A global map of roadless areas and their conservation status

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SUPPLEMENTARY MATERIALS

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CONSERVATION

A global map of roadless areas and their conservation status

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Roads fragment landscapes and trigger human colonization and degradation of ecosystems, to the detriment of biodiversity and ecosystem functions. The planet's remaining large and ecologically important tracts of roadless areas sustain key refugia for biodiversity and provide globally relevant ecosystem services. Applying a 1-kilometer buffer to all roads, we present a global map of roadless areas and an assessment of their status, quality, and extent of coverage by protected areas. About 80% of Earth's terrestrial surface remains roadless, but this area is fragmented into ~600,000 patches, more than half of which are <1 square kilometer and only 7% of which are larger than 100 square kilometers. Global protection of ecologically valuable roadless areas is inadequate. International recognition and protection of roadless areas is urgently needed to halt their continued loss.

The impact of roads on the surrounding landscape extends far beyond the roads themselves. Direct and indirect environmental impacts include deforestation and fragmentation, chemical pollution, noise disturbance, increased wildlife mortality due to car collisions, changes in population gene flow, and facilitation of biological invasions (*1*–*4*). In addition, roads facilitate "contagious development," in that they provide access to previously remote areas, thus opening them up for more roads, land-use changes, associated resource extraction, and human-caused disturbances of biodiversity (*3*, *4*). With the length of roads projected to increase by >60% globally from 2010 to 2050 (*5*), there is an urgent need for the development of a comprehensive global strategy for road development if continued biodiversity loss is to be abated (*6*). To help mitigate the detrimental effects of roads, their construction should be concentrated as much as possible in areas of relatively low "environmental values" (*7*). Likewise, prioritizing the protection of remaining roadless areas that are regarded as important for biodiversity and ecosystem functionality requires an assessment of their extent, distribution, and ecological quality.

Such global assessments have been constrained by deficient spatial data on global road networks. Importantly, recent publicly available and rapidly improving data sets have been generated by crowd-sourcing and citizen science. We demonstrate their potential through OpenStreetMap, a project with an open-access, grassroots approach to mapping and updating free global geographic data, with a focus on roads. The available global road data sets, OpenStreetMap and gROADS, vary in length, location, and type of roads; the former is the data set with the largest length of roads (36 million km in 2013) that is not restricted to specific road types (table S1). OpenStreetMap is more complete than gROADS, which has been used for other global assessments (*7*), but in certain regions, it contains fewer roads than subglobal or local road data sets [see the example of Center for International Forestry Research data for Sabah, Malaysia (*8*); table S1]. Given the pace of road construction and data limitations, our results overestimate the actual extent of global roadless areas.

The spatial extent of road impacts is specific to the impact in question and to each particular road and its traffic volume, as well as to taxa, habitat, landscape, and terrain features. Moreover, for a given road impact, its area of ecological influence is asymmetrical along the road and can vary among seasons, between night and day, according to weather conditions, and over longer time periods. We conducted a comprehensive literature review of 282 publications dealing with "road-effects zones" or including the distance to roads as a covariate, of which 58 assessed the spatial influence of the road (table S2). All investigated road impacts were documented within a distance of

