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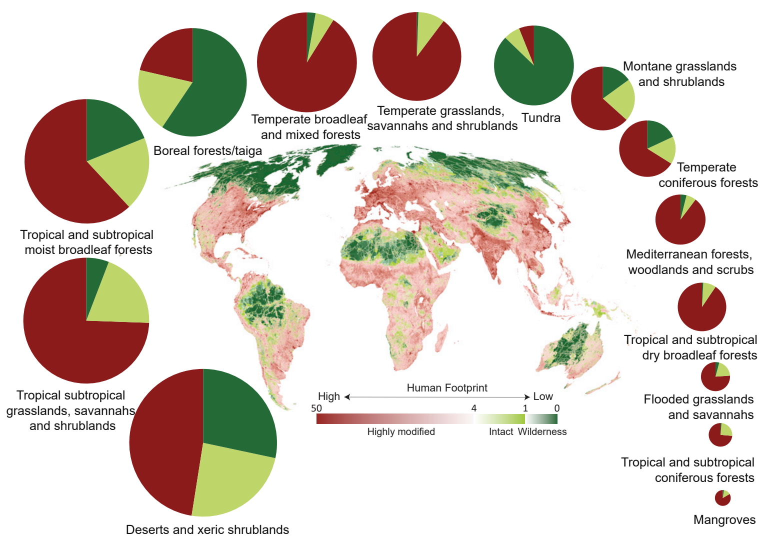
Change in Terrestrial Human Footprint Drives Continued Loss of Intact Ecosystems

Graphical Abstract



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In Brief

Human pressure mapping is important for understanding humanity's role in shaping Earth's patterns and processes. We provide the latest maps of the terrestrial human footprint and provide an assessment of change in human pressure across Earth. Between 2000 and 2013, 1.9 million km^2 of land relatively free of human disturbance became highly modified. Our results show that humanity's footprint is eroding Earth's last intact ecosystems and that greater efforts are urgently needed to retain them.

Highlights

- We show that 58.4% of terrestrial Earth is under moderate or intense human pressure
- Between 2000 and 2013, 1.9 million km^2 of intact land became highly modified
- Globally tropical grasslands and Southeast Asian forests were the most impacted
- Greater efforts are urgently needed to retain Earth's remaining intact ecosystems

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Change in Terrestrial Human Footprint Drives Continued Loss of Intact Ecosystems

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SCIENCE FOR SOCIETY Humans have influenced the terrestrial biosphere for millennia, converting much of Earth's surface to anthropogenic land uses. Nevertheless, there are still some ecosystems that remain free from significant direct human pressure (and as such, considered "intact"), thereby providing crucial habitats for imperilled species and maintaining the ecosystem processes that underpin planetary life-support systems. Our analyses show that, between 2000 and 2013, 1.9 million km^2—an area approximately the size of Mexico—of land relatively free of human disturbance became highly modified. This loss has profound implications for the biodiversity that require intact land for their continued survival and for people who rely on the services that intact ecosystems provide. Our results showcase the urgent need to safeguard Earth's last intact ecosystems and suggest that greater efforts are needed to ameliorate human pressures.

SUMMARY

Human pressure mapping is important for understanding humanity's role in shaping Earth's patterns and processes. Our ability to map this influence has evolved, thanks to powerful computing, Earth-observing satellites, and new bottom-up census and crowd-sourced data. Here, we provide the latest temporally inter-comparable maps of the terrestrial human footprint and assessment of change in human pressure at global, biome, and ecoregional scales. In 2013, 42% of terrestrial Earth could be considered relatively free of direct anthropogenic disturbance, and 25% could be classed as "wilderness" (the least degraded end of the human footprint spectrum). Between 2000 and 2013, 1.9 million km^2—an area the size of Mexico—of land relatively free of human disturbance became highly modified. The majority of this occurred within tropical and subtropical grasslands, savannah, and shrubland ecosystems, but the rainforests of Southeast Asia also underwent rapid modification. Our results show that humanity's footprint is eroding Earth's last intact ecosystems, and greater efforts are urgently needed to retain them.

INTRODUCTION

Humans have influenced the terrestrial biosphere for millennia, converting much of Earth's surface to anthropogenic land uses.[1] Nevertheless, there are still some ecosystems that remain free from significant direct human pressure, thereby providing crucial habitats for imperilled species[2,3] and maintaining the ecosystem processes that underpin planetary life-support systems.[4,5] As a consequence, calls for the global identification, monitoring, and retention of the remaining lands that are relatively free of direct anthropogenic disturbance are increasing.[6–8]

Over the past two decades, cumulative pressure maps that combine remotely sensed data with survey data are being increasingly used to assess the full range of human pressures on land spatially.[9] These advances have facilitated the mapping of Earth's remaining marine and terrestrial wilderness,[8,10,11] improved measures and estimates of species extinction risk,[12] underpinned broader assessments of human impacts on ecosystems[13] and biodiversity,[14–16] and enabled the identification of protected areas and world heritage sites in danger.[14,17,18] The results of these mapping efforts are influencing global policy discussions,[6,19] and informing on-the-ground decisions about where to undertake biodiversity conservation action.[20–22]

Here, we provide the latest global maps of cumulative human pressure[23,24] for the years 2000, 2005, 2010, and 2013, and use the maps for the years 2000 and 2013 to assess how change in human pressure is altering Earth's terrestrial ecosystems. We used a human footprint threshold of <4 (on a 0–50 scale) to identify where land is considered ecologically intact (below the threshold) or highly modified and thus ecologically degraded (equal to or above the threshold). Areas below this threshold are ecosystems that may be subject to some level of human pressure (for example, low-density transitory human populations or pasture lands grazed at a low intensity), but still contain most of their natural habitat and maintain their ecological processes.[14,25] This threshold has been found to be robust from a species conservation perspective because, once surpassed, species extinction risk increases dramatically,[12] and several ecosystem processes are altered.[12,16,26]

We assess transitions from intact to highly modified land at global, biome, and ecoregional scales[27] and ascertain which nations contain Earth's remaining intact systems, and which had the greatest amounts of habitat loss. Previous global assessments of human pressure have attempted to identify at-risk ecosystems by determining a "safe limit" of biodiversity loss for ecosystem functionality,[28,29] assessing protection levels,[30] and analyzing habitat conversion using land cover.[31,32] But all of these ignore a broad range of threats that occur beyond land use, such as accessibility via roads, railways, and navigable waterways, human population density, and light pollution. These pressures have environmental impacts well beyond the local development footprint.[33–35] As such, our results provide the latest spatially explicit understanding of the state of human pressure on the natural environment, and how it is changing over time. We demonstrate that the human footprint methodology can be continually updated and, when more data become available, allow for near real-time assessments of habitat loss at scales relevant to policy and planning activities.

RESULTS

State of Terrestrial Earth

As of 2013, 55.8 million km^2 (41.6%) of Earth's surface was intact (which includes wilderness, human footprint of <4), and 33.5 million km^2 (25.0%) was wilderness (human footprint of <1). The remaining (human footprint of $\geq$4) 78.4 million km^2 (58.4%) was under moderate or intense human pressure (and therefore highly modified), which was widespread, encompassing over half the area of 11 (or 78.6%) of Earth's 14 biomes (Figure 1). Temperate broadleaf and mixed forests were the most altered biome, with 11.6 million km^2 (91.0%) being highly modified, followed by tropical and subtropical dry broadleaf forests with 2.72 million km^2 (90.5%), and Mediterranean forests, woodlands and scrubs with 2.88 million km^2 (89.7%). Wilderness areas have all but disappeared in many biomes. For example, only 82,000 km^2 (0.81%) remained in temperate grasslands, savannahs, and shrublands, 29,000 km^2 (0.96%) in tropical and subtropical dry broadleaf forests, and just 12,000 km^2 (1.69%) in tropical and subtropical coniferous forests.

