Roadless areas as tools for the conservation of functional ecosystems

Obszary bezdrożne jako narzędzia ochrony ekosystemów funkcjonalnych

PhD thesis

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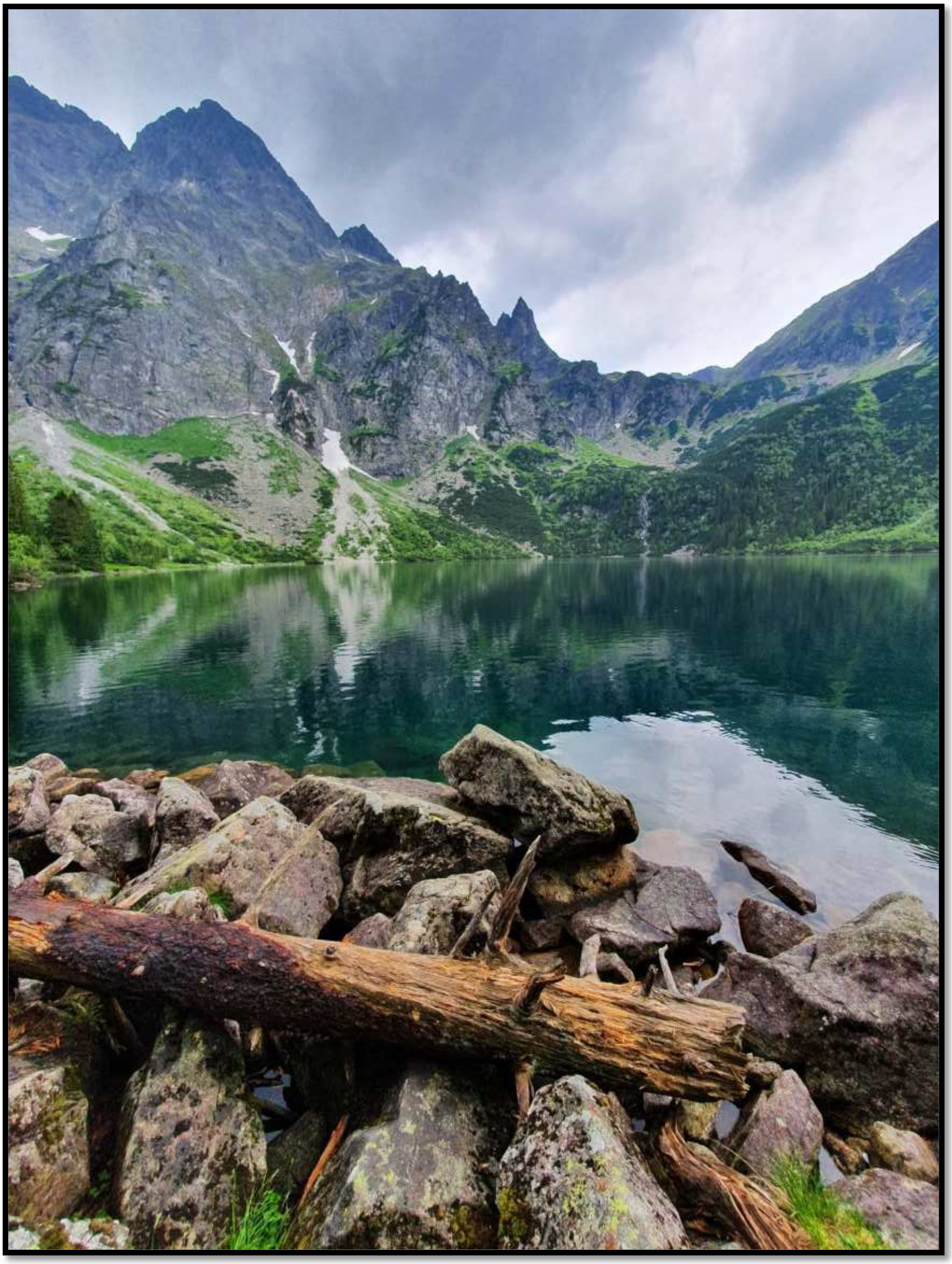

"Nature does not hurry, yet everything is accomplished." Lao Tzu

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II. **Hoffmann, M. T.**, Kreft, S., Kati, V., & Ibisch, P. L. (2020). Roadless Areas as Key Approach to Conservation of Functional Forest Ecosystems. In: Goldstein, M.I., DellaSala, D.A., Eds. Encyclopedia of the World's Biomes, vol. 3. Elsevier, pp. 237–248. ISBN: 9780128160961. https://doi.org/10.1016/B978-0-12-409548-9.11896-2.

III. **Hoffmann, M. T.**, Ostapowicz, K., Bartoń, K., Ibisch, P. L. & Selva, N. (2024). Mapping roadless areas in regions with contrasting human footprint. *Scientific Reports*, 14(1): 4722. https://doi.org/10.1038/s41598-024-55283-3.

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If someone had told me 20 years ago that I would one day write a PhD thesis, I certainly wouldn't have believed it. I was more inclined towards grassroots change, living in a community in South of France, cultivating organic food, and exploring ways to coexist harmoniously with nature, rather than exploiting it. Life has a funny way of unfolding differently from our expectations, and somehow, I found myself studying in Eberswalde, where the groundwork was laid for me to embark on this thesis journey. My need to understand and contribute, even if in a small way, to the betterment of our planet – not to change the planet itself, but to alter the way humans perceive, treat, and inhabit it – has always been an integral part of me. Thus, I am grateful to Pierre Ibisch and my colleagues at the Centre of Econics and Ecosystem Management, where I began working on real-life nature conservation projects, particularly in the realm of GIS.

Another significant milestone followed 11 years ago during my master's studies when Pierre introduced me to a remarkable group of scientists dedicated to studying roadless areas. The impact of roads had long occupied my thoughts, even during my initial desire to pursue art studies, as I traversed Germany and noticed the ubiquitous presence of roads, neatly laid out everywhere. Soon, I engaged myself in analyzing roadless areas, and I have been captivated by this topic ever since. Thus, my heartfelt appreciation goes to the Roadless Initiative, whose global efforts to study the impact of roadless areas laid the foundation for my thesis. Special thanks to Vassiliki Kati, Nuria Selva, and Pierre Ibisch for spearheading this research. Without their guidance and collaboration, my thesis topic would not have been conceivable.

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There were several moments during this journey when I doubted my ability to complete this research and thesis. So many hurdles had to be overcome, analyses that ended up in the trash bin, and constantly emerging challenges. Without your trust, assistance, encouragement, unwavering belief in me, timely guidance, and simply being the most remarkable scientist I know, I wouldn't have been able to undertake this endeavor. Therefore, I dedicate this work to you, Nuria, because without you, I would have faltered years ago. Thank you Nuria! Also, a special thank you to Lina and Adam simply because they are great people.

SUMMARY

Roads are a ubiquitous feature of human civilization, but their expansion comes at a cost to biodiversity and ecosystem integrity. The negative impact of roads on ecosystem functionality is manifold, ranging from direct impacts such as habitat fragmentation, wildlife mortality, and pollution to indirect effects including deforestation, changes in wildlife behavior, and disruption of ecological processes. As a result, the preservation of roadless areas has just emerged as a fundamental conservation tool. The main goal of this dissertation is to comprehensively evaluate if roadless areas can represent cost-effective conservation targets and proxies for functional ecosystems. Through a comprehensive synthesis of existing literature and original research contributions, this thesis aims to explore the ecological and policy implications of roadless areas conservation. By assessing their extent on a global scale and evaluating their quality I aim to provide a better understanding of their role in preserving biodiversity and ecosystem functionality. Roadless areas, characterized by the absence of roads or human infrastructure, are (partly) free from road impacts and can play a crucial role in maintaining ecological integrity and ecosystem functioning. These roadless landscapes can serve as vital refugia for biodiversity and provide essential ecosystem services globally.

In the first paper, roadless areas were defined as areas at least 1 km away from any type of road following a thorough review of the spatial extent of road impacts. Utilizing a freely available road dataset (OpenStreetMap 2013), I conducted a global assessment to determine their extent and evaluated their status, quality, and coverage by protected areas. Although approximately 80% of the Earth's terrestrial surface remained roadless, it was fragmented into approximately 600,000 patches; more than half of these patches were less than 1 km^2 and only 7% exceeded 100 km^2. Furthermore, I investigated the proportion of roadless areas classified under different protection status and developed an index (the Ecological Value Index of Roadless areas, EVIRA) incorporating three indicators (Ecosystem Functionality Index, roadless area patch size, and patch connectivity using Thiessen polygons) to assess the quality of these areas. Although the world’s protected areas cover 14% of the terrestrial surface, only 9% of roadless areas were within protected areas. Large tracts of unprotected roadless areas with high EVIRA values exist in both tropical and boreal forests. Africa and Asia have the lowest level of protection of high-value roadless areas. The only continent with strictly protected roadless areas exhibiting high EVIRA values is Australia. Roadless areas characterized by low EVIRA values constitute 35% of the total area, primarily due to their small size, fragmentation,

isolation, or high levels of human disturbance. Almost two-thirds of all roadless areas had medium to high EVIRA values. The conservation of roadless areas is in line with several United Nations' Sustainable Development Goals, particularly with goals 15 and 9.

The second paper explores the ecological significance and conservation challenges of roadless areas, particularly focusing on forest ecosystems in large, unfragmented regions such as the Amazon, Congo basin, and East and Southeast Asia. These areas play a crucial role in regulating ecosystem services, including habitat availability, maintenance of genetic diversity, water retention, and soil protection. They contribute to carbon sequestration and storage and serve as local climate buffers. However, they are also objects of resource exploitation, posing a significant conflict between short-term economic interests and long-term conservation goals. In this study, I highlight roadless areas as vital indicators of pristine ecosystems and emphasize their importance in ecosystem integrity. The number of roadless areas decreased by more than 30% between 2013 and 2018, particularly in Africa and Southeast Asia, presumably as a result of increased mapping efforts, but also due to the expansion of road infrastructure. There is substantial evidence of the ecological importance of roadless areas due to the absence of complex interacting anthropogenic factors that directly or indirectly impact ecosystems. We recommend to include prioritizing the conservation of roadless areas, integrating roadlessness as a criterion for sustainable development planning, re-routing planned roads, and exploring alternative transportation technologies to reduce the impact of roads on ecosystems.

The third paper presents a comprehensive assessment of roadless areas using the OpenStreetMap road dataset 2020 in two regions with contrasting levels of human impact: the boreal region of Canada and temperate Central Europe. I used high-resolution satellite images to visually interpret and manually add unmapped roads in randomly selected roadless areas. I analyzed road mapping completeness and its relationship with anthropogenic influences, including road density, travel time to major cities, Human Footprint Index, and Human Modification Index in 1000 random plots in both regions. Results reveal large differences in road mapping completeness between the two regions, with Central Europe exhibiting significantly higher levels of mapped roads. Roads were completely mapped in 3% of the plots in boreal Canada, compared to 40% in Central Europe. Lower Human Footprint Index and road density values were associated with greater incompleteness in road mapping, highlighting the influence of human activities on mapping quality. After manually incorporating previously unmapped roads in 30 randomly selected roadless areas in each region, I found a similar decrease in roadless areas in both boreal Canada and Central Europe (27% and 28%, respectively). While in 70% of the random plots no roads were present in boreal Canada, there were no plots without roads in Central Europe. This study underscores the urgent need for improved road mapping techniques to promote research on roadless areas and to understand their role as conservation targets.

This PhD thesis deals with the emerging topic of roadless areas and represents an important contribution to conservation science. It underscores the importance of roadless areas as conservation targets and helps lay the foundations for the emergence and development of "Roadless Ecology" to further study their positive contribution to the preservation of biodiversity and ecosystem functionality.

STRESZCZENIE

Drogi są wszechobecnym atrybutem ludzkiej cywilizacji, ale ich ekspansja odbywa się kosztem bioróżnorodności i integralności ekosystemów. Negatywny wpływ dróg na funkcjonowanie ekosystemu jest wieloraki, począwszy od skutków bezpośrednich, takich jak fragmentacja siedlisk, śmiertelność dzikich zwierząt i zanieczyszczenie środowiska, a kończąc na skutkach pośrednich, takich jak wylesianie, zmiany w zachowaniu dzikich zwierząt i zaburzenie procesów ekologicznych. W rezultacie zachowanie obszarów bezdrożnych staje się podstawowym narzędziem ochrony przyrody. Głównym celem niniejszej rozprawy doktorskiej jest kompleksowa ocena, czy bezdroża mogą stanowić ekonomicznie opłacalne cele ochrony i być wskaźnikami funkcjonalnych ekosystemów. Poprzez kompleksową syntezę istniejącej literatury i oryginalnych badań, niniejsza rozprawa ma na celu zbadanie ekologicznych i politycznych implikacji ochrony bezdroży. Oceniając ich zasięg w skali globalnej i ich jakość, dążę do lepszego zrozumienia roli bezdroży w zachowaniu różnorodności biologicznej i funkcjonalności ekosystemów. Bezdroża, charakteryzujące się brakiem dróg lub infrastruktury ludzkiej, są (częściowo) wolne od wpływu dróg i mogą pełnić kluczową rolę w utrzymaniu integralności ekologicznej i funkcjonowania ekosystemu. Bezdrożne przestrzenie mogą służyć jako ważne ostoje różnorodności biologicznej i zapewniać podstawowe usługi ekosystemowe na całym świecie.

W pierwszym artykule bezdrożna zostały zdefiniowane jako obszary oddalone o co najmniej 1 km od wszelkiego rodzaju dróg, po dokładnym zbadaniu przestrzennego zasięgu wpływu dróg. Korzystając z ogólnodostępnego zbioru danych drogowych (OpenStreetMap 2013), przeprowadziłam globalną oszacowanie ich zasięgu i oceniłam ich status, jakość i pokrycie obszarami chronionymi. Mimo że około 80% powierzchni lądowej Ziemi stanowiły obszary bezdrożne, była ona pofragmentowana na około 600 000 płatów; ponad połowa z nich była mniejsza niż 1 km^2, a tylko 7% przekraczało 100 km^2. Ponadto zbadałam udział obszarów bezdrożnych o różnej kwalifikacji statusu ochrony i opracowałam wskaźnik (wskaźnik wartości ekologicznej obszarów bezdrożnych, EVIRA) obejmujący trzy wskaźniki (wskaźnik funkcjonalności ekosystemu, wielkość obszaru bezdrożnego i łączność obszarów bezdrożnych przy użyciu poligonów Thiessena) w celu oszacowania jakości tych obszarów. Chociaż obszary chronione na świecie obejmują 14% powierzchni lądowej, tylko 9% bezdroży znajdowało się w ich obrębie. Duże połacie niechronionych bezdroży o wysokich wartościach EVIRA występują zarówno w lasach tropikalnych, jak i borealnych. Afryka i Azja mają

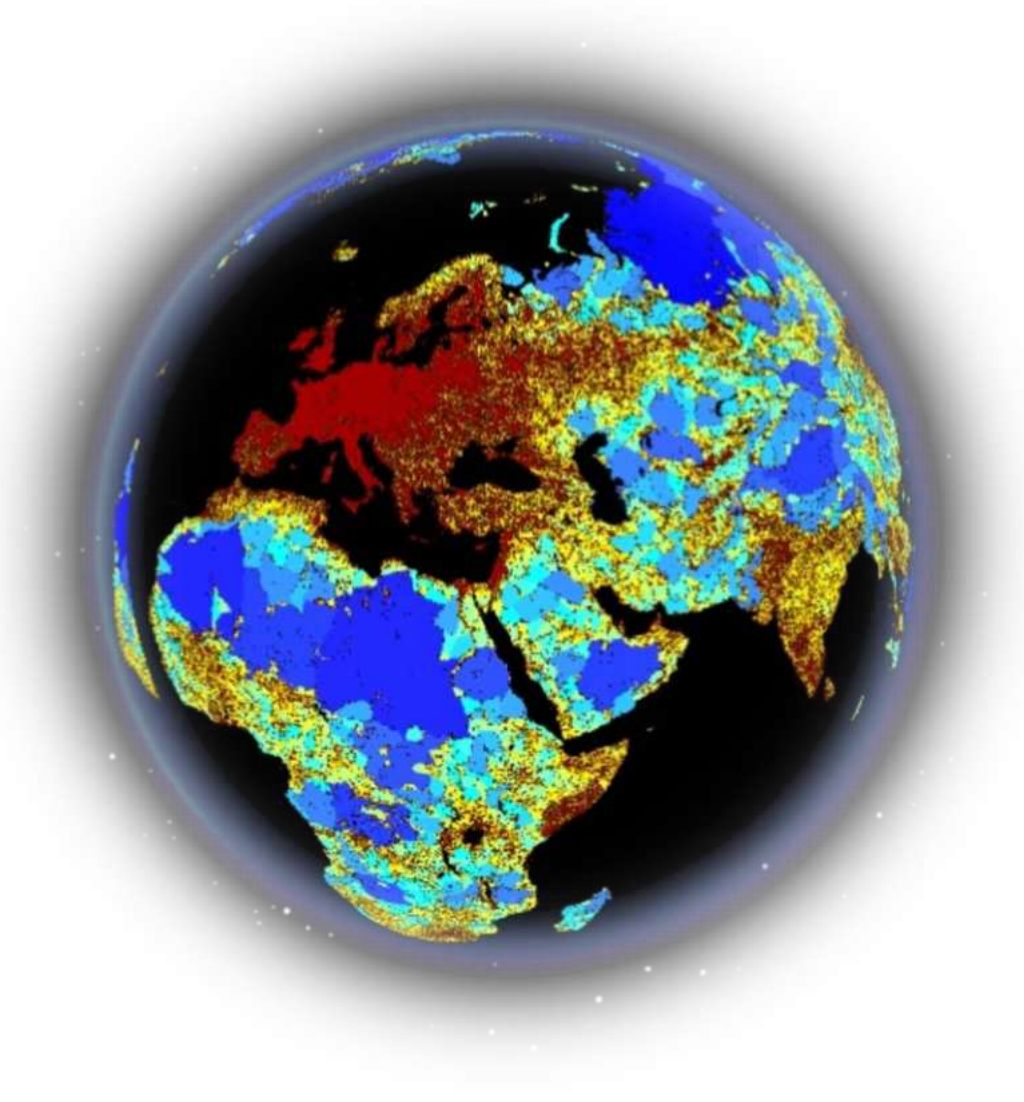
najniższy poziom ochrony obszarów bezdrożnych o wysokiej wartości. Jedynym kontynentem ze ściśle chronionymi bezdrożami wykazującymi wysokie wartości EVIRA jest Australia. Bezdroża charakteryzujące się niskim EVIRA obejmują 35% całkowitej powierzchni, głównie ze względu na ich niewielki rozmiar, fragmentację, izolację lub wysoki poziom zaburzeń spowodowanych przez człowieka. Prawie dwie trzecie wszystkich bezdroży miało średnie lub wysokie wartości EVIRA. Ochrona obszarów bezdrożnych jest zgodna z niektórymi Celami Zrównoważonego Rozwoju ONZ, w szczególności z celami 15 i 9.

Drugi artykuł zgłębia kwestie znaczenia ekologicznego i wyzwań związanych z ochroną obszarów bezdrożnych, skupiając się w szczególności na ekosystemach leśnych w dużych, niepofragmentowanych regionach, takich jak Amazonia, dorzecze Kongo oraz Azja Wschodnia i Południowo-Wschodnia. Obszary te odgrywają kluczową rolę w regulowaniu usług ekosystemowych, w tym dostępności siedlisk, utrzymania różnorodności genetycznej, retencji wody i ochrony gleby. Przyczyniają się do sekwestracji i magazynowania dwutlenku węgla oraz służą jako lokalne bufory klimatyczne. Są one jednak również miejscami eksploatacji zasobów, co stwarza znaczący konflikt między krótkoterminowymi interesami gospodarczymi a długoterminowymi celami ochrony przyrody. W badaniach tych, wraz ze współautorami, zwracam uwagę na obszary bezdrożne jako istotne wskaźniki dziewiczych ekosystemów i podkreślam ich znaczenie dla integralności ekosystemu. Liczba bezdroży zmniejszyła się o ponad 30% w latach 2013-2018, szczególnie w Afryce i Azji Południowo-Wschodniej, prawdopodobnie z powodu zwiększonych wysiłków w zakresie mapowania, ale także z powodu rozbudowy infrastruktury drogowej. Istnieją istotne dowody świadczące o ważnym ekologicznym znaczeniu obszarów bezdrożnych ze względu na to, że nie występują na nich złożone, wzajemnie oddziałujące czynniki antropogeniczne, które bezpośrednio lub pośrednio wpływają na ekosystemy. Rekomendujemy priorytetowe traktowanie ochrony obszarów bezdrożnych, włączenie bezdroży jako kryterium planowania zrównoważonego rozwoju, zmianę tras planowanych dróg oraz rozważanie alternatywnych sposobów transportu w celu zmniejszenia wpływu dróg na ekosystemy.

W artykule trzecim dokonałam, wraz ze współautorami, kompleksowej oceny obszarów bezdrożnych przy użyciu danych drogowych OpenStreetMap 2020 w dwóch regionach o kontrastujących poziomach wpływu człowieka: borealnym regionie Kanady i umiarkowanej Europie Środkowej. Wykorzystując zdjęcia satelitarne o wysokiej rozdzielczości, dokonałam wizualnej interpretacji i ręcznie naniosłam niezmapowane drogi w losowo wybranych obszarach bezdrożnych. Przeanalizowałam poziom kompletności map drogowych i jego związek z czynnikami antropogenicznymi, w tym gęstością dróg, czasem podróży do głównych miast, wskaźnikami wpływu człowieka (Human Footprint Index) i przekształcenia antropogenicznego (Human Modification Index) na 1000 losowo wyznaczonych obszarach w obu regionach. W pracy tej wykazałam duże różnice w kompletności mapowania dróg między dwoma regionami, przy czym Europa Środkowa wykazuje znacznie wyższy poziom zmapowanych dróg. Całkowicie zmapowałam drogi na 3% wybranych obszarów w borealnej Kanadzie, oraz na 40% w Europie Środkowej. Niższe wartości wskaźnika wpływu człowieka i gęstości dróg wiązały się z mniejszą kompletnością mapowania dróg, co podkreśla wpływ działalności człowieka na jakość mapowania. Po ręcznym uzupełnieniu wcześniej niezamapowanych dróg w 30 losowo wybranych obszarach bezdrożnych, stwierdziłam porównywalne zmniejszenie się obszaru bezdroży zarówno w borealnej Kanadzie, jak i Europie Środkowej (odpowiednio o 27% i 28%). Podczas gdy w borealnej Kanadzie brak było dróg na 70% losowo wybranych obszarów, w Europie Centralnej żaden z wybranych obszarów nie był wolny od dróg. W badaniu tym wskazujemy, pilną potrzebę udoskonalenia technologii mapowania dróg dla wsparcia badań nad bezdrożami i zrozumienia roli tych obszarów jako celów ochrony.

Niniejsza praca doktorska podkreśla wyłaniający się temat obszarów bezdrożnych i stanowi ważny wkład w naukę o ochronę przyrody. Praca ta zwraca uwagę na znaczenie obszarów bezdrożnych jako celów ochrony i przyczynia się do stworzenia podstaw dla powstania i rozwoju „ekologii bezdroży" w celu dalszego badania ich pozytywnego wkładu w zachowanie różnorodności biologicznej i funkcjonalności ekosystemów.

INTRODUCTION



"I am no longer accepting the things I cannot change, I am changing the things I cannot accept."

Angela Davis

GENERAL INTRODUCTION

The human-induced biodiversity loss, pollution, and climate change, endanger the future of all species on Earth and our societies (UNFCCC, 2022; Hellweg et al., 2023). These threats increasingly jeopardize ecosystem functionality on a global scale (Rands et al., 2010; Steffen et al., 2015). The accelerating rate of biodiversity loss, habitat degradation and climate change, urge for robust, proactive and efficient conservation strategies (Myers et al., 2000; Watson et al., 2019) making the conservation of functional ecosystems and biodiversity hotspots a critical priority (Butchart et al., 2010; Pollock et al., 2017).

Human encroachment into natural habitats and the division of continuous habitats into smaller, isolated patches, i.e. habitat loss and fragmentation, are a main driver of biodiversity loss (Banks-Leite et al., 2020; Kuipers et al., 2021; Caro et al., 2022). They are caused by human activities such as urbanization, deforestation, agricultural expansion, and infrastructure development (Forman, 1995; Fahrig, 2003; Foley et al., 2003; EEA, 2011; Schielein et al., 2021). About 50% of the Earth's terrestrial landscape has already been altered by habitat fragmentation, largely driven by the expansion of road networks (Haddad et al., 2015; Keeley et al., 2019) that has resulted in the isolation of populations and restriction of gene flow, increasing species' susceptibility to genetic drift, inbreeding, and local extinctions (Crooks, 2002; Williams et al., 2002; Boscolo & Metzger, 2011; Allan et al., 2019; Tokdemir et al., 2024). Eventually, fragmented habitats experience altered species compositions, reduced species richness, and shifts in community dynamics, leading to ecosystem degradation and loss of ecological resilience and functions (Echeverría et al., 2007; Wilson et al., 2016; Scanes, 2018). Ecological processes and interactions essential for maintaining ecosystem structure and functions (e.g. seed dispersal, pollination, predator-prey relationships) can be disrupted by fragmentation (Kruess & Tscharntke, 1994; Xiao et al., 2016). Fragmented landscapes are, in general, less capable of providing carbon sequestration, water purification, and climate regulation - ecosystem services that are vital for effective climate change mitigation (Haddad et al., 2015; Marques et al., 2019).

Roads are one of the primary contributors to habitat loss and fragmentation (Forman & Alexander, 1998; Laurance et al., 2014). However, habitat loss and fragmentation are only two of the numerous negative impacts roads have on the environment (Spellenberger, 1998; Laurance & Balmford, 2013). While roads play a crucial role in facilitating human mobility, economic development, and access to resources, their construction, maintenance, and associated activities can have profound, long-term and usually detrimental effects on ecosystems (Bryceson et al., 2008; Selva et al., 2011). These include habitat degradation, deforestation, habitat loss, land-use conversion, changes in ecological processes, emissions, heavy metal pollution, soil compaction, and changes in the microclimate (Trombulak & Frissell, 2000; Waller & Servheen, 2010; Chaplin-Kramer et al., 2015). Further direct and indirect impacts of roads on ecosystems range from barrier to animal movement, wildlife mortality, salt, noise, and light pollution, avoidance behavior of wildlife, spread of invasive species, and resource extraction (Bissonette & Rosa, 2009; Fahrig & Rytwinski, 2009; Benítez-López et al., 2010; Grilo et al., 2014; Ceia-Hasse et al., 2017). Road construction and the following contagious development can have devastating effects on biodiversity, particularly in pristine ecosystems (Selva et al., 2015). The severity of these impacts depends on road surface, road density, location, type and traffic volume (Barber et al., 2014; Kleinschroth & Healey, 2017). Indirect effects can be very complex, delayed in time and extend far beyond the road itself (Figure 1) (Forman, 2000; Forman & Deblinger, 2000; Forman et al., 2003; Selva et al., 2011).

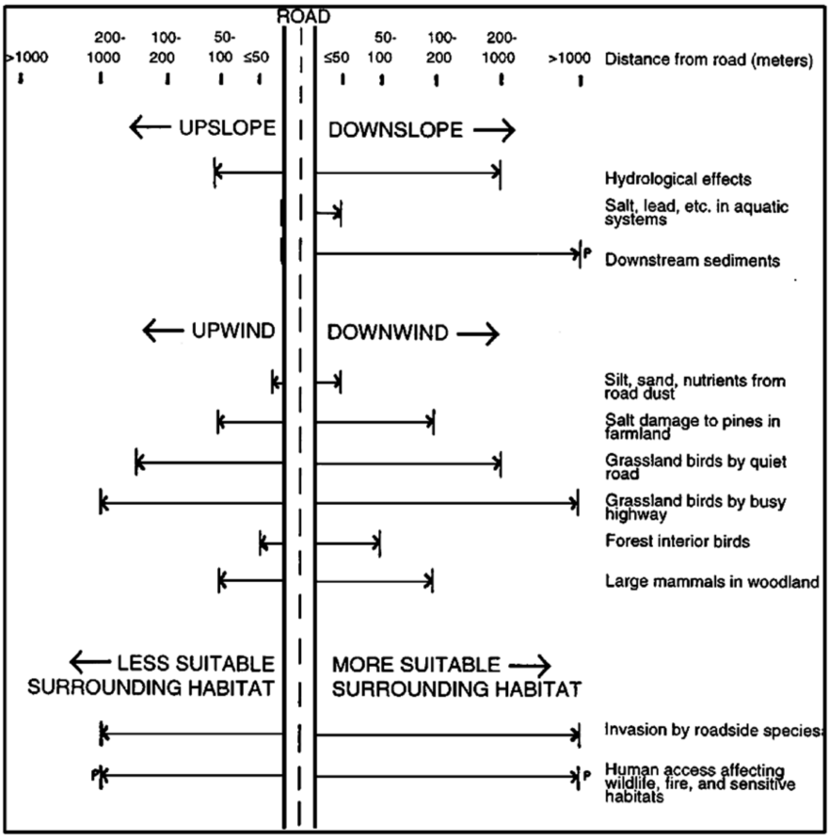


Figure 1: Road-effect zone defined by ecological effects extending different distances from a road. From Forman et al. (1997).

Forman & Alexander (1998) coined the term "road-effect zone" to describe the area beyond a road that is impacted by it. The size and extent of the road-effect zone are influenced by various factors including distance from the road, environmental conditions, weather, landscape composition, topography, time of day, and traffic volume (Forman & Deblinger, 2000). Due to the diverse impacts of roads, it is difficult to define a single road-effect zone applicable to all ecosystems and species. The size of the road-effect zone can vary significantly and can extend up to 45 kilometers from the road (Southworth et al., 2011; Altringham & Kerth, 2016). In the Amazon region, 95 % of all deforestation occurs within 5.5 km of roads (Barber et al., 2014). Population declines for mammal species extend over distances of up to 5 km from roads, and for bird species up to 1 km (Benítez-López et al., 2010). Bat activity triples between 0 and 1,600 m from the road (Altingham & Kerth, 2016). Road impacts affect desert tortoises at distances exceeding 400 m from the road (Boarman & Sazaki, 2006). Eigenbrod et al. (2009) estimated the road-effect zone for anurans in Canada to be between 250-1,000 m. Dutch birds were affected at distances ranging from 40-2,800 m from the road, depending on species and traffic volume (Reijnen et al., 1995).

The concept of roadless areas relates to terrestrial land units outside of the road-effect zone and, therefore, little to no affected by roads and minimally impacted by humans (Figure 2) (Crist et al., 2005; DellaSala et al., 2011; Selva et al., 2011). Theoretically, these areas represent natural, functioning ecosystems, characterized by limited human disturbance, considerable size, and more resilient to global environmental changes (Selva et al., 2011, 2015). Globally, roadless areas are becoming increasingly scarce, a trend driven by the rapid construction of new roads (Dulac, 2013; Selva et al., 2015; Laurance, 2018; Meijer et al., 2018). Road expansion unavoidably leads to heightened human access in areas that were once undisturbed and free from fragmentation. Compared to fragmented areas, roadless areas have a greater buffering capacity and are more resilient to the effects of climate change than fragmented areas (Selva et al., 2011, 2015; Talty et al., 2020). They can serve as quantifiable indicators of the most pristine ecosystems and play an important role in maintaining ecosystem functions and promoting biodiversity and ecological processes (Campaign, 2001; Goetz et al., 2014). They facilitate species movement, long-distance dispersal and increase connectivity between ecoregions (Gelbard & Harrison, 2003).

A highly effective strategy for mitigating biodiversity loss and protecting ecosystem services, especially in pristine regions, is the conservation of roadless areas (Laurance et al., 2014; Selva et al., 2011, 2015). Despite their conservation value, the formal recognition of roadless areas is limited, with only the USA's 2001 Roadless Areas Conservation Rule and Greece's recent policy banning road construction in roadless Natura 2000 mountain areas reflecting this concern (Kati et al., 2022). Most countries do not prioritize roadless areas, despite their crucial role in maintaining connectivity and ecosystem integrity (Selva et al., 2011). Calls for establishing roadless areas as conservation targets and implementing a "European Roadless Rule" have been made (Selva et al., 2011; Psaralexi et al., 2017; Kati et al., 2020). Current Sustainable Development Goals prioritize economic growth associated with roads (Goal 8) but have failed to consider their environmental impacts. Protecting roadless areas is a crucial step towards achieving the goal of conserving 30% of the Earth by 2030, as outlined in the Global Deal for Nature. This initiative, alongside the Paris Agreement, aims to mitigate climate change, preserve species, and maintain essential ecosystem services (Dinerstein et al., 2019). By designating roadless areas as part of the conservation network, we can increase protected lands to approximately 30% in the European Union and USA (Psaralexi et al., 2017; Talty et al., 2020). Infrastructure development should bundle transport networks and concentrate traffic on existing roads in order to avoid dissecting roadless areas. In cases where new roads must cross these areas, compensation policies like No-Net-Loss of unfragmented lands should be applied, with a focus on road reclamation and prioritizing routes that minimize fragmentation and maintain ecosystem functionality (Selva et al., 2015).

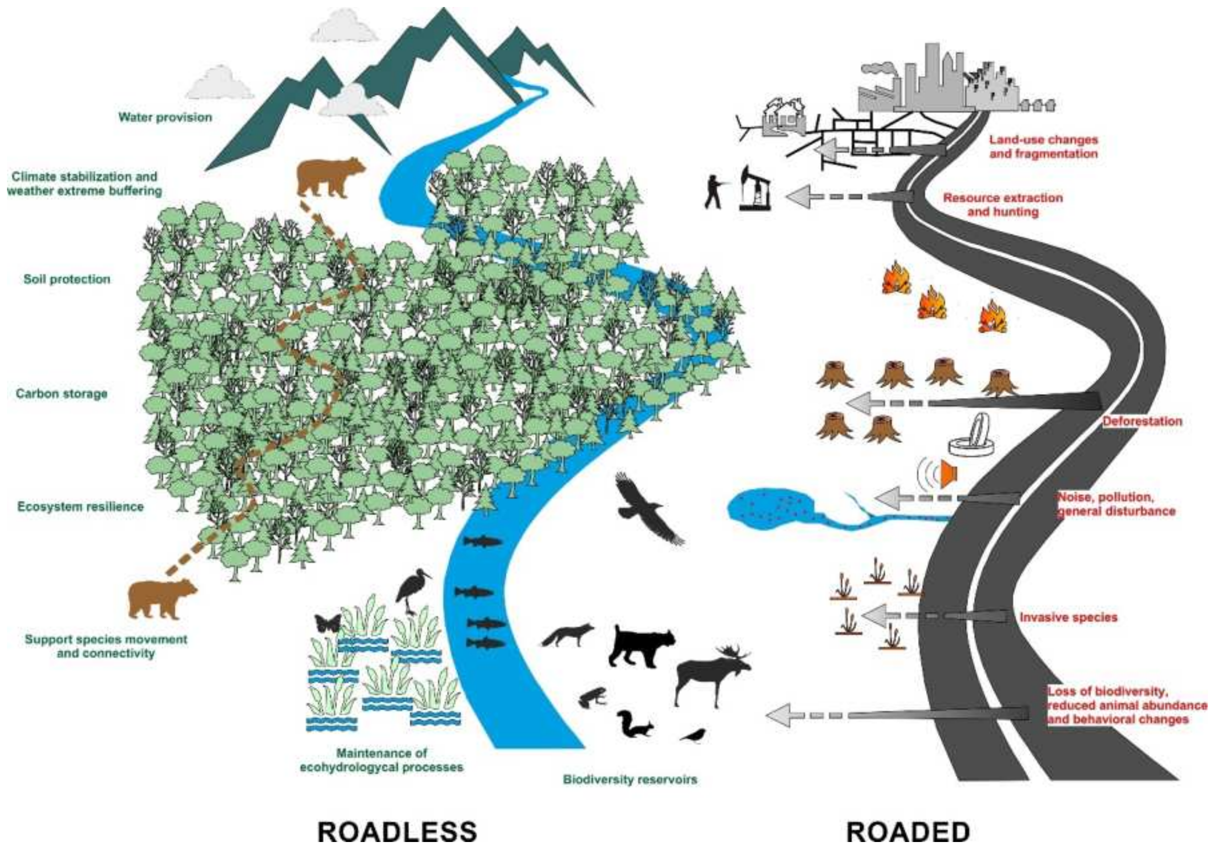


Figure 2: Schematic representation of roadless areas and their benefits (left) and different categories of road impacts on biodiversity (right). From: Selva et al. *(in press)*

The accuracy of road data plays a significant role in assessments of the extent and amount of remaining roadless areas. To date, there is no road dataset that contains all existing roads (Barrington-Leigh & Millard-Ball, 2017; Meijer et al., 2018). Road data reliability is particularly compromised concerning minor and unpaved roads, often omitted from official records despite their considerable environmental impact (Kleinschroth & Healey, 2017; Mikusiński et al., 2018; Coffin et al., 2021). In pristine ecosystems road construction and the following contagious development have the most catastrophic effects on biodiversity (Laurance et al., 2014; Selva et al., 2015). There is an urgent need for real-time systems to detect and map roads for land planning and conservation management because the global road network is constantly expanding, imperiling functional ecosystems on which societies rely (Laurance, 2018). Citizen science projects like OpenStreetMap provide valuable datasets that are updated daily, but their accuracy varies across regions, with less developed areas often exhibiting higher incompleteness (Zielstra & Zipf, 2010; Barron et al., 2014; Camboim et al., 2015; Zhang & Malczewski, 2017). Various emerging algorithms and technologies, such as Deep Learning and LiDAR, offer promising results in road detection (Sherba et al., 2014;

Stewart et al., 2020; Das & Chand, 2021; Botelho et al., 2022). However, detecting specific road types, such as logging roads, unpaved roads, or desert roads, present significant challenges due to their unique characteristic, and require different mapping approaches (Nachmany & Alemohammad, 2019; Vargas-Munoz et al., 2020; Wang & Li, 2020). This limitation is particularly acute in regions of high conservation value, where logging roads are often poorly mapped or entirely missing (Kleinschroth et al., 2019). The absence of these roads in the available maps translates into a substantial loss of roadless surface area, hampering research on intact ecosystems and pristine regions reliant on accurate road disturbance assessments. Accurately identifying roadless areas is essential for the preservation and protection of ecosystems, highlighting the necessity for precise road mapping efforts.

