38.30	27.00	55.15	31.54	32.55	11.14	3.89	32.67
Total area	29,805	44,174	7,693	9,670	23,395	17,662	412	132,811

Data on the total areas of each region are given in km^2 x 10^3. 'Conserve' zones are where road building would have relatively high environmental costs (above-median environmental values; Fig. 2a) and modest potential agricultural benefits (below-median road-benefits values; Fig. 2b). 'Agriculture' zones have the opposite attributes (above-median road-benefits values and below-median environmental values). 'Conflict' zones have both above-median environmental values and above-median road-benefits values, whereas 'low-tension' zones are lower priorities for both environment and agriculture (with below-median environmental and road-benefits values). See Supplementary Fig. 18 for a map of these zones.

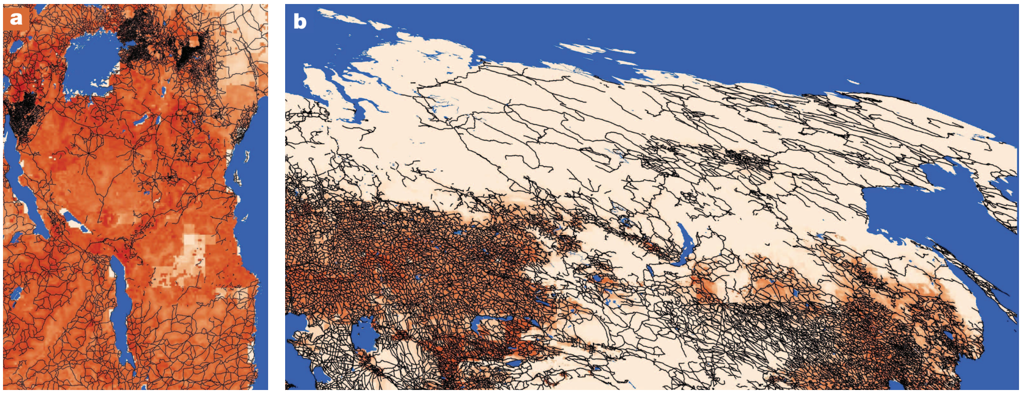

Figure 4 | Mapped roads overlaid onto the roads-benefits layer. a, b, In eastern Africa (**a**) and Siberia (**b**), roads are rapidly expanding into relatively road-free areas, but for different reasons. Narrow black lines indicate mapped roads. In both regions, areas with darker-red colours have greater agricultural potential than those with lighter colours. See Supplementary Information for data sources.

though agricultural potential is limited, by promoting forest fires and clearing[14]. In general, we expect road impacts to be lowest in unproductive, arid regions, moderate in carbon-rich ecosystems such as higher-latitude forests, and most damaging in species- and carbon-rich ecosystems such as tropical forests, particularly where few roads currently exist.

We see our global road-mapping scheme as a working model—an important first step towards strategic road planning to reduce environmental damage—that can be downscaled and tailored for particular circumstances. We believe such proactive planning should be a central element of any discussion about road expansion and associated land-use zoning[13,30]. Given that the total length of new roads anticipated by mid-century[1] would encircle the Earth more than 600 times, there is little time to lose.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Supplementary Information is available in the online version of the paper.

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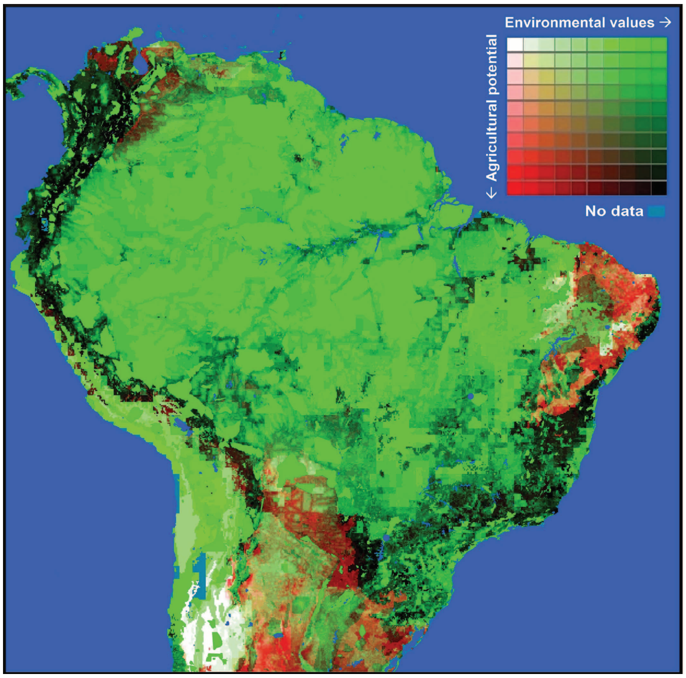
Author Contributions W.F.L. and A.B. initially conceived the study, and W.F.L. coordinated its design, analysis, and manuscript preparation. G.R.C. and S.S. conducted the spatial analyses; C.S.O., N.D.M., O.V., G.R.C., S.S. and B.P. generated or collated key datasets; and M.G., D.P.E., R.V.D.R. and I.B.A. provided ideas and critical feedback.