Earth's 14 biomes consist of 795 ecoregions, which represent distinct biotic assemblages and abiotic features (such as landforms) at a finer scale than biomes.[27] We found the entire extent of 46 (5.76%) ecoregions were highly modified. These 46 ecoregions span 10 biomes, with most located in tropical and subtropical moist broadleaf forests (n = 17, 37.0%), tropical and subtropical dry broadleaf forests (n = 6, 13.0%), and temperate broadleaf and mixed forests (n = 6, 13.0%). One-quarter of all ecoregions (n = 187) have lost all wilderness.

Most land in tundra, boreal and taiga forests, and deserts and xeric shrubland biomes remains intact. At the ecoregion level, just 52 (6.53%) still have >90% of their land intact, and a mere 21 (2.64%) are >90% wilderness. These ecoregions with >90% wilderness are found in just four biomes, tundra (n = 12), boreal forests/taiga (n = 5), tropical and subtropical moist broadleaf forests (Rio Negro campinarana and Juruá-Purus moist forests), and tropical and subtropical grasslands, savannahs, and shrublands (Northwestern Hawaii scrub).

Contemporary Changes in Human Pressure

Between 2000 and 2013, 25.4 million km^2 (18.9%) of Earth's terrestrial surface deteriorated (human pressure increased), while only 8 million km^2 (5.96%) improved (human pressure decreased; Figure 2). This increase in human pressure was substantial across 1.89 million km^2 of Earth's intact lands, an area the size of Mexico, that these places can be classified as highly modified (i.e., they transitioned from below to above the human footprint threshold of 4; Figure 3). During the same time period, over 1.1 million km^2 of wilderness was lost (human footprint increasing above 1), with 67,000 km^2 of that wilderness becoming highly modified (human footprint increasing from below 1 to above 4; Figures 2 and 3).

Intact lands were lost in all biomes during the assessment period, with the highest loss occurring in tropical and subtropical grassland, savannah, and shrublands (655,000 km^2 was lost representing 11.3% of all intact lands within the biome, an area approximately the size of France; Figure 4). The tropical and subtropical moist broadleaf forests and mangrove biomes also lost substantial areas of intact land (559,000 km^2, 6.90% and 9,000 km^2, 14.7%, respectively). While the largest absolute loss of intact lands occurred in savannah and woodland ecoregions, the largest proportional losses occurred in tropical forest ecoregion types. For example, intact areas were completely lost in seven forested ecoregions, including the Louisiade Archipelago rainforests (Papua New Guinea) and Sumatran freshwater swamp forests (Indonesia).

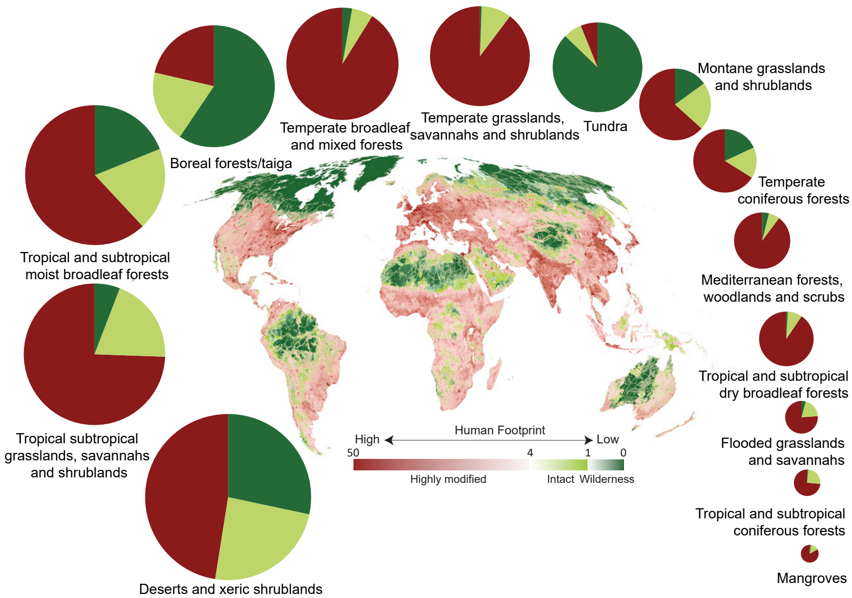

Figure 1. The Global Human Footprint Map for the Year 2013

The surrounding pie charts represent the proportion of each terrestrial biome that was completely free of mapped anthropogenic disturbance (wilderness, dark green, human footprint value of <1), relatively free of mapped anthropogenic disturbance (intact, light green, human footprint value of <4 and ≥ 1), or highly impacted by mapped anthropogenic disturbance (highly modified, red, human footprint value of ≥ 4) in the year 2013. Circles sizes represent relative biome area.

The largest losses of wilderness between 2000 and 2013 occurred in biomes that contained the largest areas of wilderness in 2000. For example, deserts and xeric shrublands lost 426,000 km^2 (5.08%) of their remaining wilderness. This was concentrated in desert, woodland, and savannah ecoregion types. Wilderness in the tundra and boreal/taiga forests suffered the most extreme transitions, with 22,000 and 15,000 km^2, respectively, changing from wilderness to highly modified land (human footprint <1 to ≥ 4) (Figure 4). The ecoregions of the Russian tundra and taiga lost the most wilderness. For example, the Yamal-Gydan tundra lost 8,000 km^2, and the East Siberian taiga lost 5,000 km^2.

National Responsibility

In 2013, only 26 nations (out of 221) had most (>50%) of their land intact. Excluding island territories, the two countries with the highest proportion of intact land included Guyana (88.8% of country; 187,000 km^2) and Suriname (88.5%; 125,000 km^2). The African continent contained 11 ecoregions that lost the largest areas of intact land. Between 2000 and 2013, more intact land was lost in the Democratic Republic of the Congo (DRC) than any other country (316,000 km^2; 13.6% of the country; 37.3% of its intact lands). This was followed by Indonesia and Brazil which lost 122,000 km^2 (6.98% of the country or 20.2% of its intact lands) and 87,000 km^2 (29% of the country or 1.88% of its intact lands), respectively.

Russia, Canada, Brazil, and Australia are responsible for the largest areas of Earth's remaining intact areas (which includes wilderness, human footprint score of <4). Combined, these four countries harbor more than 60% of Earth's wilderness (human footprint score of <1, Figure 5). Brazil also lost the most wilderness (human footprint increasing above 1) of any country (109,880 km^2, 3.87% of its wilderness area). The largest areas of wilderness lost to high levels of human modification (human footprint increasing above 4) were in Russia (23,000 km^2), Canada (10,000 km^2), and Brazil (6,000 km^2).

