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Global projections of future wilderness decline under multiple IPCC Special Report on Emissions Scenarios

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ABSTRACT

Globally, wilderness areas are being lost at a rate that outpaces their protection, which has adverse effects on the global environment. Rapid action is needed to understand the trends and consequences of global wilderness change. We present projections of global wilderness decline in 2100 under the influence of land-use change within the framework of the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (IPCC SRES). The projections revealed that the decline of wilderness was deeply affected by different global socioeconomic development pathways. The total wilderness loss (4.74%) in scenario A2 (with slow technological innovation and traditional demand for biofuels) was much higher than in the other scenarios. Around 76.51% of the loss of global wilderness globally occurs occurred in South America, which will occur in Tropical and Subtropical Moist Broadleaf Forests. The smallest loss (0.08%) occurred in scenario B1 (with a high level of environmental consciousness). We found that wilderness losses in 2100 will be concentrated in some important biomes, which have relatively high-density carbon storage. These findings stress the importance of targeted wilderness protection to ensure the long-term integrity of ecosystems and the balance of the carbon cycle.

1. Introduction

Terrestrial wilderness areas are large natural environments that are unmodified or only slightly modified and that retain the effective ecological functions of natural processes (Sharpe, 1994; Mackey et al., 1998; Watson et al., 2009; Watson et al., 2018). Wilderness has an important role in supporting the persistence of biodiversity (Hannah et al., 1995; Myers et al., 2000; Ripple et al., 2014; Marco et al., 2019). About 18% of global vascular plant species and 10% terrestrial vertebrate species are endemic to wilderness areas (Mittermeier et al., 2003). In addition to biodiversity conservation, they provide other high-value ecosystem services (Watson et al., 2009; Martin et al., 2016), which include carbon sequestration (Pan et al., 2011; Mackey et al., 2013; Houghton et al., 2015), climate regulation (Houghton et al., 2015; Marco et al., 2019) and regulation of hydrological cycles (Salati et al., 1979; Sampaio et al., 2007; Spracklen et al., 2012). However, over the past few centuries, the value of wilderness has gone largely unrecognized, which has resulted in a significant loss of wilderness globally. In 1700, nearly half of the terrestrial biosphere was wild; now, wilderness is diminishing as humans encroach upon more of the Earth's surface (Ellis et al., 2010).

Advances in remote sensing and the wide spread application of geographic information systems (GIS) have allowed unprecedented advances in developing global human footprint maps (Sanderson et al., 2002; Venter et al., 2016a,b; Li et al.,2018; Andrés et al., 2020). The human footprint, a quantitative evaluation of human impact on nature, has been applied to multi-scale wilderness mapping (Sanderson et al., 2002; Woolmer et al., 2008; Watson et al., 2016). Mapping current and historical global wilderness areas provides an important basis against which the consequences of past development on the Earth's wilderness

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can be assessed.

The wilderness mapping method grew out of a recent tradition studies (McCloskey & Spalding, 1989; Yaroshenko et al., 2001), and was used in the original "last of the wild" analysis in the early 1990s (Sanderson et al., 2002). The latest global wilderness map was created by Watson et al. in 2016, following the above-mentioned method (Venter et al., 2016a, b). Their findings demonstrated that a total of 3.3 million km^2 (approximately 9.6%) of the world's terrestrial wilderness was lost from 1993 to 2009 (Watson et al., 2016). Calls for protected areas to be increased have led to a 2.5% increase in the global terrestrial protected area between 2010 and 2020. However, one third of terrestrial protected areas are still under tremendous human pressure (Jones et al., 2018), and global wilderness areas are declining at a rate that outpaces their protection. It is important to identify the next steps for global wilderness conservation.

With calls for rapid action to prevent catastrophic declines in wilderness areas, we need to better understand the spatiotemporal trends in global wilderness change and their related consequences, thus enabling us to react appropriately. Predicting future wilderness changes can provide more intuitive information than current and historical wilderness mapping to evaluate the impacts and benefits of land-use and economic development under various future scenarios. Simulations based on a single scenario cannot incorporate the uncertainties inherent in global change research. Simulation and analysis based on multiple scenarios is a valuable and widely applied technique to explore the complicated uncertainties related to future changes and their impacts.

Various studies have indicated that small changes in land-use may affect the function of ecosystem services, built-up urban areas and crop lands apply greater human pressure compared with other land-use (Vitousek et al., 1997; Sanderson et al., 2002; Schneider et al., 2009). Li et al. (2017) proposed a global land-use and land-cover change product for 2010 to 2100 based on four major scenarios taken from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) (Sleeter et al., 2012; Walz et al., 2014) (Figure 1). This product was used in our research to analyze what global wilderness might look like under the influence of land-use change. The IPCC SRES depict several distinct global socioeconomic development pathways from which global greenhouse gas emissions can be deduced. The SRES approach involves the development of a set of four scenario "families". Each family of SRES scenarios specifies a different demographic, social, economic, technological, and policy future. The scenarios we used are distributed along two axes (Figure 1).

In this study, we collected data on human pressures globally, including: human population density, urban lands, crop lands and pasture lands, nighttime lights, navigable waterways, and roads and railways. Then we used the human footprint methodology (Sanderson et al., 2002; Watson et al., 2016; Li et al., 2018) to measure human pressures on the terrestrial environment in 2010 and 2100. The effects of future land-use change on global wilderness areas, focusing on urban land change, were assessed for 2100 using this methodology, under the four IPCC SRES (A1B, A2, B1, and B2). This paper aimed to:

1) project the change in future wilderness at 1 km resolution under SRES to provide a preview of potential wilderness decline;
2) explore the influence of different global socioeconomic development pathways on global wilderness change;
3) discuss the key points for future wilderness protection by studying the spatial relationship between wilderness areas and terrestrial biomes and global carbon storage.

2. Methods

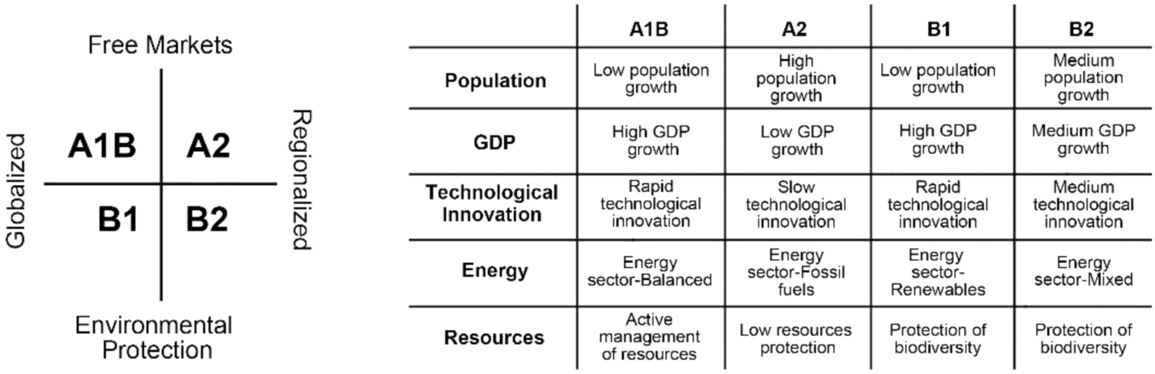
2.1. Methods for mapping wilderness

2.1.1. Overview

We mapped the world human footprint map following the methodology framework that developed by Sanderson et al. (2002) and further adopted by Venter et al. (2016a, b), Allan et al.(2017), and Li et al (2018). To calculate the total human influence on nature, we collected 9 datasets in six categories for human impact, respectively for the current and future human footprint mapping. The data categories includes: (1) human population density; (2) urban lands; (3), crop lands and pasture lands; (4) nighttime lights; (5) roads and railways; (6) navigable waterways (Figure 2, Table S1). For the mapping of current human footprint, we used the latest current data of the above six types; for the mapping of future human footprint, we used the 2100 forecast data of urban land and crop land, and for other types of data as there is no forecast for 2100, we used the latest current data of other types. Based on published studies (Sanderson, 2002; Venter et al.,2016a, b), the human impact for dataset categories were assigned into standardized scores within a 0–10 scale (the higher the value, the greater the human pressure) according to estimates of their relative levels of impact on nature. Then we overlaid the human pressures in ESRI ArcGIS to map the global terrestrial human footprint (not including Antarctica), and calculated cumulative scores ranging from 0 to 50 for each pixel on the globe at approximately 1 km resolution (Venter et al., 2016). 0 represents the lowest human influence, and 50 represents the highest influence. Area statistic were conducted in Mollweide equal area projection. From the human footprint map, the wildernesses were identified as the areas with pressure score lower than 1.