Roadless areas may represent critical conservation targets under the ongoing climate and biodiversity crises due to their ecological significance, biodiversity values, and contributions to ecosystem services and climate change mitigation. Protecting these areas from further road development and promoting further research on them is essential for maintaining global biodiversity, safeguarding ecosystem resilience, and ensuring the long-term sustainability of natural ecosystems and human societies.

OBJECTIVES AND RESEARCH QUESTIONS

The aim of this thesis is to improve our understanding of roadless areas as cost-effective conservation targets and surrogates for functional ecosystems. Six research questions were formulated, systematically investigated, and answered by the three publications presented in this thesis.

Paper I

1. RQ1: How to define roadless areas?
2. RQ2: Where are roadless areas?
3. RQ3: Which is the protection status of roadless areas?
4. RQ4: Do roadless areas represent functional ecosystems?

The main objective of this study was to identify roadless areas at a global scale, which represents a first step in understanding their importance in conservation. An essential aspect was setting a definition of roadless areas, based on published evidence; for that an extensive literature review on road impacts was conducted. All documented impacts of roads (N= 282 scientific articles) were within 1 km of the road, with 39% occurring in distances of 1-2 km, and 14% extending as far as 5 km; hence we defined roadless areas as those land units that are at least one kilometer away from any kind of road and were taken as a proxy of areas little or no affected by road impacts. I used publicly available road data from OpenStreetMap 2013 to calculate the extent of roadless areas around the world and found that 80% of the terrestrial land surface is roadless, dissected into approximately 600,000 patches, with more than 50% of the patches smaller than 1 km^2. After identifying the roadless areas, I used the world database of protected areas to calculate how many roadless areas are under protection and their degree of protection. Only 9% of roadless areas were protected. There was no major difference in the proportion of roadless areas covered by strictly protected areas (3.8%) and the general landscape coverage of strictly protected areas (4.2%). We investigated whether the absence of roads is related to functioning ecosystems, and we developed an index to assess the ecological value of roadless areas. The ecological value index of roadless areas (EVIRA) consists of three indicators: the patch size of roadless areas, the connectivity among roadless areas calculated using Thiessen polygons and the Ecosystem Functionality Index from Freudenberger et al. (2012). We found that almost two-third of all roadless areas exhibited medium to high EVIRA values, with regions with highest EVIRA values found in tropical and boreal forests. The roadless areas with low EVIRA values (35%) were fragmented, small and heavily impacted. Australia was the only continent with strictly protected roadless areas with high EVIRA values. The policy aimed at protecting biodiversity in relation to road impacts was analyzed based on the Sustainable Development Goals and Aichi targets. Only five Sustainable Development Goals show synergies with the protection of roadless areas, which particularly aligned with Goals 15 and 9.

Paper II

5. RQ5: What are the benefits of roadless areas for nature conservation?

The main goal of this book chapter was to review the potential benefit of roadless areas as conservation targets by focusing on forest ecosystems. We found that roadless areas, characterized by undisturbed ecosystems and providing crucial benefits for biodiversity, play a significant role in conserving native biodiversity and maintaining ecosystem processes. Large roadless areas can serve as quantifiable proxies for the most pristine and functional ecosystems. Among all terrestrial ecosystems, roadless forests are the most important sites for regulating ecosystem services. Large roadless areas from the Amazon to Southeast Asia and the Congo basin play an important role in regulating ecosystem services by providing habitat, preserving genetic diversity, serving as water retention zones, and acting as climate buffers. The protection of roadless areas is a proactive approach, as opposed to reactive approaches that aim to mitigate or reverse biodiversity losses after they occur. Most importantly, the long-term opportunity cost of protecting roadless areas is often lower than the cost of fragmentation by roads and subsequent use of an area. A proactive policy can also be associated with lower political costs. If regions are spared from road construction, both immediate protests from informed stakeholders and later resistance from people negatively affected by unsustainable development in the region can be avoided. Conservation measures should include temporarily stopping road construction in specific regions and encouraging the provision of ecosystem services in regions already influenced by human activities to safeguard roadless areas and reduce the adverse effects of road building. Additionally, we advocate for enhanced protection of roadless areas through the official establishment of strictly protected areas, while also emphasizing the necessity for compensatory measures and strict regulations to prevent further habitat fragmentation and degradation caused by road construction and associated human activities.

Paper III

6. RQ6: Are roadless areas in fact roadless?

In this study, I aimed to investigate the extent to which roadless areas can be accurately identified using OpenStreetMap road data and to assess the completeness of road mapping in two study regions with different level of anthropogenic influences: the boreal region of Canada and the temperate region of Central Europe, represented by the countries of Poland, Slovakia, Czechia, and Hungary. I used two methods to test road mapping completeness and to evaluate the assessment of roadless areas according to Paper I. One method was to map missing roads in a randomly selected subset of the identified roadless areas, representative of all sizes. The second method was to create 1000 randomly selected plots throughout the study regions and to verify if roads were present. I used high-resolution satellite images and visual interpretation to validate road mapping completeness. I hypothesized that in areas with low anthropogenic impact, the completeness of road mapping would be lower than in regions that are heavily modified. To test this hypothesis, I used various covariates to disentangle relationships between anthropogenic pressures and road mapping completeness in the random plots: travel time to major cities (Nelson, 2019), Human Footprint Index (Venter et al., 2018), Human Modification Index (Kennedy et al., 2022) and road density (calculated from the OpenStreetMap road data). I aimed to determine the number and surface of roadless areas in these regions using OSM road data and found that roadless areas cover 85% of boreal Canada, compared to 0.4% in Central Europe. I assessed the completeness of OpenStreetMap road data and found that lower road density and Human Footprint values were correlated with lower road mapping completeness. After adding unmapped roads to the randomly selected roadless areas in each region, I observed a comparable reduction in roadless areas in both boreal Canada and Central Europe (27% and 28%, respectively) when accounting for all roads. This study shows that many roadless areas potentially representing most functional ecosystems are not properly mapped and identified, and therefore, are at risk of being further dissected. Improving the quality of road mapping is crucial to understand and quantify the contribution of roadless areas to the conservation of functioning ecosystems and biodiversity.

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PAPER I

A global map of roadless areas and their conservation status

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/354/6318/1419/suppl/DC1
Materials and Methods
Figs. S1 to S5
Tables S1 and S2
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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 sub-global 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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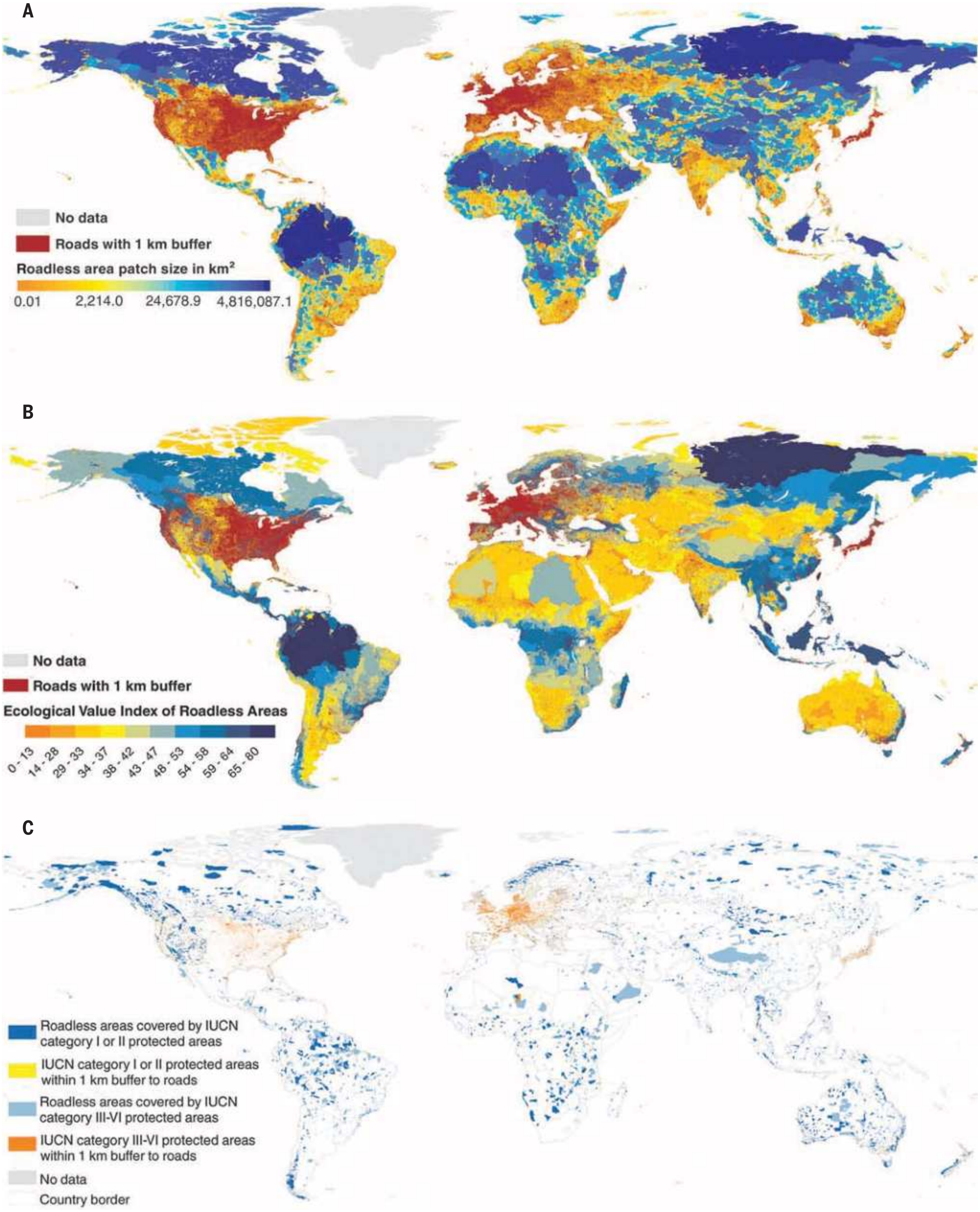

Fig. 1. The global distribution of roadless areas, based on a 1-km buffer around all roads. The distribution is depicted according to (**A**) size classes, (**B**) the ecological value index of roadless areas (EVIRA; based on patch size, connectivity, and ecosystem functionality), and (**C**) representation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

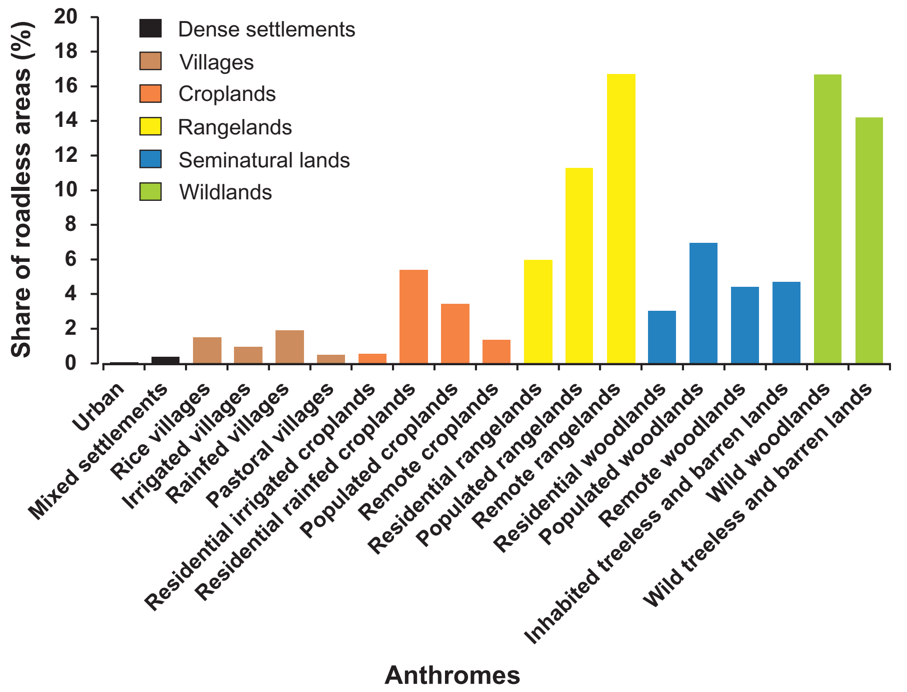

Fig. 2. Extent of roadless areas (1-km buffer) across anthromes. The majority of the world's roadless areas are in remote and unmodified landscapes, but they also occur in anthropogenically modified landscapes. The so-called anthromes were mapped according to (*10*).

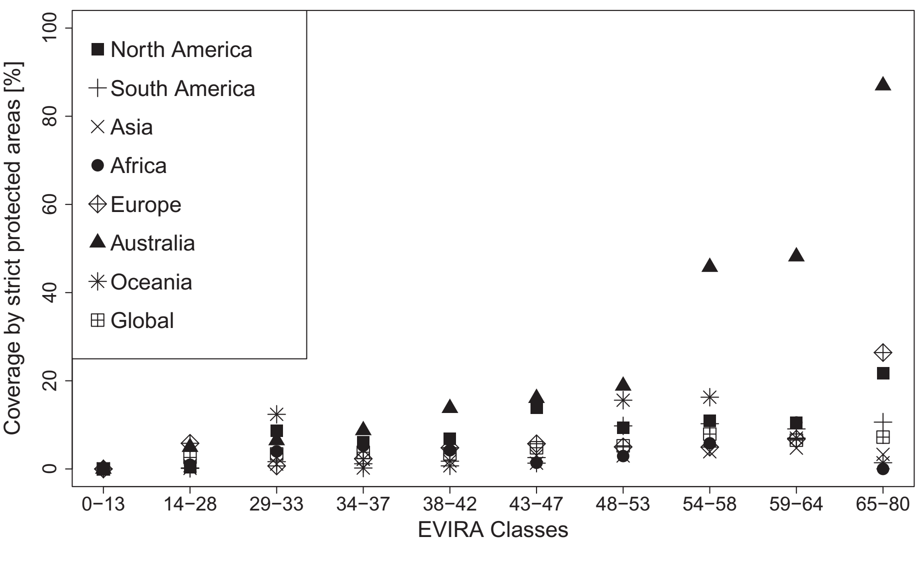

Fig. 3. Coverage of roadless areas by strictly protected areas (IUCN categories I and II) compared with global and continental EVIRA values. If priority were given to protecting roadless areas with high ecological functionality, we should see a positive correlation, with higher coverage associated with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

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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

www.sciencemag.org/content/354/6318/1423/suppl/DC1
Materials and Methods
Figs. S1 to S11
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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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Supplementary Materials for

A global map of roadless areas and their conservation status

A. Definition of roadless areas

We reviewed 282 scientific papers, out of which 58 publications provided information on the spatial influence of various road impacts and/or on the road-effect zone (Table S2). All studied impacts were documented within a distance of 1 km from the road, 39% were observed in the 1-2 km zone, and only 14% extended out to 5 km. Road effects that go beyond 50 km and to even 100 km are rarely documented; they refer to deforestation in relation to distance to main roads, not including other minor roads and paths that are necessary for forest clearings (Table S2). The 1-km buffer would therefore rather underestimate than overestimate the extension of areas impacted by roads. Still it represents a reasonable approach to excluding with high certainty those areas that are significantly affected by roads. We consider 1 km as the minimum value for road-effect zones at a global scale, taking into account landscape heterogeneity, as well as the wide range of road impacts across biomes and road categories. Consequently, we defined roadless areas as terrestrial areas not dissected by roads and low impacted by road effects (which are at least 1 km away from the nearest road).

B. Dataset and data accuracy

We used a data set of OpenStreetMap (11/2013) to create a global map of roadless areas. This data set is updated on a daily basis and can be freely downloaded. We purchased a pre-processed data set provided by Geofabrik (http://www.geofabrik.de/de/). The pre-processing did not change the road data, but instead provided a filtered data set that contained only road layers in shapefile format. OpenStreetMap is a volunteered geographic information project founded in Britain in 2004 *(16)*. It is one of the most cited, analyzed and commonly used platforms of this type and became one of the best alternative sources for geodata *(17, 18)*. The aim of OpenStreetMap is to produce and distribute free global geographic data *(19)*. The OpenStreetMap data set used in this research provides six main road categories. Examples of 'major roads' can be motorways and freeways (*category one*); 'minor roads' are categorized as small local roads, residential roads, etc. (*category two*). *Category three* is represented by 'highway links' (sliproads/ramps) that connect roads with each other. Service roads or roads for agricultural use are considered as 'very small roads' under *category four*. *Category five* is called 'path' and mainly used for horse riding and cycling, but also for small or off-road vehicles. *Category six* roads are 'unknown' types of roads. As all road categories have ecological impacts (Table S2), we included all of them in the analyses.

The CIA World Factbook estimated the road length to be 64-million km in 2013 *(20)*. The OpenStreetMap data set (2013) used in this research consists of 36-million km of roads. In contrast, the Global Roads Open Access Data Set (gROADS), published in 2013, contains 9.1-million km of roads (CIESIN 2013). The gROADS data set has been used in global studies on road impacts, in spite of containing less data than OpenStreetMap (e.g. *(7)*).

OpenStreetMap relies on the willingness of volunteers, both to contribute entries and to edit them for errors *(21)*. Therefore, the data are a crowd-sourced product with unknown data quality standards. However, a quality assessment of the OpenStreetMap data, including spatial data quality, evolution of street network, polygon geometry, comparison of user activity, development, positional accuracy, and completeness is available for different regions *(17, 22-28)*. Gröchenig et al. (2014) conducted a global evaluation of the mapping progress of OpenStreetMap history between 2006 and 2013 *(29)*. Their results state that external and internal factors significantly influence the mapping progress. Some of these factors are regional activity of the mapping community, data imports, and environmental disasters or other unforeseen events *(29)*. Demographic characteristics affect the mapping progress, and the quality of the data can vary significantly among countries (*17, 29)*.

A high number of road assessments were conducted in Europe *(30-34)*. Often, commercial or administrative data sets are used to compare and evaluate OpenStreetMap *(17)*. A study published in 2010 assessed the quality of OpenStreetMap for Germany *(32)*. Among its findings, the total length of roads was calculated as 1,204,213.69 km, whereas the road length data made available by TeleAtlas (an enterprise that provides digital maps, user content navigation, and location-based services) was 1,272,681.77 km. TeleAtlas focuses more on roads suitable for cars, whereas OpenStreetMap includes all road types *(32)*. In the case of the Brazilian Amazon it has been found that the road data from the Brazilian Institute for Geography and Statistics (IBGE) are more complete, including ca. 157,000 km of roads in contrast to ca. 114,000 km in our OpenStreetMap data set.

In areas of the tropics where land conversion is advanced, the road network may not be well reflected by OpenStreetMap. An extreme example of missing roads in the OpenStreetMap data set is Borneo. We carried out a comparative analysis of roads in the Sabah region, Malaysia, in northern Borneo. In areas considered to be roadless, closer inspection on the ground (in 2015) revealed extensive networks of vehicle tracks, for instance, throughout oil palm plantations. A similar result was found in forested areas impacted by logging roads. Indeed, cumulative data (1970-2010) compiled by the Center for International Forestry Research (CIFOR) indicate that there would be 37,498 km of logging roads in the region of Sabah alone. The 2013 OpenStreetMap data set (for Sabah created since 2009) used in this study comprises just 4,880 km, which is still more than the 2,937 km included in the road data set gROADS (1980-2010) that was the basis for other global road assessments (CIESIN 2013, *7*). Applying a 1-km buffer to each of the three road data sets for Sabah demonstrates that roadless areas are underestimated by the OpenStreetMap and the gROADS data set (Table S1). According to the gROADS data set (CIESIN 2013), 92% of Sabah is roadless. The OpenStreetMap data set shows that 91% of Sabah is roadless. In contrast, buffering the logging roads (CIFOR) reveals that only 40% of Sabah remains roadless. However, on the other hand, the CIFOR data set seems to overestimate existing logging roads. The CIFOR logging roads were mapped in four time intervals (1970, 1990, 2000 and 2010) by visual interpretation of satellite imagery. Analyzing the CIFOR logging roads with current Google Earth satellite images suggests that numerous roads have been overgrown by forest. The amount of logging roads that were either non-existent in 2010 or were <10 m wide (therefore not included in the CIFOR analysis) is high *(35)*. This simple exercise highlights the methodological problems to be overcome in future mapping. The three data sets can only be compared to a limited extent, since the roads have been mapped in different ways, time intervals and for different purposes. The gROADS data set (CIESIN 2013) focuses on roads between settlements. For Malaysia, gROADS is based on the Vector Smart Map Level 0 data. The CIFOR road data set does not include any other road category besides logging roads. In general, the three different road data sets (OpenStreetMap, gROADS, CIFOR) vary in length, location and type of roads, with OpenStreetMap being the data set with the largest length of roads at a global scale, and not limited to one type of roads (Table S1).

C. Data processing - Mapping of roadless areas and general processing

The global road data set was analyzed and processed for each continent, except for Antarctica and Greenland. All roads were buffered on both sides with a geodesic buffer of 1 km. Due to a very high number of vertices, all buffered roads were generalized with a "maximum offset tolerance" of 30 m, using the "Douglas-Peucker simplification algorithm" *(36)*. All analyses were conducted with ArcGIS 10.2. A road model tool was created with the ArcGIS model builder to facilitate the process. For the purpose of comparison, an alternative map of roadless areas was developed with a 5-km buffer to all roads (Fig. S2).

For area calculations, roadless areas were projected with the World Cylindrical Equal Area Projection. Spatial calculations and maps were made with ArcGIS Version 10.2. Protected area coverage of roadless areas was calculated based on IUCN categories of protected areas, including (a) IUCN categories Ia, Ib and II, and (b) other protected areas classified as IUCN categories III to VI (IUCN & UNEP-WCMC 2015). Protected area data sets for each country were downloaded and processed singularly instead of using the global protected area file due to inconsistencies in the global data set.

D. Data processing - Ecological Value Index of Roadless Areas (EVIRA)

There are manifold and partially contrasting approaches for defining the conservation values of given areas. Attempts at conservation priority setting have been classified as reactive and proactive *(37)*, some approaches focus on patterns rather than processes; however, in times of rapid environmental change, there are good arguments for especially targeting ecological functionality and biological viability *(9, 38)*. Therefore, we chose a functional priority-setting approach that is not based on merely anthropocentric values, such as use value or aesthetics, but comprises indicators that are defined in line with principles of modern ecosystem theory. In this context, we especially consider the capability of ecosystems to self-order and regulate abiotic and biotic conditions, which is greatly based on the capacity of uptaking and storing eco-exergy *(39, 40)*. Specifically, exergy has been used for analyzing and indicating ecosystem health *(41-46)*. As key attributes of ecosystem growth and development, Jørgensen (2006) *(42)* and Jørgensen et al. (2000) *(43)* proposed biomass, information and network as main growth forms of ecosystems.

To assess the conservation value of roadless areas, a corresponding additive index (Ecological Value Index of Roadless Areas, EVIRA) was created. Three indicators were chosen (for individual and more specific rationale of indicators see Table S5):

(1) Roadless area patch size: A larger roadless area patch size indicates less human disturbance, lower edge effects, higher populations of road-

sensitive species, as well as higher ecological integrity and self-regulating capacity.

(2) Thiessen connectivity into all directions for roadless area patches: We describe connectivity (and degree of isolation), as the ratio between the size of a roadless area patch and its surrounding Thiessen polygon. A Thiessen (or Voronoi) polygon describes the area around a sample point or area where any position taken from inside the polygon is closer to the sample point/area than to any of the other sample points/areas *(47)*. To create Thiessen polygons Euclidean distance was calculated with the formula:

$$d(x,y) = \sqrt{\sum_{i=1}^{n}(x_i - y_i)^2}$$

The larger the Thiessen connectivity value, the closer neighboring roadless patches can be found. This is important for the integrity of landscape-scale processes (e.g., genetic exchange of metapopulations and endemics with narrow geographic ranges confined to roadless areas).

(3) Ecosystem Functionality Index *(9)*: This weighted, additive dimensionless index comprises vegetation density, tree height, carbon storage, species richness of vascular plants, plant functional richness and slope. Functionality is defined as "the state of ecosystems, characterized by inherent structures, ecological functions and dynamics, that provide ecosystems with both, the necessary efficiency and resilience to develop without abrupt change of system properties and geographical distribution, and allows for flexible response to external changes" *(9)*.

All indicators (Roadless area patch size, Thiessen connectivity, Ecosystem Functionality Index) were rasterized and adjusted in resolution and projection. A resolution of 0.002 (equally to 0.2 km) was chosen. ArcGIS 10.2 was used for projection, resolution and rasterization. All indicators were normalized between 0 and 100 and a weighted additive index was calculated using the software Insensa-GIS *(48)*. Thiessen connectivity into all directions and roadless areas patch size were weighted with 25%, whereas ecosystem functionality was weighted with 50%.

E. Sensitivity analysis for the Ecological Value Index of Roadless Areas (EVIRA)

Index construction always involves steps such as indicator selection and weighting. In order to transparently highlight the sensitivity of EVIRA to changes in these steps, we performed a statistical sensitivity analysis. Three different index versions were produced using jackknifing, ten of them using random weight variation within defined borders (connectivity into all directions and roadless area patch size 10-50%; ecosystem functionality index 30-70%) and one using equal weighting. Within the jackknifing procedure, three versions were created where each indicator was removed iteratively from the index calculation procedure. Overall 14 different index versions were created to perform the sensitivity analysis.

Pearson and Spearman rank correlation coefficients were calculated for the three indicators and EVIRA (Table S6). Significant and highly positive Spearman rank and Pearson correlation coefficients were found between the Ecosystem Functionality Index (EFI) (*9*) and EVIRA (Spearman r= 0.818; p<0.0001; Pearson r= 0.881; p<0.0001; Table S6). This is likely to be a consequence of the original weighting scheme of EVIRA, where EFI was given a weight double as high as the two other indicators. A high positive and significant Spearman rank correlation was also detected for roadless area patch size and EVIRA (Spearman r= 0.768; p<0.0001; Table S6). Therefore, EFI and roadless area patch size are the best single indicators for the final index output.

Mean values over all 14 index variations are shown in figure S6 with the highest values represented in blue and low values shown in orange. Similar to the original EVIRA, highest mean values are recorded for the Amazon, followed by the tundra and taiga of the northern and eastern lowlands of Siberia, as well as south-east Asian tropical rain forests.

The coefficient of variation was calculated over all 14 index variations to evaluate the variability of EVIRA (Fig. S9). Most parts of Australia show high levels of variation, as well as parts of Africa and central- and southwest Asia. The overall pattern is that regions with relatively high index values tend to have a lower coefficient of variation, whereas areas with high levels of variation tend to occur in regions with low index values. This results in a high confidence in the prediction of the ecological value, especially of those areas with high EVIRA values. A negative correlation coefficient between EVIRA and the coefficient of variation was detected (Spearman rank correlation: -0.97; Pearson correlation: -0.94). The volatility highlights the areas which were most frequently assigned a high index value (>70% of the maximum value) within the 14 different index variations (Fig. S7). Very high readings were found for the sites with highest roadless area patch size as well as parts of Southeast Asia.

The proportion of area that changes its index value by less than 25%; between 25-50%; between 50-75%; and more than 75%, was explored for the equal weight method, and the three different index versions created by the jackknifing procedure (Fig. S8). Indicator selection seems to have a stronger effect on the output than the weighting scheme. More than half of the area changes its index value between 50 to 75% when connectivity into all directions was removed from the index, and 19% of the areas changed its index value by more than 75%. The exclusion of EFI showed that more than 60% of the area changed its index value between 25 and 50%. The removal of roadless area patch size (18% change in category 25-50%) and applying an equal weighting scheme (5% change in category 25-50%) did not change the index output significantly.

F. Policy analyses: synergies and conflicts between conservation of roadless areas and conservation and sustainability agendas

The "Aichi Biodiversity Targets" of the Convention on Biological Diversity (CBD) are part of the "Strategic Plan for Biodiversity 2011-2020" *(12)*. They circumscribe the United Nations' central agenda for the conservation of the Earth's diversity of life. They were adopted in October 2010 and comprise 20 targets that are grouped into five Strategic

Goals. Seventeen “Sustainable Development Goals” (SDGs) have been defined within “Transforming our world: the 2030 Agenda for Sustainable Development” of the United Nations *(14)*, adopted in September 2015. They replace eight “Millennium Development Goals” that were pursued from year 2000 to 2015 *(49)*. The SDGs are associated with 169 targets. Work on underlying indicators is ongoing; nevertheless, the latest report can provide direction for the interpretation of the goals and their respective targets *(50).*

Specifically, our analyses of the global sustainability agendas aim at identifying potential synergies, conflicts and ambivalences between roadless areas conservation and the achievement of conservation and sustainability goals in the policy framework of the United Nations. In addition, these analyses indicate imminent conflicts among goals within the respective policy frameworks, particularly those concerning the global sustainability agenda. Furthermore, a considerable number of conservation and sustainability targets also were found to be ambivalent.

The calculation of conflict-synergy scores for the SDGs (Table S10) and the Aichi Strategic Goals (Table S11) is based on a simple index composed of individual scores attributed to all corresponding targets to which roadless areas are in some way applicable. We excluded the targets related to governance in general (marked by a combination of number and letter, e.g. “13.a”) from the analysis, thus reducing the number from 169 to 126. The individual scores for targets can have three discrete values:

- -1 (indicated by blue color): conservation of roadless areas is in conflict with the achievement of the target;
- 0 (yellow): conservation of roadless areas has an ambivalent relationship with the achievement of the target; and
- 1 (green): conservation of roadless areas is in synergy with the achievement of the target.

Roadless areas do not relate to a number of targets; these targets are therefore excluded from the analysis (indicated by grey color). The conflict-synergy score for a goal is calculated as the mean of all values for corresponding targets. The scores can, thus, vary between -1 and +1. They are classified as follows:

- <-0.5 (indicated by blue color): conflicts with goal prevail;
- -0.5 to 0.5 (yellow): mixture of synergies and conflicts with goal; and
- >0.5 (green): synergies with goal prevail.

The conflict-synergy scores for goals are also visualized by the colors in the large boxes of Tables S10 and S11.

SUPPLEMENTARY FIGURES (S1-S11)

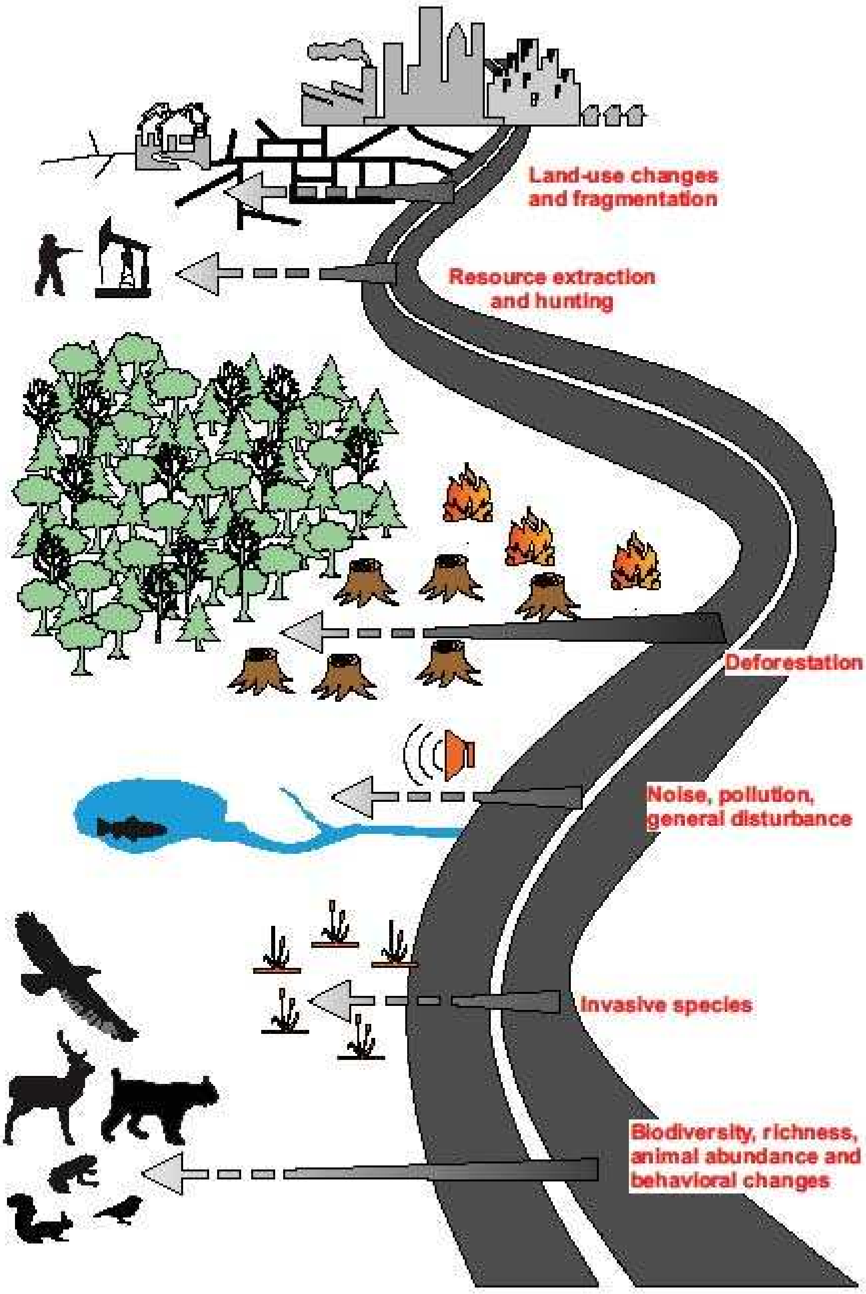

Fig. S1. Schematic representation of different categories of road impacts on biodiversity. These impacts decrease with the distance from the road. Road effects generally attenuate beyond one kilometer distance from the road (see literature review in table S2). One kilometer was therefore selected as a buffer to identify roadless areas as those areas relatively free from road disturbances.