DISCUSSION

The terrestrial human footprint presented here is one of the most comprehensive and up-to-date measures of cumulative human pressure across Earth, and will be continuously improved as more data on the eight included pressures (built environments, population density, nighttime lights, crop lands, pasture lands, and accessibility via roads, railways, and navigable waterways) become available. While this latest update is already 7 years out of date due to a lack of available compatible data after 2013, advances in data generation and modeling[36] will facilitate much needed near real-time updates of the human footprint in the near future. Our analyses show that between 2000 and 2013 substantial areas of intact land, including wilderness areas, have been lost. This loss has profound implications for the biodiversity that require intact land for their continued survival,[3,37,38] and for people who rely on the services that intact ecosystems provide.[8,39] The transition from intact ecosystems to highly modified land is the greatest predictor of why species face increasing extinction risk[12] as this transition is where habitat is considered functionally unavailable for many terrestrial vertebrates.[40,41] This transition also negatively impacts wildlife population viability, because intact ecosystems are proven strongholds for genetic diversity.[42] Climate change mitigation efforts are also undermined by these losses because intact lands make crucial contributions to the residual terrestrial carbon sink.[39,43] For example, a recent study found that carbon impacts of intact forest loss are 626% worse than originally estimated.[43]

We also demonstrate that patterns of degradation due to increasing human pressure are now changing within biomes. Past studies note that dry forested biomes have suffered the highest rates of habitat loss[25,31] but our results now show that recent increases in human pressure predominantly occurred in tropical savannah and grassland ecosystems, which lost 11.3% of their intact area between 2000 and 2013. This finding is consistent with previous evidence that savannahs are the current development frontier in many regions worldwide.[44,45] Proactive conservation planning is urgently needed to prevent the last intact savannahs, such as Australia's northern savannahs[46] and Colombia's Llanos in the Orinoquia region,[45] suffering the same losses that occurred in places, such as Brazil's Cerrado.[47] Conservation planning needs to utilize tools that take into account past and future risk, so that preventative conservation

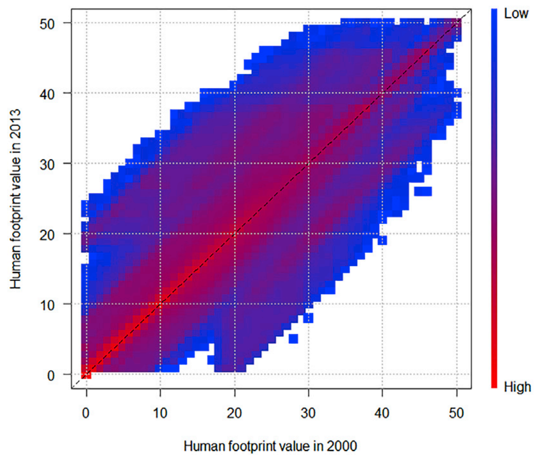

Figure 2. Density Plot Depicting Change in the Global Terrestrial Human Footprint between the Years 2000 and 2013 (n = 134,154,306)
The x axis represents the human footprint value of a pixel in the year 2000, and the y axis represents the human footprint value of that pixel in the year 2013. The number of pixels that made that particular transition are represented by the color within the plot. Red represents a high number of pixels and blue represents low. Legend is log-scaled. Between 2000 and 2013, 25,348,514 km^2 (18.9%) of pixels deteriorated (human pressure increased), while 7,995,464 km^2 (5.96%) improved (human pressure decreased).

action can be implemented in places where development is most likely to occur.[48–50] Our analysis helps inform where proactive conservation planning activity would have the highest benefit and demonstrates the potential of human pressure mapping for informing global conservation action.

Nearly three decades ago, the world came together to ratify the Rio Conventions, including the Convention on Biological Diversity, the UN Convention to Combat Desertification, and the UN Framework Convention on Climate Change. Despite the fact that almost all nations are signatories on these three international environmental agreements, intact habitats continue to be lost at a rapid rate,[51] including within the borders of many signatory nations, such as the DRC, Indonesia, and Brazil. One possible explanation for this trend is the challenge of collectively identifying intact landscapes and then using this information to take coordinated action across the globe to protect them. Given the growing body of scientific evidence demonstrating the exceptional value of intact ecosystems (including wilderness areas) for conserving biodiversity,[37] mitigating climate change,[43] and providing essential ecosystem services,[39] the importance of data on intactness should be elevated when undertaking efforts to develop international and national targets and shaping actions under these Conventions. For example, nations that are party to the Convention on Biological Diversity will soon sign off on the Post-2020 Global Biodiversity Framework that will set global targets on nature for the coming decades. Negotiations around the Post-2020 Framework present an opportunity for countries to include targets specifically for the protection and complete retention of intact ecosystems.[8]

Halting the loss of intact ecosystems cannot be achieved alongside current trajectories of development, population growth, and resource consumption.[52] Retention of Earth's remaining intact lands can only be achieved through a combination of strategic policy mixes that better regulate deleterious activities across all sectors, levels of governance and jurisdictions, and on-the-ground site-based action, such as well-resourced protected areas in conjunction with other effective area-based conservation measures, such as payment schemes for safeguarding ecosystem services.[52–55] While many pathways on how intact retention can be achieved are being developed,[8,52,55,56] the challenge is ensuring that action occurs at the scale and speed necessary to secure all intact ecosystems.

The highest losses of intact lands occurred in African nations, where the highest biodiversity impact from future socio-economic development is also predicted to occur.[57] Parts of Africa also have the largest gap between food consumption and production in the world, we can therefore only infer that increasing agricultural production is a key driver of savannah and grassland loss.[58,59] In addition, remote African forests, such as the Congo Basin, are increasingly impacted by roads, population growth, and subsistence agriculture.[60,61] Other regions experiencing extreme levels of intact ecosystem loss are the rainforests of Indonesia (which covers 1.3% of Earth but contains 10% of the world's plants, 12% of mammals, 16% of reptile-amphibians, and 17% of birds)[62] and Papua New Guinea (which covers less than 1% of Earth but contains 5% of its biodiversity).[63] This extreme habitat loss is likely due to the spike in habitat conversion to grow cash crops, such as oil palm,[64,65] driven by international demand.[66] The drivers of intact ecosystem loss are complex, and as well as biophysical, include many geo-political and socio-economic drivers. For example, much of the intact ecosystem loss experienced in tropical countries can likely be attributed to not only the availability of arable land, but also increases in human populations, their per capita consumption,[67] and international demands for product.[68] Thus, it is critical that future research be oriented to better understanding these drivers of intact ecosystem loss, and subsequently to find mechanisms that facilitate socio-economic development without further degrading intact ecosystems.[52,69]

Our analysis has the same limitations that are inherent to all cumulative pressure mapping efforts.[70] It is not possible to fully account for all human pressures, which means our assessment is likely an underestimation of intact ecosystem loss. We note that many pressures not mapped, such as invasive species, poaching, or pollution,[71] are associated with some of the pressures we mapped (e.g., roads, population density, and access) and therefore their lack of inclusion may not strongly affect the overall results. However, it is increasingly recognized that other insidious pressures, such as climate change and disease, are affecting all intact ecosystems in their biological communities.[72,73] In addition, the human footprint measures the pressure humans place on nature and not the realized impact on ecosystems or biodiversity, which likely varies between locations. Therefore, there is significant scope for future research efforts to focus on regional assessments that include a wider variety of pressures, using the tools that we have made available for mapping the human footprint. Finally, validation of the new human footprint maps follow the methodology, which has been widely adopted as standard practice,[74,75] of the previous release.[23] This validation considers the human footprint in its entirety, presenting future research opportunities to quantify the