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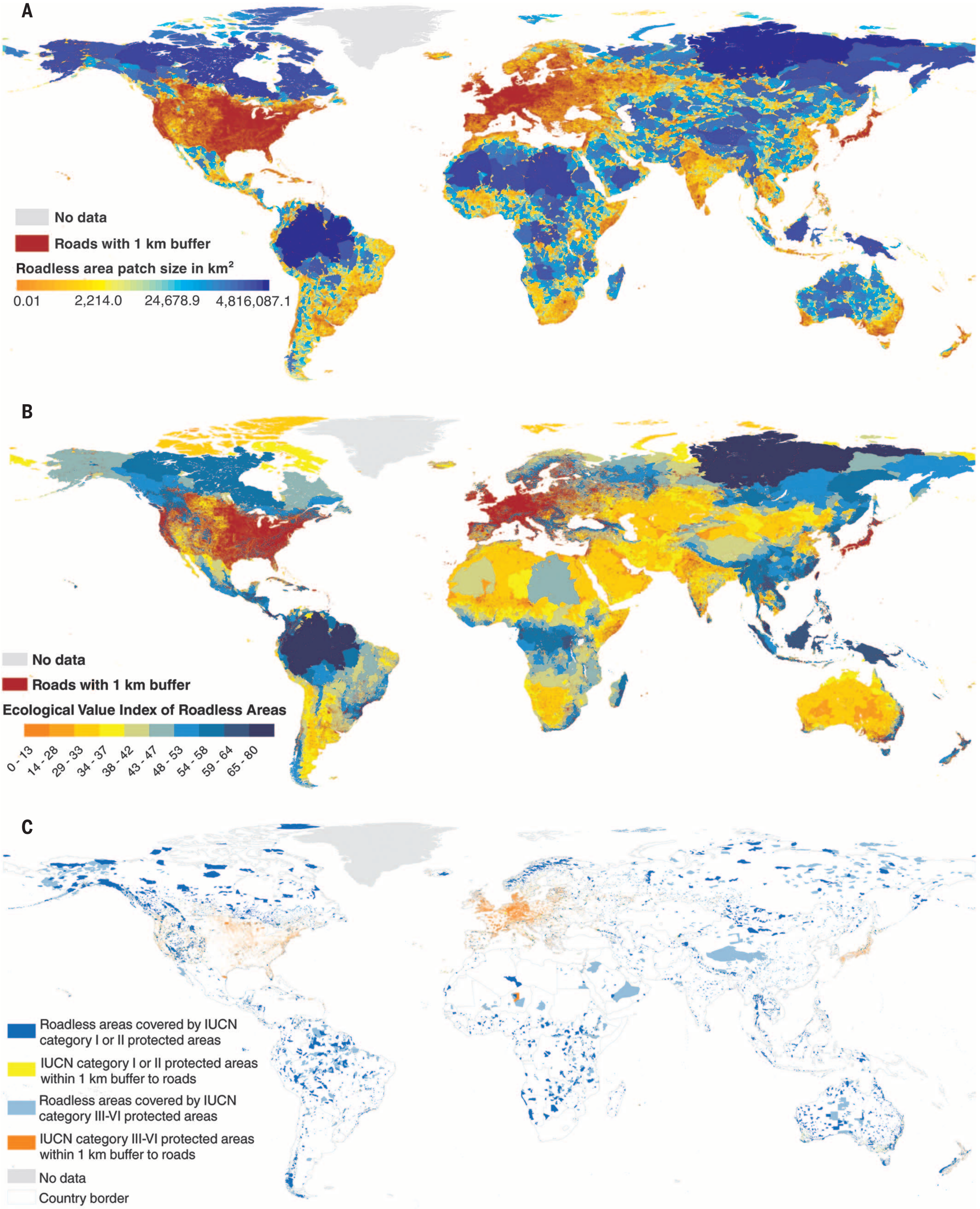


Fig. 1. The global distribution of roadless areas, based on a 1-km buffer around all roads. The distribution is depicted according to (**A**) size classes, (**B**) the ecological value index of roadless areas (EVIRA; based on patch size, connectivity, and ecosystem functionality), and (**C**) representation in protected areas (*8*).