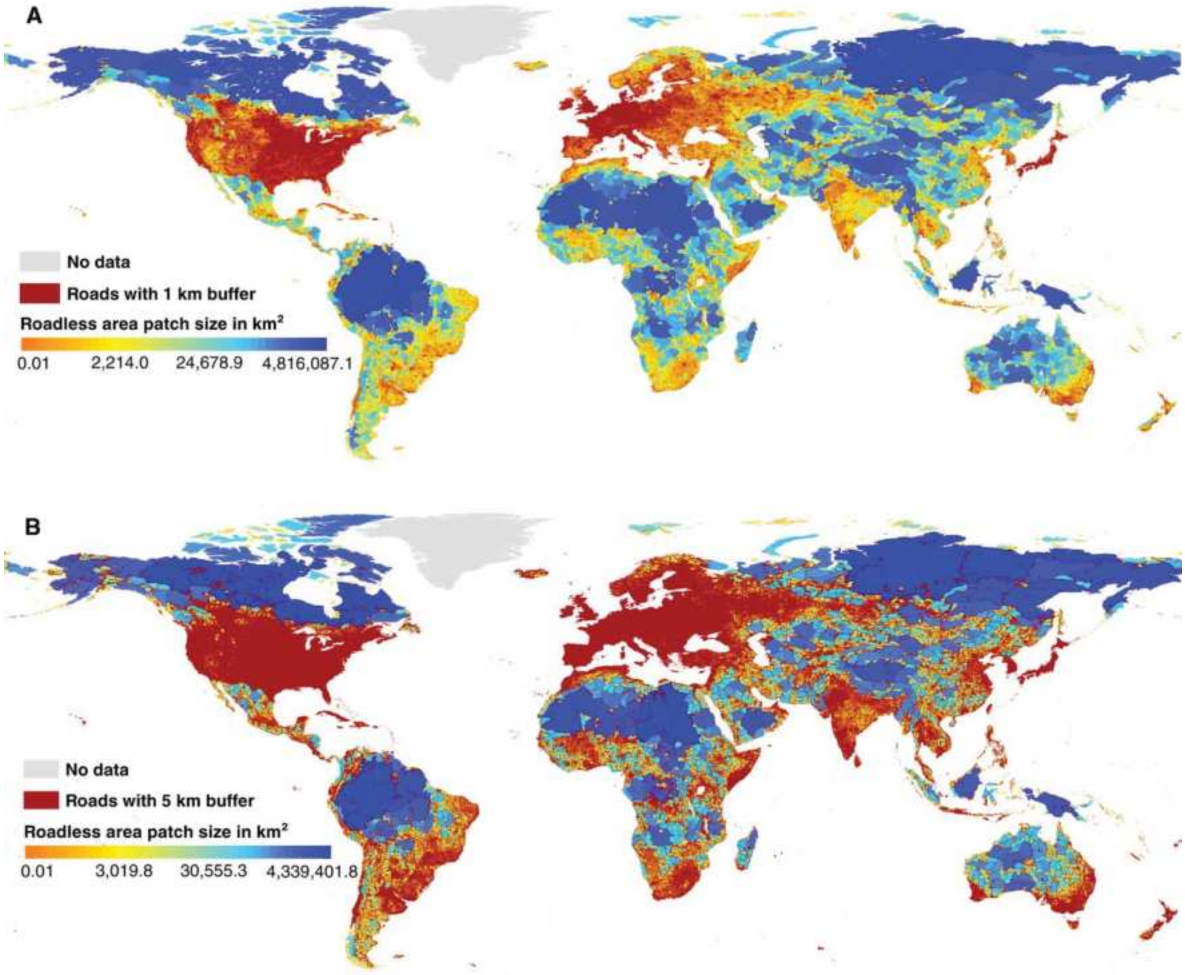

Fig. S2. The global distribution of roadless areas based on a (A) 1-km and a (B) 5-km buffer to all roads included in the OpenStreetMap data set (11/2013).

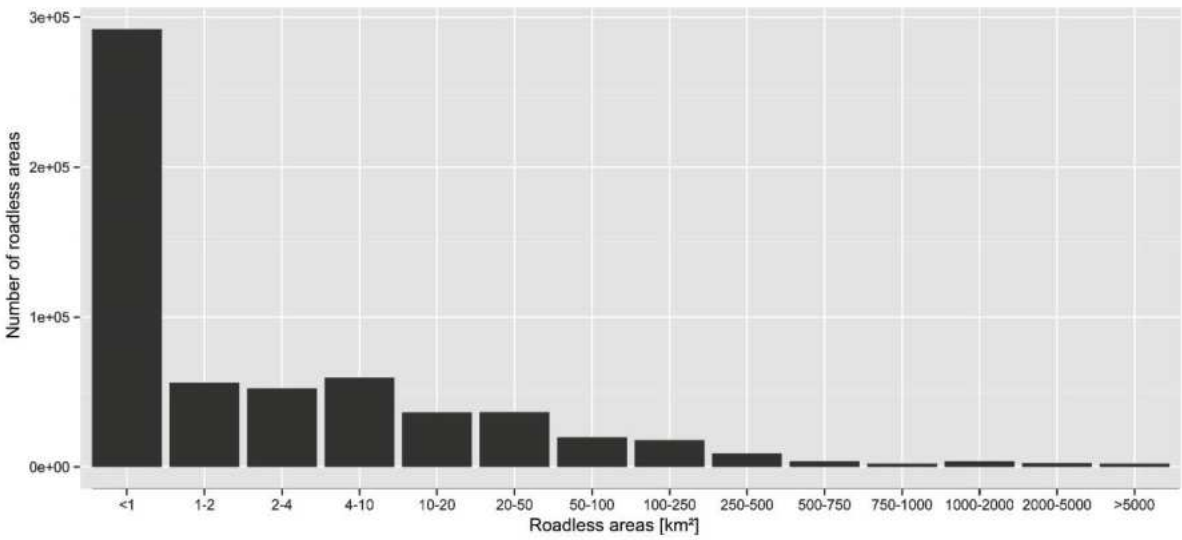

Fig. S3. Frequency of global roadless areas size classes based on 1-km buffer to all roads included in the OpenStreetMap data set (11/2013).

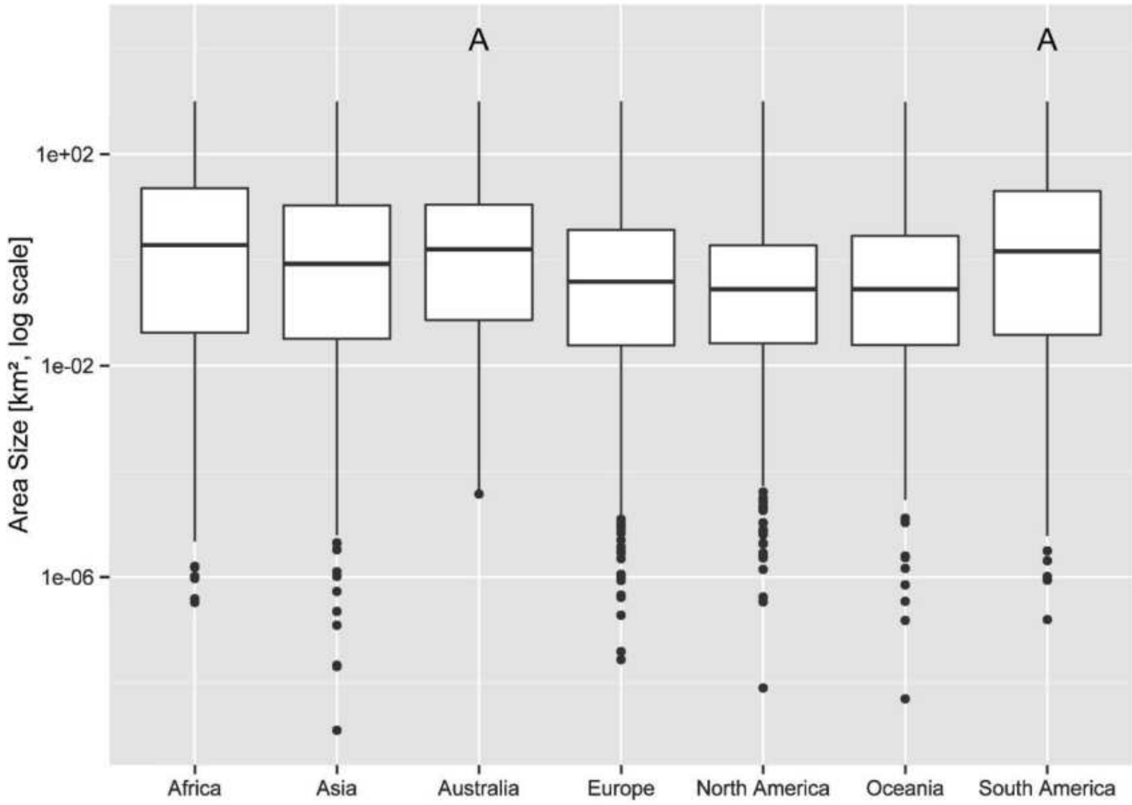

Fig. S4. Sizes of roadless areas across continents based on 1-km road buffer using the OpenStreetMap data set (11/2003) (Pairwise Wilcox test; “A” indicates that the corresponding distributions are not significantly different; p<0.001).

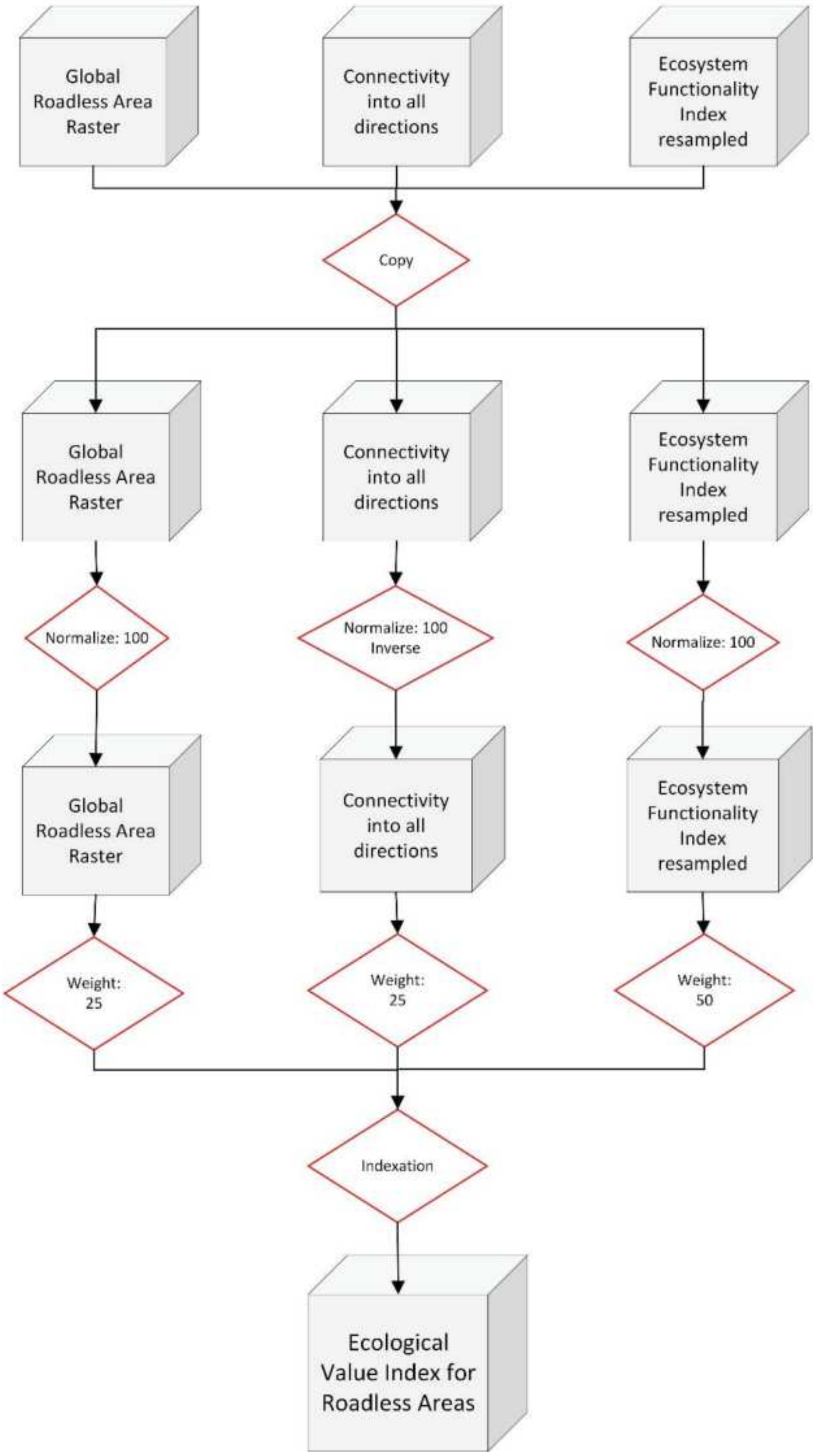

Fig. S5. **Workflow of the indexation process for creating the *Ecological Value Index of Roadless Areas* (EVIRA).**

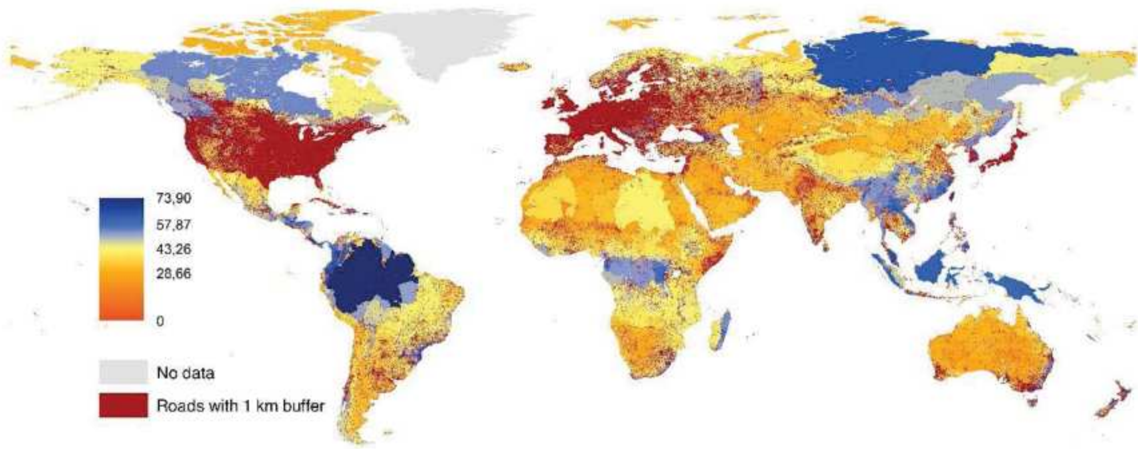

Fig. S6. Global map of mean values over 14 different index variations for the Ecological Value Index of Roadless Areas (EVIRA). Class breaks were calculated using the Jenks breaks algorithm.

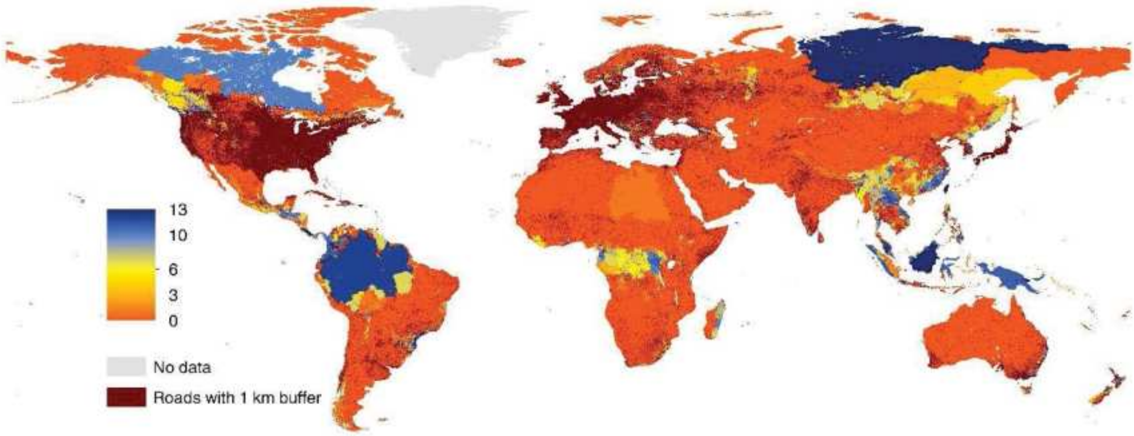

Fig. S7. Global map of volatility (frequency of that the value achieved at least 70% of the maximum index value) of the ecological value index of roadless areas (EVIRA) over all 14 index variations.

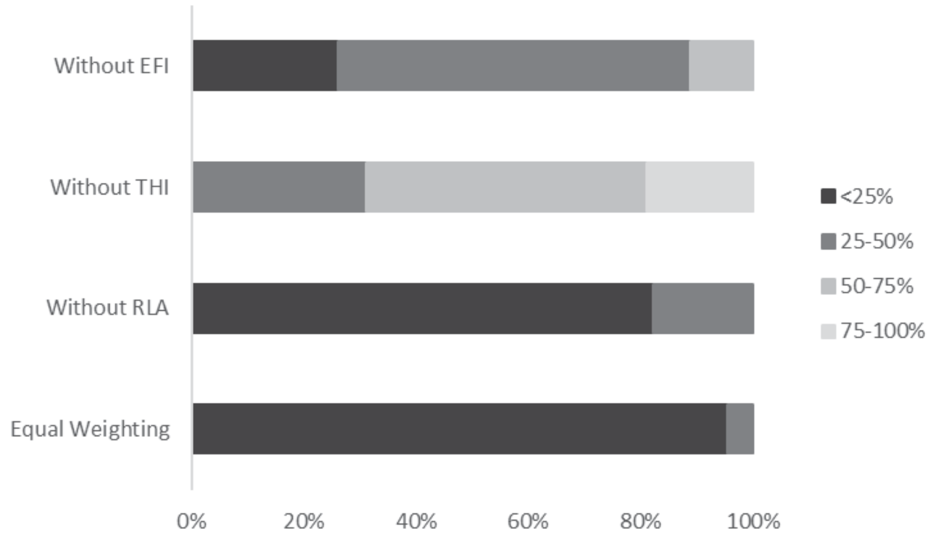

Fig. S8. Proportion of global area whose EVIRA value is changing < 25%, 25-50%, 50-75% and >75%, as shown by the sensitivity analysis. The three indicators making up the EVIRA index are the Ecosystem Functionality Index (EFI), the Thiessen connectivity into all directions (THI) and the Roadless area patch size (RLA).

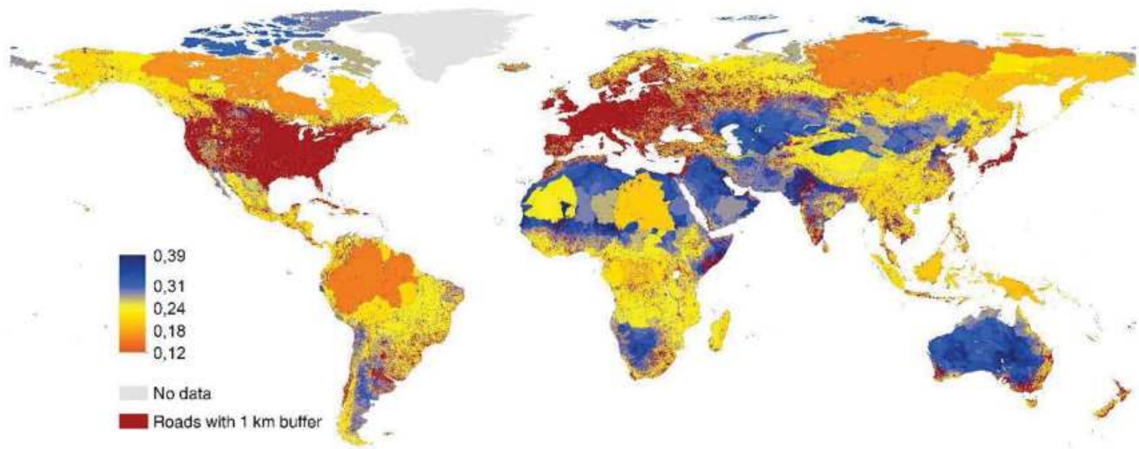

Fig. S9. Mean statistical sensitivity of the Ecological Value Index of Roadless Areas (EVIRA) as overall coefficient of variation of 14 index variations.

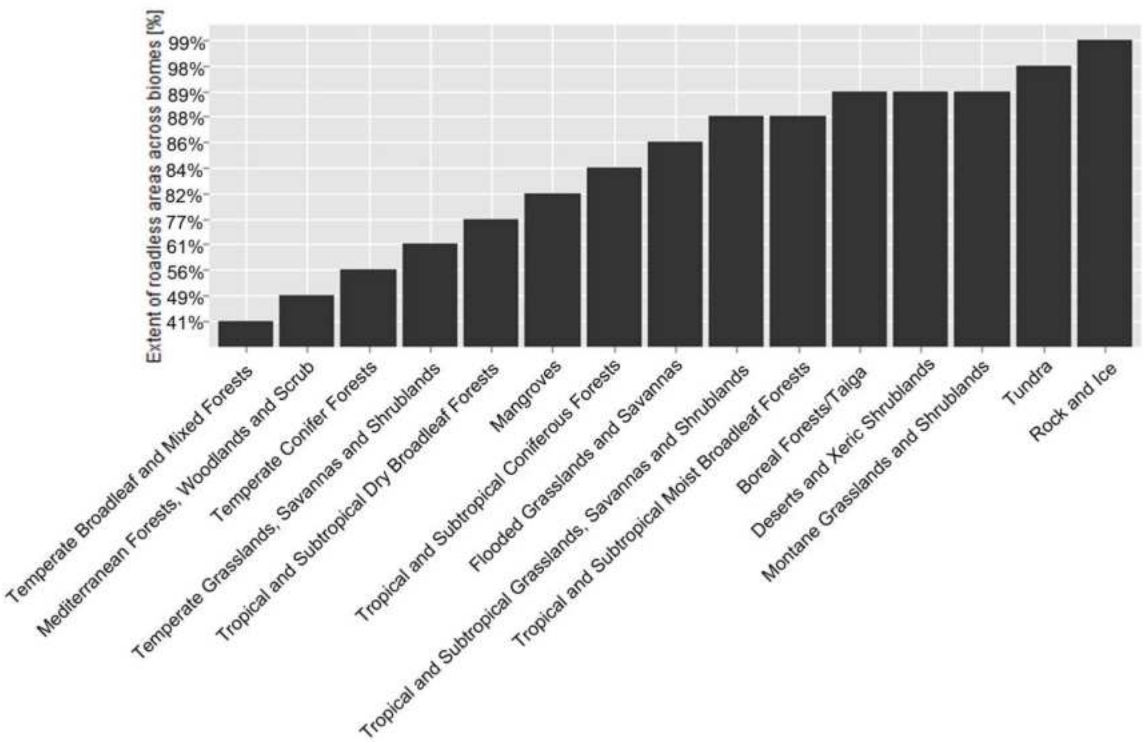

Fig. S10. Extent of roadless areas across biomes (without freshwater bodies, Antarctica and Greenland) according to classification by Olson et al. (2001) *(51)* and based on 1-km buffer to all roads included in the OpenStreetMap data set (11/2013).

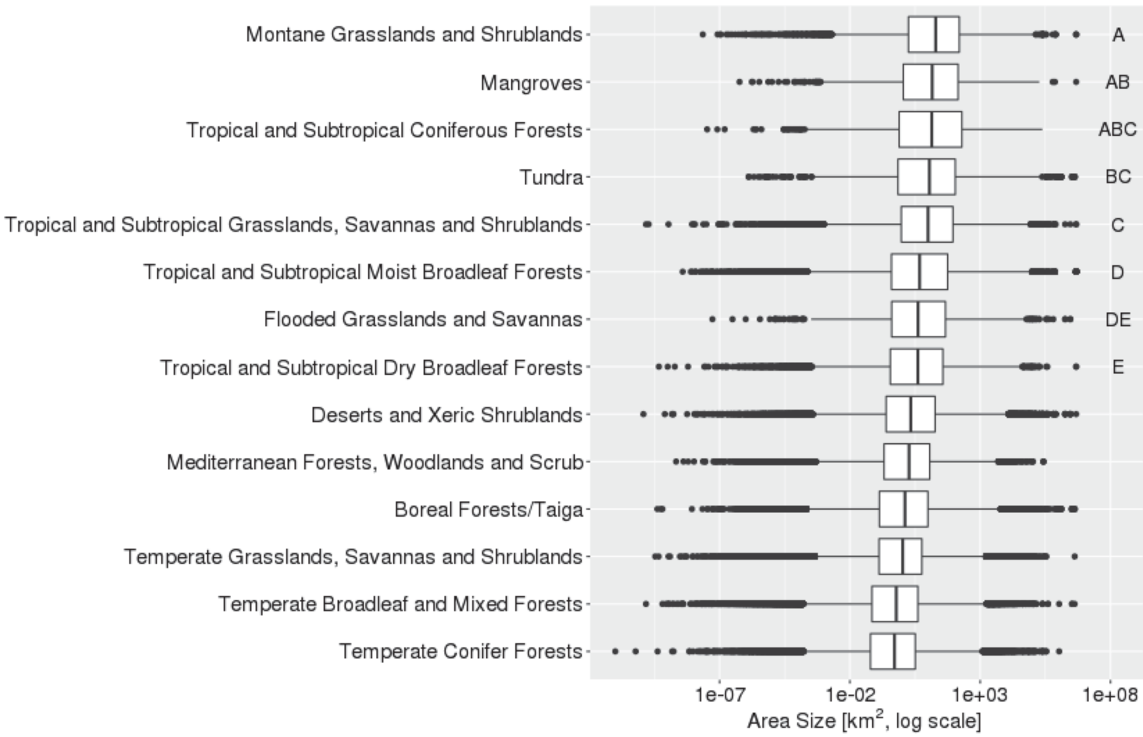

Fig. S11. Size distribution of roadless areas across different biome types assessed with a 1-km road buffer using the OpenStreetMap data set (11/2003) (Pairwise Wilcox test; if biomes share the same capital letters, then corresponding distributions are not significantly different; p<0.001).

SUPPLEMENTARY TABLES (Table S1-S11)

Table S1. Extent of 1-km-buffer roadless areas for Sabah, Malaysia, comparing three different road data sets (OpenStreetMap 11/2013, CIESIN 2013, CIFOR 2014).

	Roadless areas (km²)	Roadless areas coverage (% of the territory of Sabah)
Sabah total area	73,841.91	
Roadless areas using OSM data	66,944.69	91
Roadless areas using CIESIN data	68,271.54	92
Roadless areas using CIFOR data	29,700.56	40

Table S2. List of studies documenting or assuming road-effect zones or investigating the spatial influence of road effects. Studies are ordered according to the most important effect described (some studies dealt with more than one effect).

Road type or data	Study system and location	Road effect tested	Effect description	Spatial range of influence of the road effect	Reference
CHANGES IN ANIMAL ABUNDANCE, DENSITY AND POPULATION SIZE					
Highway, secondary, rural and cyclist road	Polders, farming areas, reclaimed marshland (Netherlands)	Changes in population density of four bird species	Population density increases with distance from the road for black-tailed godwit (*Limosa limosa*) and the lapwing (*Vanellus vanellus*), but not the other species	Up to 1,800 m	*(52)*
Highway	Willow coppices and shrubs (central Netherlands)	Density of territorial males of willow warblers (*Phylloscopus trochilus*)	Lower density of territorial males, lower presence of older males, 50% higher proportion of yearling males and 50% lower success of yearling males in the road zone Total annual output of males/ha 40% lower in the road zone	Road zone assumed as 200 m from the road; intermediate between 200-400 m, and control 400 m	*(53)*
Paved major roads with different traffic volume	Deciduous and coniferous woodland crossed by main roads (Netherlands)	Breeding density of woodland birds	Reduced density in 60% of the species adjacent to roads, due to noise	The maximum reduction of car noise at 200 m from the road The majority of the species (75%) showed maximum effect distances between 100 and 1,500 m For all species combined, the effect distances varied between: - 40-1,500 m and 70-2,800 m for roads with 10,000 and 60,000 cars/day,	*(54)*

				respectively, in deciduous woodland - 50-79 m and 100- 1,750 m for roads with 10,000 and 60,000 cars/day, respectively, in coniferous woodland	
Paved major roads with different traffic volume	Open moist grassland (N and W Netherlands)	Breeding densities of bird species, including waders	Most species had reduced density close to the road; this effect was very strong for the summed density of all species	For the density of all species combined, the disturbance distance was 120 m and 560 m for 5,000 and 50,000 cars/day, respectively. Among species, disturbance distance varied between 20-1,700 m at 5,000 cars/day, and 75- 3,530 m at 50,000 cars/day At 5,000 cars/day, 7 out of 12 species had an estimated population loss of 12-56% within 100 m of roads. At further distances, such reduction occurred in the black-tailed godwit (*Limosa limosa*, 22% in the 0-500 m zone), and the oystercatcher (*Haematopus ostralegus* 44% up to 500 m and 36% for 0-1,500 m zone). At 50,000 cars/day all species showed an estimated population loss of 40-74% within 100 m of the road and >10% at 0-500 m. Five species showed reductions of 14-44% up to 1,500 m	*(55)*
All roads	Rural area (Ontario, Canada)	Effect of traffic on population abundance of green frogs (*Rana clamitans*) and leopard frogs (*Rana pipiens*)	Negative effect of traffic density on leopard frog abundance (more vagile species), but not on green frog abundance	Leopard frog population density negatively affected by traffic density within a radius of 1.5 km	*(56)*
Highway	Desert (California, USA)	Tortoise activity and presence	Tortoise signs increasing with distance from the highway edge	Tortoise populations depressed in a zone extending at least 400 m from the road	*(57)*
Unpaved roads, mostly from oil and logging companies	Lowland tropical rainforest (SW Gabon)	Abundance of mammal species	Most species responded negatively to roads	Effects measures up to 1.2 km from the road	*(58)*