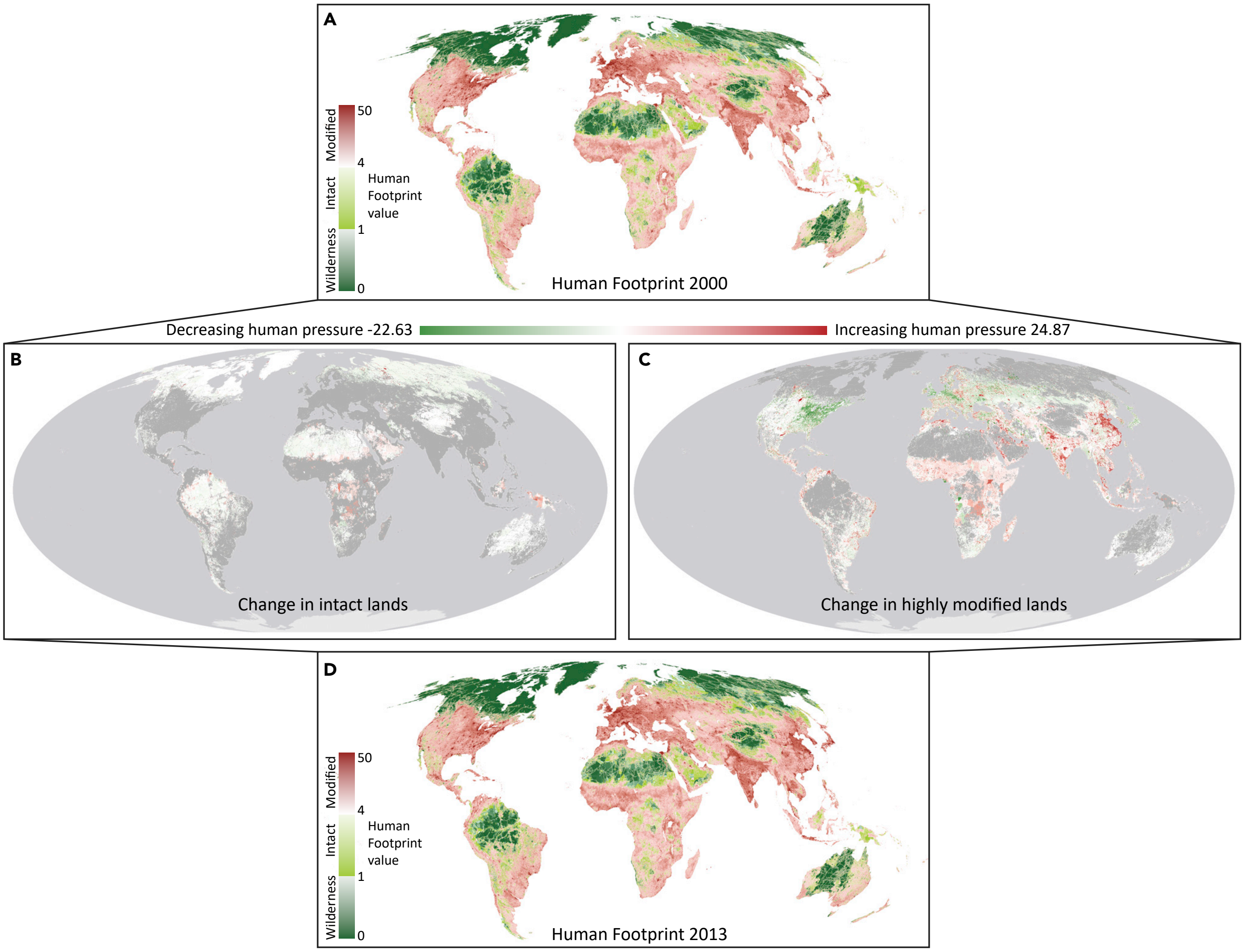

Figure 3. The Human Footprint Map for the Years 2000 and 2013 and the Change that Occured in the Intervening Time

The global human footprint map for the year 2000 (A). Areas completely free of mapped anthropogenic disturbance (wilderness, dark green, human footprint value of <1), relatively free of mapped anthropogenic disturbance (intact, light green, human footprint value of <4 and ≥1), or highly impacted by mapped anthropogenic disturbance (highly modified, red, human footprint value of ≥4). The change between 2000 and 2013 within each 2000 state can be seen for intact land (B) and highly modified land (C), which leads to the 2013 state (D).

uncertainty of each dataset used to create the human footprint, and propagate this uncertainty throughout the human footprint methodology.

Conclusion

We have presented the latest comprehensive assessment of humanity's footprint on terrestrial Earth using the best available data. We find that human pressure is extending ever further into the last ecologically intact and wilderness areas. With important policy discussions on the Convention on Biological Diversity's Post-2020 Global Biodiversity Framework well underway,[76] this is a timely opportunity for nations to take stock and to set explicit targets for retaining Earth's remaining intact lands. Proactively protecting Earth's intact ecosystems is humanity's best mechanism for protecting against climate change, ensuring large-scale ecological and evolutionary processes persist, and safeguarding biological diversity into the future.

EXPERIMENTAL PROCEDURES

Resource Availability

Lead Contact

Further information requests should be directed to and will be fulfilled by the Lead Contact, Brooke Williams (brooke.williams@uq.edu.au), or to Oscar Venter (oscar.venter@unbc.ca) in regard to the human footprint maps.

Materials Availability

The human footprint maps for years 2000, 2005, 2010, and 2013, and the excel sheets detailing the area in each state, and the area that transitioned between each state at the global, biome, ecoregional, and national scales, are available on the Dryad repository: https://doi.org/10.5061/dryad.3tx95x6d9.

Data and Code Availability

All data and code to generate the human footprint maps are available on the Dryad repository: https://doi.org/10.5061/dryad.3tx95x6d9. Terrestrial biomes and ecoregions can be downloaded from: https://www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world. World borders can be downloaded from: https://gadm.org/.

Overview

We updated the human footprint[23] terrestrial cumulative human pressure maps for the years 2000, 2005, 2010, and 2013 and used it to define the state