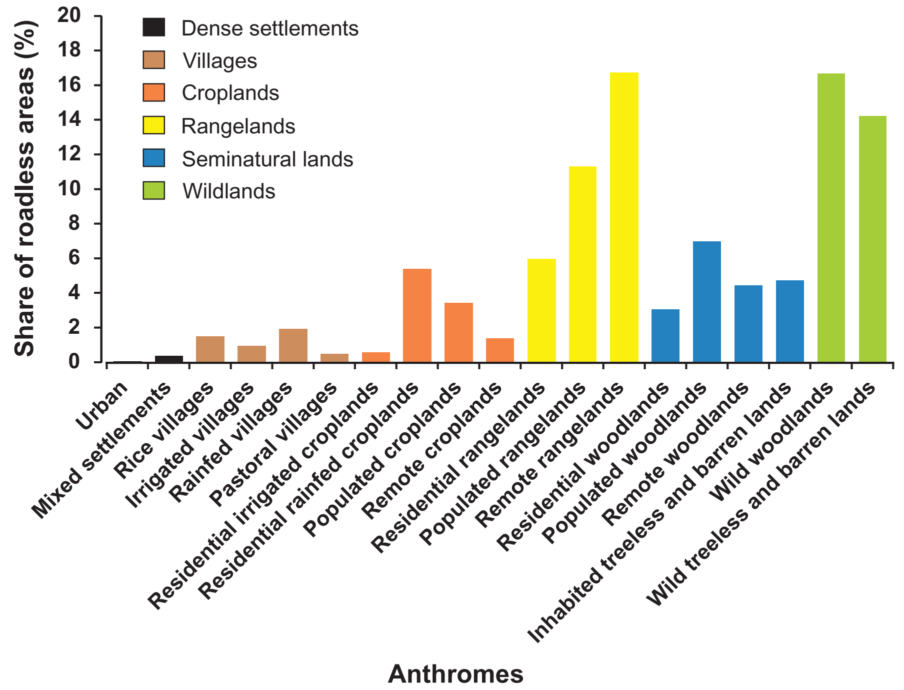


Fig. 2. Extent of roadless areas (1-km buffer) across anthromes. The majority of the world's roadless areas are in remote and unmodified landscapes, but they also occur in anthropogenically modified landscapes. The so-called anthromes were mapped according to (*10*).

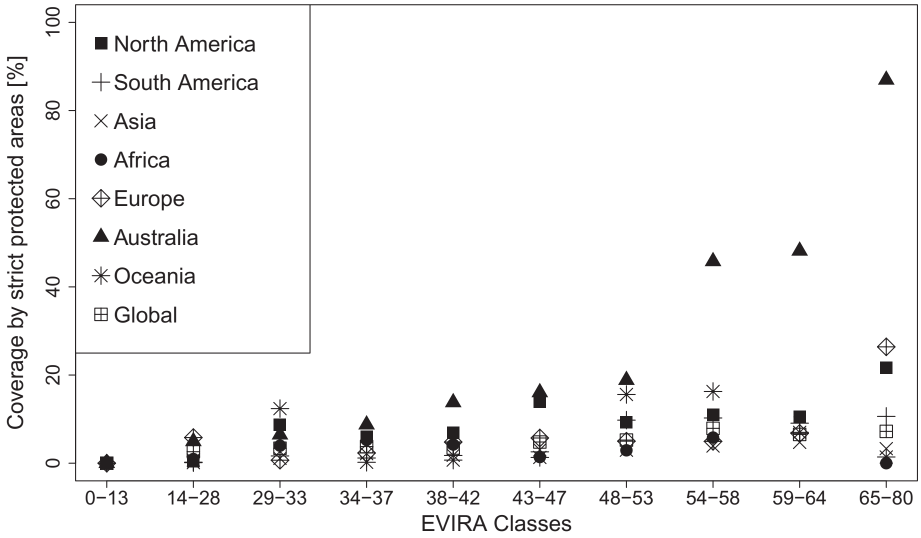


Fig. 3. Coverage of roadless areas by strictly protected areas (IUCN categories I and II) compared with global and continental EVIRA values. If priority were given to protecting roadless areas with high ecological functionality, we should see a positive correlation, with higher coverage associated with higher EVIRA values.

1 km from the road, 39% reached out to 2 km from the road, and only 14% extended out to 5 km from the road (fig. S1). Because the 1-km buffer along each side of the road represents the zone with the highest level and variety of road impacts, we defined roadless areas as those land units that are at least 1 km away from all roads and, therefore, less influenced by road effects. We compared results from using this criterion with the outcomes from using an alternative 5-km buffer (see fig. S2 and table S3). We excluded all large water bodies, as well as Greenland and Antarctica, which are mostly covered by ice, from the analyses.