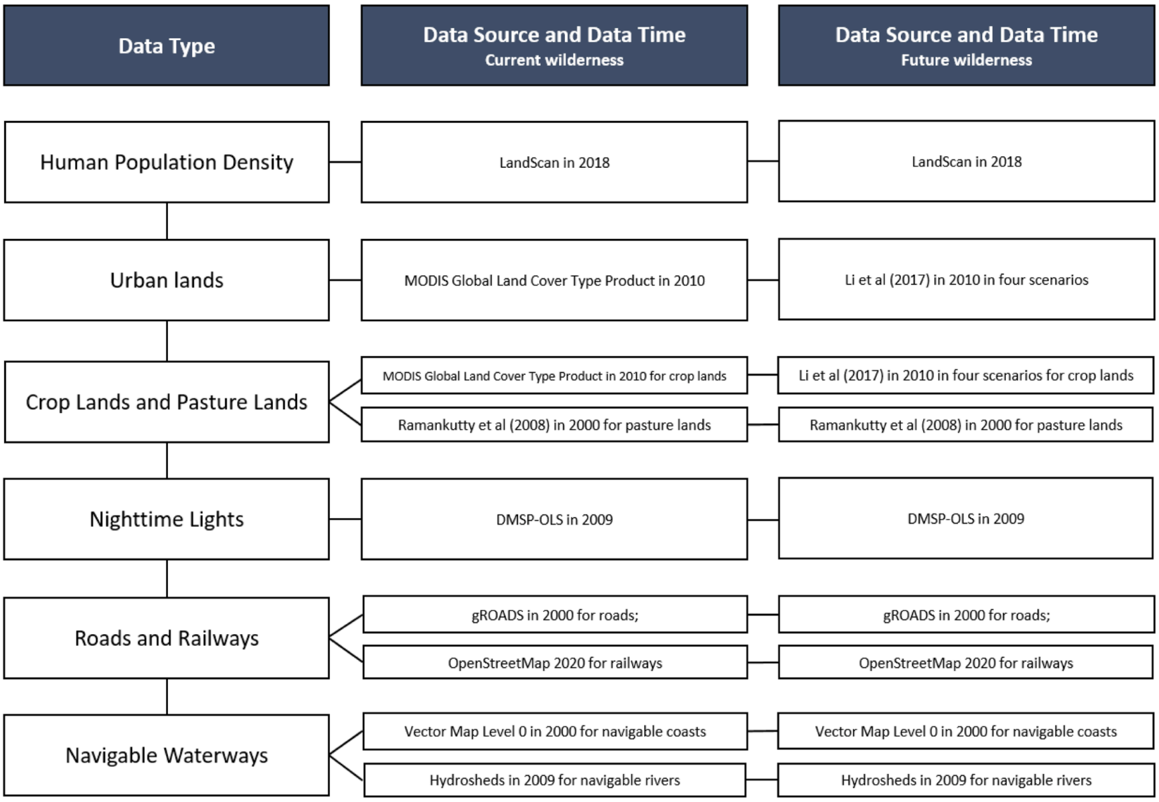
2.1.2. Human population density

Human population density impacts on biodiversity and nature (Luck et al.,2010), and is considered to be a driving factor in species extinction



	A1B	A2	B1	B2
Population	Low population growth	High population growth	Low population growth	Medium population growth
GDP	High GDP growth	Low GDP growth	High GDP growth	Medium GDP growth
Technological Innovation	Rapid technological innovation	Slow technological innovation	Rapid technological innovation	Medium technological innovation
Energy	Energy sector-Balanced	Energy sector-Fossil fuels	Energy sector-Renewables	Energy sector-Mixed
Resources	Active management of resources	Low resources protection	Protection of biodiversity	Protection of biodiversity

Figure 1. Four scenarios based on Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES). On the vertical axis, A represents an economic emphasis and B represents an environmental emphasis; on the horizontal axis, 1 represents a global orientation and 2 represents a regional orientation) (Sleeter et al., 2012).



Data Type	Data Source and Data Time Current wilderness	Data Source and Data Time Future wilderness
Human Population Density	LandScan in 2018	LandScan in 2018
Urban lands	MODIS Global Land Cover Type Product in 2010	Li et al (2017) in 2010 in four scenarios
Crop Lands and Pasture Lands	MODIS Global Land Cover Type Product in 2010 for crop lands Ramankutty et al (2008) in 2000 for pasture lands	Li et al (2017) in 2010 in four scenarios for crop lands Ramankutty et al (2008) in 2000 for pasture lands
Nighttime Lights	DMSP-OLS in 2009	DMSP-OLS in 2009
Roads and Railways	gROADS in 2000 for roads; OpenStreetMap 2020 for railways	gROADS in 2000 for roads; OpenStreetMap 2020 for railways
Navigable Waterways	Vector Map Level 0 in 2000 for navigable coasts Hydrosheds in 2009 for navigable rivers	Vector Map Level 0 in 2000 for navigable coasts Hydrosheds in 2009 for navigable rivers

Figure 2. The attributes of input datasets.

(Harcourt et al.,2001). In densely populated areas, species may be threatened by direct persecution and habitat loss (Cardillo et al.,2004).

In this study, human population density was mapped using the LandScan 2018 global population distribution models developed by the Oak Ridge National Laboratory (https://landscan.ornl.gov/). LandScan, representing an ambient population, is the finest resolution (1 km resolution) global population distribution data available (average over 24 hours) (Venter et al.,2016b). For all areas with a population density greater than 1,000 people per km^2, we assigned a pressure score of 10 (Table S1). For areas with population density less than 1,000 people per km^2, we used the following formula to scale the pressure score logarithmically (Venter et al.,2016b):

$$\text{Pressure score} = 3.333 \times \log(\text{population density } + 1) \tag{1}$$

2.1.3. *Urban lands*

Urban landis used to construct towns and cities and to provide for urban functions. They are human-produced areas which do not provide viable habitats and high levels of ecosystem services (Tratalos et al., 2007; Aronson et al., 2014). In addition, urban land expansion has a direct impact on natural habitat loss and biodiversity (Van et al.,2017). As the land use type most influenced by humans, urban lands were assigned the maximum pressure score of 10 (Table S1) (Sanderson et al., 2002;Li et al.,2018) .

To map current urban lands, we used the MODIS Global Land Cover Type Product (https://modis-land.gsfc.nasa.gov/landcover.html) in 2010, which is generated at 0.5 km spatial resolution (Friedl et al., 2010). To match the 1 km resolution, we used the Resample tool in Arcmap software to change the output cell size of the input data by choosing the Nearest parameter. To obtain projections of urban land-use in 2100, we used a new global land-use product at a 1 km resolution for 2100 developed by Li et al. (2017). MODIS Global Land Cover Type Product in 2010 is the input land cover data of this product so there is a consistency of the current and the forecast input data.

2.1.4. *Crop lands and pasture lands*

Crop lands and pasture lands are the greatest driver of land transformation (Achard et al., 2002), which leads to accelerated erosion and local extinctions of biota in adjacent areas (Ehrlich & Ehrlich, 1981; Hooke et al., 2012). Crop lands refer to areas where crops are planted, which form the basic resources for human survival. Pasture lands are the areas used for animal husbandry which is the largest user of land resources in the world. Of the global ice free land, about 10% was used for crop cultivation and another 25% was used for pasture (Tubiello et al., 2007).

Global demand for agricultural products is a main driver of crop lands and pasture lands expansion (Gibbs et al., 2010). Gibbs et al. (2010) found that between 1980 and 2000 up to 80% of new agricultural land in the tropics came at the cost of wilderness such as intact or disturbed forests. As such, agriculture lands, including crop lands and pasture lands, are partly or wholly responsible for many environmental problems such as tropical deforestation, biodiversity loss, fragmentation and loss of habitats, and carbon emissions (Foley et al., 2005; Gibbs et al., 2008).