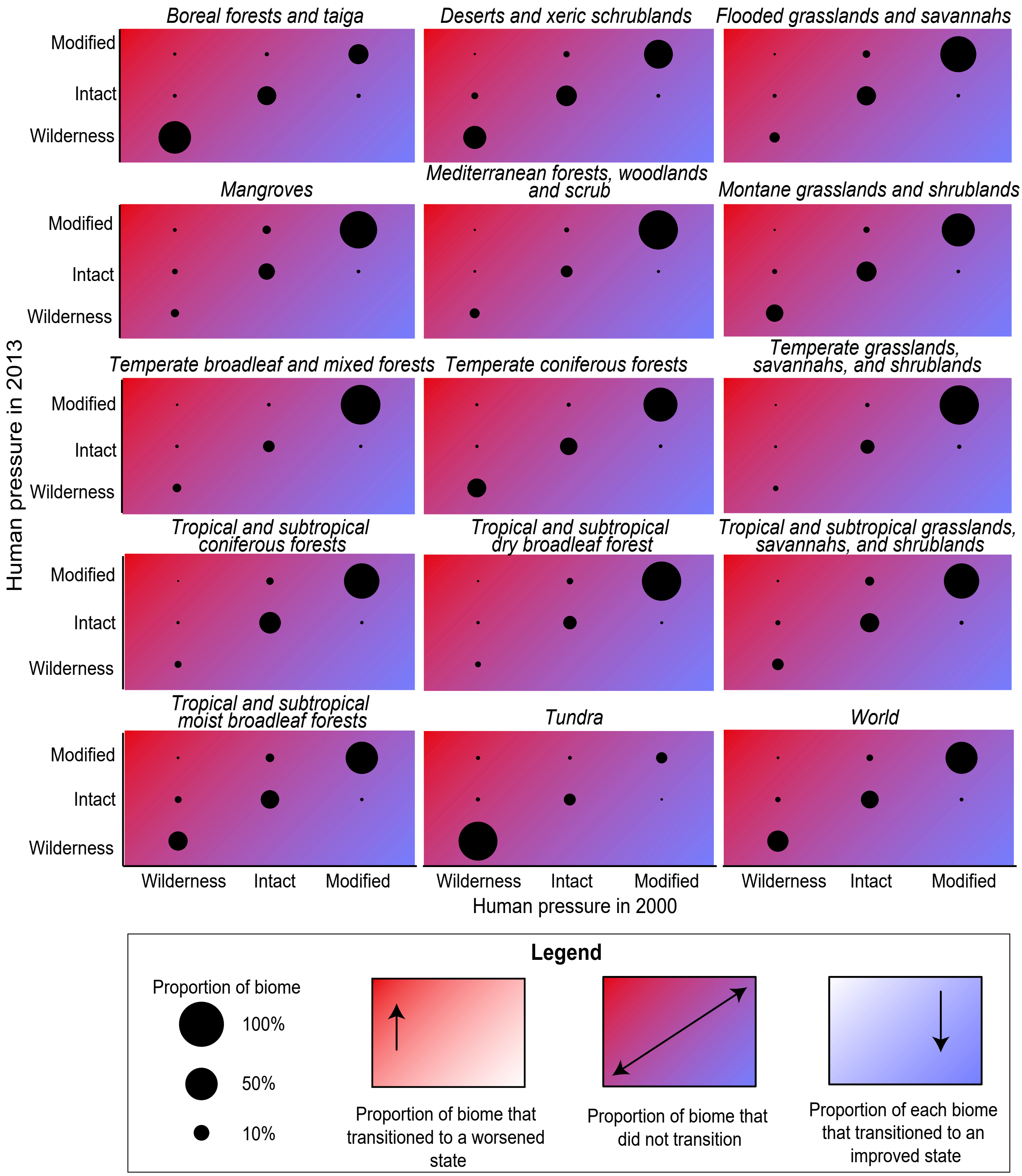

Figure 4. Transitions between States within Biomes

The proportion of biome that transitioned between wilderness (human footprint value of <1), intact (human footprint value between <4 and ≥1), and highly modified (human footprint value of ≥4) states between 2000 and 2013, represented by circles. If part of the biome transitions to a worsened condition it moves upwards into the red area, if part of the biome does not transition it remains on the diagonal, and if part of the biome improves, it moves downwards into the blue area.

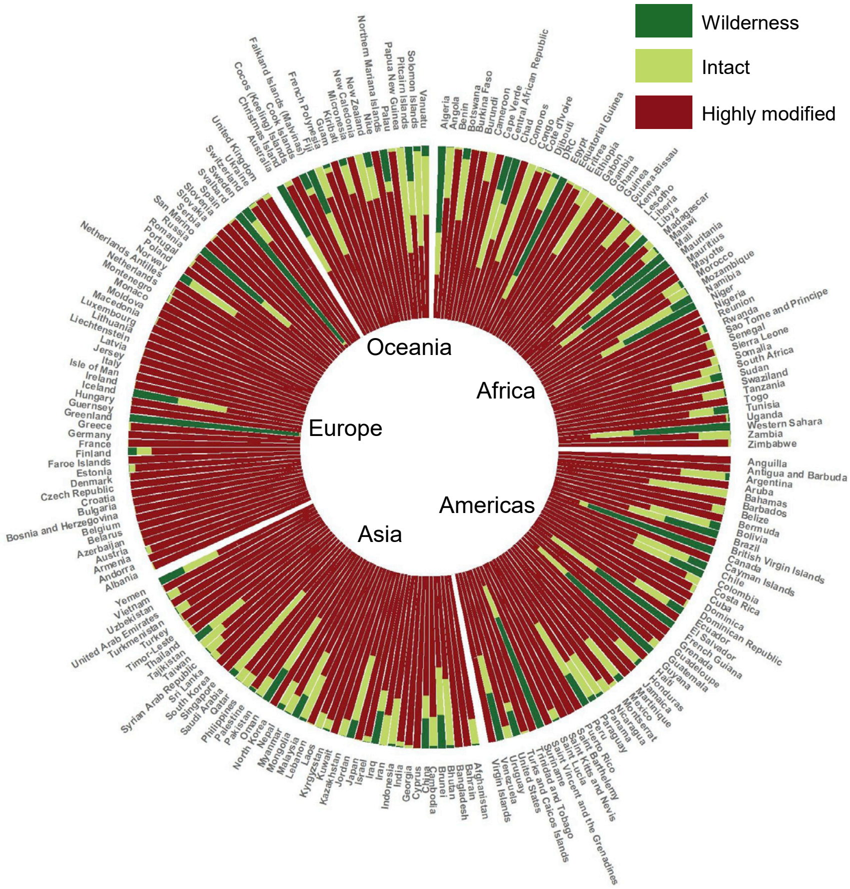

Figure 5. The State of Each Country's Terrestrial Land

Proportion of each country's terrestrial land that was completely free of mapped anthropogenic disturbance (wilderness, dark green, human footprint value of <1), relatively free of mapped anthropogenic disturbance (intact, light green, human footprint value between <4 and ≥1), or highly impacted by mapped anthropogenic disturbance (highly modified, red, human footprint value of ≥4) in the year 2013.

of Earth's biomes, ecoregions, and countries, and their transitions between states between 2000 and 2013. All analyses, and creation of the human footprint maps, were conducted in the Mollweide equal area projection at 1 km^2 resolution.

Updating the Human Footprint

To recreate the human footprint maps we followed broadly the methods developed by Sanderson and colleagues[24] and Venter and colleagues.[23] Significant areas missing in the original human footprint[23] (which carried over into subsequent releases), including Azerbaijan, areas along the western former-USSR border, and along the Orange River in South Africa, among others, have been included in this update. We used data on human pressures across the periods 2000 to 2013 to map: (1) the extent of built human environments, (2) population density, (3) electric infrastructure, (4) crop lands, (5) pasture lands, (6) roadways, (7) railways, and (8) navigable waterways. To facilitate comparison across pressures we placed each human pressure within a 0–10 scale, weighted within that range according to estimates of their relative levels of human pressure following Sanderson and colleagues.[24] The resulting standardized pressures were then summed together to create the standardized human footprint maps for all non-Antarctic land areas. Pressures are not intended to be mutually exclusive, and many will co-occur in the same location. Three pressures (pasture lands, roadways, and railways) only had data from a single time period or have poorly annotated temporal information, and these are treated as static in the human footprint maps.