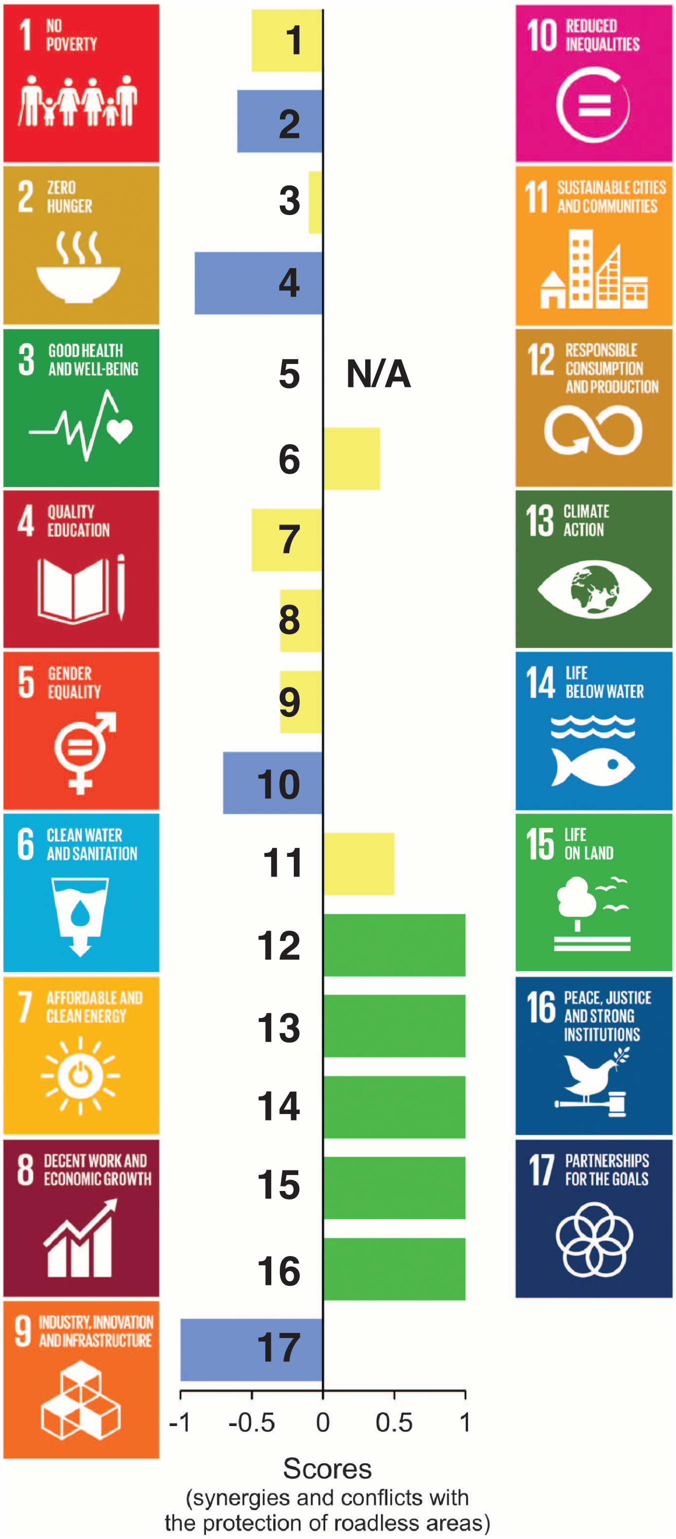
Roadless areas with a 1-km buffer to the nearest road cover about 80% of Earth's terrestrial surface (~105 million km^2). However, these roadless areas are dissected into almost 600,000 patches. More than half of the patches are <1 km^2; 80% are <5 km^2; and only 7% are >100 km^2 (table S4 and fig. S3). If the buffer is extended to 5 km, there is a substantial reduction in roadless areas to about 57% of the world's terrestrial surface (~75 million km^2), dissected into 50,000 patches (fig. S2 and table S3). The occurrence, distribution, and size of roadless areas differ considerably among continents (Fig. 1A and fig. S4). For instance, the mean size of roadless patches (1-km buffer) is 48 km^2 in Europe, compared with >500 km^2 in Africa. Because of comparatively large gaps in available spatial data on roads in many segments of the tropics, the number and size of roadless areas are overestimated and should be treated with caution (e.g., Borneo; table S1).

All identified roadless areas were assessed for a set of ecological properties that were selected to reflect their relative importance to biodiversity, ecological functions, and ecosystem resilience: patch size, connectivity, and ecosystem functionality (*9*) (table S5). We normalized these three indicators to between 0 and 100 to calculate an additive and unitless index of the ecological value of each roadless area identified (termed the ecological value index of roadless areas, or EVIRA) [Fig. 1B and fig. S5; the specific rationale and technicalities of the chosen indicators are described in table S5 (*8*)]. The EVIRA values range from 0 to 80. A sensitivity analysis shows that ecosystem functionality and patch size are the best single indicators for the final index values (table S6 and figs. S6 to S8). Areas with relatively high index values tend to have a lower coefficient of variation (fig. S9).

We used the International Union for Conservation of Nature (IUCN) and UN Environment Programme–World Conservation Monitoring Centre data set of global protected areas to determine the extent of roadless areas that are protected (*8*) (Fig. 1C). The roadless areas distribution across human-dominated landscapes was determined following the classification of so-called anthromes, defined as biomes shaped by human land use and infrastructure (*10*) (Fig. 2 and table S7).