We assigned crop lands a pressure score of 7 (Table S1) (Venter et al., 2016b). Although agriculture land expansion may lead to wilderness decline, we assigned them lower scores than urban lands because they had less impervious cover except when crops and grasses are burned to prepare land for cultivation. Compared to croplands, however conversion of wilderness into pasture lands have less soil organic carbon losses (Don et al., 2015), so we assign a pressure score of 4 according to previous study (Table S1) (Venter et al., 2016b).

We used the Collection 5 MODIS Global Land Cover Type Product in 2010 to map current crop lands, and selected the product which is the same as the urban land forecast input data (Li et al.,2017) as crop lands for 2100. The data we used to map pasture lands was a global data set that combined agricultural census data with satellite-derived land cover circa in 2000 (Ramankutty et al., 2008).

2.1.5. *Nighttime lights*

Electrical power enhances human’s ability to change the environment and can be identified as nighttime lights (Sanderson et al., 2003). The nighttime lights visible from satellites provide a proxy of population distribution and can be used to identify the location and spatial extent of human settlements which could result in loss of the wilderness areas (Sutton et al., 1997; Song et al., 2008).

The nighttime lights product, avg_lights_x_pct, is derived from the average visible band digital number (DN) of cloud-free light detection multiplied by the percent frequency of light detection. In this study, we used DMSP-OLS (https://www.ngdc.noaa.gov/eog/dmsp/downloadV4composites.html) in 2013 to map these pressures. Previous study indicated that areas with DN less than 20 are not included in urban lands layer, so it provides a means for mapping rural and suburban areas with sparser electric infrastructure (Venter et al., 2016b).

To scale the data, we divided the pixels with DN value less than 20 into 10 equal sample bins and assigned them the scores of 1 to 10, and assigned the pixels with DN value no less than 20 the score of 10 (Table S1) (Venter et al., 2016a, b).

2.1.6. *Navigable waterways*

Coasts, large lake shorelines and rivers provide access to natural ecosystems, and they are theoretically navigable. Human activities, such as fishing, exploiting resources, and discharging pollutants, damage natural ecosystems, so these areas are also under varying degrees of human pressure.

We used the Vector Map (VMAP) Level 0 (National Imagery and Mapping Agency, 1997) in 2000 to map shorelines. With reference to Venter et al. (2016a, b), we mapped the nighttime light signals with a DN greater than 6 within 4 km of the marine coasts and great lake shorelines as human settlements. To measure the area affected by navigation, the vessel’ speed was set as 40 km per hour, and shorelines were considered as navigable for 80 km in either direction from the human settlements during day time (Venter et al., 2016a,b).

We used HydroSHEDS in 2009 for navigable rivers (http://hydrosheds.cr.usgs.gov) to map global rivers. A river was considered navigable if the depth of the river was greater than 2 m and there was a nighttime light signal with a DN not less than 6 within 4 km from the river bank, or if it was adjacent to navigable coasts or great lake shorelines (Venter et al.,2016a,b). The navigable area was kept within a radius of 80 km or until stream depth is likely to prevent boat traffic (Venter et al.,2016a,b). To map rivers and their depth we used the following formulae (Bjerklie et al.,2003,2005; Venter et al.,2016a,b):

$$\text{Stream width} = 8.1 \times \left(\text{discharge}\left(\text{m}^3\text{s}^{-1}\right)\right)^{0.58} \tag{2}$$

$$\text{velocity} = 4.0 \times \left(\text{discharge}\left(\text{m}^3\text{s}^{-1}\right)\right)^{0.6} \Big/ \left(\text{width}(\text{m})\right) \tag{3}$$

$$\text{Cross} - \text{sectional area} = \text{discharge}/\text{velocity} \tag{4}$$

$$\text{depth} = 1.5 \times \text{area}/\text{width}(\text{assuming second order parabola as channel shape}) \tag{5}$$

We assigned the pressure from navigable water body boundaries a score of 4, and the score decreased exponentially with the increase of distance (scores were integers). At a distance of 15 km from the shoreline, the pressure score decayed to 0 (Table S1) (Venter et al., 2016a,b).

2.1.7. *Roads and railways*

Roads and railways are important linear infrastructure for human activities and socioeconomic development (Trombulak & Frissell., 2000). Also, roads and railways fragmented ecosystems and caused habitat destruction (Vitousek et al., 1997; Sala et al., 2000), which put pressure on the environment and natural habitat and result in loss of the wilderness areas.

To map global roads, we obtained road distribution data from the global roads open access dataset (gROADS) (https://sedac.ciesin.columbia.edu/data/set/groads-global-roads-open-access-v1/data-download) which is the most comprehensive publicly available database. The distance a person could walk in one day in a impenetrable ecosystem was set as 15 km (Wilkie et al., 2000; Sanderson et al., 2002). Within a range of 0.5 km on both sides of the roads, we assigned a pressure score of 8. The pressure was asigned a score of 4 at 0.5 km, and decreasing to 15 km both sides of the road (Table S1) (Venter et al., 2016a,b).

We used OpenStreetMap in 2020 (https://www.openstreetmap.org) to map railways. Because passengers cannot enter the surrounding environment at a location other than the station, the impact of railways on the environment is slightly different from that of roads. The pressure score within 0.5 km on either side of the railway was assigned as 8 (Table S1) (Venter et al., 2016a,b).

2.2. *Wilderness losses in terrestrial biomes*

Biomes stratify the globe into ecologically meaningful and contrasting classes (Agardy et al., 2005), which are classified according to the dominant vegetation and characterized by adaptations of organisms to specific environment (Campbell, 1996). Land-based biomes are called terrestrial biomes, which differ greatly in plant biomass (Olson et al., 1980). Terrestrial biomes are useful units for assessing terrestrial biodiversity and ecosystem services (Agardy et al., 2005).

Wilderness areas can resist extinction risks (Marco et al., 2019), that was found in every biome (Olson et al., 2001), but biomes vary enormously in the percentage of the total area under protection (Agardy et al., 2005). To protect the endangered wilderness and biodiversity of biomes, we estimated future wilderness loss in each terrestrial biome for conservation purpose. We overlaid the four simulated maps of terrestrial wilderness losses onto biomes. We used biomes of the World Wide Fund For Nature (WWF) terrestrial biome classification, based on WWF terrestrial ecoregions (geographic units with distinct environment and ecology at the global scale) (Olson et al., 2001). Then we used the erase and intersect features of ESRI ArcGIS to export excel tables and make classification statistics through PivotTable, thus the amounts of wilderness losses in each biome was obtained.

2.3. *Wilderness losses in biomass carbon density maps*

A great quantities of carbon is stored in terrestrial ecosystems in above and belowground biomass (Houghton et al., 2009), which is almost three times as high as in the atmosphere (Trumper et al., 2009). Carbon storage and sequestration occur in wilderness, thus wilderness loss not only releases carbon stored in the aboveground biomass but leads to the decomposition of roots and mobilization of soil carbon (Houghton et al., 2015; Watson et al.,2016). Therefore, wilderness declines in the future conflict with protecting carbon storage, which has negative impact on the achievement of global climate mitigation goals (Houghton et al., 2015). In order to analyze the biomass carbon density distribution within the wilderness loss area, we overlay the four simulated maps of terrestrial wilderness losses onto the biomass carbon density reclassification maps. In this study, we used harmonized global maps of above and belowground biomass carbon density developed by Spawn et al. (2020) and reclassified them into four levels with the grid reclassification tool of GIS. This dataset provides global maps of aboveground biomass carbon density (AGBC) and belowground biomass carbon density (BGBC) in 2010 with a spatial resolution of 300 m, which are available at https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1763.

3. Results

3.1. *Future global wilderness loss*

We found that 24.05% of terrestrial areas (35,846,425 km^2) in the world remained as wilderness, with the majority located in Asia, North America, Africa, and Oceania (Supplementary Material Figure S1). Asia had the largest wilderness areas, accounting for 34.53% of the total amount of global wilderness. The vast majority was distributed in North Asia and Northwest China. The total area of wilderness in North America was second to Asia, accounting for 29.46% of the global total. Africa, South America and Oceania accounted for 17.43%, 11.44% and 5.57% of the total, respectively. The wilderness area in Europe was the smallest, accounting for only 1.6% of the total amount of the world's wilderness, mainly distributed at the intersection of Norway, Finland, Sweden, and the northern part of Russia. Except for Europe, more than a fifth of the land in other continents was wilderness. The proportion of wilderness in North America was 43.56%.