We used free and open-source GRASS GIS 7.2.2[77] to create a series of scripts that integrate the spatial data on human pressures, yielding 134,064,303 pixels for Earth's terrestrial surface (excluding Antarctica). For any grid cell, the human footprint can range between 0 and 50. We carried out a validation of the human footprint map using visual interpretation of high-resolution imagery across 3,114 × 1 km^2 sample plots randomly located across the Earth's non-Antarctic land areas. We found strong agreement between the human footprint measure of pressure and pressures scored by visual interpretation of high-resolution imagery, with a root-mean-square error of 0.116 and a Kappa statistic of 0.806 ($P < 0.01$). For further details on the validation exercise see Supplemental Experimental Procedures. The following sections (and Table S2) describe in detail the source data for each pressure, the processing steps applied, and the rationale behind the pressure weighting. The code and underlying data for generating these maps is available online at https://doi.org/10.5061/dryad.3tx95x6d9, and can be used to easily regenerate them with updated or alternate datasets, as well as to apply the same methodology at national or regional scales.

Built Environments

Built environments, in the context of the human footprint, are anthropogenic areas that represent urban settings, including buildings, paved land, and urban parks. These environments do not provide viable habitats for many species of conservation concern, nor do they provide high levels of ecosystem services.[78–81] As such, built environments were assigned a pressure score of 10.

To map built environments, we used the Defense Meteorological Satellite Program Operational Line Scanner (DMSP-OLS) composite images which gives the annual average brightness of 30 arc second (~1 km at the equator) pixels in units of digital numbers (DN).[82,83] These data were collected from six different satellite missions over the period 1992 to 2013. We extracted data for the years 2000, 2005, 2010, and 2013, and all datasets were then inter-calibrated to facilitate comparison.[82] Using the DMSP-OLS datasets, we considered pixels to be "built" if they exhibited a calibrated DN greater than 20. This threshold is based on a global analysis of the implications of a range of thresholds for mapped extent of cities,[84] and visual validation against Landsat imagery for 10 cities spread globally.

The DMSP-OLS has limitations for the purpose of mapping human settlements, including hyper sensitivity of the sensors causing detection of overglow adjacent to built environments[84] and bright lights associated with gas flaring from oil production facilities.[85] However, no other data exist to map built environments in a consistent way globally over our time horizon. While more recent satellite platforms launches—such as VIIRS—offer higher spatial resolution and greater light sensitivity[86] than DMSP-OLS, they are not presently comparable or integrated across the temporal range we required.

Population Density

The intensity of human pressure on the environment is often associated with proximity to human populations, such as human disturbance, hunting, and the persecution of non-desired species.[87] Even low-density human populations with limited technology and development can have significant impacts on biodiversity.[88,89]

We incorporated human population density using the Gridded Population of the World dataset developed by the Center for International Earth Science

Information Network.[90] The dataset provides a 1 km^2 gridded summary of population census data for the years 2000, 2005, 2010, and 2013. We used linearly interpolated densities for year 2013 from data for years 2010 and 2015. For all locations with more than 1,000 people km^{-2}, we assigned a pressure score of 10. For more sparsely populated areas with densities lower than 1,000 people km^{-2}, we logarithmically scaled the pressure score using,

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

Human population density is scored in this way under the assumption that the pressures people induce on their local natural systems increase logarithmically with increasing population density, and saturate at a level of 1,000 people km^{-2}.

Nighttime Lights

The high sensitivity of the DMSP-OLS[83] dataset provides a means for mapping the sparser electric infrastructure typical of more rural and suburban areas. In 2009, 79% of the lights registered in the DMSP-OLS dataset had a DN value of less than 20, and are therefore not included in our ''built environments'' layers. However, these lower DN values are often important human infrastructures, such as rural housing or working landscapes, with associated pressures on natural environments.

To include these pressures, we used the inter-calibrated DMSP-OLS layers[82,83,91] used for the mapping of built environments. The 2013 calibration parameters were conveyed through personal communications from the creators of the dataset, and are not yet published. The equations for inter-calibrating across years are second-order quadratics trained using data from Sicily, which was chosen as it had negligible infrastructure change over this period and where DN values average roughly 14.[83] For our purposes, DN values of 6 or less where excluded from consideration before calibration of data, as the shape of the quadratic function leads to severe distortion of very low DN values. The inter-calibrated DN data from 2000 were then rescaled using an equal quantile approach into a 0–10 scale. To scale the data, we divided the calibrated night light data into 10 equal sample bins (each bin with a DN greater than 1 contains the same number of pixels) based on the DN values and then assigned them scores of 1 through 10, starting with the lowest DN bin. DN values of 0 were assigned a score of 0. The thresholds used to bin the 2000 data were then used to convert the 2005, 2010, and 2013 data into a comparable 0–10 scale. We note that the sensors used by NASA to collect nighttime light data changed in 2014, and are incomparable with previous years.

Crop and Pasture Lands

Crop lands vary in their structure from intensely managed monocultures receiving high inputs of pesticides and fertilizers, to mosaic agricultures, such as slash and burn methods that can support intermediate levels of natural values.[92,93] For the purposes of the human footprint, we focused only on intensive agriculture because of its greater direct pressure on the environment, as well as to circumvent the shortcomings of using remotely sensed data to map mosaic agriculture globally, namely the tendency to confound agriculture mosaics with natural woodland and savannah ecosystems.[94]

Spatial data on remotely sensed agriculture extent were extracted from the MERIS CCI Landcover annual dataset.[95] Although intensive agriculture often results in whole-scale ecosystem conversion, we gave it a pressure score of 7, which is lower than built environments because of their less impervious cover.

Pasture lands cover 22% of the Earth's land base or almost twice that of agricultural crop,[96] making them the most extensive direct human pressure on the environment. Land grazed by domesticated herbivores is often degraded through a combination of fencing, intensive browsing, soil compaction, invasive grasses and other species, and altered fire regimes.[97] We mapped grazing lands for the year 2000 using a spatial dataset that combines agricultural census data with satellite-derived land cover to map pasture extent.[96] While the pasture data are primarily a static dataset, we updated it using the land use exclusion principles that urban, crops, and pasture cannot co-occur, and that these land uses exclude one another following the listed order. As the crop and urban layers are dynamic, they were used to derive a modified pasture layer in each time period. We assigned pasture a pressure score of 4, which was then scaled from 0 to 4 using the percent pasture for each 1 km^2 pixel.

Roads and Railways

As one of humanity's most prolific linear infrastructures, roads are an important direct driver of habitat conversion.[98] Beyond simply reducing the extent of suitable habitat, roads can act as population sinks for many species through traffic-induced mortality.[99] Roads also fragment otherwise contiguous blocks of habitat, and create edge effects, such as reduced humidity[100] and increased fire frequency that reach well beyond the road's immediate footprint.[101] Finally, roads provide conduits for humans to access nature, bringing hunters and nature users into otherwise wilderness locations.[102]

Data from OpenStreetMaps (OSM) on roads and railways was extracted from the global OSM planet database.[103] We include all categories of tagged highway in the OSM planet database. OSM is a volunteer-driven, open-source global mapping project that has grown enormously in spatial completeness since its inception in 2004.[104] The volume and coverage of global transportation networks in the OSM database has far surpassed previously available roads data (e.g., gRoads)[105] that was used in earlier iterations of the human footprint;[23] however, the OSM dataset still does not provide full coverage outside of urban areas in some global regions, notably in central Africa, at the time of data extraction. Therefore, to benefit both from the larger OSM database while maintaining road coverages in regions that are currently poorly mapped in OSM, we merged the OSM data with gRoads data. The merged dataset performed best globally when we validated the three data layers (gRoads only, OSM only, and the union of gRoads/OSM).