When examining the density of roads within different biomes, large discrepancies in distribution are apparent. The tundra and rock and ice-covered biomes are nearly entirely roadless, whereas temperate broadleaf and mixed forests have the lowest share of roadless areas (41%; figs. S9 and S10). Boreal forests of North America and Eurasia still retain large tracts of roadless areas (figs. S10 and S11). In the tropics, large roadless landscapes (>1000 km^2) remain in Africa, South America, and Southeast Asia, with the Amazon having the single largest roadless segment. In relation to the anthromes (*10*), about two-thirds of the world's roadless areas can be described as remote and unmodified landscapes [26% uninhabited or sparsely inhabited treeless and barren lands; 21% natural and remote seminatural woodlands, with 17% wild woodlands therein (*8*); Fig. 2 and table S7]. The remaining one-third consists of rangelands, indicating that roadless areas can also occur in anthropogenically modified landscapes.

Fig. 4. Synergies and conflicts between conservation of roadless areas and the United Nations' Sustainable Development Goals. Scores <–0.5 (blue bars) indicate that conflicts with the goal prevail; scores between –0.5 and 0.5 (yellow) indicate a mixture of synergies and conflicts with the goal; and scores >0.5 (green) indicate prevailing synergies with the goal [for details, see table S11 (*8*)]. The scores reflect substantial imminent conflicts between various Sustainable Development Goals and conservation of roadless areas (table S11).



About one-third of the world's roadless areas have low EVIRA values. Patches with relatively low EVIRA values (ranging from 0 to 37; namely, <50% of the maximum value) account for 35% of the overall roadless area distribution, because most are small, fragmented, isolated, or otherwise heavily disturbed by humans. Some large tracts of roadless areas, such as arid lands in northern Africa or central Asia, occur in areas of sparse vegetation and low biodiversity and, thus, have low index values for ecosystem functionality (*9*) (Fig. 1B). High EVIRA values occur both in tropical and boreal forests. The relative conservation value of roadless areas is context-dependent. Comparatively small or moderately disturbed roadless areas have higher conservation importance in heavily roaded environments, such as most of Europe, the conterminous United States, and southern Canada.

Although the world's protected areas cover 14.2% of the terrestrial surface, only 9.3% of the overall expanse of roadless areas is within protected areas (all IUCN categories; Fig. 1C and table S8). There is no major difference in the coverage of roadless areas by strictly protected areas (IUCN categories I and II) versus the coverage of the overall landscape by strictly protected areas (3.8% roadless versus 4.2% overall). Only in North America, Australia, and Oceania are more than 6% of roadless areas under strict protection (table S8). If conservation efforts were to prioritize functional, ecologically important roadless areas, we would find a positive relation between strict protection coverage and EVIRA values of roadless areas. However, with the exception of Australia, this is not the case (Fig. 3 and table S9). Asia and Africa have particularly low protection coverage for roadless areas with high EVIRA values. For instance, we found gaps in the Asian tropical southeast, as well as in boreal biomes.

The recent Global Biodiversity Outlook (*11*) gives a bleak account of the progress made toward reaching the United Nations' biodiversity agenda as specified in the 20 Aichi Targets of the Convention on Biological Diversity (*12*). Governments have failed on several accounts to keep their use of natural resources well within safe ecological limits (target 4); to halt or at least halve the rate of habitat loss and substantially reduce the degradation and fragmentation of natural habitats (target 5); and to appropriately protect areas of particular importance for biodiversity and ecosystem services (target 11). To achieve global biodiversity targets, policies must explicitly acknowledge the factors underlying prior failures (*13*). Despite increasing scientific evidence for the negative impacts of roads on ecosystems, the current global conservation policy framework has largely ignored road impacts and road expansion. Furthermore, key policies on road infrastructure and development, such as the Cohesion Policy of the European Union, fail to take into account biodiversity.

In the much wider context of the United Nations' Sustainable Development Goals, conflicting interests can be seen between goals intended to safeguard biodiversity and those promoting economic development (*14*). We analyzed how roadless areas relate to the global conservation and sustainability agendas. As a transparent synthesis, we calculated simple scores of conflicts versus synergies of Sustainable Development Goals and Aichi Targets with the conservation of roadless areas (tables S10 and S11). Roads are explicitly mentioned in the Sustainable Development Goals only for their contribution to economic growth (goal 8), promoting further expansion into remote rural areas, and consideration is given neither to the environmental nor the social costs of road development. The resulting scores reflect substantial imminent conflicts (Fig. 4 and table S10); only in five Sustainable Development Goals do synergies with conservation of roadless areas prevail, and four Sustainable Development Goals are predominantly in conflict with conservation of roadless areas. Maybe even more surprisingly, several of the Aichi Targets are ambivalent with respect to conserving roadless areas, rather than being in synergy entirely [six conflicting versus 11 synergistic targets (*8*); table S11].