Low-traffic road within forest	Deciduous forest (USA)	Change in abundance of salamander species	Reduction in salamander abundance	>35 m	*(59)*
Highway	Protected forest and commercial timberland (Adirondack Mountain, New York, USA)	Impact of road de-icing salts on the reproduction of adults and growth and survival of embryonic and larval of spotted salamander (*Ambystoma maculatum*) and wood frog (*Rana sylvatica*)	High concentration of salt reduced amphibian species survival close to the road (decline of embryo and larvae survival rate) A demographic model predicting population size decrease due to exposure to road salt (embryo and larva mortality effect); stronger effect closer to the road	Salt traveled up to 172 m from the highway into wetlands The negative effect of road salt on population sizes up to 200 m	*(60)*
Highway	Desert (Utah, USA)	Abundance and density of small mammals	No clear abundance, density, or diversity effects relative to distance from the road Species-specific response	No road-effect zone measured up to 400 and 600 m from the road in each of the two study years	*(61)*
All road types and also other infrastructure	Various; meta-analysis of 49 studies on 234 mammal and bird species	Road avoidance and reduced population density of birds and mammals	Mammal and bird population densities declined with their proximity to infrastructure Stronger avoidance in open areas compared to forested areas Habitat- and species-specific response	Up to about 1 km for birds, and up to about 5 km for mammal populations	*(62)*
Paved highway	Boreal forest (Canada)	Population density of brook charr (*Salvelinus fontinalis*) in streams	Population density differed markedly between upstream and downstream sites near highway crossings (of intermediate and low passability)	Up to 800 m from highway	*(63)*
Phantom road	Fir forest and cherry bushes (Idaho, USA)	Simulated traffic noise effect on bird abundance	Serious (25%) decline in bird abundance and almost complete avoidance by some species between noise-on and noise-off periods along the phantom road; such effect was not detected at control sites	Control sites at ca 800 m	*(64)*
Highway	Mountainous area with shrub-steppe vegetation (Ghamishloo Wildlife Refuge, Iran)	Loss of suitable habitat and disruption of the distribution pattern of two ungulate species, the goitered gazelle (*Gazella subgutturosa subgutturosa*) and the wild sheep (*Ovis orientalis*	51% and 10% of high quality habitat unavailable for gazelle and sheep, respectively, due to road construction Presence points increased with road distance	Large increase in presence at > 3km from the road	*(65)*

		isphahanica)			
Highways and national roads	Mediterranean agricultural landscape and cork oak woodland (Alentejo, Portugal)	Likelihood of owl species (barn owls *Tyto alba*, tawny owls *Strix aluco* and little owls *Athene noctua*) occurrence	Higher probability of owl occurrence at longer distance from major roads, particularly for barn owl	Owl presence occurred at further distances (1,591 ± SD 960 m) than absences (1,097 ± SD 826 m)	*(66)*
Paved interstate and county roads	Desert (Mojave, California, USA)	Signs of Mojave Desert tortoise presence (*Gopherus agassizii*)	Tortoise signs increased significantly with distance from roads	Reductions in signs extended farther from the high-traffic interstate than from the smaller, lower-traffic county roads (306 m versus 230 m)	*(67)*
Wide paved and minor unpaved roads	Mediterranean scrubland, dunes and wetlands (Doñana Biosphere Reserve, S Spain)	Presence probability of two ungulates, red deer (*Cervus elaphus*) and wild boar (*Sus scrofa*)	Presence probabilities for both species increased with the distance to the nearest road, in most cases were unpaved roads with negligible traffic volume	At 180 m from the nearest road, wild boar presence probability was lower than 0.2, and for red deer was lower than 0.7	*(68)*
MODIFICATION OF ANIMAL BEHAVIOR					
Highway	Willow coppices and shrubs (central Netherlands)	Breeding dispersal of male willow warblers (*Phylloscopus trochilus*)	Higher proportion of yearlings dispersing and longer dispersal distance in the road-zone	Road zone assumed as 200 m from the road; intermediate between 200-400 m, and control 400 m	*(69)*
Highway and major railroad line	Mountain areas covered mostly with mixed coniferous forest, valleys and prairies (Montana, USA)	Movements of grizzly bears (*Ursus arctos*)	Highway crossing frequency declined exponentially with increasing traffic volume Avoidance of areas close to the highway	Bears strongly avoided areas within 500 m of the highway (asymptote within the 500-600 m category)	*(70)*
Roads in rural areas	Steppe (Patagonia, Argentina)	Flying and feeding behavior of scavenger species	Flying activity and carcass detection was greater near roads (500 m buffer) Andean condors (*Vultur gryphus*) and black-chested buzzard-eagles (*Geranoaetus melanoleucus*) fed far from roads, while other species fed close to roads	Optimal distance for feeding activities for condors and eagles was 3,110 and 10,460 m from the road, respectively, and for the other species, from 218 to 365 m	*(71)*
Paved and unpaved roads	Steppe (Patagonia, Argentina)	Andean condor (*Vultur gryphus*) behavior at carcasses	In the patches far from roads many more condors came to feed, the average time spent per individual was longer, the proportion of time spent vigilant was lower, and the amount of food left uneaten	Up to 350 m	*(72)*

			on the carcasses was lower		
Two-lane roads	Arid shrublands and grasslands (California, USA)	Changes in survival, reproduction, space use, den-site selection, prey availability, and diet of San Joaquin kit foxes (*Vulpes macrotis mutica*)	No effects of the distance to the road on survival, reproduction, litter size, space-use patterns and diet	No effects from 0 m to > 1,760 m from the road	*(73)*
Several types, from highways to unpaved roads	Lentic water bodies including ponds, lakes, dams, and quiet pools within streams (S Victoria, Australia)	Traffic noise effect on the pitch of advertisement calls in two species of frogs, the southern brown tree frog (*Litoria ewingii*) and the common eastern froglet (*Crinia signifera*)	Tree frogs call at a higher pitch in traffic noise and shift the call frequency	Maximum noise at 40 m from highway	*(74)*
Paved roads	Various, review of 25 studies on 13 raptor species	Raptor nest location	Meta-analysis showed an overall positive impact on the displacement of nests from roads Big raptors nesting in trees exhibited greater displacement distances from nests to roads than big raptors nesting in cliffs Distance from nests to roads increase 20–30% compared to control random points	The absolute magnitude of the displacement distance of raptor nests ranged between 200 and 800 m from the road, and 1,400 m for tree nesting raptors of big size, such as large eagles and vultures	*(75)*
Highway and railway line	Mixed woodland (Buunderkamp , Netherlands)	Traffic noise and effects on vocal activity and reproductive success of great tits (*Parus major*)	Traffic noise strongly decreased with distance from the motorway and varied with the time of day, season and weather conditions Noise levels affected negatively the reproductive success of great tits (smaller clutches and fewer fledged chicks in noisier areas)	Average drop of 20 dB SPL in sound levels over less than 500 m from the road Over 400 m from the motorway, mainly bird vocal activity influenced variation in sound levels in the 4 kHz band	*(76)*
Highway	Road verges, bushes, open fields, intermittent trees, woodland (UK)	Bat activity and diversity	Total bat activity, the number of species and the activity of *Pipistrellus pipistrellus* (the most abundant species) were all positively correlated with distance from the road	Activity and diversity increased up to 1.6 km either side of the road	*(77)*
Several road types (paved roads, gravel roads, unimproved roads, truck	Montane ecosystem (Rocky Mountains,	Alteration of red deer (*Cervus elaphus*) behavior	Deer close to roads decreased their feeding time and increased vigilance and time spent travelling	Switch into a more-alert behavior closer than 500 m to roads with more than 12 vehicles/day	*(78)*

trails and ATV trails)	Canada)		More evident when traffic surpasses 12 vehicles per day	Twice longer foraging bouts, 20% increase in feeding time, 23% vigilance decrease and 10% decrease in travelling time in deer >1 km from roads	
Forest and main roads	Fir–beech forests (Dinaric Mountains, Slovenia)	Home-range size of red deer (*Cervus elaphus*)	Home-range size increased as the distance of main roads from the edge of the home range increased	Home range stabilizes at ca 1,800 m from the road	*(79)*
Highway and dirt roads	Tropical forest in metropolitan area (SE Brazil)	Scavenger removal of experimentally-placed carcasses	High carcass removal for both road categories, with a peak during the day on the highway and at night on dirt roads	Road-effect zone as assumption: >1 km from the highway there is no effect of highway on the carcass removal rate in dirt roads	*(80)*
Forest roads	Scrublands and oak and mixed forests, and portions of natural grasslands, and agricultural areas (central and northern Greece)	Rendezvous site selection by wolves (*Canis lupus*)	Rendezvous sites were located away from forest roads (most important factor at home-range scale)	Wolves selected rendezvous sites farther from forest roads (mean= 435 m, range=73–1,614 m)	*(81)*
Paved and unpaved roads for visitors use	Open grasslands, bush, savanna and woodlands (Kruger National Park, South Africa)	Behavioral response and local spatial distribution of impala (*Aepyceros melampus*)	Impalas change their local spatial distribution near paved and well-traveled roads; unpaved roads largely unaffected their local distribution Greater tolerance distances on paved roads compared to unpaved roads. More flight response in unpaved roads Few flight response (19.5%); habituation may exist	Mean flight distance from the road 30.5 m (range 0–154) vs 35.0 m (range 0–215) for those animals that did not respond. Animals avoid close proximity (first 10 m) to paved roads	*(82)*
REDUCTION OF SPECIES RICHNESS AND DIVERSITY					
Two-lane roads	Mosaic of forest, shrubland and pastures, among 12 cities and close to cities (NW Madrid, Spain)	Abundance and species richness patterns of the native avifauna in fragmented landscape	Total number of bird species, total bird abundance and number of threatened species was negatively influenced by the distance to the nearby roads The abundance of urban-exploiter bird species increased closer to roads	In general, significant threshold distances averaged 300 m for roads, but varied among parameters Mean species richness was lowest <110 m from the road and highest >1,030 m Number of threatened species decreased <400 m from road Highest bird abundance at 290-540 m from the road	*(83)*

				in deciduous forest areas Abundance of urban exploiters increased if roads <510 m	
Paved roads	Wetlands (Southern Ontario, Canada)	Richness of four different wetland taxa (birds, mammals, herptiles, and plants)	Plant, bird, and herptile species richness diminishes with increasing density of paved roads on adjacent lands	Strongest relationships at distances up to 1,000 to 2,000 m from the wetland edge Critical distance for plants is between 1 and 2 km from the wetland edge; for birds, between 0.5 and 1 km, and for herptiles and mammals at least 2 km	*(84)*
Unpaved forest roads	Forest (S Appalachian Mountains, Tennessee, USA)	Abundance and richness of the macroinvertebrate fauna of the soil and leaf-litter depth	Reduced both the abundance and the richness of the macroinvertebrate soil fauna and the depth of the leaf-litter	Effects on faunal abundance and leaf-litter depth up to 100 m into the forest (max distance tested), whereas persists to 15 m	*(85)*
Unpaved forest roads	Temperate deciduous forest (USA)	Change in the distributions of understory plants, and site variables (species cover, canopy cover, litter depth and cover, and bare ground)	Richness and diversity of native species were lower on roadsides Exotic species were most prevalent near roads Roads created a disturbance corridor that affected site variables	Native species richness back to normal levels after 5 m distance Prevalence of exotic species and effects on site variables up to 15 m	*(86)*
Highways (plus other anthropogenic barriers)	Desert regions (California, USA)	Genetic diversity in metapopulation of desert bighorn sheep (*Ovis canadensis nelson*)	Reduction in the relative gene flow among study populations Decline in genetic diversity at a rate of 0.4% per year	Barrier effect distance (at which relative gene flow decrease equivalently) estimated at c. 40 km	*(87)*
Several road types (highway, paved rural road, unpaved dirt road)	Second-growth forest (Orange County, New York, USA)	Diversity, abundance and species density of carrion beetles	No consistent effects of distance from road on the diversity, abundance or species density of beetles across road types Forests near highways and paved rural roads were less diverse than near dirt roads	No effect up to 120 m from the roads (suggestion that road effect can permeate further)	*(88)*
Highway	Rural area (Ontario, Canada)	Anuran species richness and relative abundance for seven species	Species richness and abundance declined closer to the road Suggestion that new roads should be at least 500 m from wetlands (conservative estimate of the road-effect zone for species richness), but greater buffer distances	Road-effect zones of 250–1,000 m for four of seven species and species richness, and well beyond 1,000 m for two species. Breakpoint at approximately 450-800 m from the highway for species richness; 200-300	*(89)*

			recommended (at least 3,000 m for leopard frogs *Rana pipiens*)	m for the spring peeper (*Pseudacris crucifer*), American toad (*Bufo americanus*), and gray treefrog (*Hyla versicolor*); 600–1,000 m for the wood frog (*Rana sylvatica*); and 1,100 to 2,400 m for the chorus frog (*Pseudacris triseriata*)	
High-traffic paved roads	Boreal forest (Canada)	Change in breeding bird occurrence	Bird species richness increased with increasing distance from roads Traffic noise declined with distance from the roads	Bird species richness reached a maximum at about 350 m from the road Traffic noise reached a minimum at about 450 m from the roads	*(90)*
Low-traffic unpaved roads	Tropical rainforest (Amazon, Ecuador)	Change in species richness and diversity of amphibians, butterflies and birds	Amphibian richness and understory bird richness and diversity decreased near roads Butterfly and overall diurnal bird richness increased near roads Taxon-specific response to roads	Up to 200 m from the road for butterflies, up to 250 m for amphibians and up to 350 m for birds	*(91)*
PROMOTION OF INVASIVE SPECIES					
Paved roads	Grasslands (California, USA)	Native and exotic plant diversity	In non-serpentine grasslands the percentage cover by native species, the percentage of species that were native, and the number of native grass species increased with distance from roads, while the cover by exotic species and number of exotic forb species decreased No effect of road proximity in serpentine grasslands	Native cover was greatest in sites >1,000 m from roads (23%) and least in sites 10 m from roads (9%) Percentage of species that were native was significantly greatest in sites >1,000 m from roads (44%) and least in those 10 m from roads (32%)	*(92)*
Paved roads	Grasslands (California, USA)	Survival and biomass of the invasive plant yellow starthistle (*Centaurea solstitialis*)	In non-serpentine grasslands, *Centaurea* survival and biomass was greater in sites closer to roads No effect of road proximity on the performance of planted *Centaurea* on serpentine soil	Survival and biomass greater in near (10 m) than in distant (>1,000 m) plots	*(93)*
All types, from highways to dirt roads, typically two-lane dirt and paved roads	Mature sugar maple-dominated forests (W Great Lakes, Minnesota and Wisconsin, USA)	Extent and patterns of earthworm invasion	Distance to the nearest road was the best predictor of earthworm invasion in Wisconsin Negative relationship between the distance to the nearest road and the presence of four taxonomic groups, except *Dendrobaena* which	The invasion of the *Lumbricus–Aporrectodea* assemblage generally extends nearly 1,200 m from roads. The probability of occurrence does not decline below 50% until 470-930 m, and to 5% until the nearest road is > 1,300 m away	*(94)*

			had positive	Probability of finding *Dendrobaena* alone increases with road distance crossing 50% at >1,540 m.	
Paved and forest roads	Deciduous forest (Maryland, USA)	Presence and percent cover of invasive plant species	More invasive species close to roads; sites containing three or more invasive species observed along paved roads Spread rates are higher in roadsides; roadside populations occupied a larger patches and expand more rapidly	Effects measured up to 150 m from the road; the range of influence is greater following the spread of the species	*(95)*
High, medium and low traffic roads	Dry deciduous forest (India)	Presence of invasive plants	Increase in the presence of invasive plant species near roads, especially in medium and high traffic roads	Up to 100 m (not measured further)	*(96)*
Primary roads	Terrestrial, freshwater and marine ecosystems (NW Europe, encompassing Great Britain, France, Netherlands and Belgium)	Distribution of invasive species (72, including 17 terrestrial plants, 19 terrestrial animals, 17 freshwater and 19 marine organisms)	Roads promote the dispersal of non-native species Proximity to roads was a particularly important driver for plant species distribution	Maximum probability of invasion of two plants, the Kudzu (*Pueraria lobata montana*) and Kahili ginger (*Hedychium gardnerianum*) within 2 km from roads	*(97)*
INDUCING DEFORESTATION					
Highways	Tropical rainforest (Amazon, Brazil)	Deforestation through forest conversion to crops, pastures and secondary forest	Deforestation has claimed 29-58% of the forests within 50 km of paved roads	More than two-thirds of Amazon deforestation within 50 km of major paved highways	*(98)*
Highways and unpaved roads	Tropical rainforest and adjoining woodlands and savannas (Amazon, Brazil)	Deforestation	Proximity to roads, particularly to highways, increased deforestation	Deforestation rose mostly sharply within 50-100 km of highways and within 25-50 km of unpaved roads	*(99)*
Paved and unpaved roads	Tropical rainforest (Amazon, Brazil)	Deforestation spillover	Deforestation rises in sites that lack roads but are in the same county as site with a new paved or unpaved road	100 km	*(100)*
State and federal roads, some private roads	Tropical rainforest (Amazon, Brazil)	Deforestation fires (measured by hot pixels)	Exponential declines in hot pixel frequency with increasing distance from roads Fewer deforestation fires within protected areas than outside	Almost 90% fires were ≤10 km from roads	*(101)*

Paved and unpaved roads	Tropical rainforest (Southern Amazon, Peru, Brazil, Bolivia)	Deforestation	Deforestation rates drop with distance from major roads, although the distance before this drop off appears to relate to degree of road paving at regional level	45 km for roads where paving is complete; 18 km where paving is underway	*(102)*
Highway	Cerrado Savannas (Brazil)	Deforestation and habitat degradation	Deforestation increases closer to the roads, with pasture growing near the road, and forest cover growing further away	32.6% loss of Cerrado up to 9 km from the highway	*(103)*
Official and unofficial roads	Tropical rainforest (Amazon, Brazil)	Deforestation	Deforestation was much higher near roads Protected areas near roads had lower deforestation than did unprotected areas near roads	Nearly 95% of all deforestation occurred within 5.5 km of roads Highways begin to have a rapidly diminishing influence only at 32 km	*(104)*
CHANGE OF LANDSCAPE PATTERNS AND FRAGMENTATION					
All road network, mainly composed of minor roads	17 townships across three ecoregions of forested landscapes (n. Wisconsin, USA)	Changes in landscape patterns and road density in a six-decade study period	Substantial changes in landscape patterns Road density doubled and the immediate area affected by roads increase twofold (5% to 10%). Reduction of median, mean and largest roadless patch size by a factor of four. Increases in housing density and fragmentation	Road-effect zone as assumption: 15 m	*(105)*
FACILITATION OF RESOURCE EXTRACTION AND HUNTING					
Road for oil extraction and access from rivers	Amazon Basin (Yasuní Biosphere Reserve, Ecuador)	Probability of hunting by the Waorani indigenous group	Spatial extent of hunting doubled in the presence of road, and include remote areas	Mean distance walked from a point of access (road, river) to a kill site was 1.36 km (SD=1.18), and the maximum distance was 7 km (99% records <5 km)	*(106)*
NOISE INCREASE					
Busy roads (and other sources of noise)	Various (review paper)	Effect of noise (sound pressure level) on response curve of species occupancy (general model)	Spatial propagation of elevated noise levels from a point source (such as a single car, which decays at a spreading loss of 6 dB or more per doubling of distance, line sources (such as a busy highway) lose only 3 dB per doubling of distance	The sound pressure level of noise decreases with increasing distance but may not reach "baseline" ambient levels until ~1 km away (this distance will vary depending on noise source and the environment)	*(107)*
VARIOUS					
Highway	Suburban landscape,	Alteration of streams, wetland	The effects of all factors extended >100 m from road.	The road-effect zone averages approximately	*(108)*

	including swamps, streams, wetlands, deciduous forest, open-fields, residential areas (Massachusetts, USA)	drainage, road salt reaching water bodies, invasion by exotic species, changes in habitat and movement patterns of large mammals such as moose *Alces alces* and deer *Odocoileus virginianus*, forest and grassland birds, and amphibians	Moose corridors, road, avoidance by grassland birds and road salt extended >1 km	600 m wide and is asymmetric	
Highways, secondary and primary roads	Various, all USA	Estimation of the percentage of land ecologically affected by the public road system	One-fifth of the U.S. land area is ecologically affected by public roads system	Road-effect zone as assumption: primary roads (10,000 vehicles/day): 305 m in woodland and 365 m in grassland primary roads (50,000 vehicles/day): 810 m in natural ecosystems in urban areas secondary roads: 200 m	*(109)*

Table S3. Extent and amount of roadless areas (5-km-buffer) per continent using the OpenStreetMap data set (11/2003) (without Antarctica, Greenland, and freshwater bodies).

	Asia	Africa	North America	South America	Europe	Australia	Oceania	Global land
Total area (million km²)	44.32	29.70	21.51	17.64	9.75	7.64	0.43	130.00
Total roadless area cover (million km²)	28.62	19.36	9.88	11.09	1.30	5.09	0.11	75.45
Percentage of roadless coverage (%)	64.58	65.19	45.93	62.89	13.33	66.62	25.58	58.04

Table S4. Extent and amount of roadless areas (1-km buffer) per continent using the OpenStreetMap data set (11/2003) (without Antarctica and Greenland, and freshwater bodies).

	Asia	Africa	North America	South America	Europe	Australia	Oceania	Global land
Total area (million km²)	44.32	29.70	21.51	17.64	9.75	7.64	0.43	130.00
Total roadless area cover (million km²)	38.83	26.53	13.20	15.52	4.06	6.75	0.27	105.16
Percent roadless cover	87.60	89.30	61.39	88.00	41.64	88.26	63.87	80.28
Mean roadless area patch size (km²)	308.69	522.51	59.69	418.07	47.85	248.58	47.85	176.94
Maximum roadless patch size (million km²)	4.23	2.88	3.33	4.82	0.24	0.27	0.03	4.82
Median roadless patch size (km²)	2.85	6.75	0.48	4.81	0.85	2.98	0.84	1.07
Total no. roadless patches	101,992	50,770	221,197	37,124	153,323	24,216	5,691	594,312
No. roadless patches >1 km²	63,555	36,223	86,112	24,817	73,148	15,673	2,699	302,227
No. roadless patches >5 km²	43,854	27,237	36,787	18,420	40,268	10,178	1,463	178,207
No. roadless patches >10 km²	35,274	22,864	23,502	15,431	28,363	7,782	1,073	134,289
No. roadless patches >50 km²	18,356	12,992	7,609	9,189	9,561	3,223	453	61,383
No. roadless patches >100 km²	13,124	9,505	4,580	6,893	5,210	2,055	295	41,662
No. roadless patches >1000 km²	3,077	2,187	769	1,653	432	539	49	8,706

Table S5. Rationale of indicators used for *Ecological Value Index of Roadless Areas* (EVIRA).

Indicators	Rationale	Description
Roadless area patch size	Large roadless areas provide a much wider range of ecological benefits than smaller ones where road edge effects impact a larger share of the roadless patch (see Table S2).	Habitat fragmentation and corresponding negative environmental changes have been extensively treated in many studies (a comprehensive overview is given by Bennett et al. (2010) *(110)*. The impacts do not just relate to gene flow, population viability and loss of (less dispersive) species in habitat fragments, but also to ecosystem functioning. For example, there is certain evidence related to nutrient cycling, dung removal, pollination, and seed dispersal *(111)*. "The impacts of fragmentation on ecosystem functioning are often exacerbated by synergistic effects such as interactions with the matrix and increased hunting pressure in fragmented forests" *(111)*. There is growing evidence that certain species avoid areas with even minimal anthropogenic disturbance *(112, 113)*, which is another argument for conservation of large roadless areas. Especially in tropical regions, many species exist at rather low population densities, are seasonal migrants (often across different altitudinal belts) following scarce resources, or otherwise require large habitats for maintaining viable populations *(114, 115).*
Thiessen connectivity into all directions for roadless area patches	The larger the Thiessen connectivity value, the closer neighboring roadless patches can be found. This is important for the integrity of ecological landscape-scale processes (e.g., genetic exchange of populations confined to roadless areas).	Roaded forest ecosystems, for instance, are far more vulnerable than intact ones to predatory logging, wildfires, illegal mining, exotic species invasions, and other anthropogenic threats *(7, 114)*.
Ecosystem Functionality Index	Ecosystem Functionality is defined as the state of ecosystems, characterized by inherent structures, ecological functions and dynamics, that provide ecosystems with both, the necessary efficiency and resilience to develop without abrupt change of system properties and geographical distribution, and allows for flexible response to external changes.	This Ecosystem Functionality Index has been published by Freudenberger et al. (2012a) *(38)*.
comprising the following sub-indicators:		
- Vegetation density	Vegetation density is an indicator for biomass and the ecosystems' ability to dissipate incoming solar energy. Furthermore, a higher number of primary producers increase the capture of solar energy thereby improving ecosystem functionality.	Rationale from Freudenberger et al. (2012a, b) *(9, 38)*. Further references and sources provided in the corresponding methods sections.
- Tree height	Tree height is used as an indicator for biomass as well as structural complexity of an ecosystem. Old-growth forest conditions and complex vegetation stratification including foliage layering is dependent on tree height, thereby enhancing biodiversity and ecosystem functioning. Furthermore, it plays an important part in the absorption of solar radiation and in moderating microclimatic conditions.	Rationale from Freudenberger et al. (2012a, b) *(9, 38)*. Further references and sources provided in the corresponding methods sections.
- Carbon storage	Carbon storage is considered as an indicator for biomass and the ability of ecosystems to dissipate incoming solar energy. Areas with higher carbon storage are also characterized	Rationale from Freudenberger et al. (2012a, b) *(9, 38)*. Further references provided in the corresponding methods sections.

- Species richness of vascular plants	by more intensive interactions with the atmosphere and higher regulating capacity. Species richness is considered to represent functional and structural redundancy, which is relevant for the resistance and resilience of ecosystems to e.g. climate change. Additionally, species richness is also associated with complex trophic structure and higher cycling rates of biomass, energy and information.	Rationale from Freudenberger et al. (2012a, b) *(9, 38)*. Further references and sources provided in the corresponding methods sections.
- Plant functional richness	Plant functional richness is an indicator derived from modelling survival probabilities of different plant functional types under climate change. Ecosystems with higher functional species richness are more likely to adapt to environmental change and therefore increase the adaptive capacity of an ecosystem.	Rationale from Freudenberger et al. (2012a, b) *(9, 38)*. Further references and sources provided in the corresponding methods sections.
- Slope	Topographical heterogeneity is connected to habitat diversity and species richness. At macro-scale habitat diversity increases along altitudinal gradients. Geographical barriers increase opportunities for allopatric speciation, and contribute to the genetic information that is stored within an ecosystem.	Rationale from Freudenberger et al. (2012a, b) *(9, 38)*. Further references and sources provided in the corresponding methods sections.

Table S6. Pearson (dark grey) and Spearman rank (light grey) correlation coefficient matrix for the three indicators of the ecological value index for roadless areas (EVIRA). All correlation coefficients are highly significant with $p<0.0001$. Correlation coefficients with values higher than 0.7 are displayed in bold.

	Ecological value index of roadless areas (EVIRA)	Roadless area patch size	Thiessen connectivity into all directions	Ecosystem functionality index (EFI)
Ecological value index of roadless areas (EVIRA)	1.000	**0.768**	-0.005	**0.818**
Roadless area patch size	0.488	1.000	-0.006	0.260
Thiessen connectivity into all directions	-0.272	-0.875	1.000	-0.002
Ecosystem functionality index (EFI)	**0.881**	0.155	0.048	1.000

Table S7. Distribution of roadless areas (1-km buffer) across anthromes (km^2) (according to Ellis et al. 2010; analysis based on OpenStreetMap data set 11/2013).

Anthrome classes	South America	Central and North America	Europe	Asia	Africa	Australia	Oceania	Global	Share of global roadless areas (%)
Urban	4,007	4,387	2,374	32,332	9,058	706	263	53,129	0.05
Mixed settlements	18,372	18,749	5,295	233,664	93,038	1,070	1,556	371,746	0.36
Rice villages		444		1,561,288	358			1,562,090	1.50
Irrigated villages	9,099	18,415	8,092	917,304	31,193			984,105	0.94
Rainfed villages	48,983	70,791	48,853	1,307,198	514,561		85	1,990,474	1.91
Pastoral villages	67,829	16,127	1,748	233,641	195,302			514,649	0.49
Residential irrigated croplands	34,121	50,856	52,030	401,213	47,493	497	191	586,40	0.56
Residential rainfed croplands	453,081	324,541	779,233	2,209,022	1,853,242	7,405	6,051	5,632,575	5.39
Populated croplands	567,180	302,940	531,100	1,484,977	606,286	70,433	15,408	3,578,326	3.43
Remote croplands	161,957	345,517	21,507	360,306	135,530	391,144	7,822	1,423,783	1.36
Residential rangelands	1,252,057	177,381	62,984	1,404,975	3,314,670	9,205	2,844	6,224,116	5.96

Populated rangelands	2,800,656	572,493	261,741	3,430,646	4,634,380	67,350	27,188	11,794,455	11.29
Remote rangelands	2,214,349	737,996	94,936	5,999,912	2,294,862	6,047,983	76,368	17,466,406	16.72
Residential woodlands	230,507	141,898	106,706	1,322,994	1,343,634	4,246	20,478	3,170,464	3.04
Populated woodlands	1,464,277	490,479	709,214	2,397,132	2,134,048	29,333	60,523	7,285,006	6.97
Remote woodlands	2,182,821	485,807	201,057	1,241,981	448,189	29,731	27,679	4,617,265	4.42
Inhabited treeless and barren lands	781,593	248,646	49,804	2,183,217	1,665,865	508	1,056	4,930,688	4.72
Wild woodlands	2,710,257	5,929,872	829,528	7,534,326	332,290	71,611	17,868	17,425,751	16.68
Wild treeless and barren lands	484,370	2,976,033	171,235	4,345,674	6,858,975	1,771	444	14,838,501	14.21

Table S8. Protection status of roadless areas (1-km buffer) per continent (without Antarctica, Greenland, and large freshwater bodies) based on WDPA 2014 and OpenStreetMap (11/2003).

	Asia	Africa	North America	South America	Europe	Australia	Oceania	Global land
Protected areas cover (all categories) (km^2)	4,977,721	4,112,914	2,646,754	4,087,773	1,510,183	1,196,688	93,123	18,625,157
Protected area cover (%)	11.2	13.8	12.3	23.2	15.5	15.7	21.8	14.2
Roadless areas in IUCN categories (km^2)	3,989,458	2,056,657	2,146,627	2,364,065	410,437	1,074,445	72,177	12,113,866
Percent IUCN coverage of roadless areas	9.0	6.9	10.0	13.4	4.2	14.1	17.0	9.3
Strictly protected areas (IUCN I & II) (km^2)	1,029,356	1,028,218	1,511,100	997,502	272,877	589,763	33,848	5,462,664
Strictly protected areas (IUCN I & II) (%)	2.3	3.5	7.0	5.7	2.8	7.7	7.9	4.2
Roadless areas in strictly protected areas (IUCN I & II) (km^2)	966.322	969.151	1.370.853	974.208	180.903	525.068	28.492	5.014.999

Roadless areas strictly protected (IUCN I & II) (%)	2.2	3.3	6.4	5.5	1.9	6.9	6.7	3.8
Protected areas (IUCN III-VI) (km²)	3,215,796	1,194,583,5 5	1,006,467,51	1,450,552,58	701,944,89	581,476,89	54,291,11	8,205,112,91
Protected areas (IUCN III-VI) (%)	7.3	4.0	4.7	8.2	7.2	7.6	12.7	6.3
Roadless areas in protected areas (IUCN III-VI) (km²)	3,023,136	1,087,506	775,773	1,389,857	229,534	549,377	43,683	7,098,867
Roadless areas in protected areas (IUCN III-VI) (%)	6.8	3.7	3.7	7.9	2.3	7.2	10.2	5.4

Table S9. Extent and coverage of roadless areas of 1-km buffer under strict protection (IUCN I-II) category, according to their Ecological Value Index of Roadless Areas (EVIRA) using the OpenStreetMap data set (11/2003).

EVIRA values	North America (km²)	South America (km²)	Asia (km²)	Africa (km²)	Europe (km²)	Australia (km²)	Oceania (km²)	Global (km²)
0 - 13	0	0	0	0	0	0	0	0
14 - 28	109,7	8,0	5,430	6,092	1,700	50,525	2.2	63,868
29 - 33	86,441	9,367	98,425	269,842	2,042	274,650	855	741,622
34 - 37	81,286	20,640	108,467	201,490	13,496	82,089	36	507,500
38 - 42	75,476	45,810	81,685	240,560	44,801	29,444	106	517,883
43 - 47	454,357	64,917	100,975	85,371	66,762	23,597	417	796,396
48 - 53	204,952	151,089	173,866	50,750	40,796	11,856	15,446	648,755
54 - 58	444,939	132,629	147,985	88,619	7,878	34,984	8,074	865,107
59 - 64	17,582	31,144	105,544	25,579	2,437	16,871	3,466	202,623
65 - 80	3,617	518,198	143,008	0.0	227	82	0.3	665,132
Sum	**1,368,760**	**973,802**	**965,384**	**968,299**	**180,140**	**524,099**	**28,401**	**5,008,886**

Table S10. Synergies and conflicts between conservation of roadless areas and the United Nations' Sustainable Development Goals (SDGs) and their corresponding targets. The level of synergy or conflict of the SDGs (left column, large boxes) with roadless areas conservation is indicated by the different colors: grey (at most weak synergies and conflicts with goal), blue (conflicts with goal prevail), yellow (mixture of synergies and conflicts with goal), green (synergies with goal prevail). The level of synergy or conflict of the corresponding targets is shown in the insert boxes. The colors indicate: grey (not applicable), blue (conflict), yellow (ambivalent relationship), green (synergy). The numbers in italics represent the target numbers. The bold number at the bottom indicates the conflict-synergy score of goals.

Sustainable Development Goals and targets	Brief analysis of synergies and conflicts between conservation of roadless areas and Sustainable Development Goal targets
Goal 1. End poverty in all its forms everywhere *1* *2* *3* *4* *5* **-0,5** Compare AICHI BIODIVERSITY TARGETS 2, 14.	**Synergies:** The SDGs explicitly acknowledge the importance of integrating ecosystem and biodiversity values into poverty reduction strategies and accounts (compare to 15.9). In remote areas inhabited by indigenous or traditional people in the developing world, where governance is weak, road development may trigger uncontrolled frontier expansion and associated poverty. In the Amazon, frontier expansion through road construction has fostered large-scale economic activities (e.g. oil extraction, livestock and soy production), but often at the expense of the local communities. Road development in the region is associated to dire conflicts over land and natural resources *(117, 118)*. A better planning of the road development process and a prioritization of roadless areas for conservation purposes can help to reduce risks related to poverty (→ targets 1.1, 1.2, 1.4). In the Amazon, for instance, a more sensitive proposed development strategy should focus on strengthening governance in areas where roads have been established for a long time (and human population is relatively large and human development indices are low), while leaving more remote areas roadless or with roads unpaved *(119)*. Functional ecosystems, as they exist in roadless areas, effectively reduce human exposure to environmental shocks and disasters, including climate-related extreme events [such as floods: e.g., *(120)*, water scarcity: e.g., *(121)*, compare goal 6, fires: e.g., *(122)*; → target 1.5]. It is of great importance to maintain ecosystem functionality on the landscape scale, e.g. by prioritizing conservation of roadless areas around the headwaters of rivers against extreme fluctuations in run-off along the densely populated and intensively managed tailwater.
	Conflicts: Poverty often is related to the lack of access to markets and employment options (compare goal 8), health (compare goal 3) and education infrastructure (compare goal 4; *(123-126)*). Case studies have shown how roads significantly reduce poverty and increase consumption growth (→ targets 1.1, 1.2, 1.4; *(127-129)*). Reduced mobility also hampers organizational capacities, especially in remote rural areas, where it is difficult for poor people to meet and coordinate activities. In general, poor people will ask for better roads and mobility. Goal 9 explicitly addresses the relevance of infrastructure (see below). The conservation of roadless areas seems to represent a serious conflict and obstacle to development – if this development is thought along conventional lines and without exploring more sustainable alternatives for providing mobility.

Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture *1* *2* *3* *4* *5* **-0,6** Compare AICHI BIODIVERSITY TARGETS 7, 8, 14.	**Synergies:** In remote regions, as they are found in parts of the western Amazon forests, the subsistence of many indigenous communities depends on forest products. However, new roads built into previously remote areas of low human population density have often triggered conversion of forest to croplands and pastures *(130)* and unsustainable exploitation of wildlife that can then be marketed easily as bushmeat in cities. Bushmeat can thus become scarce for residents who rely on this protein source *(131, 132)*. Functional ecosystems, as they exist in roadless areas, effectively reduce human exposure to environmental shocks and disasters, including climate-related extreme events (→ target 2.4; compare goal 1).
	Conflicts: At many places of the world, undernourishment increases with distance from roads and with it from markets and health services, among others *(133)*. Hunger can also be promoted by limited options for reaching poor rural people with food aid and development assistance (*(134)*; → targets 2.1-2.3, 2.5; compare goals 1, 3, 4, 6, 9).
Goal 3. Ensure healthy lives and promote well-being for all at all ages *1* *2* *3* *4* *5* *6* *7* *8* *9* **-0,1** Compare AICHI BIODIVERSITY TARGETS 6, 14.	**Synergies:** In general, roadless areas guarantee high ecosystem functionality (compare goal 1) and with it a variety of ecosystem services that are fundamental to people's health. Among others, tropical forest-dwelling indigenous communities use a variety of medicinal forest plants that can become scarce in the course of road construction and subsequent deforestation *(135).* Roadless areas exclude deaths and injuries from road traffic accidents (→ target 3.6), as well road and traffic-related hazardous chemicals and air, water and soil pollution and contamination (*(136, 137)*; → target 3.9; compare goal 6). Road development in the Amazon and Indonesia has been shown to be associated with the spread of diseases (*(117);* → target 3.3). Abrupt contact with modern life-styles via new roads increases the vulnerability of formerly remote human populations to drug abuse and alcohol consumption (*(138);* → target 3.5).
	Conflicts: Remote rural populations mostly have reduced access to health care and medical assistance (*(133);* → targets 3.1, 3.2, 3.4, 3.7, 3.8).
Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all *1* *2* *3* *4* *5* *6* *7* **-0,9** Compare AICHI BIODIVERSITY TARGETS 1.	**Synergies:** Experiencing wilderness has become an important element of education. While roadless areas are less accessible by motorized ways, they provide opportunities for this kind of education (*(139)* compare goal 8: nature tourism).
	Conflicts: With increasing distance from roads, access to "quality" education becomes more difficult. Among others, remote rural populations often lack literacy in the use of emerging technological devices (computers, internet etc., *(140);* → targets 4.1-4.7).
Goal 5. Achieve gender equality and empower all women and girls	**Synergies and conflicts:** -
Goal 6. Ensure availability and sustainable management of water and sanitation for all *1* *2* *3* *4* *5* *6* **0,4** Compare AICHI BIODIVERSITY TARGETS 6, 8, 14.	**Synergies:** Roads significantly harm the integrity and functionality of ecosystems and several services they provide to people (compare goal 1). Roads (including their construction) and traffic have been known for a long time as a source for water pollution (*(141);* → targets 6.1, 6.3, 6.5, 6.6).
	Conflicts: In general, remote rural populations often have reduced access to technology, infrastructural development and assistance. It is cost-efficient, and practical for maintenance, to install water and sewer systems in the course of road construction (→ targets 6.1, 6.2).

Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all 1 2 3 **-0,5** Compare AICHI BIODIVERSITY TARGETS 7, 8, 14.	**Synergies:** none.
	Conflicts: In general, remote rural populations often have reduced access to technology and infrastructural development (compare goal 6). Electric wires can relatively easily be installed and maintained along roads (→ targets 7.1, 7.2). However, small-scale renewable (solar, wind) energy plants can be an alternative with additional advantages (low cost, energy autonomy; → target 7.2).
Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all 1 2 3 4 5 6 7 8 9 10 **-0,3** Compare AICHI BIODIVERSITY TARGETS 2.	**Synergies:** Roadless areas can contribute substantially to slowing down environmental degradation (→ target 8.4; compare goal 15, 13). In addition, certain micro- and small enterprises can arise in spite of relatively great distances from roads (→ target 8.3) – or even depend on remoteness (nature tourism, e.g., *(142);* → target 8.9). It has been shown for the Amazon region that road development is associated with slave labor (*(118);* → target 8.7). Facilitated access to markets by roads may not always improve the income levels of poor people, as they will not be able to afford goods such as cars and petrol.
	Conflicts: Ease of mobility of people and goods promotes economic productivity and growth (*(143)*; → targets 8.1, 8.2; compare goals 9, 1). Young people of remote rural areas mostly have reduced access to good education and training opportunities (compare goal 4) and subsequently lower chances on the labor market (*(144);* → target 8.6).
Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation 1 2 3 4 5 **-0,3** Compare AICHI BIODIVERSITY TARGET 2.	**Synergies:** Upgrades of roads in the existing network can be a cost-efficient and environmentally less problematic alternative to building new roads (*(4);* → target 9.4).
	Conflicts: Economic development, especially in developing economies or those in transition, depends on an effective road network (*(143)*; → targets 9.1, 9.2; compare goals 8, 1).
Goal 10. Reduce inequality within and among countries 1 2 3 4 5 6 7 **-0,7**	**Synergies:** none.
	Conflicts: Modern road traffic has increased the mobility of people and goods, but comes with an increased risk of accidents (*(145);* → target 10.7). Roads have a variety of homogenizing effects - in terms of biological diversity (e.g., aided dispersal of invasive species: *(146)*, culturally (*(147);* → target 10.2) etc. Economically, road building provides poor rural societies a better access to economic dynamics and is thus a standard element of economic development strategies (*(143)*; → target 10.1; compare goals 9, 8, 1).
Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable 1 2 3 4 5 6 7 **0,5**	**Synergies:** "Indigenous peoples in voluntary isolation" request participation in road and human settlement planning and want to be exempted from any such development *(117)*. Targeting roadless areas will help concentrate development in urban areas and their immediate surroundings (*(105);* → target 11.3). Failing to do so regularly results in "contagious development", i.e., unleashing a positive feedback of road construction and intensive land-use in a formerly road-free landscape *(4, 7)*. Remote areas, which provide vital ecosystem services to cities, can thus be kept functioning (→ target 11.5; compare goal 13, 1, 2). The status of natural heritage sites ("Criteria for the assessment of Outstanding Universal Value": vii, ix

Compare AICHI BIODIVERSITY TARGET 14.	and x; *(148)*) is vitally coupled with remoteness (→ target 11.4). **Conflicts:** Further road construction may be deemed necessary to provide convenient access to public transport for a larger part of the population. However, people in remote rural regions may not be able to pay for public transport (*(149);* → target 11.2).
Goal 12. Ensure sustainable consumption and production patterns *1* *2* *3* *4* *5* *6* *7* *8* **1,0** Compare AICHI BIODIVERSITY TARGET 4.	**Synergies:** Road construction and maintenance consume significant amounts of material (and energy) and thus enlarge the national and per capita material footprint (*(150);* → target 12.2). Including roadless and other important areas for biodiversity and ecosystem services for people would make sustainability reports of companies *(151)* more diagnostic and could thus provide guidance for the adoption of sustainable practices (→ target 12.6). **Conflicts:** none.
Goal 13. Take urgent action to combat climate change and its impacts *1* *2* *3* **1,0** Compare AICHI BIODIVERSITY TARGETS 15, 10, 14.	**Synergies:** Functional ecosystems, as they exist in roadless areas, strengthen the resilience and adaptive capacity of human societies to climate-related hazards and natural disasters (→ target 13.1; compare goals 1-3). Roadless areas conservation would thus form a meaningful element of policies, strategies and planning for climate change adaptation (*(2);* → target 13.2). Road construction and maintenance (with cement production being a relevant source of greenhouse gas emissions *(152)*) as well as traffic *(153)* also contribute large shares to overall greenhouse gas emissions. Policies, strategies and planning for climate change mitigation should therefore strive to reduce these activities to the lowest level possible (→ target 13.2). **Conflicts:** none.
Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development *1* *2* *3* *4* *5* *6* *7* **1,0** Compare AICHI BIODIVERSITY TARGET 6.	**Synergies:** Considerable river sediment loads can result from road construction and erosion along roads *(121)*. Runoff from subsequent development, such as logging in mountain areas *(154)*, or agriculture, can also impact rivers and, finally, estuaries and near-coast marine waters (→ target 14.1). **Conflicts:** none.
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 *1* *2* *3* *4* *5* *6* *7* *8* *9* **1,0**	**Synergies:** The conservation of roadless areas represents an effective and inexpensive means to conserving terrestrial and inland freshwater biodiversity and ecosystem services (*(2, 4);* → targets 15.1, 15.4, 15.5, 15.7, 15.8). This includes halting deforestation (*(98);* → targets 15.2) and combating desertification (*(155);* → targets 15.3). The inclusion of roadless areas would be a meaningful contribution to integrating ecosystem and biodiversity values into national and local planning as well as development processes, as is already the case in the United States of America and Germany (*(2, 4);* → targets 15.9). The present study demonstrates roadless areas are a tangible and transparent indicator for environmental accounting (→ target 15.9). **Conflicts:** none.

Compare AICHI BIODIVERSITY TARGETS 5, 11, 15, 12, 10.	
Goal 16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels *1* *2* *3* *4* *5* *6* *7* *8* *9* **1,0**	**Synergies:** Road development in the Brazilian Amazon is associated with an increase in homicide rate (*(118)*; → target 16.1). **Conflicts:** none.
Goal 17. Strengthen the means of implementation and revitalize the global partnership for sustainable development *1* *2* *3* *4* *5* *6* *7* *8* *9* *10* *11* *12* *13* *14* *15* *16* *17* *18* *19* **-1,0**	**Synergies:** none. **Conflicts:** Roads connect national economies (compare goal 8) and thus facilitate import-export traffic across borders (→ target 17.11), especially for landlocked regions or countries *(156).*

Table S11. Synergies and conflicts between conservation of roadless areas and the United Nations' Aichi Strategic Goals and Biodiversity Targets. The color scheme indicates the level of synergy or conflict of goals and targets with roadless areas conservation (green: synergies prevail; grey: not applicable; yellow: ambivalent relationship). The numbers in insert boxes represent the conflict-synergy score of goals.

Aichi Strategic Goals and Biodiversity Targets	Brief analysis of synergies and conflicts between conservation of roadless areas and Aichi Biodiversity Targets
Strategic Goal A: Address the underlying causes of biodiversity loss by mainstreaming biodiversity across government and society **0,5**	
Target 1. By 2020, at the latest, people are aware of the values of biodiversity and the steps they can take to conserve and use it sustainably. Compare Sustainable Development Goal 4.	On the one hand, pristine ecosystems, such as they occur in roadless areas, are key for effective biodiversity conservation *(2)*. In agreement with modern concepts of sustainable land use, such as in biosphere reserves, these ecosystems are an essential element of sustainable use of the overall landscape *(157)*. Remote roadless areas provide opportunities for learning about natural ecosystems, i.e., wilderness (see goals B and C). On the other hand, roadless areas reduce accessibility of nature in general, thus making it more difficult to value biodiversity emotionally.
Target 2. By 2020, at the latest, biodiversity values have been integrated into national and local development and poverty reduction strategies and planning processes and are being incorporated into national accounting, as appropriate, and reporting systems. Compare Sustainable Development Goals 9, 8, 1.	While road infrastructure is related to economic growth and poverty alleviation *(158, 159)*, it has a crucial impact on biodiversity loss (see goal C), which in turn is directly linked with poverty aggravation *(160, 161)*. In remote areas inhabited mostly by indigenous or traditional people, road development may increase the spread of diseases, trigger conflicts over land and natural resources, and disrupt the traditional modes of production (which then have to compete with the global market), ultimately pushing these people towards poverty *(117, 162)*. The role of road development on poverty alleviation is hence conflicting, which calls for a better planning integrating roadless areas prioritization for biodiversity maintenance towards poverty alleviation.
Target 3. By 2020, at the latest, incentives, including subsidies, harmful to biodiversity are eliminated, phased out or reformed in order to minimize or avoid negative impacts, and positive incentives for the conservation and sustainable use of biodiversity are developed and applied, consistent and in harmony with the Convention and other relevant international obligations, taking into account national socio economic conditions.	Road transport receives between one- and two-thirds of worldwide conventional subsidies that are harmful in the long run to both the economy and the environment *(163)*. Road transport sector figures among the five most prominent sectors receiving such perverse subsidies *(164)*. An outstanding example refers to road infrastructure subsidies in the Amazon that have led to cattle ranching, extensive deforestation and biodiversity loss *(165)*. Alternatively, the integration of roadless areas into governmental policies could help in reducing and eliminating a substantial part of the harmful subsidies for the road transport sector.
Target 4. By 2020, at the latest, Governments, business and stakeholders at all levels have taken steps to achieve or have implemented plans for sustainable production and consumption and have kept the impacts of use of natural resources well within safe ecological limits. Compare Sustainable Development Goal 12.	Roadless areas, and relatively undisturbed areas in general, are of high resilience and ecosystem functionality *(2)*. Conserving these areas therefore contributes to maximizing ecosystem functionality of the wider landscape - they are an essential element of its sustainable use (compare targets 1, 7).
Strategic Goal B: Reduce the direct pressures on biodiversity and promote sustainable use **0,8**	
Target 5. By 2020, the rate of loss of all natural habitats, including forests, is at least halved and where feasible brought close to zero, and degradation and fragmentation is significantly reduced. Compare Sustainable Development Goal 15.	Road development is a major driver of habitat loss and fragmentation *(166)*. Roads act as barriers for species *(167)* and deforestation has been shown to increase along roads [*(98)*, Table S2]. Conserving roadless areas therefore directly helps to achieve this target.
Target 6. By 2020 all fish and invertebrate stocks and aquatic plants are managed and harvested sustainably, legally and applying ecosystem based approaches, so that overfishing is avoided, recovery plans and measures are in place for all depleted species, fisheries have no significant adverse impacts on threatened species and vulnerable ecosystems and the impacts of fisheries on stocks, species and ecosystems are within safe ecological limits. Compare Sustainable Development Goals 14, 6, 3.	Roads facilitate the accessibility to remote terrestrial or freshwater ecosystems and increase the efficiency of natural resources exploitation and exportation, which are often depleted above their safe ecological limits *(1)*. For instance, a single road construction has been reported to have severe effect to a lake trout population, due to improved access for fishermen *(168)*. In addition, roads, their construction and traffic emit water pollutants *(137, 141)*. Similarly, road construction and roads can produce large sediment loads in rivers, particularly detrimental in wetlands and mountain areas. Roads also open up a landscape for logging and agriculture, and resulting runoff equally enters rivers *(154)*. Large part of this sediment ends up in estuaries and coastal waters.

Target 7. By 2020 areas under agriculture, aquaculture and forestry are managed sustainably, ensuring conservation of biodiversity. Compare Sustainable Development Goal 2.	On one side, roadless areas exclude certain types of local development and even sustainable land use. And to keep up with demand for natural resources, any additional roadless area may require the intensification of land use in developed areas. On the other side, conservation of functional ecosystems, as they are still found in roadless areas, is essential for the larger landscape to stay functional. From this perspective, the remaining roadless areas can be seen as key elements of sustainably managed landscapes (compare targets 1, 4, 8).
Target 8. By 2020, pollution, including from excess nutrients, has been brought to levels that are not detrimental to ecosystem function and biodiversity. Compare Sustainable Development Goals 6, 2.	Agricultural intensification might be necessary to make up for setting aside roadless areas (compare target 7). This might lead to increased use of fertilizers and pollution. It should be noted, however, that in many developing countries in particular there is a large amount of degraded land that can be restored and replace set-asides. However, conservation of roadless areas as relatively pristine ecosystems are a cost-efficient way of maximizing the provisioning of regulating ecosystem services such as nutrient uptake and water purification *(121)*.
Target 9. By 2020, invasive alien species and pathways are identified and prioritized, priority species are controlled or eradicated, and measures are in place to manage pathways to prevent their introduction and establishment.	Road density is a strong correlate of spatial patterns in biological invasions *(146)*. Limiting road development in roadless areas can, therefore, help to directly reduce the spread of invasive species (Table S2).
Target 10. By 2015, the multiple anthropogenic pressures on coral reefs, and other vulnerable ecosystems impacted by climate change or ocean acidification are minimized, so as to maintain their integrity and functioning. Compare Sustainable Development Goals 13, 15.	Roadless areas often represent areas with large carbon pools and sequestration potential. Furthermore, they represent areas of high ecosystem functionality important for climate regulation and long-term climate change adaptation. The conservation of roadless areas, thus, helps to mitigate and adapt to the impacts of climate change *(2, 4)*. Regarding marine ecosystems in particular, roadless areas prevent road-related sediment and agricultural runoff from impacting near-shore waters (compare target 6).
Strategic Goal C: To improve the status of biodiversity by safeguarding ecosystems, species and genetic diversity **0,3**	
Target 11. By 2020, at least 17 per cent of terrestrial and inland water, and 10 per cent of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved through effectively and equitably managed, ecologically representative and well connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscapes and seascapes. Compare Sustainable Development Goal 15.	The conservation of roadless areas directly contributes to the conservation of valuable terrestrial ecosystems for biodiversity conservation. These areas also typically provide a wide array of ecosystem services, especially regulating services, and do this in large quantities. Furthermore, the conservation of these unfragmented and pristine areas directly contributes to the target of increasing connectivity. Conservation of the functionality of the watershed is highly dependent on the preservation of vegetation cover *(169)*, which benefits from conservation of roadless areas.
Target 12. By 2020 the extinction of known threatened species has been prevented and their conservation status, particularly of those most in decline, has been improved and sustained. Compare Sustainable Development Goal 15.	Threatened species typical of anthropogenically disturbed ecosystems, such as old cultural landscapes in Europe and elsewhere, depend on certain semi-intensive, often historical, land use regimes (170). Therefore, in human-modified landscapes, the conservation of roadless areas in cases may be found little useful, or even counterproductive, to the target of improving the conservation status of some species. At the same time, other species (e.g., some amphibians) may experience reduced mortality in the absence of roads. After all, most threatened species are endangered by man-made loss of pristine ecosystems *(171)*. Roadless areas can retain populations of threatened species, supporting the native flora and fauna and buffering changes in the environmental conditions. Roadless areas which are large enough to host source populations can then serve as the origin for recolonization of areas where threatened species had disappeared *(172)*.
Target 13. By 2020, the genetic diversity of cultivated plants and farmed and domesticated animals and of wild relatives, including other socio-economically as well as culturally valuable species, is maintained, and strategies have been developed and implemented for minimizing genetic erosion and safeguarding their genetic diversity.	For one thing, on-farm conservation and use of cultivated species often requires the application of rather extensive agricultural practices *(173)*. This could lead to competition for area between the conservation of roadless areas and more extensive agricultural practices for the preservation of the diversity of cultivated plants and animals. Then again, wild relatives of domesticated plant and animal species can often only be found in pristine natural areas *(174)*.
Strategic Goal D: Enhance the benefits to all from biodiversity and ecosystem services **1,0**	
Target 14. By 2020, ecosystems that provide essential services, including services related to water, and contribute to health, livelihoods and well-being, are restored and safeguarded, taking into account the needs of women, indigenous and local communities, and the poor and vulnerable.	Functional ecosystems, as they exist in roadless areas, provide large quantities of many ecosystem services, especially of regulating services. They effectively reduce human exposure to extreme environmental events [e.g., fires, *(122)*]. Remote areas are often also of high value especially to indigenous and traditional people *(117)*. Remote areas also provide vital ecosystem services to poor city dwellers, such as purification and stable provisioning of water *(121)*.

Compare Sustainable Development Goals 6, 11, 1, 2, 3, 13.	
Target 15. By 2020, ecosystem resilience and the contribution of biodiversity to carbon stocks has been enhanced, through conservation and restoration, including restoration of at least 15 per cent of degraded ecosystems, thereby contributing to climate change mitigation and adaptation and to combating desertification. Compare Sustainable Development Goals 15, 13.	Roadless areas comprise relatively little disturbed areas. Many of these harbor large carbon pools and sinks, e.g., peatlands and intact forests in tropical and boreal regions *(175)*. Furthermore, they provide many regulating ecosystem services and high ecosystem functionality and are, therefore, crucial for ecosystem-based adaptation to climate change (see above targets 1, 4, 7). They also provide a natural buffer against increasing desertification through maintenance of vegetation cover *(155)*.
Target 16. By 2015, the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization is in force and operational, consistent with national legislation.	
Strategic Goal E: Enhance implementation through participatory planning, knowledge management and capacity building **1,0**	
Target 17. By 2015 each Party has developed, adopted as a policy instrument, and has commenced implementing an effective, participatory and updated national biodiversity strategy and action plan.	
Target 18. By 2020, the traditional knowledge, innovations and practices of indigenous and local communities relevant for the conservation and sustainable use of biodiversity, and their customary use of biological resources, are respected, subject to national legislation and relevant international obligations, and fully integrated and reflected in the implementation of the Convention with the full and effective participation of indigenous and local communities, at all relevant levels.	Indigenous communities are most vulnerable to the impacts of road development. Road construction in former roadless areas can cause traditional environmental knowledge loss and even a depopulation of indigenous communities *(176)*. Indigenous people may lose their land *(177)*, or use it less after road construction *(178)*, benefit less from biological resources and face an alteration of traditional roles and practices *(179)*.
Target 19. By 2020, knowledge, the science base and technologies relating to biodiversity, its values, functioning, status and trends, and the consequences of its loss, are improved, widely shared and transferred, and applied.	Natural ecosystems, as they still exist in remote roadless areas, are unique learning sites not only for education (see above target 1). They also provide important insights into ecosystem properties and processes such as biomass stocks, ecological dynamics, or resistance and resilience to natural disturbances *(180)*.
Target 20. By 2020, at the latest, the mobilization of financial resources for effectively implementing the Strategic Plan for Biodiversity 2011-2020 from all sources, and in accordance with the consolidated and agreed process in the Strategy for Resource Mobilization, should increase substantially from the current levels. This target will be subject to changes contingent to resource needs assessments to be developed and reported by Parties.	

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PAPER II

Roadless Areas as Key Approach to Conservation of Functional Forest Ecosystems

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Roadless Areas as Key Approach to Conservation of Functional Forest Ecosystems

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Abstract

Roadless areas are free from any kind of road(-like) infrastructure and their direct or indirect impacts on the ecosystems. The largest tracts of ecologically most valuable roadless areas refer to large unfragmented forests regions, both in the tropics and the boreal zone (Amazon, Congo basin, East and Southeast Asia). Among all terrestrial ecosystems, roadless forests are the single most important strongholds of regulating ecosystem services: among others, soil protection, water retention, buffering of the local and regional climate and mitigation of global climate change via capturing of atmospheric carbon. But roadless areas also comprise much demanded natural resource assets, such as timber, often also minerals and space for agricultural development. There is a substantial conflict between diverse short-term economic interests and the long-term conservation of roadless areas. Large roadless areas can serve as a measurable surrogate for the most pristine and functional ecosystems. Roadlessness is a property of areas, which are not impacted by roads; it can be used as a proxy for assessing ecosystem integrity and the absence of many anthropogenic disturbances. We recommend that policy-makers give roadless areas conservation priority over areas that have already been fragmented. It is essential to establish roadlessness as a criterion for the planning of ecosystem-based, cost-effective sustainable development. In parallel with measures to protect roadlessness, we recommend alternative approaches to mobility that can work under roadless conditions, e.g., related to railroads, blimps and other low-energy technologies with low infrastructure requirements. Even if "climate-friendly" renewable energy was available for road transport on a large scale, the construction, existence and operation of roads would continue to severely impair ecosystem functionality.

How Do Roads Impact Ecosystems?

The manifold impacts of roads on ecosystems start with local and direct effects caused by construction, continue when the road is used and maintained, and then radiate into the wider landscape (Font et al., 2014; Forman and Alexander, 1998; Riley, 1984). Environmental degradation, changes in ecological processes, and decline of biodiversity on all hierarchical levels are the consequence (Chaplin-Kramer et al., 2015; Fahrig and Rytwinski, 2009; Forman, 2000; Forman et al., 2003; Kleinschroth and Healey, 2017; Martin et al., 2000; Riitters and Wickham, 2003; Young, 1994) (**Figs. 1 and 2**).

Direct impacts of road construction include the physical conversion of sites, soil compaction, dust, salt, and heavy metal pollution, changes to the microclimate by creating extended surfaces that heat up and do not retain water as well as the creation of edges that are vulnerable to windthrow of trees. Noise and light pollution degrade the quality of faunal habitats, and vehicle collisions cause increased wildlife mortality (Benítez-López et al., 2010; Ferreras et al., 2001; Gibbs and Shriver, 2005; Jaarsma et al., 2007; Kaphegyi et al., 2013; van Langevelde et al., 2009; Seiler, 2001; Wadey et al., 2018). Furthermore, roads cause the fragmentation of continuous ecosystems and the isolation of remnant landscape patches, create barriers, cutting off populations and restricting gene flow, which can eventually lead to local extinction (Ceia-Hasse et al., 2017; Epps et al., 2005; Rytwinski and Fahrig, 2015). The barrier effect of roads is species-specific and depends on body size, mobility and speed of fauna. In addition to the road itself, fragmentation of populations of certain species can become much more severe by building fences along roads to prevent wildlife

Encyclopedia of the World's Biomes, 2020, 237–248

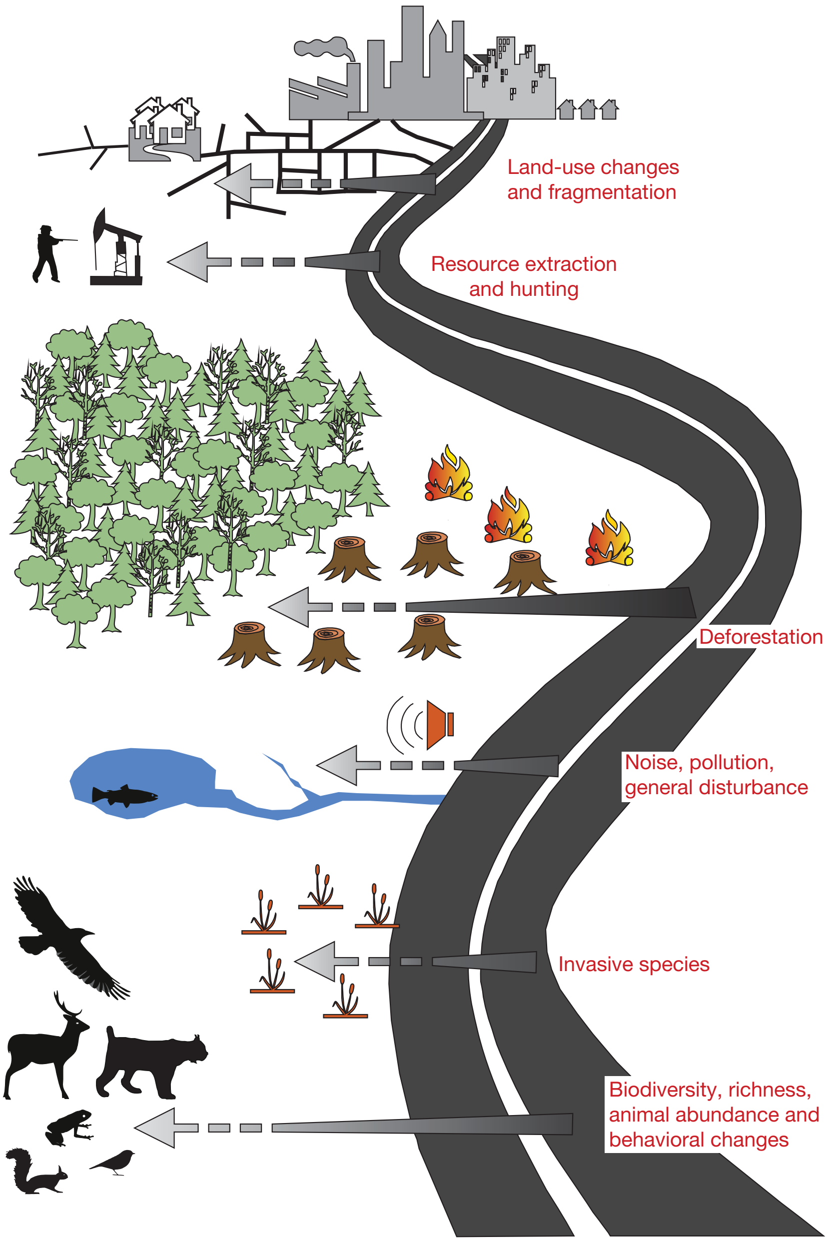

Fig. 1 Schematic representation of different categories of road impacts on biodiversity. Road impacts diminish with the distance from the road. From Ibisch, P. L., Hoffmann, M. T., Kreft, S., et al. (2016). A global map of roadless areas and their conservation status. *Science* **354**(*6318*), 1423-1427, supplementary material.

crossings and accidents (Epps et al., 2005; Linnell et al., 2016). Roads reduce landscape connectivity, alter species behavior, and can lead to changes in species composition (Forman et al., 2003; Hansen and Clevenger, 2005; Freudenberger et al., 2012).

The "contagious effect" of roads (Selva et al., 2015) describes how newly constructed roads in previously inaccessible areas trigger a cascade of disturbances and impairments of ecosystems. Indirect impacts of roads are caused by promoting socioeconomic activities such as resource extraction, agriculture or tourism, which previously were rather restricted or even absent. They provide access to remote and scarcely inhabited areas and often lead to deforestation, urbanization, mining, human-caused wildfires, hunting, poaching, and fishing, all together resulting in further degradation of habitats and ecosystem functionality (Laurance, 2009; Laurance and Arrea, 2017; Liu et al., 2008; Selva et al., 2011; Trombulak and Frissell, 2000). Especially in forest ecosystems the microclimatic and biotic changes along the road edges can increase the risk of wildfires and trigger further destabilizing consequences for ecosystem functionality (e.g., Chaplin-Kramer et al., 2015; Lembrechts et al., 2017; Foley et al., 2003; Norris et al., 2012; Eigenbrod et al., 2015).

Fig. 2 Impressions of diverse road impacts on forests. Logging roads and trails often start the cascade of degradation. Among the most prominent impacts are soil compaction and opening up forest canopies (A: Skidding trail in temperate Carpathian beech forest, Ukraine; B: Harvester providing access to planned clearcut area in boreal forest, Arkhangelsk region, Russian Federation). In mountain areas downstream road impacts multiply first direct effects; they commonly lead to erosion, destabilization of slopes and disturbance of rivers (C: Recently improved road in Andean montane rain forest, Ecuador). Roads provide access to highly vulnerable areas such as peatlands, drive land use change and cause changes in the landscape hydrology (D: Oil palm plantation on peatlands replacing a former tropical peat swamp forest at the edge of the Klias reserve in Sabah, Borneo, Malaysia). Roads become veins of colonization in remote regions introducing contagious effects into the wider landscape (E: Main road with a belt of increasing settling and land use activities such as cattle ranching in northern Kalahari, Kavango region, Namibia). Roads are often built even in the centre of protected areas leading to loss of habitat, change of microclimate and increasing the risk of wildfires or neobiota (F: Road with tourists within Ku-Ring-Gai National Park, Australia). All photographs by Pierre Ibisch.

Direct impacts of roads can be quantified in various ways by counting wildlife road kills or measuring habitat loss and fragmentation, whereas indirect impacts can be very complex, time-lagged and go far beyond main roads that often trigger the development of smaller trails and paths, which makes it more difficult to understand and assess them (Forman et al., 2002; Freitas et al., 2015; Jędrzejewski et al., 2018; Selva et al., 2011; Shilling et al., 2015; Wilkie et al., 2000). Direct and indirect effects of roads on ecosystems are scale-dependent and have to be analyzed with regard to their spatial scopes. Forman and Alexander (1998) termed the area influenced by roads "road-effect zone" (REZ). A REZ comprises the areas which extend beyond an actual road but are still affected by road construction, usage or maintenance. Type and degree of impact changes, depending on the zone that is affected. The REZ is determined by various factors such as the distance from the road surface, environmental conditions, season, landscape structure, topography, or traffic intensity (Forman and Deblinger, 2000).

Species and ecosystems react specifically to the diverse combinations of road effects and landscape conditions; impacts can be asymmetrical along roads and vary temporally or seasonally (Ibisch and Selva, 2017; Kleinschroth et al., 2016; Morán-López et al., 2017). Hence, it is not possible to identify a single road-effect zone combining all direct and indirect road effects on biodiversity and species. For instance, a highly altered and structurally impoverished grassland impacted by a new concrete road with heavy traffic cannot be compared to a complex, intact and functional forest ecosystem crisscrossed by narrow dirt roads used by poachers and illegal loggers. In mountains, there are also downstream effects of roads that can extend over large distances. These would be related to run-off, soil erosion, and river water quality, among others (Ibisch and Selva, 2017; Seutloali and Beckedahl, 2015). In the Southwest Amazon rainforest region, indirect effects have been recorded up to 45 km around main roads (Southworth et al., 2011). In contrast, the road-effect zone for desert turtles in California is over 400 m from the road (Boarman and Sazaki, 2006). Bat activity increases more than threefold between 0 and 1600 m from the road (Altringham and Kerth, 2016). For anurans in Canada, Eigenbrod et al. (2009) estimated a REZ of 250–1000 m. Dutch birds were affected by roads within a distance of 40–2800 m from the road, depending on the species and traffic volume (Reijnen et al., 1995). A population decline extends over distances up to 5 km for mammal species and up to 1 km for bird species (Benítez-López et al., 2010). Most of the direct negative impacts caused by roads are at a distance of one kilometer to the nearest road (Ibisch et al., 2016).

Roads and Roadless Areas in Forests

Often, forests are mapped as roadless within heavily roaded landscapes such as in Germany. However, upon closer inspection these areas are by no means truly road-free ecosystems; rather, there are countless forest trails and forest roads that have not yet been mapped (Hoffmann and Ibisch, 2017). Even if these are not public roads and characterized by very low traffic intensity, they can contribute to ecosystem vulnerability:

- As forests are the most biomass-rich and structurally most complex terrestrial ecosystems, they are especially vulnerable to physical, chemical and biological degradation mechanisms that can be referred to the presence of roads. The complex, three-dimensional structure established by trees—often organized in various strata—together with high biomass facilitate a pronounced physical moderation and regulation of environmental conditions. For instance, forests produce their own cooler, more buffered and moister microclimate, which is a key property to their resistance and resilience against disturbance (e.g., Norris et al., 2012). By opening up the canopy and creating linear breaches, roads affect the self-regulating capacity of forest ecosystems, reducing the microclimatic buffering capacity.
- The combination of higher temperatures and lower humidity along roads, the presence of combustible fuel such as remnants of cut or dying trees, often amplified by secondary vegetation with combustible plants, and the presence of people, who tend to inconsiderately light fires, multiplies the risk of forest fires.

What Are Roadless Areas and Where Are They?

Roadless areas are free from any kind of road(-like) infrastructure and their direct or indirect impacts on the ecosystems. In the research for the first global map of roadless areas (Ibisch et al., 2016), a 1 km buffer was chosen as a relatively conservative measure, acknowledging that there are impacts that can be recorded beyond this distance from the road. Due to the absence of the road impacts described above, roadless areas play a special role in the conservation of biodiversity and ecosystem functionality (Martin et al., 2000; Strittholt and DellaSala, 2001; Crist et al., 2005; Selva et al., 2011). They increase landscape connectivity between habitat patches and protected areas (Strittholt and DellaSala, 2001; Goetz et al., 2009) and can contribute to the conservation of native, vulnerable, and endangered species (Campaign, 2001; Gelbard and Harrison, 2003). They are particularly essential for species that require and move across large territories (Crooks, 2002; Blake et al., 2008; Kaphegyi et al., 2013; Kuemmerle et al., 2018). Roadless functioning ecosystems have a higher buffer capacity and are more resilient than roaded areas, making them less vulnerable to the effects of climate change (McGarigal et al., 2001; Crist et al., 2005). Even small roadless areas can be of importance, as they serve as habitat, stepping-stones, and climate refugia for certain species, as well as reference areas for restoration. Clearly, biological diversity is positively related to the size of a conservation area (Develice and Martin, 2001), and larger roadless areas are especially valuable.

The very first OpenStreetMap (OSM)-based global analysis of roadless areas distribution across Earth's biomes showed substantial geographical differences (Ibisch et al., 2016). The Tundra and Rock and ice-covered biomes were nearly roadless. A high share of roadless areas was also found in Tropical and Subtropical Grasslands, Savannas, Shrublands, and Moist Broadleaf Forests in Montane Grasslands and Shrublands, Deserts and Xeric Shrublands, as well as in Boreal Forests/Taiga. Half of the Mediterranean Forests, Woodlands, and Scrublands appeared to be roadless, whilst in Temperate Broadleaf and Mixed Forests the roadless share was $<50\%$. In the Tropical Forests large roadless areas exist in South America, Africa, and Southeast Asia. The largest tracts of roadless areas exist in the Sahara, but also in forest regions such as the northern and western Amazon and the boreal forests in northern and northeastern Russia and Canada (**Figs. 3 and 4**).

Highest road density can be observed in the Temperate Broadleaf and Mixed forests biome, especially in industrialized countries with high population density and economic outputs, such as the (eastern and central) USA, most European countries, South Korea or Japan. This reflects both the completeness of the road data sets and actual economic development. In Asia, South America and Africa road infrastructure is rapidly developing. In Africa and Southeast Asia, in many countries, the national share of (1 km OSM)

Fig. 3 Roadless area in eastern Noel Kempff Mercado National Park in Bolivia. Vast tracts of tropical moist forests in contact to Cerrado woodlands and savannas represent huge complexes of free-willed, functional ecosystems Photograph: Pierre Ibisch.

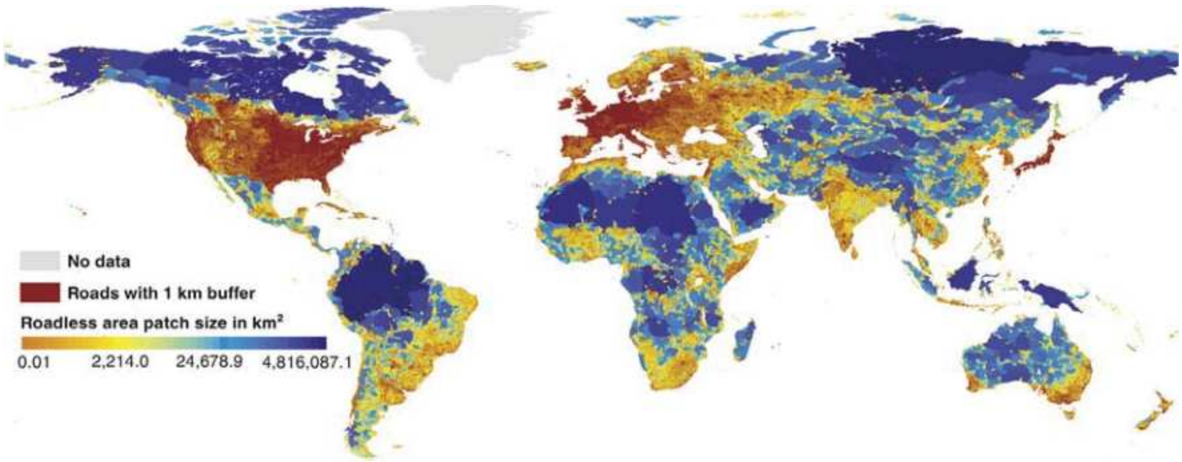

Fig. 4 Map of global roadless area patch sizes in km^2. From Ibisch, P. L., Hoffmann, M. T., Kreft, S., et al. (2016). A global map of roadless areas and their conservation status. *Science* **354**(*6318*), 1423-1427.

roadless areas between 2013 and 2018 has substantially decreased by >30% (e.g., Sri Lanka from 66% to 26%; own unpublished data). This would mainly be due to intensified OSM mapping efforts, but should also reflect progressing road infrastructure (see below, following section).

To understand the relative importance and ecological value of roadless areas it is important to assess their ecologically relevant features and the presence of non-road related threats. An example for roadless, but used landscapes are rangelands. Often large, intensively managed agricultural areas, mining or military sites appear as roadless areas if the distance to the road is > 1 km. Still, they are not necessarily free from traffic, and land use can have severe degradation effects on ecosystems (Hoffmann and Ibisch, 2017). As in the context of assessing the quality of wilderness areas, certain criteria can be applied for further understanding the relative ecological value and conservation priority of roadless areas. In the context of the first global map, Ibisch et al. (2016) proposed the Ecological Value Index of Roadless Areas (EVIRA). This index encompasses three indicators. The first indicator consists of the Ecological Functionality Index (EFI) (Freudenberger et al., 2012), the second is patch size and the third is connectivity of the patches using Thiessen polygons. Ecological Functionality was weighted by 50% the last two by 25% each. The largest tracts of ecologically most valuable roadless areas refer to large unfragmented forests regions, both in the tropics and the boreal zone (Amazon, Congo basin, East and Southeast Asia; Fig. 5). There are also very important roadless areas in some temperate and subtropical regions (e.g., Himalaya, eastern Russia, Caucasus, eastern Mediterranean).