We mapped the direct and indirect influence of roads by assigning a pressure score of 8 for 0.5 km out for either side of roads, and access pressures were awarded a score of 4 at 0.5 km and decaying exponentially out to 15 km either side of the road. While railways are an important component of our global transport system, their pressure on the environment differs in nature from that of our road networks. By modifying a linear swath of habitat, railways exert direct pressure where they are constructed, similar to roads. However, as passengers seldom disembark from trains in places other than rail stations, railways do not provide a means of accessing the natural environments along their borders. The direct pressure of railways were assigned a pressure score of 8 for a distance of 0.5 km on either side of the railway. We exclude railways tagged as abandoned or disused.

Importantly, neither gRoads nor OSM datasets provide true and comprehensive temporal information (gRoads not at all); as such, both datasets were used in their most up-to-date version in all time periods considered.

Navigable Waterways

Like roads, coastlines and navigable rivers act as conduits for people to access nature. While all coastlines are theoretically navigable, for the purposes of the human footprint we only considered coasts[106] as navigable for 80 km either direction of signs of a human settlement, which were mapped as a night lights signal with a DN[83] greater than 6 within 4 km of the coast. We chose 80 km as an approximation of the distance a vessel can travel and return during daylight hours. As new settlements can arise to make new sections of coast navigable, coastal layers were generated for the years 2000, 2005, 2010, and 2013.

Large lakes can act essentially as inland seas, with their coasts frequently plied by trade and harvest vessels. Based on their size and visually identified shipping traffic and shore side settlements, we treated the great lakes of North America, Lake Nicaragua, Lake Titicaca in South America, Lakes Onega and Peipus in Russia, Lakes Balkash and Issyk Kul in Kazakhstan, and Lakes Victoria, Tanganyika, and Malawi in Africa as we did navigable marine coasts.

Rivers were considered as navigable if their depth was greater than 2 m and there were signs of night-time lights (DN $\geq$ 6) within 4 km of their banks, or if contiguous with a navigable coast or large inland lake, and then for a distance of 80 km or until stream depth is likely to prevent boat traffic. To map rivers and their depth we used the hydrosheds (hydrological data and maps based on shuttle elevation derivatives at multiple scales)[107] dataset on stream discharge, and the following formulae:[108,109] and

$$\text{stream width} = 8.1 \times (\text{discharge } [m^3/s])\ 0.58 \quad \text{(Equation 2)}$$

and

$$\text{velocity} = 4.0 \times (\text{discharge } [m^3/s])\ 0.6/(\text{width}[m]) \quad \text{(Equation 3)}$$

and

$$\text{cross-sectional area} = \text{discharge/velocity} \quad \text{(Equation 4)}$$

$$\text{depth} = 1.5 \times \text{area/width} \quad \text{(Equation 5)}$$

Assuming Second-Order Parabola as Channel Shape

Navigable river layers were created for the years 2000, 2005, 2010, and 2013, and combined with the navigable coasts and inland seas layers for the same years to create the final navigable waterway layers. The access pressure from navigable water bodies were awarded a score of 4 adjacent to the water body, decaying exponentially out to 15 km.

Defining Low-Pressure Areas and Wilderness

We defined intact areas with low human pressure as a human footprint value of <4, and the areas of high human pressure, or "damaged" areas, as ≥ 4. This value of ≥ 4 equates to a human pressure score equal to pasture lands, representing a reasonable approximation of when anthropogenic land conversion has occurred to an extent that the land can be considered human-dominated and no longer "natural." This threshold, which is considered significant at the landscape level,[25] is also the point where species are far more likely to be threatened by habitat loss.[12]

Within the intact state, we defined areas that are pressure free (i.e., free from pressures captured by the human footprint), or wilderness, as a human footprint value of <1, following previous global wilderness assessments.[10] For our definition of wilderness we are referring to the least degraded end of the human footprint spectrum, which, importantly, does not exclude indigenous peoples and communities, who have been part of wilderness areas for millennia.[10] We defined wilderness because it increasingly holds special importance in global policy dialogue, as they contain the highest densities of Earth's biomass, remaining intact mega-faunal assemblages, provide life-supporting ecosystem services, act as controls against which to measure planetary health, provide the last strongholds for many of the world's languages, and have spiritual and cultural value for many of the world's people of many religions.[7,8,110,111]

Units of Analysis

Biomes and ecoregions are ecologically distinct geographical units that reflect the distributions of a broad range of fauna and flora across the entire planet.[27] These entities are now critical for policy and decision makers, being considered core units of reporting in global treaties, and as such can direct legislation, management, and conservation efforts toward crisis locations and ecosystems.[6,30,31,112,113] We use biomes and ecoregions described by Olson and colleagues in 2001[27] to define terrestrial biomes and ecoregions, excluding Lakes and Rock and Ice. We excluded ecoregions that either fell within the Lakes, Rock, and Ice biomes or were not covered by the human footprint. World borders were described by Sandvik (2009),[114] both datasets are freely downloadable.

Assessing Human Footprint Change

We calculated transitions in levels of human pressure by first assessing human footprint scores for the year 2000, then identified pixels that had changed to a different intensity through to the year 2013. We assume that once a pixel has moved from a score of 0 (a wilderness state), it cannot return to this condition as, by definition, once transformed an area is no longer wilderness.[8,115] Therefore, any pixel that was <1 in 2013, but greater than 1 in any other year, was given a value of 1 so that it is considered intact land rather than wilderness. All other comparisons directly report changes between 2000 and 2013, including positive changes when a pixel has a lower human footprint value in the year 2013 than it did in the year 2000. We assess both total area and proportional losses, as smaller losses in smaller units may potentially be more significant to those unique assemblages as large ones.[116] In addition to calculating the overall state of biomes and ecoregions for the years 2000 and 2013, we calculated the state for each time period in the human footprint dataset (2000, 2005, 2010, and 2013). All spatial analyses were carried out using ArcMap 10.5.[117] We report on values rounded to the nearest 10 throughout for readability.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.oneear.2020.08.009.

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AUTHOR CONTRIBUTIONS

J.E.M.W. conceived the idea, and B.A.W. and J.E.M.W. designed the research. B.A.W. carried out the analysis, supported by J.A.R., and B.A.W. led the writing of the manuscript. O.V. and S.C.A. created the updated human footprint maps with the support of J.E., S.J.G., A.J.H., P.J., R.P., S.R.-B., C.S., and A.L.S.V. All authors contributed to and edited the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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One Earth, Volume *3*

Supplemental Information

Change in Terrestrial Human Footprint Drives Continued Loss of Intact Ecosystems

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Supplemental Experimental Procedures

Technical validation for the human footprint

High resolution images were used to visually interpret human pressures in 3460 × 1 km^2 sample plots randomly located across the Earth's non-Antarctic land areas. Images for these plots were obtained from World Imagery[1], which provides one meter or better satellite and aerial imagery in many parts of the world and lower resolution satellite imagery worldwide. The map features 0.3m resolution imagery across the continental United States and parts of Western Europe, as well as many parts of the world, with concentrations in South America, Eastern Europe, India, Japan, the Middle East and Northern Africa, Southern Africa, Australia, and New Zealand. The imagery used for the validation plots had a median resolution of 0.5 meters and a median acquisition year of 2010. Therefore, only the 2010 map underwent validation.