There is an urgent need for a global strategy for the effective conservation, restoration, and monitoring of roadless areas and the ecosystems that they encompass. Governments should be encouraged to incorporate the protection of extensive roadless areas into relevant policies and other legal mechanisms, reexamine where road development conflicts with the protection of roadless areas, and avoid unnecessary and ecologically disastrous roads entirely. In addition, governments should consider road closure where doing so can promote the restoration of wildlife habitats and ecosystem functionality (*4*). Our global map of roadless areas represents a first step in this direction. During planning and evaluation of road projects, financial institutions, transport agencies, environmental nongovernmental organizations, and the engaged public should consider the identified roadless areas.

The conservation of roadless areas can be a key element in accomplishing the United Nations' Sustainable Development Goals. The extent and protection status of valuable roadless areas can serve as effective indicators to address several Sustainable Development Goals, particularly goal 15 ("Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss") and goal 9 ("Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation"). Enshrined in the protection of roadless areas should be the objective to seek and develop alternative socioeconomic models that do not rely so heavily on road infrastructure. Similarly, governments should consider how roadless areas can support the Aichi Targets (see tables S10 and S11). For instance, the target of expanding protected areas to cover 17% of the world's terrestrial surface could include a representative proportion of roadless areas.

Although we acknowledge that access to transportation is a fundamental element of human well-being, impacts of road infrastructure require a fully integrated environmental and social cost-benefits approach (*15*). Still, under current conditions and policies, limiting road expansion into roadless areas may prove to be the most cost-effective and straightforward way of achieving strategically important global biodiversity and sustainability goals.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Figs. S1 to S11
Tables S1 to S11
Data Sources
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PLANT PATHOLOGY

Regulation of sugar transporter activity for antibacterial defense in *Arabidopsis*

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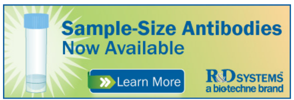
Microbial pathogens strategically acquire metabolites from their hosts during infection. Here we show that the host can intervene to prevent such metabolite loss to pathogens. Phosphorylation-dependent regulation of sugar transport protein 13 (STP13) is required for antibacterial defense in the plant *Arabidopsis thaliana*. STP13 physically associates with the flagellin receptor flagellin-sensitive 2 (FLS2) and its co-receptor BRASSINOSTEROID INSENSITIVE 1–associated receptor kinase 1 (BAK1). BAK1 phosphorylates STP13 at threonine 485, which enhances its monosaccharide uptake activity to compete with bacteria for extracellular sugars. Limiting the availability of extracellular sugar deprives bacteria of an energy source and restricts virulence factor delivery. Our results reveal that control of sugar uptake, managed by regulation of a host sugar transporter, is a defense strategy deployed against microbial infection. Competition for sugar thus shapes host-pathogen interactions.

Plants assimilate carbon into sugar by photosynthesis, and a broad spectrum of plant-interacting microbes exploit these host sugars (*1*, *2*). In *Arabidopsis*, pathogenic bacterial infection causes the leakage of sugars to the extracellular spaces (the apoplast) (*3*), a major site of colonization by plant-infecting bacteria. Although leakage may be a consequence of membrane disintegration during pathogen infection, some bacterial pathogens promote sugar efflux to the apoplast by manipulating host plant sugar transporters (*4*, *5*). Interference with sugar absorption by bacterial and fungal pathogens reduces their virulence, highlighting a general



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Mariana M. Vale, Peter R. Hobson and Nuria Selva (December 15,
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Editor's Summary

Too many roads

Roads have done much to help humanity spread across the planet and maintain global movement and trade. However, roads also damage wild areas and rapidly contribute to habitat degradation and species loss. Ibisch *et al.* cataloged the world's roads. Though most of the world is not covered by roads, it is fragmented by them, with only 7% of land patches created by roads being greater than 100 km^2. Furthermore, environmental protection of roadless areas is insufficient, which could lead to further degradation of the world's remaining wildernesses.

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