We found substantial differences in projected future global wilderness across the four scenarios (Figure 3, Figure S2, Table S2).

The projected wilderness losses on each continent are shown in Figure 3, which showed that scenario A2 presented an obvious decreasing trend and yielded the greatest wilderness decline (1,699,654 km^2). Around 76.51% of the loss of wilderness globally occurred in South America, and the wilderness areas in South America were reduced to 31.68% of their current amount. The wilderness loss in Asia (241,827 km^2, 14.23%) and North America (140,387 km^2, 8.26%) accounted for 22.49% of the global total.

Scenarios A1B and B2 yielded trends similar to that in A2, but with much smaller estimated wilderness losses. The total loss of wilderness in scenario A1B was 195,669 km^2, and the three continents with large decrease were South America (74,011 km^2, 37.82%), Asia (60,651 km^2, 31.00%) and North America (57,583 km^2, 29.43%). In scenario B2, the total area of wilderness lost by 2100 was 155,520 km^2. The wilderness areas of Asia declined the most, accounting for 74.32% (115,582 km^2) of the total, followed by Africa (18,678 km^2, 12.01%) and South America (14,780 km^2, 9.50%).

The wilderness loss in scenario B1 was the smallest (29,082 km^2), with the most loss occurring in Asia (16,310 km^2, 56.08% loss). The wilderness loss in North America (5093 km^2, 17.51%), South America (4232 km^2, 14.55%) and Africa (2992 km^2, 10.29%) accounted for 42.35% of the global total.

According to the simulation results under the four scenarios, we found that global wilderness losses were concentrated in north Asia, northern South America and northern North America. We selected three

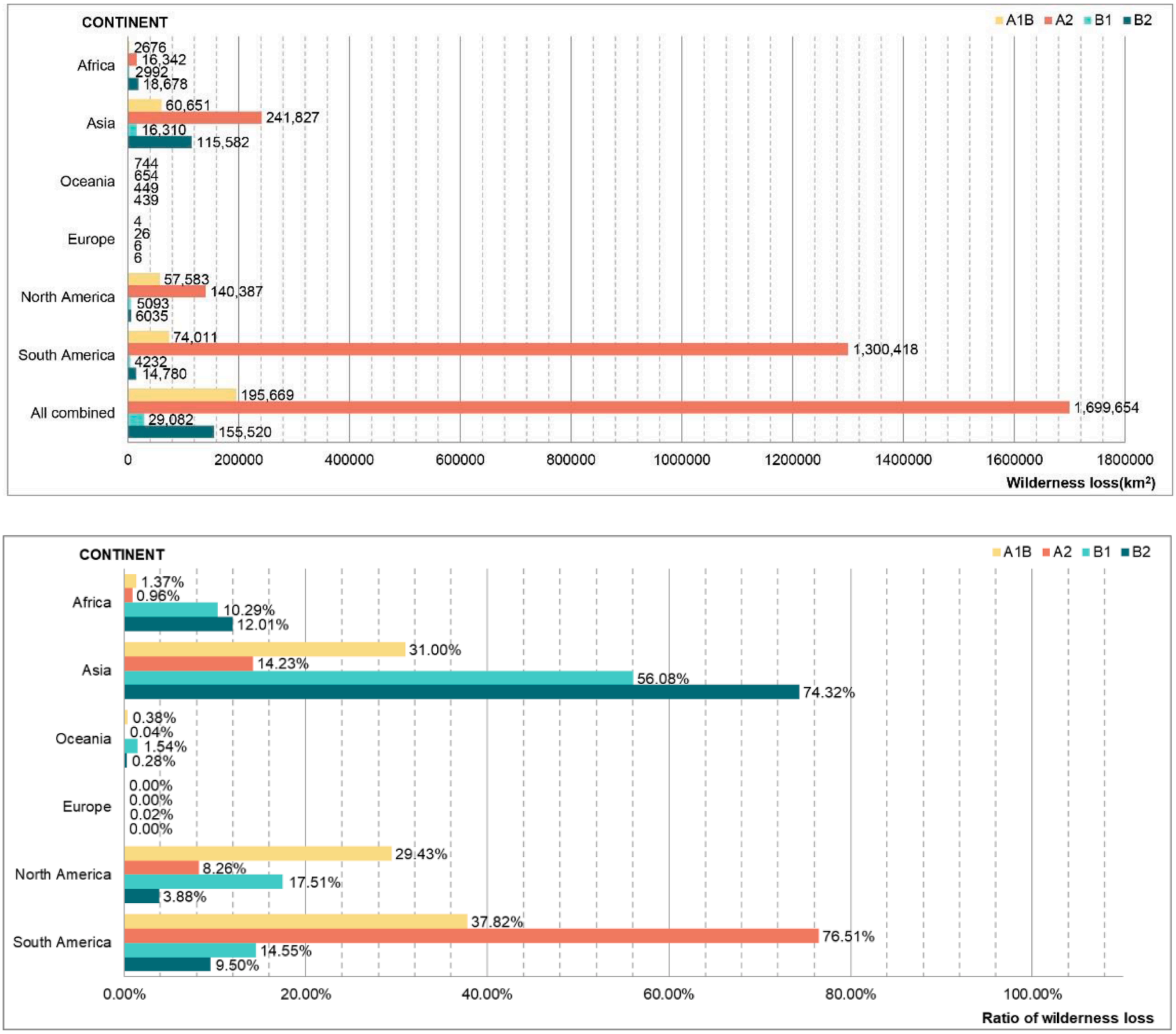


Figure 3. The area of simulated wilderness losses on each continent by 2100.

representative regions: the Alaskan Peninsula (A), the Amazon (B), and the southern part of Russia (C), to demonstrate the differences in wilderness losses under different scenarios (Figure 4). Figure 4 shows that the disappearing wilderness areas coalesce in scenario A2, especially in the southern part of Alaska and the Amazon.

3.2. *Future wilderness loss in terrestrial biomes*

The current wilderness map indicated that almost 86% of wilderness areas were concentrated in Boreal Forests/Taiga (10,155,874 km^2, 28.34%), Deserts and Xeric Shrublands (9,473,744 km^2, 26.44%), Tundra (6,538,326 km^2, 18.25%), and Tropical and Subtropical Moist Broadleaf Forests (4,638,797 km^2, 12.95%). The wilderness losses in biomes under the four IPCC SRES compared with the present period are given in Figures 5 & 6, and Table S3 &S4. We mapped the three biomes with the highest wilderness losses in each scenario (Figure 7) and found that (1) Boreal Forests/Taiga, and Tropical and Subtropical Moist Broadleaf Forests will suffer large losses under all scenarios; (2) Temperate Broadleaf and Mixed Forests will have larger losses in scenarios B1 and B2; (3) Tundra will suffer larger wilderness losses in scenario A1B, and Tropical and Subtropical Grasslands, Savannas and Shrublands will have larger wilderness losses in scenario A2.

By calculating the proportion of wilderness lost to total wilderness in each biome, we found that the ratio of the five biomes was less than 5% across all scenarios. In terms of the amount of wilderness lost in each biome, we found that the loss in three of the five biomes will be less than 1% of the global total. These biomes are Deserts and Xeric Shrublands, Mediterranean Forests, Woodlands and Scrub, and Montane Grasslands and Shrublands.

In scenario A1B, wilderness loss in Tropical and Subtropical Moist Broadleaf Forests and Boreal Forests/Taiga accounted for more than half of the global wilderness decline. Large contiguous areas of wilderness decline (>10,000 km^2) will occur in some ecoregions of North and South America, such as Canadian Aspen Forests and Parklands, Alberta-British Columbia Foothills Forests, Mato Grosso Seasonal Forests, and Tocantins/Pindare Moist Forests.

In scenario A2, 76.40% of global wilderness loss will occur in Tropical and Subtropical Moist Broadleaf Forests. The wilderness decline is mainly concentrated in the Amazon: the wilderness loss in the Mato Grosso Seasonal Forests, such as Madeira-Tapajós Moist Forests, will be as high as 200,000 km^2. The total area of wilderness loss in Boreal Forests/Taiga will be higher than that in other biomes, accounting for 6.32% of the global losses. Compared with the present period, four biomes will experience a loss of over 25% of existing wilderness areas by 2100, including Tropical and Subtropical Coniferous Forests, Tropical and Subtropical Dry Broadleaf Forests, Tropical and Subtropical Moist Broadleaf Forests, and Temperate Grasslands, Savannas and Shrublands. In particular, all existing wilderness areas in Tropical and Subtropical Coniferous Forests are predicted to disappear completely (Table S3), which will have a devastating impact on the biome.