For the visual interpretation, the extent of built environments, crop lands, pasture lands, roads, human settlements, infrastructures and navigable waterways, were recorded using a standard key for identifying these features (See Supplementary Appendix 1 of Venter et al. 2016[2]). Shape, size, texture and colour of features in the imagery were important characteristics for identifying human pressures on the environment. Interpretations were also marked as 'certain' or 'uncertain', and the year and resolution of the interpreted image was recorded. The 346 'uncertain' plots were discarded, leaving 3114 validation plots. In general, plots were classified as 'uncertain' for two reasons; either because cloud cover obscured the image, or because only medium resolution (15 m) imagery was available for the plot, preventing accurate interpretation of the image. The human footprint score for each plot was determined in ArcGIS, and the visual and Human Footprint scores were then normalized to a

0–1 scale. As we only retained plots for which visual interpretations of the images were determined to be 'certain', we consider the visual score to be the true state of in-situ pressures for the plots.

Two statistics were used to determine Human Footprint performance, root mean squared error (RMSE)[3] and the Cohen kappa statistic of agreement[4]. The RMSE is a dimensioned (expresses average error in the units of variable of interest) error metric for numerical predictions, and tends to heavily punish large errors. The Kappa statistic expresses the agreement between two categorical datasets corrected for the expected agreement, which is based on a random allocation given the relative class sizes. When calculating the kappa statistic, the Human Footprint score was considered as a match to the visual score if they were within 20% of one another on the 0–1 scale.

There is strong agreement between the Human Footprint measure of pressure and pressures scored by visual interpretation of high resolution imagery. The RMSE for the 3114 validation plots was 0.116 on the normalized 0-1 scale. The Kappa statistic was 0.806 ($P<0.01$), also indicating strong agreement between the Human Footprint and the validation dataset. Of the 3114 1 km^2 validation plots, the Human Footprint scored 143 of them 20% higher than the visual score and 140 of them 20% lower, indicating a balance between overestimation and underestimation of pressures. The remaining 2831 plots (90.9%) were within 20% agreement. The Kappa statistic measure of agreement is sensitive to the threshold used to consider plots as a 'match'. If we apply a more stringent threshold for agreement of within 15% of one another, the Kappa statistic falls to 0.645 (moderate agreement), and if we apply a less stringent threshold of within 25%, the Kappa statistic increases to 0.906 (almost perfect). While agreement is generally strong, there is some geographic variation in the RMSE results comparing the Human Footprint scores and those derived from visual interpretation. By calculating RMSE for all biomes that contain at least 100 of the 3114 sample plots, we found that agreement was strongest in Montane grasslands biome and the Temperate grasslands, savannah and shrubs biome. Agreement was weakest in the Tropical and subtropical moist broadleaf forests and the Deserts and xeric shrublands biomes.

Table S1 - Root Mean Square Errors results comparing the Human Footprint scores with 3114 validation plots globally, and for biomes with at least 100 plots within them.

Region	**RMSE**
RMSE Global	0.115551
RMSE Boreal	0.110667
RMSE Deserts and xeric shrublands	0.124895
RMSE Montane grasslands	0.093302
RMSE Temperate broadleaf and mixed forests	0.112171
RMSE Temperate grasslands, savannahs, and shrublands	0.108985
RMSE Tropical and subtropical grasslands, savannahs, and shrublands	0.109195
RMSE Tropical and subtropical moist broadleaf forests	0.116537
RMSE Tundra	0.112789

Table S2 - Summary of the data and methodology used to create the human footprint maps for the years 2000, 2005, 2010 and 2013

Description	Source	Data used	Temporal range	Source Resolution	Data processing	Outputs used in Human Footprint
Built environments	[5–7], personal comms for year 2013 coefficients.	Average, stable lights, & cloud free coverages	2000 – 2013	30 arc second, ~1 km at equator	1) Preprocessing to reclass all digital number (DN) values < 6 to 0 2) Inter-calibrate across range of years 3) Re-project and resample to 1 km raster basemap (Mollweide projection) using a bilinear interpolation methodology 4) Convert to binary map of areas exhibiting a DN equal to or above 20 5) Assign these areas a pressure score of 10.	built_areas2000.tif, built_areas2005.tif, built_areas2010.tif, built_areas2013.tif
Population density	[8]	Gridded Population of the World (GPWv4), density grids	2000, 2005, 2010, 2015	30 arc second, ~1 km at equator	1) Reproject and resample to 1 km raster basemap (Mollweide projection) 3) Linearly interpolate values for year 2013 from 2010/2015 data 2) Assign pressure score using equation (1) in methods	popden2000.tif, popden2005.tif, popden2010.tif, popden2013.tif
Night-time lights	[5–7]	Average, stable lights, & cloud free coverages	2000 – 2013	30 arc second, ~1 km at equator	1) Intercalibrate across years. 2) Reproject and resample to 1 km raster basemap (Mollweide projection.) 3) Create 10 equal quantile bins for year 2000. 4) Assign pressure scores to bins from 0–10, for 2000, and using the same DN thresholds for all other years.	nightlights2000.tif, nightlights2005.tif, nightlights2010.tif, nightlights2013.tif
Crop lands	[9]	CCI Land cover	2000 – 2013	300 m	1) Reproject and resample to 1 km raster basemap (using mode resampling) (Mollweide projection) 2) Convert to binary map showing only crop lands	crops_meris2000.tif, crops_meris2005.tif, crops_meris2010.tif, crops_meris2013.tif

					(pixels classified as crops – e.g., 10, 11, 12, 20) 3) Reclass all areas already mapped as built to 0. 4) Assign crop lands a pressure score of 7	
Pasture lands	[10]	M3-Pasture data	2000	5 min, ~10 km at equator	1) Reproject and resample to 1 km raster basemap (Mollweide projection) 2) Reclass all areas already mapped as built or crop lands to 0 3) Assign pressure score of 4, weighted by percent pasture lands	pastures2000.tif, pastures2005.tif, pastures2010.tif, pastures2013.tif
Roads	[8,11]	OSM roads (Planet.osm dated 29 May 2017); gRoads	2017	Vector data	1) Extract features from OSM where the tag 'highway' includes values 'motorway*', 'primary*', 'residential*', 'secondary*', 'tertiary*', 'trunk*', 'track*', or 'unclassified*' 2) Merge two datasets 3) Reproject and covert to 1 km raster basemap (Mollweide projection) 4) Assign pressure score of 8 to roaded pixels, and 4 to adjacent pixels, exponentially decaying to 0 at a distance of 15 km	roads.tif
Railways	[11]	Railways (Planet.osm dated 29 May 2017)	2017	Vector data	1) Extract features from OSM where the tag 'railway' does not include values 'abandoned' or 'disused' 2) Reproject and covert to 1 km raster basemap (Mollweide projection) 2) Assign pressure score of 8 to rail pixels	railways.tif
Navigable waterways	[12]	HydroSHEDS, stream discharge	No timeframe	3 arc second, ~100 m at equator	1) Reproject and covert to 1 km raster basemap (Mollweide projection) 2) Use equations 2, 3, and 4 to determine stream depth 3) Exclude all stream reaches with water depth less than 2 m deep 4) Exclude all reaches	navwaters2000.tif, navwaters2005.tif, navwaters2010.tif, navwaters2013.tif

		not within 80 km of a stream bank which is within 4 km of a pixel with a DN>4, in the years 2000, 2005, 2010, or 2013 5) Add coastlines within 80 km of a coastal bank which is within 4 km of a pixel with a DN>4, in years 2000, 2005, 2010, or 2015 6) Assign pressure score of 4 to adjacent pixels, exponentially decaying to 0 at distance of 15 km	

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