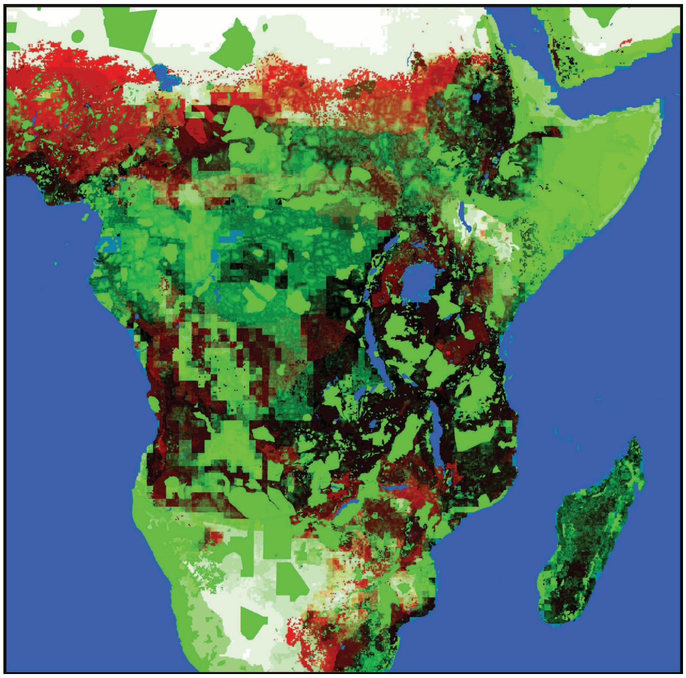
Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to W.F.L. (bill.laurance@jcu.edu.au).

METHODS

We used ArcGIS 10.1 and IDRISI Selva to integrate spatial data relevant to our global roadmap. Analyses were conducted using Goode's homolosine equal-area projection and a 1-km^2 pixel size, yielding $\sim$132.8 million pixels for Earth's terrestrial surface (excluding Antarctica). Larger freshwater bodies ($>$50 km^2) were removed before analysis but land areas under ice or permafrost were not excluded. A small fraction (2.21%) of all pixels lacked data (mostly in Greenland) and so were excluded from the analysis.

We created the environmental-values layer (Fig. 2a) by integrating global data sets on biodiversity (number of threatened terrestrial-vertebrate species, estimated number of plant species per ecoregion); key wilderness habitats (G200 terrestrial ecoregions, important bird areas and endemic bird areas, biodiversity hotspots, frontier forests, high-biodiversity wilderness areas); and carbon storage and climate-regulation services of the local ecosystem (Supplementary Figs 1–11). Areas that scored highly on the road-benefits layer (Fig. 2b) were defined by having: a high proportion of land already under farming or grazing; soils and climates that are broadly suitable for agriculture; large agricultural yield gaps; large projected increases in future agricultural production; and the potential to access urban markets with improved transportation (Supplementary Figs 12–16). The global data sets that comprise the environmental-values and road-benefits layers, and the methods by which they were integrated, are described in detail in the Supplementary Information.





Extended Data Figure 1 | Roadmaps for northern South America and Sub-Saharan Africa. Magnified images such as these could be integrated with local-scale data to facilitate actual road planning. Values of the environmental-values and road-benefits layers are each divided into deciles, yielding 100 unique colour combinations. See Supplementary Information for data sources.