In scenario B1, over 60% of global wilderness loss will occur in three biomes, namely Temperate Broadleaf and Mixed Forests, Boreal Forests/Taiga, and Tropical and Subtropical Moist Broadleaf Forests. Some ecoregions in Asia will suffer large wilderness losses (>2000 km^2), such as Manchurian Mixed Forests, Ussuri Broadleaf and Mixed Forests, and Okhotsk-Manchurian Taiga. Compared with the present period, only three biomes will lose more than 1% of their existing wilderness, which suggests that the wilderness areas in each biome will be well preserved.

In scenario B2, the wilderness loss of four biomes accounted for

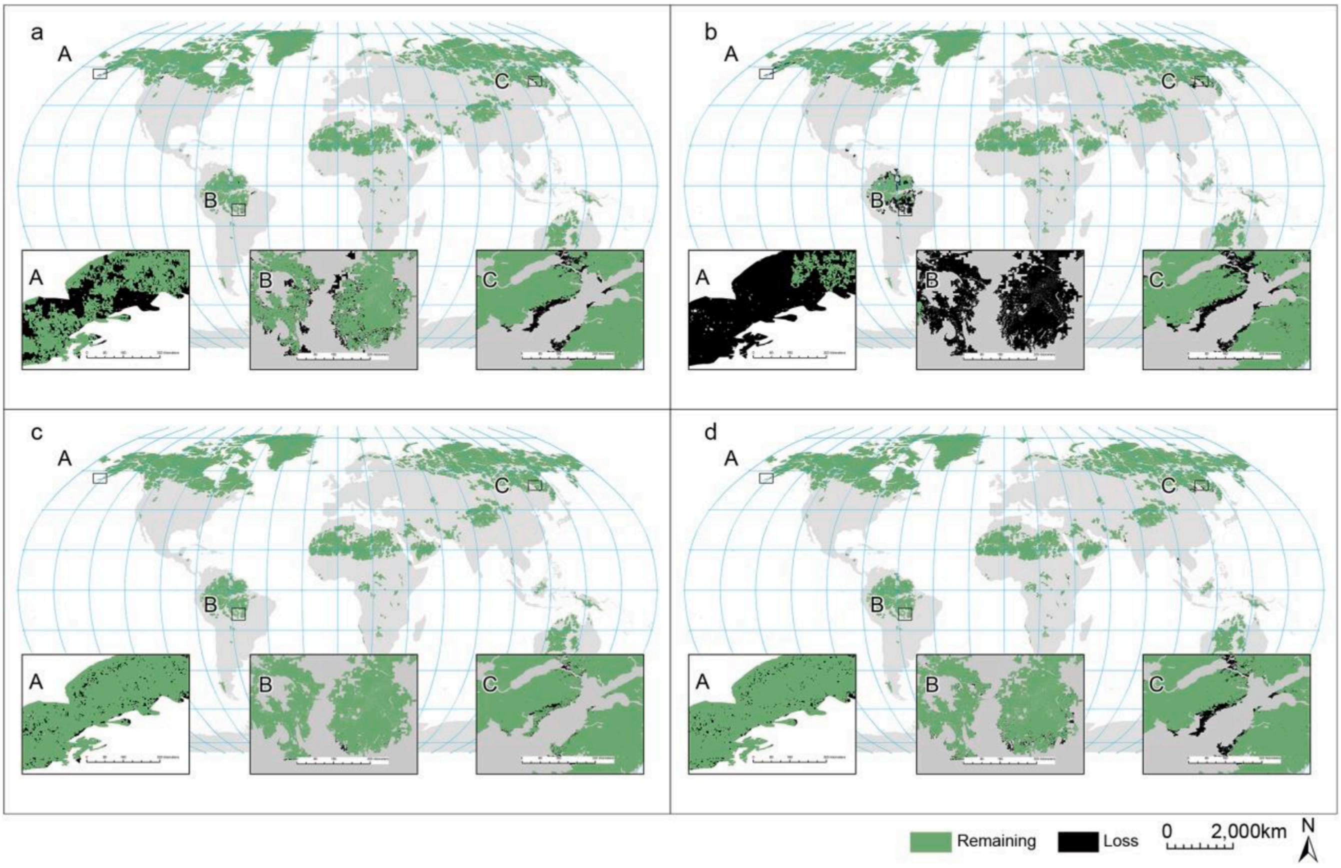


Figure 4. The simulated wilderness losses by 2100 in four scenarios (a: Scenario A1B; b: Scenario A2; c: Scenario B1; d: Scenario B2), taking the Alaskan Peninsula (A), the Amazon (B), and the southern part of Russia (C) as examples.

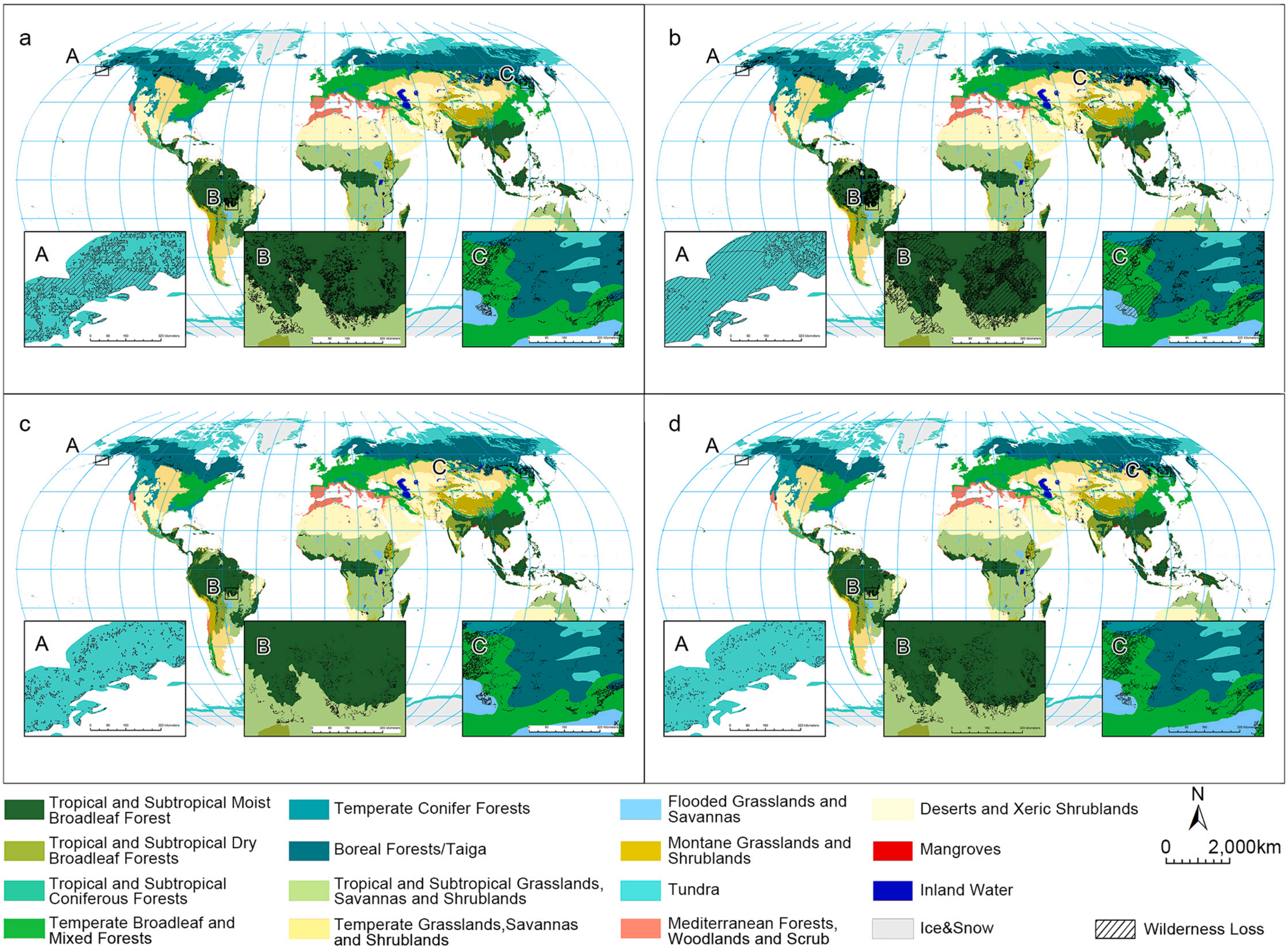


Figure 5. Simulated wilderness loss within terrestrial biomes by 2100 in the four scenarios (a: Scenario A1B; b: Scenario A2; c: Scenario B1; d: Scenario B2), taking the Alaskan Peninsula (A), the Amazon (B), and the southern part of Russia (C) as examples.

