Global Environmental Change 63 (2020) 102084

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

A global assessment of the human pressure on the world's lakes

Christos Mammides*

Guangxi Key Laboratory of Forest Ecology and Conservation, College of Forestry, Guangxi University, Daxuedonglu 100, Nanning, 530004, China

ARTICLE INFO

Keywords:
Biodiversity Conservation
Human Footprint Index
Human Modification Index
Population Densities
Protected Areas
Waterbodies

ABSTRACT

Millions of humans across the globe depend on lakes for numerous ecosystem services. Furthermore, humans use lakes as a food source and for a multitude of economic activities. Lakes are also essential to a plethora of taxa that rely on them for survival. Yet, despite the importance of lakes, we still lack an assessment of the extent lakes worldwide are being influenced by anthropogenic activities. In this study, I use the global database of lakes, the human footprint index from 1993 and 2009, and the more recent human modification index to measure the human pressure on the world's lakes. I found that one-third of the lakes are under considerable pressure. However, during the 16-year period examined, human pressure had increased in only 16% of the lakes, while it remained unchanged in 66%, and has even decreased in 18%. These patterns, though, were not uniform across the globe. Many lakes within tropical and subtropical regions, particularly in Africa—but also in South America and Asia—experienced sizeable increases in human pressure. Moreover, the percentage of lakes within Key Biodiversity Areas in which the human pressure had increased was three times larger the overall number. Although increases in human pressure were lower in lakes within protected areas—compared to lakes outside—there were numerous exceptions, particularly in the tropics. To protect biodiverse lakes in regions where human pressure is intensifying, it is important to improve the effectiveness of the protected areas and to address the socioeconomic factors driving the increases in human pressure.

1. Introduction

Humans are altering the planet at such a rate that many scientists are calling for the current geological era to be renamed as the 'Anthropocene' (Corlett, 2015), meaning the human epoch. The modification of the planet's biophysical environment (Corlett, 2015; Venter et al., 2016a) is affecting the world's ecosystems and its biodiversity. Recent reports show that more than 75% of the planet is now affected by measurable levels of human impact (Kennedy et al., 2019; Venter et al., 2016a). Much of this impact occurs within the planet's most biodiverse areas (Kennedy et al., 2019; Venter et al., 2016a; Watson et al., 2016), including protected areas (Anderson and Mammides, 2020; Jones et al., 2018).

Freshwater systems, including lakes (Brinson and Malvárez, 2002), may be affected the most (Abell, 2002; Abell et al., 2008; Carpenter et al., 2011; Dudgeon, 2014; Reid et al., 2019). Lakes, particularly large lakes, hold most of the planet's liquid surface freshwater (Carpenter et al., 2011; Vadeboncoeur et al., 2011) and provide a range of key ecosystem services. Among other things, humans rely on lakes for food, clean water, flood control, navigation, and numerous economic activities (Brönmark and Hansson, 2002; Carpenter et al., 2011; Vadeboncoeur et al., 2011). Lakes are also important to many taxa (Vadeboncoeur et al., 2011), including plants, invertebrates, fish, and birds, which depend on them either fully or partially for survival (Butchart et al., 2010). For instance, according to Vadeboncoeur et al. (2011), the world's largest 14 lakes support approximately 15% of the global fish diversity and 3% of insects, mollusks, and crustaceans. Lake Tanganyika, alone, supports more than 630 endemic animal species (Abell et al., 2008).

Lakes, however, are being degraded continuously (Brönmark and Hansson, 2002; Lewis, 2000; Vadeboncoeur et al., 2011). Information from local and regional assessments suggests that lakes are being affected by multiple anthropogenic activities (Otiang'a-Owiti and Oswe, 2007), many of which threaten the lakes' sustainability (Borre et al., 2001; Lewis, 2000). Anthropogenic pollution, for instance, caused by intensive agriculture and urbanization, often results in eutrophication and acidification, and represents a major threat for many of the world's lakes (Beeton, 2002). Overexploitation, including overfishing, driven by increasing human population densities (Otiang'a-Owiti and Oswe, 2007), results in severe biodiversity declines (Beeton, 2002). Exotic species, often introduced for subsistence and commercial purposes, such as the Nile Perch in Lake Victoria

* Corresponding author.
E-mail address: cmammides@outlook.com.

https://doi.org/10.1016/j.gloenvcha.2020.102084
Received 9 February 2019; Received in revised form 3 March 2020; Accepted 30 March 2020

(Beeton, 2002), exacerbate further the decline of native species. Many lakes are being drained (Brönmark and Hansson, 2002) or have their shoreline modified—to reclaim land for human settlements and agricultural activities—affecting littoral biodiversity (Vadeboncoeur et al., 2011) and causing cascading effects (Porst et al., 2019; Radomski and Goeman, 2001; Zhang et al., 2017).

Despite the importance of lakes, and the numerous threats they are facing, we are still lacking detailed information about many of the world's lakes—including information about the extent they are being influenced by human activities (Abell, 2002)—especially in Africa, the Neotropics, and Oceania (Davidson, 2014). A global assessment of the human pressure on the world's lakes is thus essential to allow us to understand better the current patterns of anthropogenic disturbance on lakes (Davidson, 2014). The recent availability of globally consistent datasets on lakes (Messager et al., 2016) and human pressures (Kennedy et al., 2019; Venter et al., 2016b) make this a timely topic to study.