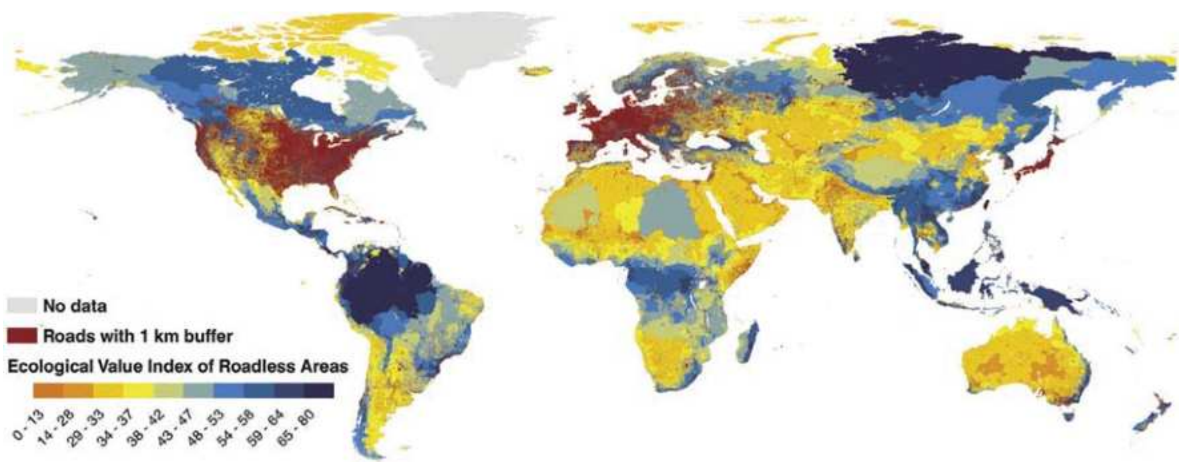

Fig. 5 Map of Ecological Value Index of Roadless Areas (EVIRA). From Ibisch, P. L., Hoffmann, M. T., Kreft, S., et al. (2016). A global map of roadless areas and their conservation status. *Science* **354**(*6318*), 1423-1427.

What Are the Data Needs and Prospects Regarding Roadless Big Data Management and Research?

Cartographically, roadless areas are identified as areas that remain once roads and buffers (on each side of the road) are removed from the country data set. The buffer can be adapted to the road category or condition of the ecosystem (e.g., 1 or 5 km, see Ibisch et al., 2016). For the first global map of roadless areas open-source data was used, created by OpenStreetMap (OSM). OpenStreetMap works with volunteered geographic information (VGI), where citizens collect confirmable geodata (Goodchild, 2009; Mooney and Corcoran, 2013). The 1 km buffer was applied on each side of all roads across all road categories that are included in the OSM road data set (Ibisch et al., 2016) (**Fig. 4**).

The road network from 2013 was used in the roadless area study. It showed gaps in some regions, especially in Southeast Asia (Ibisch et al., 2016; Hoffmann and Ibisch, 2017). Because OSM is a crowd-sourcing project, data collection is an ongoing process (Mocnik et al., 2017). The OSM dataset of 2013 comprised almost 37 million km of roads. By 2018, the worldwide OSM data on roads has doubled. The OSM data set is updated constantly, missing roads but also newly constructed roads are added. Several quality assessments were conducted to evaluate the quality of OSM data (Koukoletsos et al., 2011; Barron et al., 2014; Zhao et al., 2015). In a study published in 2017, the authors found that OSM is 83% complete in >40 countries (Barrington-Leigh and Millard-Ball, 2017). The popularity of OSM is increasing and with it the number of mapped roads. Citizens shall be encouraged to actively participate in creating geodata for open access purposes. A new road data set was published by GLOBIO in 2018 with 21 million kilometers of roads that also incorporated OSM road data for the European Union (Meijer et al., 2018). An automated road mapping algorithm that would use artificial intelligence identifying different road types on satellite images would be highly useful for a reliable global monitoring (Laurance, 2018).

One of the downsides of global data sets is the size of the data and the consequent processing time and required computer capacities. Big data has become an issue in many scientific fields. The amount of data is increasing exponentially, but systems that can process this large amount of information are more likely to exist in commercial enterprises than in conservation-oriented research entities. Big data processing is challenging (Demchenko et al., 2012). This is related both to the amount of data and to the existing infrastructure and architecture, which, due to the volume, diversity, speed, truthfulness, volatility and quality of the data, cannot process the information the way it was previously processed (Nasser and Tariq, 2015). Big data with high resolution need storage space and proper running systems to handle and maintain them (Marx, 2013; Bargellini et al., 2013). This field is developing fast, and hopefully, in the future, it will be affordable for a broader public. Although the roads are well mapped in OSM according to their location in most of the regions the meta data or attributes accompanying the data are often insufficient. Information on the road category, lane and or width would be helpful in assessing the impact of roads more precisely. Traffic intensity is not yet included in the OSM data, but can be used together with population density information to assess roadless areas at risk of conversion due to demographic pressure. Even though there is an increasing amount of freely available data, geodata are not always accessible and not consistent enough to be used on a large scale. Download times for large datasets can easily exceed 24 h (unless they are integrated into systems like Google Earth Engine) and companies offering cloud computing services for data processing are initially very expensive.

Roadless Areas and Society

The societal view on roadless areas shifts with changes in socioeconomic lifestyles. Indigenous, forest-dwelling people often recognize disadvantages and risks related to roads such as diseases, poachers or invading settlers (e.g., Finer et al., 2008; Clements et al., 2018). Abrupt contact with modern life-styles via new roads has been observed to socially disrupt local communities in remote forest regions.

Worldwide attention was paid to the case of a road project through the Isiboró-Securé National Park and Indigenous Territory in Bolivia, where indigenous peoples effectively protested against the government's development plans (El Deber, 2018).

In remote rural areas with predominantly agriculture-based livelihoods, local people by tendency would strive for improved road access. Case studies have indicated that roads reduce poverty and increase consumption growth, and the incidence of hunger seems to increase with distance to roads (compare Ibisch et al., 2016, Table S10, supplementary material), but there are also socio-economic risks (Alamgir et al., 2017). Today, most relevant actors would consider road infrastructure an essential condition for economic development (Fan and Chan-Kang, 2005; Turner, 2006; Calderón and Servén, 2014). Especially in the case of forests, roadless areas comprise much demanded natural resource assets, such as timber, but often also minerals and open space for agricultural development. The substantial conflict between short-term economic interests and the long-term conservation of roadless areas must not be denied.

The general awareness for the impacts of the global road network on ecosystems is relatively underdeveloped. When the first global map of roadless areas was published in 2016 there was a substantial global media echo reflecting that journalists recognized the importance of the topic, several of them acknowledging that the fragmentation of Earth took place largely unnoticed, although virtually everyone uses roads. Theoretically, the current challenges to conventional mobility that led to overcrowded and polluted cities and faces the need to move away from fossil energy sources, could trigger innovation towards more ecosystem-friendly solutions. Unfortunately, the recent hypes around electro-mobility and autonomous smart driving perpetuate visions related to individual automobiles that require roads. Currently, roadless mobility options, including railroads or low-energy flying devices with limited requirements for permanent infrastructure (e.g., zeppelins, blimps), do not seem to be sufficiently developed for representing an attractive alternative.

Roadless Areas Policy: What Are the Messages for Policy Makers?

With the global population expected to reach over 11 billion by 2100 (United Nations, 2017) and the global ecological deficit gradually increasing up to 8380 million global hectares (Gha) (Global Footprint Network, 2018), a bold policy statement of setting aside half of Earth as permanently protected areas for biodiversity conservation has been suggested for humanity to stave off a cataclysmic extinction event (Wilson, 2016). Large roadless areas can serve as a measurable surrogate for the most pristine and functional ecosystems. Given the importance of roadless areas for sustaining essential services to society, and their rapid diminishment globally, the key message to policy-makers is clear: Give roadless areas conservation priority over areas that have already been fragmented. *Roadlessness* is a more or less easily measurable condition of an ecosystem serving as a meaningful proxy for its integrity and the absence of many anthropogenic disturbances. It is essential to establish roadlessness as a criterion for the planning of ecosystem-based, cost-effective sustainable development (Ibisch et al., 2016).

Roadlessness is tightly linked to the concepts of wilderness or intactness. Such global templates focus mainly on forests and include the "High-biodiversity wilderness areas" (developed by Conservation International), "Last of the Wild" (The Wildlife Conservation Society and Center for International Earth Science Information Network, Columbia University) and "Intact Forest Landscapes" (Greenpeace and partners). Another global prioritization scheme was suggested focussing on ecologically functional regions under climate change (EcoSocioClimateWise priority setting model; Freudenbergeret al., 2012). Global priorities according to all these templates turn out to focus heavily on roadless forests. To ascertain that development is sustainable on the long-term, it is important to secure regulating and maintaining ecosystem services. Among all terrestrial ecosystems, roadless forests are the single most important stronghold of regulating services: among others, soil protection, water retention, buffering of the local and regional climate and mitigation of global climate change via capturing of atmospheric carbon (**Fig. 6**). As a possible solution, some have proposed balancing the value of an area for species conservation, as a proxy indicator for maintaining ecosystem services, with its value for food production, as an essential provisioning ecosystem service (Laurance et al., 2014).

The added value and novelty of roadlessness is that it is based on one of the most important direct and indirect key drivers of biodiversity loss. The extent of roadless areas or even simply road density can be easily used as a measurable entity assessing the extent of anthropogenic pressures at multiple scales. The conservation of roadless areas represents a proactive approach, in contrast to reactive approaches that are directed at mitigating or reversing biodiversity losses ex post (see Brooks et al., 2006, for a comparison of proactive and reactive priority-setting in global conservation). A proactive approach favoring policies for ecosystem-based sustainable development bears several advantages. Most importantly, the long-term opportunity costs for protection of roadless areas will often turn out to be lower than the ones resulting from dissection by roads and subsequent exploitation of an area. Proactive policies may also come with a lower political cost. Sparing regions from road development will help forego both immediate protests by informed stakeholders and posterior opposition by people negatively affected by unsustainable development unfolding in the region.

There is an urgent need for a global strategy and relevant legal frame development for the effective conservation, restoration and monitoring of roadless areas and the ecosystems they encompass. The USA initiated this process by protecting over 20 million ha of roadless area $>$2000 ha each, amounting to approximately 1/3 of its national forest system (see Strittholt and DellaSala, 2001). Starting with the US Wilderness Act (1964), indirectly promoting conservation of roadless areas, the US Forest Service adopted the Roadless Area Conservation Rule (2001) hampering road construction, road reconstruction, and timber harvesting in inventoried roadless areas on National Forest System lands, clearly enhancing species conservation (Loucks et al., 2003), but not without severe political conflicts (Bies, 2006). No such legal frame exists in other more densely populated parts of the world such as Europe, where the importance of roadless areas has only been underlined in some reports on fragmentation (Jaeger et al., 2011), besides scientific calls for roadless areas conservation (Selva et al., 2011; Psaralexi et al., 2017).

Fig. 6 Tropical moist forest in a protected roadless area with the Maya Biosphere Reserve, Guatemala, providing important regulating ecosystem services such as water retention and mesoclimatic cooling and buffering Photograph: Pierre Ibisch.

As an important first step, policy-makers should commission a fine-scale inventory of roadless areas and their value for sustainable development (see above: Roadless areas and society). In the official national report of Greece towards the European Environmental Agency (Kati, 2018) the number and extent of roadless areas have been introduced for the first time as a fragmentation index and as an indicator for monitoring the fragmentation rate of natural and semi-natural areas (SEBI 13). Such national reports adopt the system of Streamlining European Biodiversity Indicators 2020 (EEA, 2012) under the scope of monitoring the progress of each Member State towards achieving Aichi targets (UNEP/CBD/COP, 2010) and the European Unions' 2020 Biodiversity Strategy targets (EC, 2011).

The most direct proactive measure for roadlessness is a regional moratorium for road construction in roadless areas with an identified high priority. A complementary policy may consist in proactively reducing the future demand for roads. This may be achieved by efforts to promote provisioning ecosystem services elsewhere, e.g., by ecologically intensifying agricultural production in already cultivated and disturbed areas. There is the urgent need to discuss sufficiency in the context of road infrastructure: Although options for further shortening travel routes may exist, certain densities of road infrastructure should be acceptable without the need for ever reducing travel times (Hoffmann and Ibisch, 2017). A maximum threshold of an ecologically tolerable road density should be lower in regions that have yet experienced only moderate disturbance from road development. Additionally, any approach should take into account ecosystem-specific vulnerability.

A moratorium for road construction can be accomplished through establishment of protected areas that are managed according to legal prescriptions that exclude road construction and thus conserve the state of roadlessness. So far, the global system of protected areas has performed poorly in effectively conserving roadless areas, as these are not recognized by governments as sui generis (unique) conservation targets (Ibisch et al., 2016). Many roadless areas enjoy de facto protection due to natural factors that hamper physical access, such as steep or swampy terrain (**Fig. 7**). However, with technological progress, enhancing economical resources and increasing pressures from population growth and more or less justified economical interest, this de facto protection is precarious. In addition, the economic value of resources harbored in a roadless area may increase. For example, forest in a roadless area may become more attractive to extraction in an otherwise exploited landscape, and with it for road construction. For these reasons, a wise policy will proactively impose a moratorium for road building in key roadless areas, for instance, by establishment of strict protected areas.

Cases may occur where a road construction moratorium is considered impossible, or not opportune under given sociopolitical circumstances. If avoidance is no option, decision-making on roadless areas should explore all options for maximum reduction of road impacts. These options (in order of decreasing preference) include: re-routing a planned road, bundling it together with existing linear infrastructure, and maximizing size of roadless fragments left over from dissection (Laurance et al., 2014).

Proactive policies and measures, despite their above described advantages, may still be overturned by road development interests. In these cases, policy-makers should recur to reactive approaches. In the course of compensatory measures that would target minimizing net loss of biodiversity, environmentalists should vehemently insist for an appropriate quid pro quo: Any loss of a roadless area through the construction of a new road should at least be compensated with the dismantling of another road that recreates a roadless area of the same ecological value (Hoffmann and Ibisch, 2017). As long as roads are continued to be built, however, the

Fig. 7 Intact Southwest Amazon rain forest in Peru. Large remote roadless areas allow for conserving vast tracts of valuable ecosystems with their functions and services, even without formal protection. But with progressing development they are at risk if protected area policies do not recognize roadlessness as key criterion for nomination and priorization. Photograph: Pierre Ibisch.

single most important policy is strict regulation of subsequent human activities in the region. First and foremost, areas to the side of a new road must be kept safe from "contagious development," a cascade of exploitative land use leading to the short-sighted desire for new roads (Ibisch et al., 2016). This then generates new economic interests, thus perpetuating the process until a former roadless area and its functional ecosystems are "used up" (Laurance et al., 2014; Selva et al., 2015).

In parallel with measures to protect roadlessness, work on alternative approaches to roadless mobility needs to be intensified. Even if environmentally friendly renewable energy might turn out to supply road transport on a large scale, roads will continue to severely impair ecosystem functionality. The currently observable megatrends such as electromobility and autonomous driving illustrate the path dependency, which masters the current (and future) mobility discourse.

Conclusions and Outlook

- There is strong evidence for the ecological importance of roadless areas. It is related to the absence of complexly interacting, direct and indirect anthropogenic drivers of ecosystemic stresses.
- Roadlessness, in many ecosystems, is becoming a rare attribute. It is a proxy for ecosystem integrity that can be assessed more or less easily, and shall serve as criterion for conservation and land use planning. Extent and ecological quality of roadless areas (such as Ecological Value Index of Roadless Areas—EVIRA) are recommended for the global reporting on the accomplishment of the Sustainable Development Goals, especially those targeting sustainable infrastructure and the conservation of terrestrial ecosystems.
- First existing models that show the way to develop monitoring systems and policies for conserving roadless areas deserve special attention.
- Published maps and datasets of roadless areas substantially underestimate the extent of roads, but data quality is rapidly improving.
- The enhanced and dynamic mapping and monitoring of both extent and ecological quality of roadless areas is urgently needed for building up a global observation system and informing regional, national, and local policy makers.
- As dozens of millions of road kilometers crisscross the global terrestrial ecosystems and the negative impacts of roads on biodiversity have been extensively studied, there is the need to establish a *roadless ecology* that further proves and quantifies the multiple environmental and socioeconomic benefits of roadlessness.
- A discourse on "road sufficiency" is needed ("How many roads should be enough under given conditions?"). Slight improvements in access and reduction of travel time cannot be justified at the cost of degrading the last ecologically valuable roadless areas.
- The evolution of mobility technologies seems to be trapped in a path-dependency carefully maintained by the stakeholders involved in road-dependent mobility. It is therefore equally important that research highlights the benefits and avoided damage of alternative approaches to mobility and transport, which are likely to include more conventional technologies such as railways or modern, environmentally friendly, low-energy flying vehicles.

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PAPER III

Mapping roadless areas in regions with contrasting human footprint

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Mapping roadless areas in regions with contrasting human footprint

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In an increasingly human- and road-dominated world, the preservation of functional ecosystems has become highly relevant. While the negative ecological impacts of roads on ecosystems are numerous and well documented, roadless areas have been proposed as proxy for functional ecosystems. However, their potential remains underexplored, partly due to the incomplete mapping of roads. We assessed the accuracy of roadless areas identification using freely available road-data in two regions with contrasting levels of anthropogenic influence: boreal Canada and temperate Central Europe (Poland, Slovakia, Czechia, and Hungary). Within randomly selected circular plots (per region and country), we visually examined the completeness of road mapping using OpenStreetMap 2020 and assessed whether human influences affect mapping quality using four variables. In boreal Canada, roads were completely mapped in 3% of the plots, compared to 40% in Central Europe. Lower Human Footprint Index and road density values were related to greater incompleteness in road mapping. Roadless areas, defined as areas at least 1 km away from any road, covered 85% of the surface in boreal Canada (mean size ± s.d. = 272 ± 12,197 km^2), compared to only 0.4% in temperate Central Europe (mean size ± s.d. = 0.6 ± 3.1 km^2). By visually interpreting and manually adding unmapped roads in 30 randomly selected roadless areas from each study country, we observed a similar reduction in roadless surface in both Canada and Central Europe (27% vs 28%) when all roads were included. This study highlights the urgent need for improved road mapping techniques to support research on roadless areas as conservation targets and surrogates of functional ecosystems.

Keywords Roadless areas, OpenStreetMap, Road mapping, Road ecology, Anthropogenic impact, Human footprint index, Human modification index, Travel time to major cities

Habitat fragmentation, one of the greatest threats to biodiversity[1], has already altered more than 50% of the Earth's terrestrial landscapes[2], with the road network emerging as a major driver of ecosystem fragmentation and degradation[3]. Its effects on the environment are numerous, including defaunation, deforestation, land use changes, and urban sprawl. These factors collectively drive the loss of biodiversity and ecosystem functionality i. e. the capacity of ecosystems to sustain essential ecological processes and services over time[3–6]. Other ecological impacts of roads include pollution, soil erosion, isolation of populations, alterations in species behavior, wildlife mortality, changes in gene flow, facilitation of invasive species and increase in fire risk[5,7–10]. The intensity of these impacts varies based on factors such as road surface, density, location, type, and traffic volume[11,12]. While road development is often associated with economic growth and urbanization[13,14], its environmental impacts may not always align with sustainable development and its goals[3,15,16]. Road construction continues to meet the growing demand of natural resources by providing access to unexploited regions and facilitating resource extraction[4]. Especially in pristine and natural areas, the consequences of road construction and the following contagious development may have a catastrophic effect on ecosystems[5,17]. In recent years, road networks have penetrated areas previously considered remote and devoid of human infrastructure, leading to unprecedented accessibility[11,18]. Growing evidence emphasizes that roads disrupt and degrade the functionality of ecosystems[3].

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Therefore, it is crucial to identify the remaining areas still unfragmented by roads and prevent the first cut into these functioning ecosystems and the subsequent contagious development[5].

In the current global biodiversity and climate crisis, understanding the extent and condition of unfragmented regions and their role in biodiversity conservation is critical to maintaining ecosystem resilience at different scales[19]. Roadless areas are relatively free from all human impacts associated with the road network and have been proposed as conservation targets for functional ecosystems[3,5,9,20]. To protect them effectively, they must first be accurately identified. This is not only essential but also urgent, given the current pace of road construction[21,22]. Roadless areas can serve as quantifiable indicators for the most pristine ecosystems and can play an important role in maintaining ecosystem functions and contributing to biodiversity and ecological processes[9,23]. They facilitate species movement, long-distance dispersal, and increase connectivity among ecoregions[24]. Roadless areas have a greater buffering capacity and are more resilient than fragmented areas to the impacts of climate change[3,25].

It has been estimated that the length of paved roads will increase by 14–23%[26] or even to 59%[21] by 2050, therefore, many current roadless areas are likely to disappear before they have even been mapped. Accurate and up-to-date road mapping is urgent but presents significant challenges due to the continuous expansion of roads, the multitude of road types with varying surface reflectance, the extensive length of road networks, the limited accessibility to some road data, and the proliferation of illegal and undocumented roads, particularly notable in regions such as the Amazon basin[11]. The availability and accessibility of high-resolution satellite imagery can support accurate road mapping, but it is also a critical component as it varies around the world. In some regions, imagery can be limited or outdated, affecting the accuracy of road mapping[27]. Environmental conditions such as dense forests, deserts or mountainous terrain can hinder the visibility of roads, making mapping in these areas more challenging. Diverse road types, such as paved, unpaved, forest, or desert roads, have unique characteristics and require different mapping approaches[28,29]. The complexity increases when attempting to differentiate and accurately represent various road surfaces and terrains[30]. This requires sophisticated data processing methods to handle the large amount of data and numerous vertex points involved. On a global level, open-source road datasets are provided by the Center for International Earth Science Information Network (CIESIN), the Global Roads Inventory Project (GRIP) dataset, and the volunteer-based geographic information OpenStreetMap (OSM) road dataset[26,31,32]. For now, OSM is the most complete, up-to-date, and freely available road dataset on a global scale and is constantly being improved[3,33]. However, in some regions, OSM road data does not reflect the full extent of existing roads[3,34,35], especially in regions of conservation value holding valuable natural resources, where the construction of new roads is a constant threat[16].

Our goal was to evaluate to what extent roadless areas can be accurately identified and characterized with OSM road data and to assess the completeness of road mapping in two study regions with a priori contrasting road densities—boreal Canada (covering approximately 5.4 million km^2) and a region in temperate Central Europe covering Poland, Slovakia, Czechia, and Hungary (approximately 533,000 km^2). The selection of these study regions was based on their contrasting human footprint. Boreal Canada represents a vast wilderness with relatively low human population density and infrastructure development, in contrast to the densely populated and heavily modified landscapes of temperate Central Europe. We expected considerable differences in the completeness of road mapping as well as in the number and size of roadless areas between the two regions related to varying levels of anthropogenic influence. We predicted more incomplete road mapping with lower human footprint, i.e. in areas where significant roadless areas may still remain. We aimed to (a) identify the number and surface of roadless areas in these regions using OSM road data, (b) assess the completeness of OSM road data and to examine the potential effect of anthropogenic influences on road mapping completeness, and (c) compare the quantity and size of roadless areas in the two study regions using OSM road data and road mapping through visual interpretation of high-resolution satellite imagery.

Results

Mapping accuracy and associated factors

According to OSM, the road density in the study region of temperate Central Europe was 11 times higher than in boreal Canada, with a maximum of 41.5 km/km^2 and 3.9 km/km^2, respectively. The mean road density was 3.5 km/km^2 (± 2.4 s.d.) in Central Europe and 0.1 km/km^2 (± 0.2 s.d.) for boreal Canada (Fig. 1a, b). There was a spatial pattern of increasing road density in boreal Canada from north to south (Fig. 1a). In the study region of temperate Central Europe, the main cities were clearly recognizable due to their high road density, but no latitudinal patterns were observed (Fig. 1b). Road length in both study areas highly varied between the OSM and the Global Roads Inventory Project road datasets; the latter contained only 23% of the OSM road length in the region of temperate Central Europe and 12% in the boreal region of Canada (Table S1). In general, OSM had the longest road network, also when compared with regional road datasets.

The visual interpretation of the randomly selected circular plots (n = 1000 per region, 3.14 km^2 each) confirmed that 70% of the circular plots in boreal Canada had no roads, while only 3% of the plots had all roads completely mapped by OSM users, making a total of 73% of the plots properly mapped. However, in 12% of the plots roads were partially mapped, i.e., not all road sections were included in OSM, and in another 12%, the plots contained only unmapped roads (Table 1, Fig. 1c). This results in 24% of the plots missing roads in the OSM road dataset for boreal Canada. Out of the 271 plots containing roads, only 11% were properly mapped. In the Central European region, the visual interpretation confirmed that there were no plots without roads and that 40% of the plots were accurately mapped, while 60% of the plots contained partially unmapped roads within the OSM road dataset. Notably, only one plot contained unmapped roads (Table 1, Fig. 1d). To explore potential variations in road mapping across different European countries, we created an additional set of circular plots (n = 4000, 1000 plots per country), and our findings demonstrated that Czechia exhibited the highest percentage of plots with correctly mapped OSM roads, whereas Slovakia had the lowest percentage. Most plots in Central

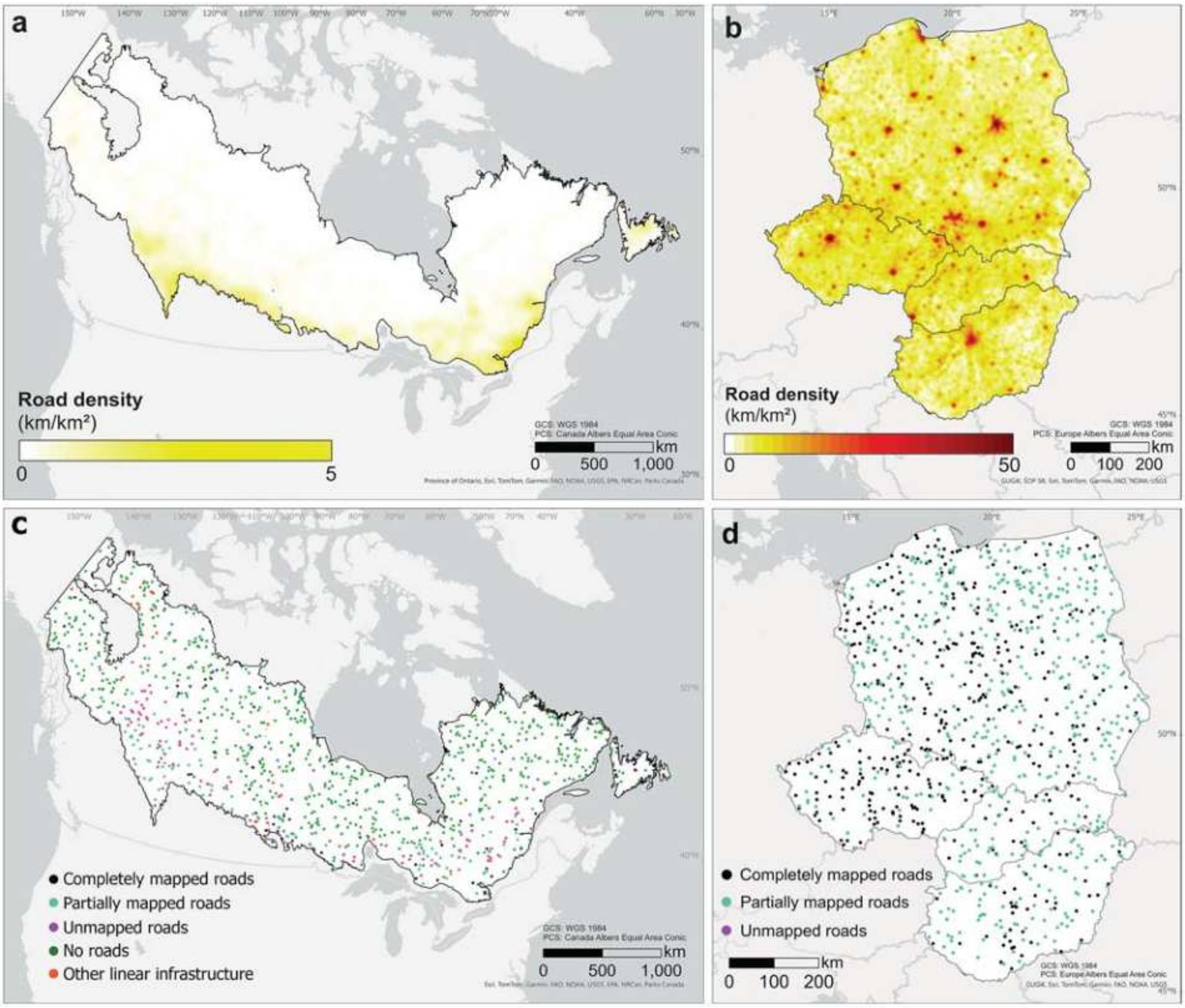

Figure 1. Road density and spatial distribution of the 1000 randomly selected circular plots in each of the two study areas (**a,c**) the boreal region of Canada and (**b,d**) a selected region in temperate Central Europe covering Poland, Slovakia, Czechia, and Hungary. Road densities were estimated using all OSM 2020 road categories and a 5 km^2 snap raster (**a,b**). Circular plots of 1 km radius were randomly selected and classified after the visual interpretation into the following categories: plots with completely mapped roads, with partially mapped roads, with only unmapped roads, without roads, and with other linear infrastructures (**c,d**). This figure was created using ArcGIS Pro 3.2 (https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview).

Europe were partially mapped. However, examining individual countries, completely mapped roads emerged as the most frequent category (Table 1, Table S2).

Road-free plots were mainly located in the northern part of boreal Canada (Fig. 1c). Some linear infrastructures were detected in the north-western part of the Canadian study region, including powerlines, seismic lines for oil and gas exploration, and fire breaks, intended to control wildfires. Most of the plots with unmapped and partially unmapped roads were detected in the southern and central parts of boreal Canada. In temperate Central Europe, we did not identify any plot without roads. Plots with partially mapped roads were the most common, followed by plots with completely mapped roads; only one plot had only unmapped roads (Fig. 1d, Table 1).

We investigated the relationship between the completeness of road mapping and different proxies of human impact in the selected plots at the country level (boreal Canada, Poland, Slovakia, Czechia, Hungary): road density, travel time to major cities, the Human Footprint Index, and the Human Modification Index[32,36–38].

In both regions, there was a negative correlation between road completeness and road density, although the correlation was lower in Central Europe, indicating that higher road density was associated with more comprehensive road mapping. There was also a strong negative correlation between road density and travel time to major cities in Boreal Canada, which was lower in Central Europe. The Human Footprint Index and the Human Modification Index both showed a positive association with road density, while the two indices were moderately correlated (Table 1, Table S3, Fig. S1).

Accounting for spatial autocorrelation in the data had little effect on the coefficient values, as shown by the comparison of alternative Generalized Least Squares models (Fig. S2). Including the spatial correlation structure

Plot categories	Completely mapped roads	Partially mapped roads	Unmapped roads	No roads	Other linear infrastructures
Boreal Canada					
No. plots	31	119	121	703	26
Road density (km/km^2)	0.4 ± 0.3	0.4 ± 0.3	0.2 ± 0.2	0.0 ± 0.1	0.1 ± 0.1
Travel time to major cities (min)	544.4 ± 338.6	428.8 ± 325.6	763.4 ± 549.4	1737.0 ± 873.2	2067 ± 1164.7
Human footprint index	2.0 ± 3.3	3.6 ± 6.2	0.5 ± 1.6	0.1 ± 0.7	0.2 ± 0.8
Human modification index	0.0 ± 0.1	0.1 ± 0.2	0.0 ± 0.1	0.00 ± 0.0	0.0 ± 0.0
Central Europe					
No. plots	399	600	1	0	0
Road density (km/km^2)	4.1 ± 2.9	3.2 ± 1.8	–	–	–
Travel time to major cities (min)	77.9 ± 62.5	86.9 ± 60.7	–	–	–
Human footprint index	18.1 ± 9.8	15 ± 8.2	–	–	–
Human modification index	0.6 ± 0.2	0.5 ± 0.2	–	–	–

Table 1. Summary of the visual interpretation of the randomly selected circular plots (n = 1000, 3.14 km^2 each) in each of the two study regions (boreal Canada and temperate Central Europe including Poland, Slovakia, Czechia, and Hungary). It shows the number of circular plots within the following categories: plots with all roads completely mapped, plots with roads partially mapped, plots with all roads unmapped, plots without roads, and plots containing other linear infrastructures. The table shows the mean ± s.d. values of road density (km/km^2), travel time to the nearest city of 50,000 or more people (minutes), Human Footprint Index (ranging from 0 to 50, low values indicated low human footprint), and Human Modification Index (ranging from 0 to 1, low values indicated low degree of landscape modification by humans).

only moderately improved the model fit (Δ AIC_c = 3.3, Tables S4). The Ordinal Regression model showed that road completeness was differently associated with the explanatory variables in the two regions (Table 2). Based on the AIC_c, including the differences between the European countries did not improve the model (Table S5). Human Footprint Index and road density were the most significant predictors overall, and the effect of travel time to major cities and Human Modification Index varied between region (Table 2). The effects of the Human Footprint Index and road density were positive throughout, i.e., the proportion of correctly mapped plots (only plots containing roads were considered) increased as these variables increased, but the effect of the former was lower in the European region. In contrast, travel time to major cities and Human Modification Index had a negative effect in mapping completeness in boreal Canada and a weak positive effect in the Central European countries (Fig. 2).

Identification, characterization, and mapping of roadless areas

In total, 16,786 roadless areas were identified in the boreal region of Canada using the OSM 2020 road dataset. Overall, 85% of the surface of boreal Canada was roadless, with an average patch size of 272 km^2 but a median size of 0.7 km^2 (Fig. 3a, Table 3). Over half of the identified roadless areas (54%, 9,112 patches) were smaller than 1 km^2, and less than 5% (821 roadless patches) were larger than 100 km^2 (Fig. 3a, Table 3, Table S6).

Model term	x^2	Df	p value
Region	222.1	1	< 0.0001
Human Footprint Index	19.0	1	< 0.0001
Road density	14.0	1	0.0002
Travel time to major cities	4.6	1	0.03
Human modification index	8.1	1	0.004
Country	51.1	4	< 0.0001
Country × Human footprint index	2.7	1	0.1
Country × Travel time to major cities	5.4	1	0.02
Country × Human modification index	18.9	1	< 0.0001

Table 2. Analysis of deviance table (type II tests) for the ordinal regression model of road completeness (completely mapped = 3, partially mapped = 2, completely unmapped = 1). The columns show model terms, x^2 test value with degree of freedom, and associated p-value. The reference region and country was boreal Canada.