almost 72% of the global loss, including Tropical and Subtropical Moist Broadleaf Forests (33,744 km^2, 21.71%), Boreal Forests/Taiga (26,996 km^2, 17.36%), Temperate Broadleaf and Mixed Forests (26,393 km^2, 16.98%), and Temperate Conifer Forests (24,732 km^2, 15.91%). Large contiguous areas of wilderness loss (>10,000 km^2) mainly occurred in Asia, including Kayah-Karen Montane Rain Forests, Da Hinggan-Dzhagdy Mountains Conifer Forests, and Trans-Baikal Conifer Forests.

3.3. *Future wilderness loss and biomass carbon distribution*

By overlaying the biomass carbon density reclassification maps with terrestrial biomes around the world, we found that the distribution of AGBC and BGBC above 120 MgC per ha is mainly located in Boreal Forests/Taiga, Tropical and Subtropical Moist Broadleaf Forests, accounting for more than half of the global terrestrial areas with high AGBC/BGBC (Figure S3, S4). Results showed that most of the wilderness losses was distributed in areas with AGBC/BGBC above 120 MgC per ha (Figures S5, S6). Then, for all the four IPCC SRES, there are more than 50% of wilderness loss located in areas with AGBC/BGBC above 120 MgC per ha. In A2 scenario, 84.14% of wilderness loss will occur in areas with AGBC above 120 MgC per ha, and 79.86% of wilderness loss will occur in areas with BGBC above 120 MgC per ha.

We calculated the area of wilderness losses with AGBC and BGBC by biomes (Figures S7, S8) and compared the distribution of wilderness loss in areas with AGBC/BGBC above 120 MgC per ha of each scenario, we found that they were mainly concentrated in two biomes, namely Boreal Forests/Taiga, Tropical and Subtropical Moist Broadleaf Forests. In scenario A2, almost 80% of potentially wilderness loss in areas with AGBC above 120 MgC per ha are from Tropical and Subtropical Moist Broadleaf Forests, for belowground the proportion is 80.09%. In scenario B2, the wilderness losses in areas with AGBC/BGBC above 120 MgC per ha will also occur in Temperate Conifer Forests, Tropical and Subtropical Moist Broadleaf Forests. Meanwhile, we found that more than half of wilderness loss in above-mentioned biomes will occur in areas with AGBC/BGBC above 120 MgC per ha.

4. Discussions

4.1. *Comparison with previous studies*

We adapted the global method for mapping the human footprint and took six categories of human pressure into consideration to construct the method framework of predicting wilderness loss. Human pressure proxies provide only an incomplete description of human influence on nature (Sanderson et al., 2002), many important global threat such logging, hunting, grazing, pollution and climate change cannot be included in global mapping. However, more accurate data and targeted scores were used in human footprint mapping at the regional scale by taking the regional characteristics and data availability into consideration. For example, to reflect the human impact of grazing in Tibet, Li et al (2018) divided grassland into three categories and scored respectively, they also considered grazing intensity to be a human pressure and

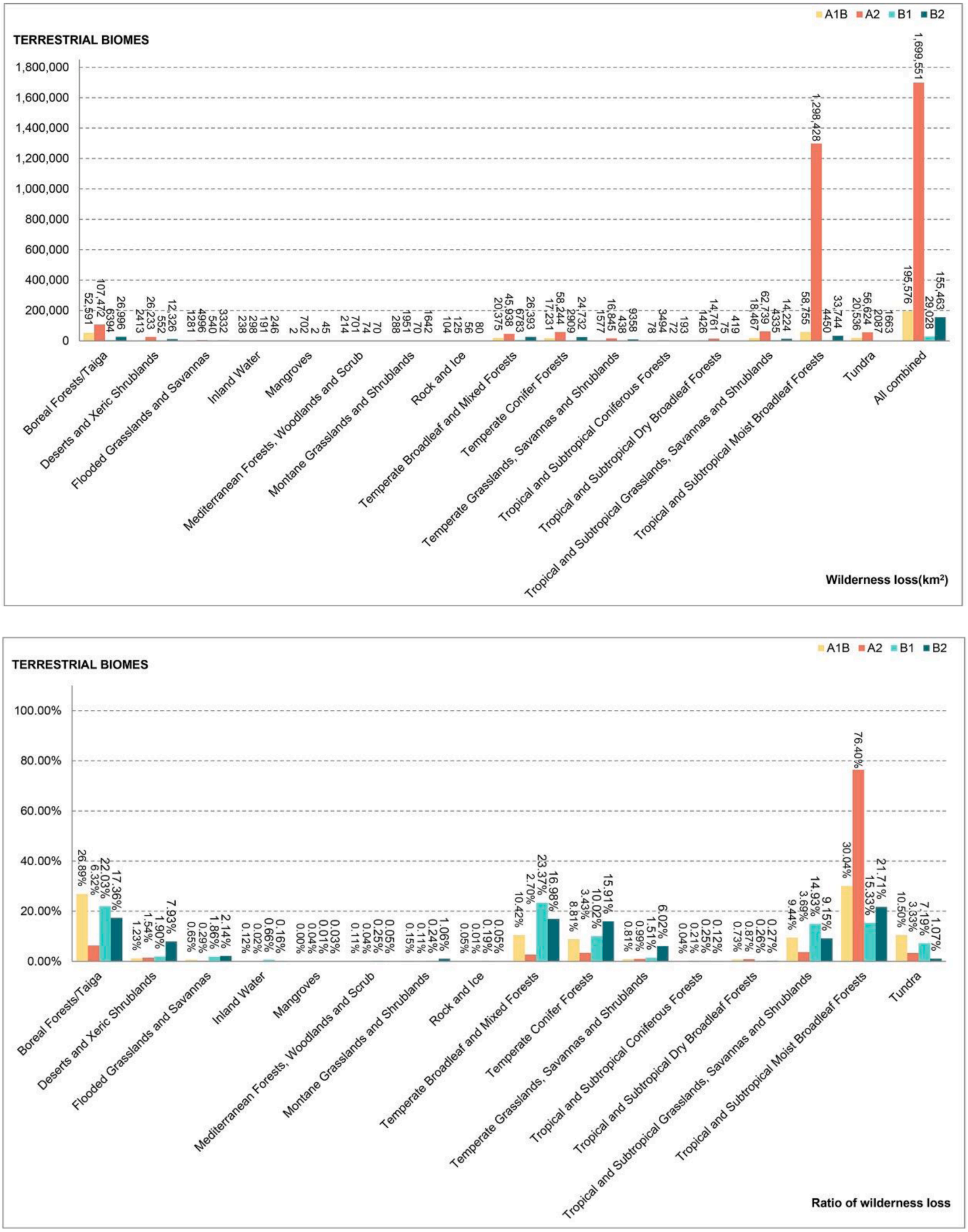


Figure 6. The wilderness loss in each terrestrial biome by 2100.

used county-scale data. In the study on the Northern Appalachian/Acadian ecoregion, the effects of resource extraction (forestry and mining), and major alteration of hydrology (dams) were considered and scored based on the local scoring system (Woolmer et. al, 2008). In future study, human pressure should be selected and assigned of scores according to research objectives, research scale and regional characteristics, thus it will make results closer to true human footprint value by using more comprehensive and accurate data.

On the other hand, it is also important to evaluate the impacts of different human pressures on nature, which determine the scoring criteria. In the future, we will pay more attention to the most pressing issue that requires attention for wilderness protection.

4.2. *Wilderness areas requiring special attention*

Future losses will further exacerbate the existing biases in the geographical distribution of globally significant wilderness in four scenarios, so it is important to identify wilderness areas requiring special attention. Overall, the spatial distribution of wilderness loss in the future is consistent with previous studies. We found that wilderness losses in

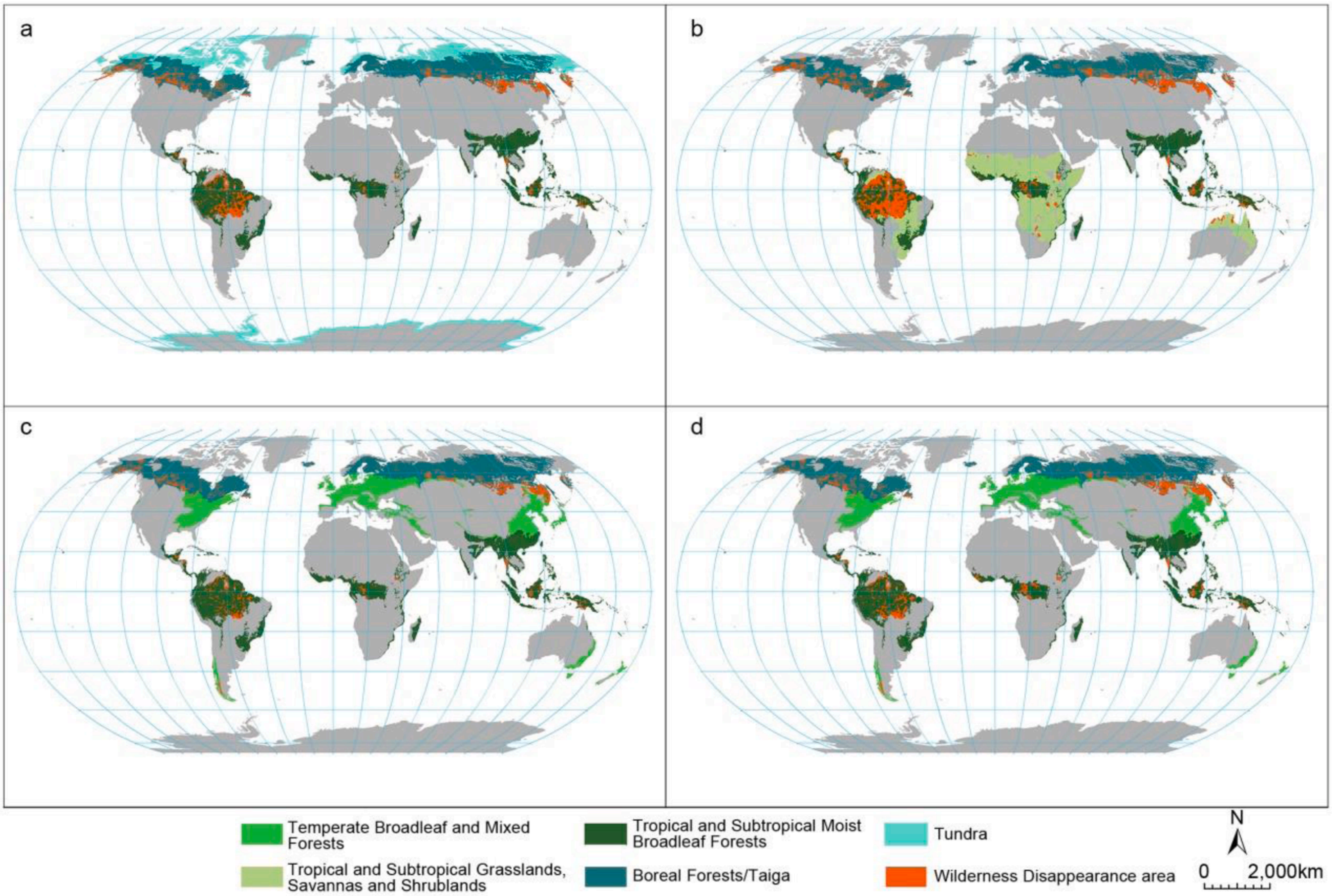


Figure 7. The three biomes with the highest wilderness loss in each scenario by 2100 (a: Scenario A1B; b: Scenario A2; c: Scenario B1; d: Scenario B2).

Boreal Forests/Taiga and Tropical and Subtropical Moist Broadleaf Forests are relatively large in all four scenarios, which follow the past trends (Watson et al., 2016; Williams et al., 2020). Although the two biomes will suffer serious wilderness loss and degradation in all scenarios, they still support significant wilderness areas in the world and persistence of plant and animal species (Marco et al., 2019). We also found that the two biomes will suffer great majority of wilderness decline in areas with AGBC/BGBC above 120MgC per ha. These areas include tropics and boreal region. If the wilderness losses in these biomes can be effectively controlled, it will make a significant contribution to global climate regulation by avoiding emissions and stabilizing atmospheric concentrations of CO2 (Bradshaw et al., 2009). Furthermore, many areas of high value for biodiversity could be protected by carbon-based conservation (Strassburg et al., 2010). Based on the past and simulated future loss, we considered that the effective protection of global wilderness needs a much greater focus on wilderness areas in the Boreal Forests/Taiga and Tropical and Subtropical Moist Broadleaf Forests.

Our projection of biomes such as Boreal Forests and Temperate Broadleaf and Mixed Forests, Deserts and Xeric Shrublands reflected different results from previous study. They suffered the lowest overall average increase in footprint during 1993-2009 (Anderson & Mammides, 2019), but we found that wilderness losses in Boreal Forests and Temperate Broadleaf and Mixed Forests will be pretty high in scenario A1B, B1, B2. Therefore, we should also pay attention to the protection of wilderness in the biomes.

Deserts and Xeric Shrublands suffered relatively large wilderness loss (Watson et al., 2016; Williams et al., 2020), but our projection showed that Deserts and Xeric Shrublands won't have much wilderness loss in the future. This is possibly because the pressure proxies selected did not reflect regional characteristics and the method we used cannot include impacts of non-human factors on the wilderness, such as global climate change. That should be avoided in future studies by evaluating the impacts of different pressures according to reginal characteristics.

Furthermore, we found that large amounts of wilderness loss will be concentrated where biomes intersect (Figure 8). For example, wilderness loss will occur on the southern border of the Amazon in all scenarios. This area is an extensive ecotone between the two largest biomes in South America (Marimon et al., 2006), Tropical and Subtropical Moist Broadleaf Forests, and Tropical and Subtropical Grasslands, Savannas and Shrublands. The intersections between Boreal Forests/Taiga and other biomes (including Tundra, Temperate Conifer Forests, and Temperate Broad leaf and Mixed Forests) will also be key areas of wilderness decline. These wilderness losses at ecotones may increase the vulnerability of remaining forest to habitat fragmentation (Nogueira et al., 2008), which can result in declines in biodiversity, ecosystem degradation, and shifts in the carbon cycle and other elements related to regional climate change (Isabelle et al.,2013;Bonini et al.,2018;Fábio et al.,2018). Therefore, it is also very important to conserve wilderness areas in the ecotones between biomes.