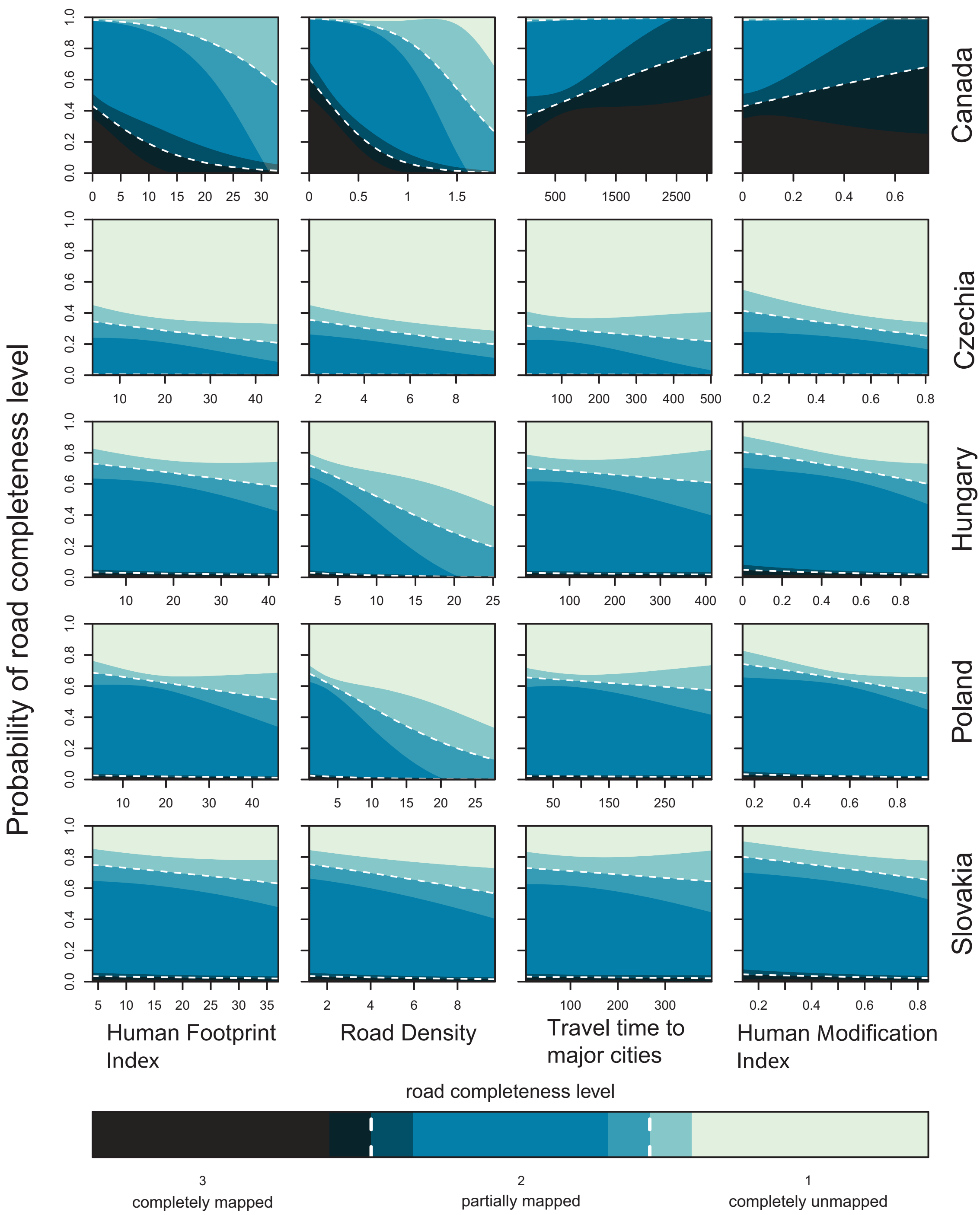

Figure 2. Proportion of plots with three categories of road completeness (completely mapped = 3, partially mapped = 2, completely unmapped = 1), as predicted by the ordinal regression model, in relation to the four variables of anthropogenic influence in each of the five study countries. Shaded regions represent the levels of completeness. Mean values are shown by dashed lines, and intermediate shading indicates 95% confidence intervals.

Our data highlight the substantial difference in the extent and size of roadless areas between the two regions, with boreal Canada having a much larger percentage of roadless areas, including some substantial patches, compared to Central Europe, where roadless areas were relatively small and accounted for only a small proportion of the total area (Table 3, Fig. 3a, b). The total number of roadless areas in Central Europe was 3,524. Only 0.4% (2161 km^2) of its surface remained roadless with a median size of 0.2 km^2 and an average roadless patch size of 0.6 km^2 (Table 3, Fig. 3b). The median and mean size of Canadian roadless areas were much larger 0.7 and 272 km^2, respectively. The only roadless area above 100 km^2 in the European region was the Biebrza National Park in Poland. In the entire Central European study region only 4 areas were larger than 50 km^2, whereas more than

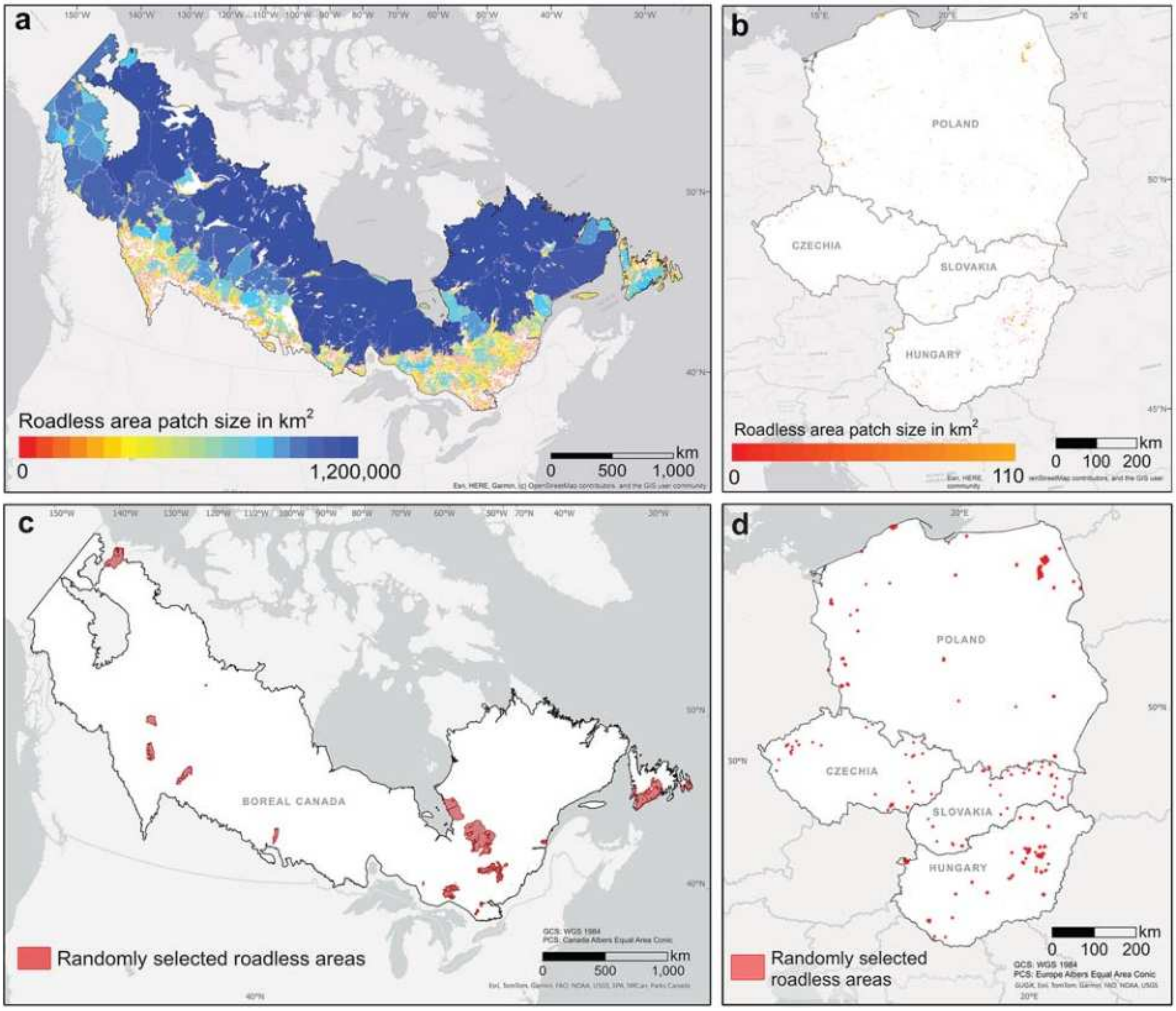

Figure 3. Distribution of roadless areas and their sizes (km^2). Roadless areas were identified based on a 1 km buffer on each side of every road, for (**a**) the boreal region of Canada, and (**b**) a selected region of temperate Central Europe represented by Poland, Slovakia, Czechia, and Hungary. The spatial distribution of the 30 randomly selected roadless areas (**c**) in the boreal region of Canada, and (**d**) in each of the four selected countries of temperate Central Europe. For more detailed views, in the Supplementary Material Fig. S4 and Fig. S5 provide enlarged versions of (**c,d**), indicating the randomly selected roadless areas with the corresponding numbers. This figure was created using ArcGIS Pro 3.2 (https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview).

1,200 were identified in boreal Canada (Table 3). Across the four European countries, over 85% of roadless areas were smaller than 1 km^2 (Fig. 3b, Table S6).

Visual interpretation of very high-resolution satellite images within the 30 randomly selected roadless areas in the boreal region of Canada (Fig. 3c) revealed a high number of unmapped roads. A total of 34,787 km of additional roads were found to be absent from the OSM dataset in these areas in boreal Canada and required manual mapping. After the visual interpretation and manual road mapping process, the roadless surface within these 30 areas decreased from 127,200 km^2 to 93,498 km^2 and their number increased from 30 to 1,408 new roadless areas (Table 3). This represented a loss of 26.5% of the OSM-based roadless surface. One of the 30 roadless areas disappeared completely (Table 3, Table S7, Fig. S3), and only two (below 150 km^2) were actually roadless and did not change after visual interpretation. The largest loss of roadless surface within a single roadless area was 7597 km^2, representing 23% of the total initial surface of that patch and resulting in 253 new roadless patches (Fig. S3, ID 21 in Table S7). Most of the manually mapped roads were forest roads with surrounding logging scars. The mean size of the 30 roadless areas decreased from 4223 km^2 (± s.d. 6531.5 km^2) to 58 km^2 (± s.d. 644.2 km^2). Fifty-nine percent of the newly mapped roadless areas (N = 833) were smaller than 1 km^2. Two-thirds of the 30 randomly selected roadless areas were in forests, 20% in wetlands, and the remaining 13% in shrubland and herbaceous landscapes (Table S7). After the visual interpretation and road mapping in

Identified roadless areas	Boreal Canada	Temperate Central Europe
Study region surface (km^2)	5,432,563	532,983
No. roadless areas identified	16,786	3,524
Roadless surface (%)	84.5	0.4
Roadless surface (km^2)	4,560,608.3	2,160.6
Mean size of roadless areas (km^2)	271.7	0.6
Median size of roadless areas (km^2)	0.72	0.1
Maximum size of roadless areas (km^2)	1,173,889	106.8
No. roadless areas (0, 1] km^2	9,112	3,062
No. roadless areas (1, 10] km^2	4,762	442
No. roadless areas (10, 50] km^2	1,673	19
No. roadless areas (50, 100] km^2	418	3
No. roadless areas (100, 1,173,889] km^2	821	1
Selected roadless areas for visual interpretation and road mapping		
No. roadless areas (before)	30	120
No. roadless areas (after)	1408	100
Mean size of roadless areas (before) (km^2)	4223	4.9
Mean size of roadless areas (after) (km^2)	58	4.2
Total roadless surface (before) (km^2)	127,199.5	586.6
Total roadless surface (after) (km^2)	93,497.6	422.8
Roadless surface lost (%)	33,701.9 (26.5)	164.1 (27.97)
No. original roadless areas lost	1	20
Length of roads manually mapped (km)	34,787	257

Table 3. Extent and amount of roadless areas for the two study regions boreal Canada and temperate Central Europe using the OSM road dataset (2020). Roadless areas were calculated by creating a 1 km geodesic buffer around each road and extracting the remaining area. The table provides information on the number of roadless areas in different size classes, along with the mean, median, and maximum size, as well as the total roadless surface as the sum of all roadless areas patches and the corresponding percentage of the region surface**.** The second part of the table includes similar metrics for the 30 randomly selected areas before and after visual interpretation and manual road mapping in both regions.

temperate Central Europe, an additional 257 km of roads were mapped within the 120 selected roadless areas (30 per country, Fig. 3d), which represented a total loss of OSM roadless surface of 164 km^2 (Table 3). Notably, this led to the complete disappearance of 20 OSM roadless areas while generating 11 new, smaller roadless areas (Table 3). Most newly mapped roads were located in Poland, while the fewest number was manually mapped in Czechia (Tables S8–S11). In Hungary and Czechia most roadless areas were within agricultural fields, whereas in Poland and Slovakia, the selected areas covered more diverse land cover types (Tables S8–S11). Interestingly, the effects of visual interpretation and manual road mapping in Central Europe and Canada, while occurring on vastly different scales and under different road densities, exhibits a remarkable similarity in terms of the proportion of area lost. In Central Europe, the added unmapped roads represented a loss of 28% of the original roadless surface, very similar to the 27% obtained for Canada (Table 3).

Discussion

Our study revealed considerable shortcomings in the mapping of roadless areas with OSM road data, particularly in remote and relatively intact ecosystems. We proposed two combined methods to provide a comprehensive perspective on the status of roadless areas and road mapping completeness in two contrasting study regions using OSM and high-resolution satellite images. On the one hand, the visual interpretation of random circular plots across the study regions provided a broad overview and contributed to better understanding of the general patterns of roadlessness while offering an objective assessment of road mapping quality in relation to road density and Human Footprint Index. On the other hand, the detailed analysis of the randomly selected roadless areas allowed for a more focused and in-depth examination, revealing a similar reduction of OSM roadless surface (27% and 28%) when unmapped roads were manually included. Up to date, OSM is the most complete, freely available road dataset at a global scale[3,33]. The deficiencies in OSM road mapping were more pronounced in regions with low anthropogenic impact, and therefore, with the greatest potential to contain roadless areas of considerable size that represent functional ecosystems, and where their proper identification and avoidance of further fragmentation would be of high conservation concern[3].

Our results showed that the challenges of road mapping completeness, including factors such as user interest and the speed of road construction, are particularly pronounced in remote regions with low human influence, like boreal Canada. The quality of OSM road data largely varies due to differences in mapping accuracy and completeness across regions and user contributions[39]. Smaller OSM communities in certain areas result in fewer updates and additions to the road database, particularly in remote or relatively intact regions[35,40]. Infrequent updates and the use of diverse mapping tools by contributors add to inconsistencies in data representation, impacting the overall accuracy and completeness[41]. While OSM remains the most complete open-source global road dataset in terms of road length, its data coverage still tends to concentrate around larger cities, and mapping accuracy decreases with increasing distance from urban areas[40,42], as found in our study. The absence of roads and inaccurate road mapping in the Canadian OSM road dataset have already been acknowledged by other studies[34,35,43,44]. While Jacobs and Mitchell[43] and Zhang and Malczewski[34] focused their quality assessment on a very small scale, specifically on the accuracy of road segments within cities, Zhang and Malczewski[44] compared OSM road data to a proprietary dataset. Poley et al.[35] examined the completeness of Canadian road datasets and found that regional (provincial) datasets provided the most complete representation of roadless areas in five provinces, covering nearly 4.1 million km^2 of Canada. Although freely available regional datasets provided better coverage, the study found that OSM road data was the best alternative when regional datasets were not available (Table S1). The analysis highlighted the difficulty of accurately mapping roadless areas, especially in less developed regions, and emphasized the limitations of global and national road network that underestimated the actual extent of roads in Canada[35].

Most studies assessing the accuracy and completeness of OSM data are concentrated in Europe, reflecting the substantial user base in that region[34]. In temperate Central Europe, despite a more established mapping community and higher road density and anthropogenic impacts, unmapped roads were still present, albeit in smaller numbers compared to boreal Canada, showing that even in areas almost devoid of roadless areas the pressure on the remaining unfragmented areas persists. Of the randomly selected roadless areas for road mapping, 93% of boreal Canada and 35% of Central Europe had unmapped roads, highlighting the differences in completeness of mapping between the two regions. While 70% of the circular plots in Canada were actually free of roads, 85% of the total area was identified as roadless following the method by Ibisch et al.[3] with OSM road data. This discrepancy suggests a possible overestimation of roadlessness in the OSM dataset for boreal Canada, indicating considerable incompleteness. In Central Europe, our findings revealed a much higher mapping completeness. The circular plots showed no road-free plots, and the total roadless area surface accounted for only 0.4%. The 15% disparity between the roadless surface and the proportion of road-free plots in boreal Canada, compared to a mere 0.4% difference in Central Europe, provides valuable insights into roadless areas identification and suggest that in some regions, the roadless identification used by us can be quite accurate. We propose that this method should be complemented by an assessment of OSM completeness using the circular plots. Within the OSM road data, predominantly logging roads were underrepresented in the boreal region of Canada, an issue that seems to be common in other forested regions of conservation interest, and which raises concerns due to their overall negative ecological effects[12,45,46].

Road mapping completeness was notably influenced by anthropogenic factors, with the highest values for road density and the Human Footprint Index observed in plots with both completely and partially mapped roads. The effects of travel time to major cities and the Human Modification Index varied by region, with a stronger influence in boreal Canada. Areas with high anthropogenic impact have generally more populated and developed regions which can lead to a higher road mapping effort and, thus, completeness[33]. This raises questions about the factors influencing road mapping in remote regions and highlights the need to capture local and logging roads, which are critical for ecosystem change and subsequent alteration of biodiversity and ecological processes[46,47]. Visual interpretation allowed us to identify contagious development processes in the boreal region of Canada, where the construction of one road triggers building of new roads and further development[5]. Object-based classification with LiDAR has also proven to be a very effective way to detect logging and gravel roads on a small scale which can be later extrapolated to larger scales[48,49].

The dynamic growth of the road network, with its continuous construction, modification, and expansion, poses an important challenge for road mapping. Limited financial, technical, and human resources affect the ability to comprehensively map and update road data on regional and global scales[50]. To illustrate it, mapping almost 35,000 km of roads in this study required over 200 working hours. Manual road mapping is highly demanding in terms of human resources, relies on subjective data, can be challenging to interpret, e.g. satellite images, and depends on the competence and accuracy of the cartographer. Deep learning-based techniques, such as convolutional neural networks, have shown promising results in updating road maps and detecting missing roads[29,51]. However, the availability of accurate road data and classifications as training data remains crucial for the effectiveness of these algorithms[27,52]. Although our study relied on manual road mapping, it provided a training dataset of approximately 35,000 km of roads, which can be used for automated road detection and can contribute to improving the accuracy and completeness of road data. Automated road detection methods, coupled with up-to-date satellite images and powerful data processing capabilities, have the potential to enhance road mapping also at a global scale, considering various road types and regions[53,54]. Particularly in remote regions, training an artificial intelligence network capable of detecting logging roads would be highly beneficial, not only to quickly discover illegal logging, but also to prevent the disappearance of valuable roadless ecosystems[28,29,55]. To our knowledge, training of artificial intelligence networks to identify unpaved roads has been done in deserts and in the Brazilian Amazon with promising results[28,29]. Looking ahead, the establishment of a platform and community similar to the Humanitarian OpenStreetMap Team (HOT), but tailored for ecological purposes specifically focused on road mapping in biodiversity-rich regions, would be a valuable initiative.

In both regions, we observed a much lower extent of roadless areas compared to the estimates based on 2013 data by Ibisch et al.[3], a finding corroborated by several studies[35,56,57]. This may indicate not only better map completeness in the last years, but also the real disappearance of roadless areas due to increasing road construction, even in the highly modified Central Europe. The challenge of accurately assessing the extent of roadless areas is greatest in remote regions, as OSM road mapping is mostly incomplete and these regions are usually subject to uncontrolled and intensive resource extraction which is channeled through roads, leading to irreversible, time-lagged and complex detrimental impacts on ecosystems[9]. Especially in pristine and natural areas severely threatened by the expansion of the road network, an automated system for real-time detection and mapping of roads is urgently needed (Laurance 2018). The impacts of road construction and usage in such areas have severe consequences for biodiversity and ecosystem integrity[11], can create negative cascading effect, leading to subsequent degradation[58,59].

This continuous road development highlights the importance of having accurately mapped roads to know where the remaining roadless areas are and to proactively protect them as well as consider them in transport planning avoiding their dissection[3,5,60]. Pristine, unfragmented roadless areas serve as vital strongholds for biodiversity, acting as refuges for numerous species[20] and are proxies for functional ecosystems, especially forests[23]. It is imperative that these areas are properly identified and road construction banned within them, as a way of protecting them de facto[3,5,17,58]. Such initiatives are possible, even in Europe[20]. Our study highlights the significant challenges and limitations associated with mapping roadless areas, particularly in remote and undisturbed ecosystems, using OSM road data. Here, we introduced a combined approach designed to provide a nuanced view of roadless areas and the extent of road mapping across diverse landscapes. We found notable differences in mapping precision and completeness, with the greatest deficiencies observed in regions with low human impact, such as boreal Canada.

Conclusion

Our findings emphasize the importance of enhancing roadless area mapping, while acknowledging existing methodological constraints. The combination of up-to-date visual interpretation of random plots and selected roadless areas can provide a reliable assessment of the accuracy of the roadless areas identified. Additionally, enhancing road mapping with deep learning techniques and integrating national or proprietary road data into freely available datasets will substantially improve mapping quality. These advances are crucial to understand the benefits of unfragmented lands and to quantify their contributions to mitigating climate change and preserving functioning ecosystems and biodiversity.

Materials and methods

Study areas

The study areas were located in two regions with a priori contrasting road density: the boreal region of Canada and a region in temperate Central Europe, comprising four countries: Poland, Slovakia, Czechia, and Hungary (Fig. 4). The temperate region in Central Europe is regarded as a landscape heavily modified by humans, whereas the Canadian boreal region, and particularly the boreal forests, holds few signs of human modification[61,62].

Canada is the second largest country in the world, with a relatively low population density of 4.2 people per km^2 and an area of 9.99 million km^2, of which 5.4 million km^2 are within the boreal region[63]. Approximately 50% of the boreal region is covered with forests, which were primarily shaped by natural disturbances such as winds, fires, and insect outbreaks[64]. However, these forests are facing increasing risk from industrial activities, deforestation, and climate change, which is resulting in an increasing number of wildfires and rising temperatures[65]. In contrast, the study region in temperate Central Europe has a much higher population density of more than 100 people per km^2[66]. It has a surface area of ~ 533,000 km^2, which corresponds to approximately 10% of the study region in boreal Canada. About 35% of the Central European study region is covered with forests, while up to 80% of the land consists of infrastructure, settlements, and production systems, including agriculture and forestry. As a result, the pressure on the remaining biodiversity and ecosystems is relatively high due to intensive agriculture, transport infrastructure, urban sprawl, deforestation, and climate change-related impacts such as

Figure 4. Study regions: boreal region of Canada and temperate Central Europe, including Poland, Slovakia, Czechia, and Hungary. This figure was created using ArcGIS Pro 3.2 (https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview).

droughts, water scarcity, and floods[67]. Hence, both regions differed in their level of road fragmentation and, therefore, of human footprint[68].

The Terrestrial Ecoregions dataset was used to delineate the study areas. These data layers were modified by The Nature Conservancy for use in biodiversity planning as part of the process known as "Ecoregional Assessments"[69]. We selected and exported the attribute field 'Boreal forests/Taiga' for Canada and for temperate Central Europe, we used the entire country surface which are part of the 'Temperate Broadleaf and Mixed Forests' ecoregion. For the boreal region of Canada, land cover data were extracted from the 2015 'Land Cover of Canada' dataset[70]. For temperate Europe, land cover data were extracted from the Copernicus Land Monitoring Service[71].

Evaluation of OSM road data completeness

OSM is an inclusive citizen science platform that enables volunteers to collaboratively create, use, and continuously update geographic information[72] and is regarded as the most complete road dataset in terms of road length on a global scale[3,73]. To comprehensively assess the scope of existing road data, we conducted a comparative analysis involving multiple datasets (Table S1) alongside OSM road data from the year 2020. This initial comparison was done with the Global Roads Inventory Project and a regional Canadian and European road dataset (Table S1). It was confirmed that the total length of mapped roads in the OSM road dataset was the highest in both regions compared to the other available datasets. Road density serves as an indicator of human activity and development and allows for cross-regional comparisons and analysis of human impact on the environment. Higher road density indicates greater fragmentation of the landscape and ecosystems. To assess road-related environmental impacts, such as the degree of road fragmentation, we created a road density raster from the 2020 OSM road dataset. The raster was computed for both study regions by dividing the total road length within a 5 km^2 grid by its area. This approach highlighted variations in road density between the temperate Central European and the Canadian boreal regions. We hypothesized that regions with higher anthropogenic impact would exhibit better mapping compared to regions with lower human influence. To investigate this hypothesis, we analyzed the relationship of road mapping completeness with human-related variables such as road density, travel time to major cities, Human Footprint Index, and Human Modification Index[32,36–38]. The Human Footprint Index dataset used in this study, which was updated by Venter et al.[37] contains data for the year 2009, whereas the Human Modification Index, developed by Kennedy et al.[38] consists of data from 2016. Oaklead and Kennedy[74] conducted a comparative analysis between the Human Footprint Index and their Human Modification Index, providing valuable insights into the similarities and differences between these two indices.

To assess the completeness of the 2020 OSM road dataset, we randomly selected 1000 cells per country from a 500×500 m square grid that fully covered both study regions. Within each random cell, we generated circular buffers with a radius of 1 km around the cell's centroid, generating circular plots of 3.14 km^2. The circular plots encompassed 0.06% of the boreal region in Canada ($N = 1000$ plots), and in the temperate region of Central Europe, they encompassed 0.6% ($N = 1000$ plots). To address differences among the four European countries, we further randomly selected 1000 plots per country, including the previously 1000 selected, encompassing 2.4% of the study area ($N = 4000$ plots).

We reviewed the completeness of the OSM road data through visual interpretation of Esri's high-resolution base map within the circular plots. Visual interpretation of a satellite image consists of analyzing an image recorded by a satellite sensor and interpreting the features and patterns visible on the image. This process involves examining the image at different scales and using visual landmarks to identify and interpret different features on the ground. In this case, roads were identified and mapped as features on the ground. We used the ArcGIS Pro 2.8 World Imagery base map at a scale of 1:30,000 for the visual interpretation. Satellite images from various sources from the period 2010–2020 with a resolution of 0.3–0.5 m were available for the respective sections of the examined base map. Any section that was not available in the time frame of 2019–2020 was later verified in Google Earth Pro and on Sentinel-2 satellite images from the Sentinel-2 hub to ensure that roads or linear infrastructures were still visible in the year 2020. After visual interpretation, each circular plot was classified according to the following categories of road map completeness: plots with all roads completely mapped by OSM, plots with roads partially mapped by OSM, plots where all roads were unmapped by OSM, plots with no roads, and plots containing other linear infrastructures. Linear infrastructures that could not be verified as roads could be powerlines, seismic lines for oil and gas exploration, firebreaks (to prevent wildfires) or other anthropogenic structures. We computed road density, travel time to major cities, Human Footprint Index, and Human Modification Index for each of the 1000 random circular plots in both study regions and for all countries[32,36–38]. The values from each of the aforementioned datasets were extracted for each of the 1000 circular plots for both study regions. Histograms were constructed for each variable to analyze the frequency distribution of data values, providing a visual representation of the spread and concentration of observations within each variable (Fig. S1). To assess the relationships between variables, correlation matrices were computed using Spearman correlation coefficient (Table S3). The mean, and standard deviation of these explanatory variables were then calculated for every plot category.

To assess whether road completeness was associated with the explanatory variables indicating human influence, we initially evaluated if spatial autocorrelation affected the results by fitting a Generalized Least Squares (GLS) model[75]. We represented the categorical completeness index as a continuous variable for use as a response in the model, using values ranging from 1—not mapped to 3—completely mapped. For the analyses, we took a subset of locations where roads were present, excluding the categories 'no roads' and 'other linear infrastructure'. Explanatory variables included road density, travel time to major cities, the Human Footprint Index and the Human Modification Index, and their interaction with country. We accounted for spatial autocorrelation in the data by including a spatial correlation structure in the GLS model. Location coordinates were transformed to equidistant projection (UTM/WGS 84), so that the distances were comparable. Numerical explanatory variables were standardized prior to model fitting to facilitate model convergence. We compared GLS models with alternative spatial correlation structures as well as an ordinary linear regression model (i.e. not accounting for spatial autocorrelation) by ranking the models using the second-order Akaike Information Criterion (AIC_c) and further by examining model coefficients. Next, we applied an ordinal logistic regression model, which allows the use of categorical response where groups have a natural order[76], to the categorical road completeness index. This model included the same explanatory variables as previously and their interactions with region (Boreal Canada/Central Europe) and country. Alternative models with an additive or multiplicative effect of a country were ranked by AIC_c[77]. We used R packages 'ordinal'[78] for ordinal regression and `nlme`[79] for GLS models.

Assessing roadlessness

We followed the roadless areas definition by Ibisch et al.[3], by creating a geodesic buffer of 1 km on each side of every road (Fig. S6). This threshold was chosen as a conservative measure based on an extensive literature review[3], which found that the most intense, direct, and negative impacts of roads are within 1 km of the road. This buffer is called the road-effect zone and encompasses the surrounding area with significant ecological impacts caused by roads[7]. The roadless areas are therefore defined as areas more than 1 km away from any kind of road, and thus, relatively free of road impacts. We mapped roadless areas for the year 2020 based on OSM road data for both the boreal region of Canada and the temperate region of Central Europe, after delimiting both areas as explained in the previous section. We extracted the number of the resulting roadless areas and their surface for both regions.

Out of the identified roadless areas, we selected 30 per country for verification to confirm the real absence of roads by visual interpretation as described above. The selection process was carried out randomly but aiming for a comprehensive representation of all roadless area sizes. To achieve this, we employed a weighting factor based on the proportion of an individual roadless area's size relative to the total roadless area size for both study regions. This approach prevented a bias towards solely selecting smaller roadless areas, which are more abundant[3], and allowed for a representation of all available sizes. We visually checked 30 roadless areas for boreal Canada and 30 for each of the temperate Central European countries. In cases where roads were found, we manually mapped the missing road segments. This method of road mapping involved visually identifying, tracing and delineating road features on maps. To ensure accurate and efficient visual interpretation and mapping using the Esri basemap satellite imagery as described above, a scale of 1:30,000 was chosen, balancing the need for detailed mapping, and working effort. Once all identifiable missing roads were mapped within each roadless area, their length was calculated, and they were buffered with a 1 km geodetic buffer and incorporated into the existing roadless area layer. Then, we identified the new roadless areas and calculated their number and size, as well as the total loss of roadless surface after including the unmapped roads (Tables S7–S11, Fig. S5).

All analyses were conducted with ArcGIS Pro 2.9[80], and R 4.1.3[81].

Data availability

Manually mapped roads are available from the corresponding author on request. Data of circular plots and roadless areas for both study regions are available from the Zenodo repository.

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Author contributions

M.T.H., N.S., K.B. and K.O. conceived and designed the study. M.T.H wrote a first draft of the paper with substantial contributions from N.S. and K.O. Spatial analysis and maps were conducted by M.T.H., while K.B. designed and formulated the statistical approaches with contributions from K.O. and N.S. All authors actively participated in shaping the final version of the manuscript.

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Competing interests

The authors declare no competing interests.

Additional information

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Scientific Reports

SUPPLEMENTARY MATERIAL

Mapping roadless areas in regions with contrasting human footprint

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Supplementary Materials and Methods

Roadless areas definition and data processing

This study is based on the OpenStreetMap (OSM) road dataset, a dynamic and openly accessible database that is updated daily and allows copying, reproduction, redistribution, and modification with proper attribution to OSM and its contributors [1]. Roads were obtained from OSM for 2020 and included 36 different road categories [2, 3]. All categories have been incorporated into our analysis, given their characteristic of facilitating human and (motorized) access, a factor recognized as a potential threat and risk to various species and ecosystems, as revised by Ibisch et al. [4]. Each road was buffered with a geodesic buffer of 1 km on each side of every road (Figure S5). After creating the buffer around each road, the area of boreal Canada and temperate Central Europe were extracted to obtain a layer containing only roadless areas located 1 km away from the nearest road. 'Natural Earth data' provided the layer for lakes, which were extracted from the country layer to exclude large water bodies from this analysis [5]. Wetlands, smaller lakes, and streams were included in the roadless area assessment.

Anthropogenic influences and road mapping within the circular plots randomly selected

We hypothesized that regions with higher anthropogenic influences would exhibit better mapping compared to regions with lower anthropogenic impact. To investigate this, we analyzed various datasets related to road mapping completeness, including road density, Travel time to major cities, Human Footprint Index, and Human Modification Index [2, 6, 7, 8]. The distribution of all four explanatory variables and the completeness of roads was examined and a correlation matrix was created (Fig. S1, Table S3). We then examined only circular plots containing roads (mapped and unmapped) for statistical testing (Tables S4, S5).

Forest cover and roadless areas

The Canadian boreal region comprises approximately 2.2 million km² of forest, with 1.4 million km² designated as forested roadless areas [9]. Conversely, Central Europe's forest cover spans 187,447 km², as per Copernicus data, with a mere 821 km² representing forested roadless areas [10]. In both regions the forest cover within the 30 selected roadless areas was calculated before and after road mapping. In both regions a loss of 40% of roadless forest cover was detected.

Table S1. Road network length of the two study regions according to different road datasets. The references to the dataset links are provided in the reference list.

Road dataset	Boreal Canada	Central Europe	Dataset links
CIESIN gROADS, v1. 2013 [11]	52,177 km	62,782 km	https://sedac.ciesin.columbia.edu/data/set/groads-global-roads-open-access-v1
GRIP 2018 [12]	63,365 km	403,457 km	https://www.globio.info/download-grip-dataset
OSM 2020 [2]	528,127 km	1,761,143 km	https://download.geofabrik.de/
Canadian National Road Network (NRN) 2020 [13]	319,245 km		https://canadiangis.com/national-road-network-nrn-canadian-open-data.php
EuroGeographics [14]		115,738 km	https://public.opendatasoft.com/explore/dataset/europe-road/export/?refine.icc=BE

Table S2. Summary of the visual interpretation of the randomly selected circular plots (n = 1000 per country, 3.14 km^2 each) for each of the Central European countries. It shows the number of circular plots within the following categories: plots with all roads completely mapped, plots with roads partially mapped, plots with all roads unmapped, and plots without roads.

Country	Plot categories	No. of plots
Poland	Completely mapped roads	639
	Partially mapped roads	355
	Unmapped roads	1
	No roads	5
Slovakia	Completely mapped roads	523
	Partially mapped roads	473
	Unmapped roads	4
Czechia	Completely mapped roads	713
	Partially mapped roads	286
	No roads	1
Hungary	Completely mapped roads	657
	Partially mapped roads	335
	Unmapped roads	3
	No roads	5

Table S3. Correlation matrix between variables of human influences in the 1000 randomly selected plots in Central Europe and boreal Canada. Correlation coefficients (Spearman) range from -1 to 1.

Central Europe	Road completeness	Road density	Travel time to major cities	Human Footprint Index	Human Modification Index
Road completeness					
Road density	-0.16				
Travel time to major cities	0.10	-0.63			
Human Footprint Index	-0.16	0.65	-0.35		
Human Modification Index	-0.23	0.39	-0.36	0.18	
Boreal Canada	**Road completeness**	**Road density**	**Travel time to major cities**	**Human Footprint Index**	**Human Modification Index**
Road completeness					
Road density	-0.64				
Travel time to major cities	0.60	-0.82			
Human Footprint Index	-0.46	0.43	-0.3		
Human Modification Index	-0.66	0.59	-0.55	0.54	

Table S4. Model selection table and coefficient values of the Generalized Least Squares models. Models ranked by AIC_c. The response variable is road completeness (fully mapped = 3, partially mapped = 2, not mapped = 1) and the explanatory variables are road density (km/km^2), travel time to major cities (min), Human Footprint Index (ranging from 0 to 50, low values indicated low human footprint) and Human Modification Index (ranging from 0 to 1, low values indicated low degree of landscape modification by humans).

(Intercept)	Human Modification Index	Human Footprint Index	Road density	Travel time to major cities	Correlation	df	Delta AIC_c	Akaike weight
3.47	0.24	-0.08	1.49	-0.04	Exponential	28	0	0.47
3.47	0.24	-0.08	1.48	-0.04	Rational	28	0.15	0.44
3.90	0.22	-0.08	1.67	-0.04	Spherical	28	3.3	0.09
3.46	0.24	-0.09	1.55	-0.05	Gaussian	28	20.4	0
3.47	0.24	-0.09	1.57	-0.05	None	26	21.76	0
3.47	0.24	-0.09	1.57	-0.05	Linear	28	25.94	0

Table S5. Model selection table of the Ordinal Regression models accounting for country differences in Europe in relation to road completeness**.** Models ranked by AIC_c.

	df	Delta AIC_c	Akaike weight
country effect additive	14	0	0.58
country effect none	26	0.61	0.42
country effect multiplicative	11	48.83	0

Table S6. Extent and amount of roadless areas (calculated by creating a 1km geodesic buffer around each road and extracting the remaining area) across boreal Canada and each of the selected Central European countries. The table provides information on the number of roadless areas in different size classes, along with the total roadless surface.

Country	Size of the roadless area in km²	No. roadless areas	Total roadless surface in km²
Boreal Canada	(0, 1]	9,112	2,051
	(1, 2]	1,784	2,604
	(2, 4]	1,494	4,325
	(4, 10]	1,484	9,576
	(10, 20]	832	11,802
	(20, 50]	841	26,803
	(50, 100]	418	29,822
	(100, 250]	357	55,743
	(250, 500]	173	61,332
	(500, 1,000]	130	93,597
	(1,000, 10,000]	131	386,848
	(10,000, 100,000]	23	733,672
	(100,000,1,000,000]	6	1,968,548
	(1,000,000, 1,173,890]	1	1,173,889
	Total	16,786	4,560,608.4
Poland	(0, 1]	1,781	288
	(1, 2]	128	177
	(2, 4]	73	202
	(4, 10]	34	200
	(10, 20]	7	81
	(20, 50]	2	57
	(50, 100]	2	143
	(100, 250]	1	107
	Total	2,028	1,256
Slovakia	(0, 1]	375	65
	(1, 2]	35	47
	(2, 4]	14	38
	(4, 10]	3	20
	(10, 20]	1	12
	Total	428	182
Czechia	(0, 1]	124	16
	(1, 2]	9	12
	(2, 4]	7	21
	(4, 10]	2	12
	(10, 20]	1	13
	Total	143	7
Hungary	(0, 1]	782	141

(1, 2]	74	108
(2, 4]	41	109
(4, 10]	22	127
(10, 20]	3	37
(20, 50]	2	74
(50, 100]	1	53
Total	925	649

Table S7. Outcome of the visual interpretation of 30 randomly selected roadless areas in boreal Canada, showing the assigned ID, the surface of the largest roadless area after road mapping, the sum of all roadless areas created after road mapping, the reduction in size of roadless areas after road mapping, the median size of the newly identified areas after road mapping and the main landcover type.

ID	No. of newly identified roadless areas after road mapping	Roadless area surface before road mapping (km^2)	Roadless area surface after road mapping (largest patch, km^2)	Total surface of mapped roadless areas (sum of all new roadless areas after road mapping, km^2)	Reduction of roadless area surface after road mapping (km^2)	Reduction of roadless area surface after mapping (%)	Median size of roadless areas after road mapping (km^2)	Landcover type
1	2	25.2	23.5	23.5	1.7	0.1	11.7	Forest
2	19	526.7	129.8	301.4	225.3	42.8	15.9	Forest
3	26	456	119.6	262.6	193.4	42.4	0.3	Herbs
4	1	1.0	1.018	1.0	0	0	-	Forest
5	33	504.1	13.3	37.6	466.5	92.5	0.2	Forest
6	1	760.9	720.1	720.09	40.8	5.4	-	Forest
7	8	1,989.6	1,791.9	1,819.2	170.4	8.6	2.5	Forest
8	103	6,738.6	1,804.5	4,546.2	2,192.4	32.5	0.4	Wetland
9	0	13.5	0	0	13.5	100	-	Forest
10	11	541.0	221.2	276	265.0	49	0.5	Forest
11	112	4,437	397.8	2,023.2	2,413.8	54.4	1.0	Forest
12	7	215.8	92.5	117.1	98.7	45.7	1.7	Forest
13	150	5,329.4	513.9	2,367.8	2,961.6	55.6	0.7	Forest
14	38	7,190.5	6,320.8	6,466.7	723.8	10.1	0.2	Wetland
15	31	943.2	136.4	479.9	463.3	49.1	1.1	Wetland
16	12	328.1	92.6	113.3	214.8	65.5	0.7	Herbs
17	29	13,776.5	11,346.2	12,947.7	828.8	6.0	0.8	Forest

18	16	1,234.1	839.4	887.7	346.4	28.1	0.4	Forest
19	115	4,115.6	432.3	1,721.4	2,394.2	58.3	0.8	Forest
20	1	55.0	55.0	55.0	0	0	-	Forest
21	253	32,504.6	16,302.6	24,907.2	7,597.4	23.4	0.3	Forest
22	7	9,364.7	9,181.7	9,246.5	118.2	1.3	0.3	Forest
23	7	2,614.9	2,448.2	2,506.2	108.7	4.2	2.2	Forest
24	2	6,463.9	6,408.1	6,408.0	55.9	0.9	3.2	Shrubland
25	211	5,655.9	130.6	475.6	5,180.3	91.6	0.3	Wetland
26	21	1,236.5	5	17.4	1,219.1	98.6	0.1	Wetland
27	78	3,508.6	358.1	1,321.7	2,186.9	62.3	0.6	Shrubland
28	112	3,980.2	262.9	927.3	3,052.9	76.7	0.6	Forest
29	1	125.2	125.2	125.2	0	0	-	Forest
30	1	12,563.3	12,395.0	12,395.0	168.3	1.3	-	Forest
	1408	127,199.5		93,497.6	33,701.9	26.5		

Table S8. Outcome of the visual interpretation of 30 randomly selected roadless areas in Poland, showing the assigned ID, the surface of the largest roadless area after road mapping, the sum of all roadless areas created after road mapping, the reduction in size of roadless areas after road mapping, and the main landcover type.

ID	No. of newly identified roadless areas after road mapping	Roadless area surface before road mapping in (km^2)	Roadless area surface after road mapping (largest patch, km^2)	Total surface of mapped roadless areas (sum of all new roadless areas after road mapping, km^2)	Reduction of roadless area surface after road mapping (km^2)	Reduction of roadless area surface after mapping (%)	Landcover type
1	0	0.03	0	0.03	0	0	Agriculture
2	0	0.1	0	0.1	0	0	Lake
3	0	0.1	0	0.1	0	0	Agriculture
4	0	0.2	0	0.2	0	0	Agriculture
5	0	0.3	0	0.3	0	0	Forest
6	0	0.6	0	0.6	0	0	Forest
7	0	0.6	0	0.6	0	0	Grassland
8	-1	0.6	0	0	0.6	100	Forest
9	0	0.8	0	0.8	0	0	Forest
10	-1	1.2	0	0	1.2	100	Forest
11	0	1.7	0	1.7	0	0	Forest
12	0	1.8	0	1.8	0	0	Forest
13	0	2.6	0	2.0	0.6	24.1	Forest
14	0	2.7	0	2.7	0	0	Lake
15	0	2.8	0	2.1	0.7	24.3	Wetland
16	2	3.9	0.3	0.5	3.4	87.2	Grassland
17	0	3.9	0	3.9	0	0	Forest
18	0	3.9	0	3.9	0	0	Lake
19	-1	4.3	0	0	4.3	100	Forest

20	-1	4.5	0	0	4.5	100	Forest
21	-1	4.7	0	0	4.7	100	Forest
22	0	5.7	0	5.7	0	0	Lake
23	2	8.2	0.3	0.5	7.7	93.7	Forest
24	0	9.0	0	1.5	7.5	83.1	Forest
25	0	10.8	0	10.8	0	0	Lake
26	-1	13.1	0	0	13.1	100	Forest
27	0	21.8	0	21.8	0	0	Forest
28	0	61.6	0	61.6	0	0	Lake
29	2	81.5	76.6	76.7	4.8	5.9	Agriculture
30	2	106.8	61.2	96.2	10.6	9.9	Grassland
Total	0	359.7		295.9	63.7		

Table S9. Outcome of the visual interpretation of 30 randomly selected roadless areas in Slovakia, showing the assigned ID, the surface of the largest roadless area after road mapping, the sum of all roadless areas created after road mapping, the reduction in size of roadless areas after road mapping, and the main landcover type.

ID	No. of newly identified roadless areas after road mapping	Roadless area surface before road mapping in (km^2)	Roadless area surface after road mapping (largest patch, km^2)	Total surface of mapped roadless areas (sum of all new roadless areas after road mapping, km^2)	Reduction of roadless area surface after road mapping (km^2)	Reduction of roadless area surface after mapping (%)	Landcover type
1	0	1.8	0	0	1.8	99.2	Agriculture
2	-1	0.4	0	0	0.4	100	Agriculture
3	0	0	0	0	0	0	Agriculture
4	0	0	0	0	0	0	Forest
5	0	0	0	0	0	0	Agriculture
6	-1	0.7	0	0	0.7	100	Agriculture
7	0	0.1	0	0.1	0	0	Agriculture
8	0	0	0	0	0	0	Agriculture
9	0	0.1	0	0.1	0	0	Forest
10	0	1.0	0	0.2	0.7	75.8	Agriculture
11	0	0.7	0	0.7	0	0	Agriculture
12	0	0	0	0	0	0	Forest
13	0	0	0	0	0	0	Agriculture
14	0	0	0	0	0	0	Forest
15	0	0	0	0	0	0	Forest
16	0	0	0	0	0	0	Agriculture
17	2	2.0	0.2	0.3	1.7	86.2	Forest
18	0	0	0	0	0	0	Forest
19	0	1.6	0	0.1	1.5	95.8	Forest

20	0	0	0	0	0	0	Mountain
21	0	0.4	0	0.4	0	0	Agriculture
22	0	0.4	0	0.4	0	0	Agriculture
23	-1	0.5	0	0	0.5	100	Forest
24	0	0	0	0	0	0	Forest
25	0	0.1	0	0.1	0	0	Forest
26	0	0	0	0	0	0	Forest
27	0	0.1	0	0.1	0	0	Forest
28	0	0.1	0	0	0	0	Forest
29	0	2.1	0	2.1	0	0	Lake
30	0	0.5	0	0.5	0	0	Forest
Total		12.6		5.2	7.3		

Table S10. Outcome of the visual interpretation of 30 randomly selected roadless areas in Czechia, showing the assigned ID, the sum of all roadless areas created after road mapping, the reduction in size of roadless areas after road mapping, and the main landcover type.

ID	No. of newly identified roadless areas after road mapping	Roadless area surface before road mapping in (km^2)	Total surface of mapped roadless areas (sum of all new roadless areas after road mapping, km^2)	Reduction of roadless area surface after road mapping (km^2)	Reduction of roadless area surface after mapping (%)	Landcover type
1	0	0.4	0.4	0	0	Agriculture
2	0	0	0	0	0	Agriculture
3	0	0.1	0.1	0	0	Agriculture
4	0	0.9	0.9	0	0	Agriculture
5	-1	0.3	0	0.3	100	Agriculture
6	0	1.7	1.7	0	0	Agriculture
7	-1	0.3	0	0.3	100	Agriculture
8	0	0.2	0.2	0	0	Agriculture
9	-1	0.2	0	0.2	100	Agriculture
10	0	0	0	0	0	Agriculture
11	0	0	0	0	0	Agriculture
12	0	0.1	0.1	0	0	Forest
13	0	0	0	0	0	Grassland
14	0	0.1	0.1	0	0	Forest
15	0	0	0	0	0	Agriculture
16	0	0.1	0.1	0	0	Grassland
17	0	0.1	0.1	0	0	Grassland
18	0	0.1	0.1	0	0	Grassland
19	0	0	0	0	0	Forest
20	-1	0	0	0	100	Forest
21	0	0	0	0	0	Forest
22	0	0	0	0	0	Agriculture

23	0	0	0	0	0	Forest
24	0	0	0	0	0	Forest
25	0	0.3	0.3	0	0	Agriculture
26	0	0.3	0.3	0	0	Forest
27	0	0	0	0	0	Grassland
28	0	0	0	0	0	Agriculture
29	0	0	0	0	0	Lake
30	0	0	0	0	0	Forest
Total		5.3	4.5	0.8		

Table S11. Outcome of the visual interpretation of 30 randomly selected roadless areas in Hungary, showing the assigned ID, the surface of the largest roadless area after road mapping, the sum of all roadless areas created after road mapping, the reduction in size of roadless areas after road mapping, and the main landcover type.

ID	No. of newly identified roadless areas after road mapping	Roadless area surface before road mapping in (km^2)	Roadless area surface after road mapping (largest patch, km^2)	Total surface of mapped roadless areas (sum of all new roadless areas after road mapping)	Reduction of roadless area surface after road mapping (km^2)	Reduction of roadless area surface after mapping (%)	Landcover type
1	-1	0.4	0	0	0.4	100	Forest
2	-1	0.5	0	0	0.5	100	Agriculture
3	0	0.4	0	0.4	0	0	Agriculture
4	2	12.7	0.3	0.7	12.1	94.9	Agriculture
5	0	8.2	0	2.3	5.9	72.2	Agriculture
6	-1	2.8	0	0	2.8	100	Agriculture
7	0	1.1	0	1.1	0	0	Agriculture
8	-1	0.1	0	0	0.1	100	Agriculture
9	0	2.7	0	1.1	1.6	58.6	grassland
10	0	2.2	0	2.2	0	0	Agriculture
11	2	6.1	0.2	0.2	5.9	97.3	Agriculture
12	0	1.9	0	1.9	0	0	Agriculture
13	0	2.5	0	0	2.5	100	Agriculture
14	0	1.8	0	1.8	0	0	Agriculture
15	0	0.4	0	0.4	0	0	Agriculture
16	0	0.1	0	0.1	0	0	Agriculture
17	0	4.5	0	4.5	0	0	Agriculture
18	-1	0.6	0	0	0.6	100	Agriculture
19	3	53.0	11.8	14.0	39.0	73.6	Agriculture
20	2	7.6	0.5	0.5	7.0	92.8	unknown

21	0	0.5	0	0.5	0	0	unknown
22	-1	1.5	0	0	1.5	100	Agriculture
23	0	29.2	0	29.2	0	0	Lake
24	0	4.3	0	2.8	1.4	33.5	unknown
25	0	4.8	0	2.4	2.4	50.1	Agriculture
26	0	5.7	0	5.7	0	0	Agriculture
27	0	44.9	0	44.9	0	0	unknown
28	0	2.4	0	0.2	2.2	90.2	Forest
29	2	3.1	0	0	3.1	99.4	Agriculture
30	-1	3.5	0	0	3.5	100	Forest
Total		209.0		116.8	92.2		

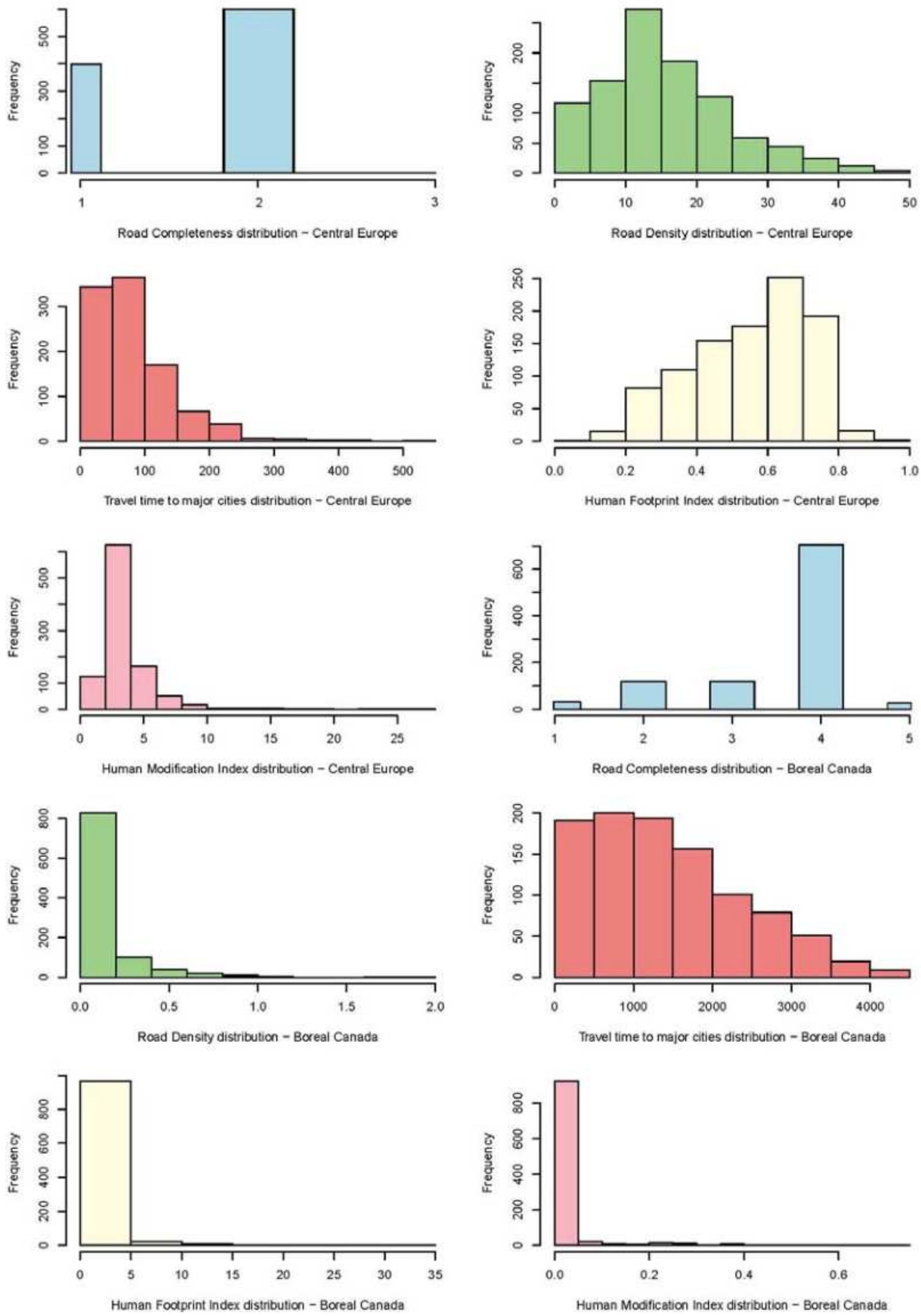

Figure S1: Histograms showing the frequency distribution of road completeness, road density, travel time to major cities, Human Footprint Index and Human Modification Index for boreal Canada and temperate Central Europe in the randomly selected 1000 circular plots of 3.14 km^2 each (as indicated in Table 1, road completeness refers to plots with all roads completely mapped = 1, plots with roads partially mapped = 2, plots with all roads unmapped = 3, and plots without road = 4, and plots containing other linear infrastructures = 5), road density (km/km^2), travel time to major cities (min), Human Footprint Index (ranging from 0 to 50, low values indicated low human footprint) and Human Modification Index (ranging from 0 to 1, low values indicated low degree of landscape modification by humans).

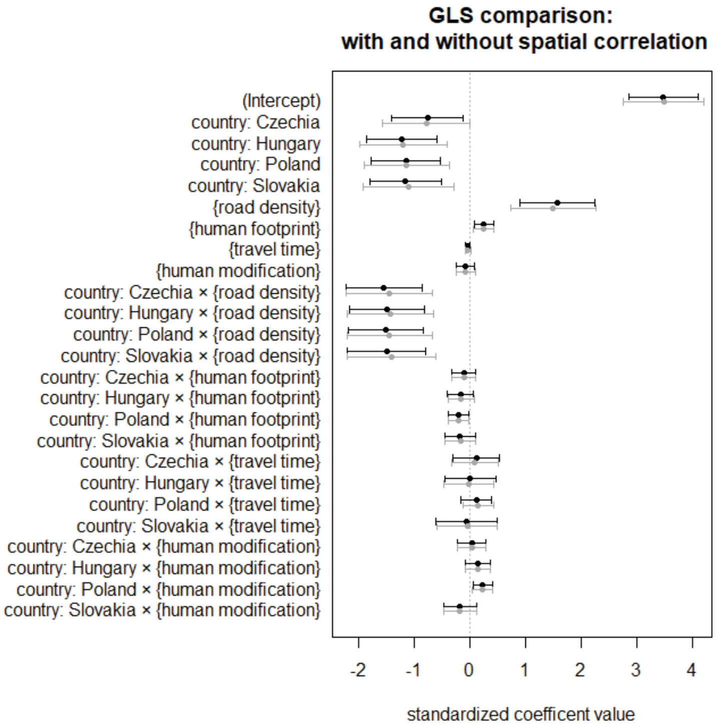

Figure S2. Comparison of (standardized) model coefficients of Generalized Least Squares models without (black) and with (grey) accounting for spatial autocorrelation (exponential correlation structure) in the response variable (road completeness). Road completeness encompassed the following three categories, fully mapped = 3, partially mapped = 2, not mapped = 1. The explanatory variables were road density, Human Footprint Index, travel time to major cities and Human Modification Index. The reference country category was boreal Canada.

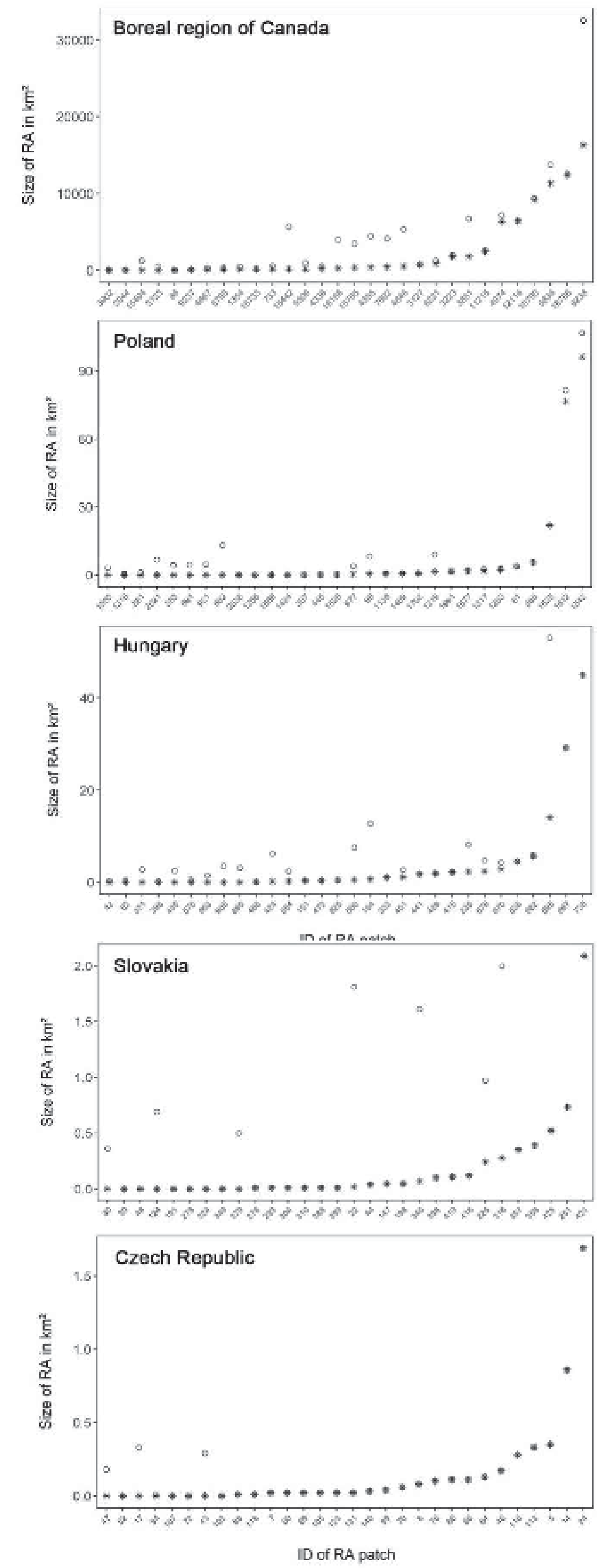

Figure S3. Comparison of 30 randomly selected roadless areas in boreal Canada and the four temperate Central European countries before and after visual interpretation and road mapping. The size order was based on the largest roadless area obtained post-mapping. Open circles denote roadless areas before manual mapping, while stars represent the generated largest roadless patches after mapping. Note the different scales.

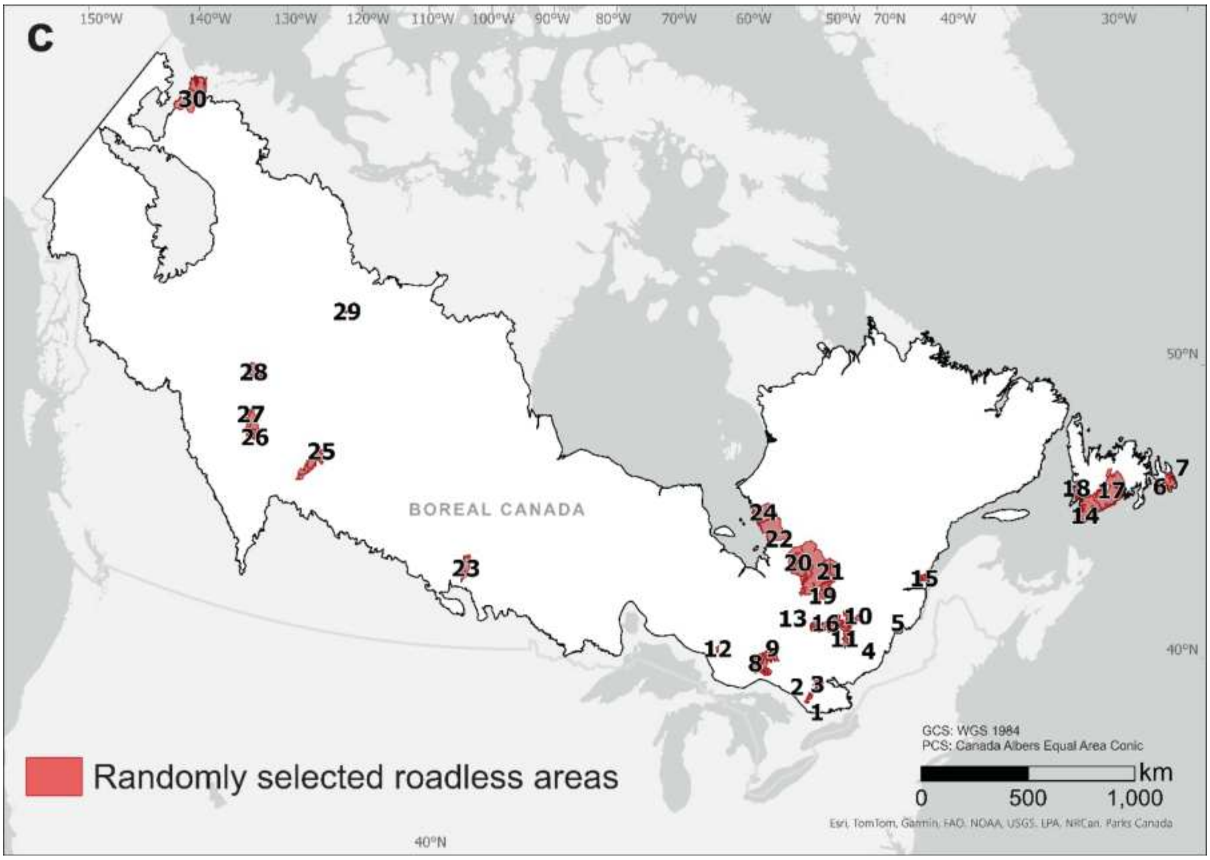

Figure S4. The spatial distribution of the 30 randomly selected roadless areas in the boreal region of Canada with their corresponding ID number. See Table S7 for details on each roadless area. This figure was created using ArcGIS Pro 3.2 (https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview).

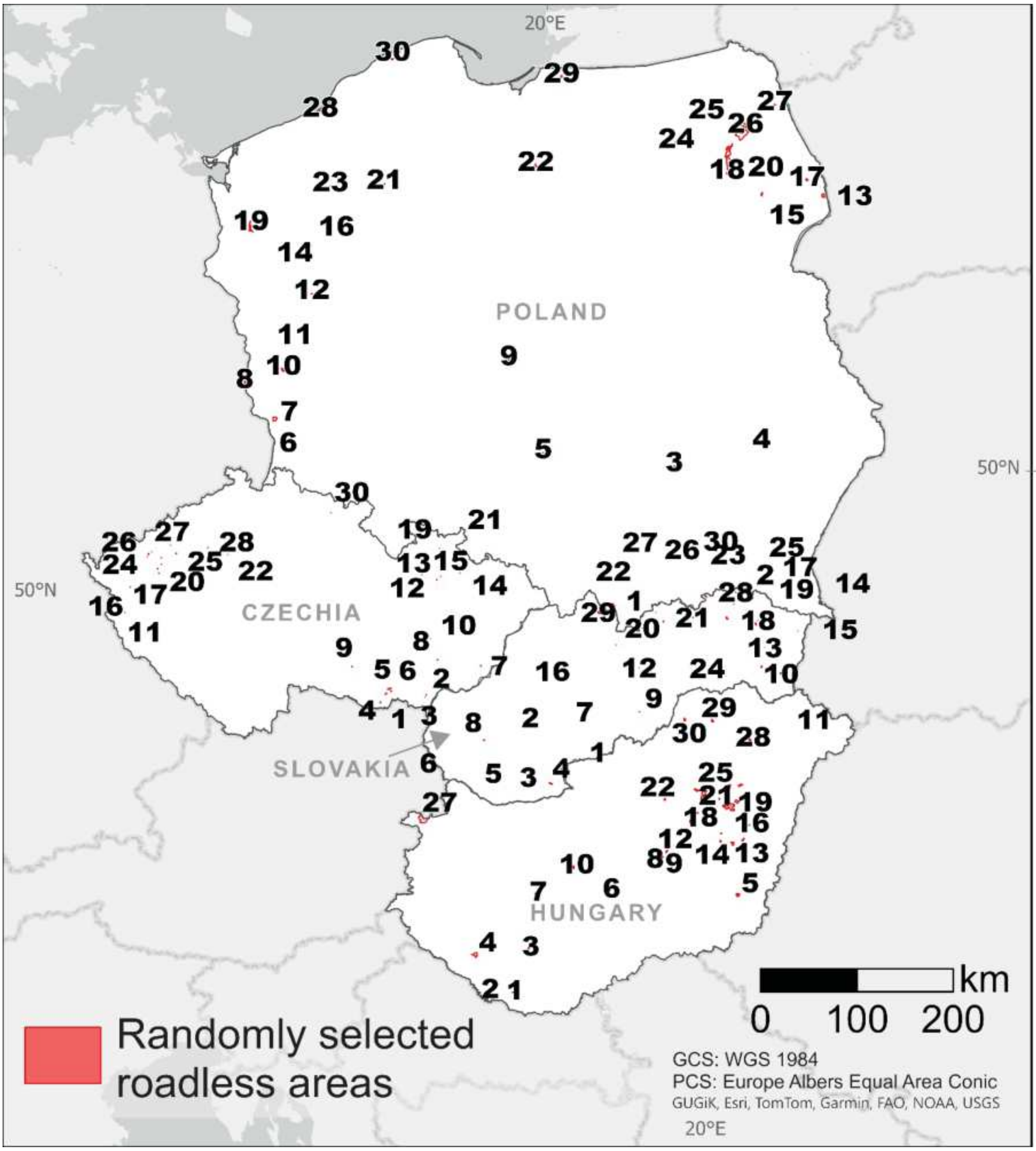

Figure S5. The spatial distribution of the 30 randomly selected roadless areas in each of the four selected countries of temperate Central Europe represented by Poland, Slovakia, Czechia, and Hungary are indicated with ID numbers. See Tables S8-S11 for details on each roadless area. This figure was created using ArcGIS Pro 3.2 (https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview).

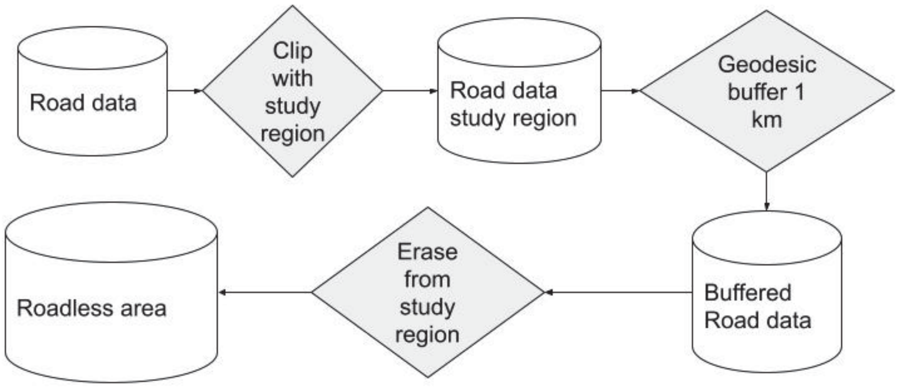

Figure S6. Workflow of roadless area calculation.

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CONCLUSIONS

Image: Google Earth Pro
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus Image
IBCAO Image U.S Geological Survey

"What you do makes a difference, and you have to decide what kind of difference you want to make."

Jane Goodall

GENERAL CONCLUSIONS

- Roadless areas are defined as areas at least one kilometer away from any road type and characterized by minimal or no negative impacts from roads. As each type of road has an impact on the surrounding environment, all road types were considered. One kilometer was the road-effect zone (Forman & Alexander, 1998) in which all negative impacts from roads were documented.

- The size of roadless areas varied greatly around the globe. Europe, Japan, and North America are heavily fragmented with only a few remaining large tracks of roadless areas. Although 80% of the terrestrial land was still roadless, these areas were fragmented into 600,000 patches, more than half of which were smaller than 1 km^2. The largest roadless areas with high ecological values were found in the boreal and tropical forests. These regions provide essential ecosystem services and avoiding their fragmentation should therefore be a conservation priority. At the same time small roadless areas can potentially have ecological relevance in heavily fragmented landscapes.

- Protected roadless areas made up only 9% of the global land surface, with 3.8% under strict protection. The comparative analysis of the 20 Aichi Targets of the Convention on Biological Diversity and the Sustainable Development Goals in relation to roadless areas revealed a concerning trend regarding roadless area conservation. The protection of roadless areas aligns primarily with five Sustainable Development Goals, but it is in conflict with four goals. Aichi Targets show ambivalence, with six conflicting and 11 synergistic objectives. These findings emphasize the importance of carefully considering ecological impacts of roads and long-term sustainability when weighing the trade-off between economic development and roadless area conservation. Policy measures should aim to minimize the ecological footprint linked to infrastructure development while meeting societal needs. At the same time, protecting ecologically valuable roadless areas from further fragmentation will enhance landscape connectivity, contribute to climate change mitigation, and maintain ecological integrity.

- Two-thirds of the roadless areas showed medium to high EVIRA values. Despite their significance as functional ecosystems, the majority of roadless areas with high EVIRA values lack any form of protection. Australia is the only continent that strictly protects high-value roadless areas. Notably, large roadless forests, particularly in tropical and boreal regions, merit particular attention due to their provision of crucial ecosystem services. Ensuring the protection of these forests from road-induced fragmentation is paramount, given the well-documented negative impacts and subsequent contagious development following road construction.

- Road mapping is incomplete, particularly in areas with low Human Footprint Index and road density. This translates in roadless areas being overrepresented in spatial assessments; as much as 28% of roadless surface is lost when road mapping becomes complete. Further research and road data collection efforts are necessary to better understand the ecological value of roadless areas and the benefits they provide for conservation, as well as to identify where relevant roadless areas still exist. Road mapping improvements are especially needed in regions with low human impacts and high biodiversity. Advances in data management, deep learning techniques, including the use of crowdsourced data, will enhance our knowledge on roadless areas and their contribution to biodiversity and ecosystem conservation.

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