4.3. Scenario analysis and policy implications

The Aichi Biodiversity Targets, which were targeted to be met by 2020, have not been achieved. Despite on-going efforts, biodiversity continues to decline worldwide and this decline is projected to worsen with business-as-usual scenarios. Wilderness areas have an important role in supporting the persistence of biodiversity (Mittermeier et al., 2003); indeed, they halve the extinction risk of terrestrial biodiversity (Marco et al., 2019). A higher target for protected areas was launched by

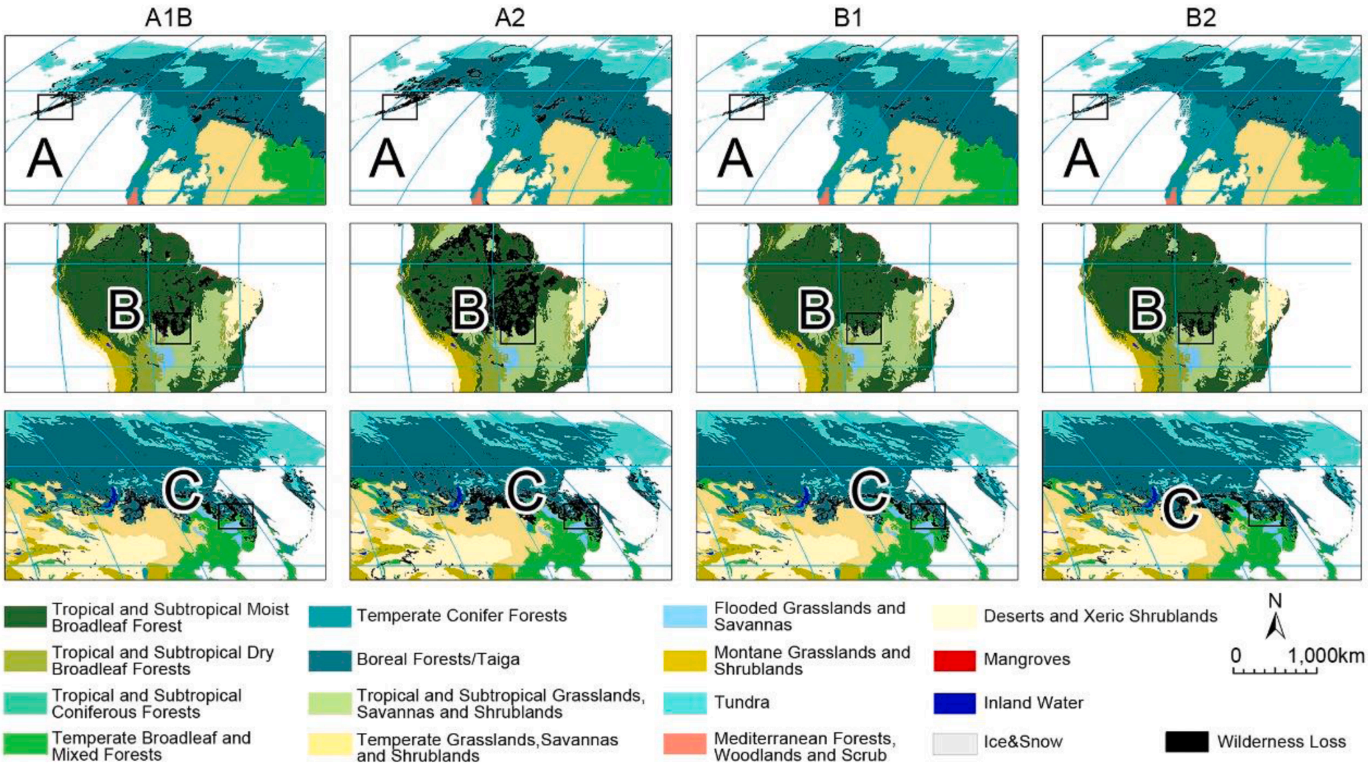


Figure 8. Patterns of wilderness loss in intersections between biomes under four scenarios (a: Scenario A1B; b: Scenario A2; c: Scenario B1; d: Scenario B2), taking the Alaskan Peninsula (A), the Amazon (B), and the southern part of Russia (C) as examples.

the WILD Foundation in 2009, the Nature Needs Half (NNH) initiative (Pimm et al., 2018). The NNH initiative called for the protection of at least 50% of the Earth's land and ocean areas. Some studies have discussed the feasibility of the NNH initiative and set global and national targets for terrestrial protected areas (Jonathan et al., 2018; Yang et al., 2020) . However, our results suggest that it will be difficult to realize these targets when considering predicted global social and economic conditions.Once the importance of wilderness is recognized within the international policy framework and the governments reach a consensus on wilderness protection. Choosing a sustainable socioeconomic development path through coordinated global collaboration can address human impact on the remaining wilderness areas, especially endangered ones.

The projection results from the IPCC SRES show large variations in potential wilderness loss futures, which can provide us with policy guidance with allowing for uncertainty over the pathway for future development. Our results demonstrated that the decline of wilderness will be deeply affected by socioeconomic development pathways over the coming century, both in terms of aggregate amounts and spatial distribution. The most pessimistic scenario for 2100 was A2 (4.74% loss of global wilderness). In scenario A2, the urban land has a dramatic growth by 2100 due to high population growth and low resources protection, which will lead to the maximum amount of wilderness loss. Four biomes will lose more than a quarter of the remaining wilderness area, and the wilderness will completely disappear in Tropical and Subtropical Coniferous Forests. Once that happens, their component ecosystems and ecosystem services will never be fully restored (Watson et al., 2018). Therefore, we need to strengthen the protection of vulnerable wilderness areas to preserve their unique ecosystems and carbon storage capability. Conversely, in scenario B1, the most optimistic scenario (0.08% loss of global wilderness), the total area of wilderness increased due to low population growth, high level of environmental consciousness and technological innovation. The new wilderness areas will be converted from grassland, forest, water and barren land. Therefore, this development pathway is the most beneficial to global wilderness conservation.

In conclusion, the human pressures are linked in some way to socioeconomic activities, which have deeply influence on global wilderness. We hope that the world can develop according to scenario A2. We also call on the governments to concentrate on evaluating the status of wilderness, fomulating laws and policies on wilderness protection, linking wilderness protection to social-economic decision-making, catalysing systematic planning and conservation action, promoting expanded and improved management of wilderness areas.

The 15th meeting of the Conference of the Parties to the Convention on Biological Diversity will be held in Yunnan, China in October 2021. The conference will decide on the post-2020 global biodiversity framework. We believe that it is extremely significant to explore biodiversity conservation under the background of socioeconomic development. This research highlights the adjustments that are needed to the pathways of global economic development to achieve biodiversity conservation targets.

Furthermore, based on our finding that over three-quarters of the predicted terrestrial wilderness in 2100 is not within the scope of global protected areas. Although the effectiveness of protected areas appears to differ across regions (Joppa & Pfaff, 2011; Jones et al., 2018), protected areas tend to effectively mitigate human impact on wilderness (Jones et al., 2018; Anderson & Mammides, 2019). That is to say, it is essential to better target new protected areas to protect wilderness, stem habitat loss and maintain terrestrial carbon stocks (Campbell et al., 2009; Watson et al., 2016; Pimm et al., 2018; Jonathan et al., 2018), especially in the most vulnerable wilderness areas identified above.

5. Conclusions

This study is the first spatiotemporal projection of global wilderness loss by 2100 and it provides the first examination of the spatial distribution and quantity of wilderness loss affected by different degrees of human activities in the future. In this study, we used 9 datasets to represent the six categories of human influence, and assigned them scores to reflect their relative impact the terrestrial environment in current and in 2100. These pressures were coded into standardized scores within a 0–10 scale according to published studies (Sanderson, 2002; Venter et al.,2016a,b). For the mapping of current human footprint, we used the latest available data of six proxies; for the mapping of future human footprint, we used the 2100 forecast data of urban lands and crop lands within the framework of the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (IPCC SRES). For other types of data as there is no forecast for 2100, we used the latest available data of other types. We identified the areas with pressure score lower than 1 as wilderness areas and projected the wilderness loss by 2100.

The projections revealed that the decline of wilderness was deeply affected by different global socioeconomic development pathways. The most pessimistic scenario for 2100 was A2 (4.74% loss of global wilderness), and the most optimistic was B1 (0.08% loss of global wilderness). According to the simulation results under the four scenarios, we found that Boreal Forests/Taiga, and Tropical and Subtropical Moist Broadleaf Forests will suffer large losses under all scenarios in 2100.

To estimate the impact of future wilderness loss on terrestrial carbon storage, its spatial relationship with global AGBC/BGBC maps was analyzed quantitatively and used to assess the impacts of wilderness loss on global carbon storage. Results showed that terrestrial wilderness loss in the future will lead to the decline of carbon storage globally.

Our study also highlight wilderness areas that required special attention, and address global socioeconomic development pathways as the dominant factor affecting wilderness protection.

CRediT authorship contribution statement

Fangzheng Li: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Wenyue Li:** Conceptualization, Methodology, Software, Validation, Resources, Data curation. **Fengyi Li:** Writing – original draft, Writing – review & editing, Visualization. **Ying Long:** Conceptualization, Methodology, Software, Validation, Resources. **Shiyi Guo:** Resources, Writing – review & editing. **Xiong Li:** Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Chensong Lin:** Resources, Writing – review & editing. **Jing Li:** Software, Formal analysis, Investigation, Data curation, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare no competing interests.

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Supplementary materials

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