Indices of human pressures have been used successfully by researchers to assess the environmental and ecological condition of natural systems (Gergel et al., 2002; Jørgensen et al., 2016), including lakes and other waterbodies (Lomnicky et al., 2019; Reiss et al., 2014). Brown and Vivas (2005), for instance, created the Landscape Development Index (LDI), which can be used to assess the condition of watersheds and waterbodies by measuring a number of anthropogenic pressures, including agriculture (e.g., the extent of croplands and pastures), built-up areas, and roads. Using data from 114 wetlands in Florida, USA, Brown and Vivas (2005) showed that LDI correlated with water quality—particularly nitrogen and phosphorous loads. They also showed that LDI correlated with the "Wetland Rapid Assessment Procedure Score", which is a qualitative measure of the ecological condition of the waterbodies that takes into account multiple factors, such as wildlife presence, vegetation cover, and water pollution (Brown and Vivas, 2005). Other researchers have also shown that analogous indices—that incorporate a range of pressures, e.g., human settlements, agriculture, and transportation infrastructure—can serve as good proxies for key aspects associated with the ecological condition of waterbodies (Beuel et al., 2016; Chen and Lin, 2011; Gergel et al., 2002; Reiss et al., 2014; Rooney et al., 2012; Wardrop et al., 2016).

At the global level, two such indices are available, which can be used to measure human pressure on natural systems: (1) the human footprint index (Venter et al., 2016b), and (2) the human modification index (Kennedy et al., 2019). The indices include a range of pressures (8 and 13 respectively), which individually have been shown to affect significantly natural systems, including lakes (Table 1). In this study, I use the database of the world's lakes (Messager et al., 2016), the human footprint index from 1993 and 2009 (Venter et al., 2016b), and the human modification index from 2016 (Kennedy et al., 2019) to answer a series of key questions related to the pressure humans exert on lakes worldwide: (1) What proportion of the world's lakes is under considerable human pressure? (2) To what extent has human pressure increased within the world's lakes? (3) Which biomes and geographical regions have been affected the most? (4) Are biodiverse lakes more likely to experience increases in human pressure? (5) Are protected areas successful in mitigating human pressure within the world's lakes? This is the first study to address these questions at a global level.

2. Methods

2.1. Data collection

To answer the above questions, I used the database of the world's lakes, available online at https://www.hydrosheds.org/page/hydrolakes. The database was compiled by Messager et al. (2016), using multiple sources, and is considered to be one of the most authoritative datasets on the spatial distribution of the lakes across the globe. Among other information, the database includes each lake's boundaries, elevation and slope, and the country in which it is located. To identify each lake's geographical region, I used the spatial boundaries of the world's continents available by ESRI at https://www.arcgis.com/home/item.html?id=a3cb207855b348a297ab85261743351d.

Likewise, to identify each lake's biome, I used the spatial layer of the world's biomes (Olson et al., 2001), available at https://www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world.

The human footprint index was compiled by Venter et al. (2016b) and it is a composite measure of the human pressure across the globe at a resolution of 1 km^2. It was built using eight different human pressures: (1) built-up areas, (2) cropland, (3) pasture, (4) human population density, (5) nighttime lights, (6) railways, (7) roads, and (8) navigable waterways (Venter et al., 2016b). Each pressure was standardized and given a score according to its potential threat to natural systems (Sanderson et al., 2002; Venter et al., 2016a). The human footprint index ranges from 0 (i.e., no human pressure) to 50 and it is available for two different years (i.e., 1993 and 2009), thus appropriate for temporal analyses (Venter et al., 2016a). Moreover, each pressure is also available separately and therefore it is possible to measure its unique contribution to the overall human footprint and how that varies across geographical regions.

The human modification index ranges from 0 to 1 (Kennedy et al., 2019) and it serves a similar purpose as the human footprint index (i.e., to measure the human pressure on natural systems across the globe at a resolution of 1 km^2). However, it has two advantages over the human footprint index. First, it includes more pressures and therefore it is more encompassing (Table 1). Specifically, it includes the following thirteen pressures, which can be grouped into five main categories: (i) human settlements (1. population densities, 2. built-up areas), (ii) agriculture (3. cropland, 4. livestock), (iii) transportation (5. major roads, 6. minor roads, 7. two tracks, 8. railroads), (iv) mining and energy production (9. mining sites, 10. oil wells, 11. wind turbines), (v) electrical infrastructure (12. powerlines, 13. nighttime lights). In other words, the main difference between the two indices in terms of their underlying datasets is that the human modification index includes pressures related to mining and energy production activities, it measures the pressure from roads in a more detailed manner (by including also minor roads and two tracks, using the OpenStreetMap data), and it includes powerlines while it excludes navigable waterways (Kennedy et al., 2019).

The second advantage of the human modification index is that it is based on more recent data and therefore it probably represents better the current situation on the ground. The median year of the datasets underlying the human modification index is 2016 (Kennedy et al., 2019)—compared to 2009, which is the corresponding year for the datasets underlying the most recent human footprint index (Venter et al., 2016b). A disadvantage, however, of the human modification index is that it is only available for one time period and therefore it is not suitable for exploring temporal patterns, i.e., changes in human pressure over time. For that specific purpose, the human footprint index is still preferred (Jones et al., 2018; Venter et al., 2016a) and therefore used in the related analyses described below.

2.2. Measuring human pressure within lakes

To measure the mean values of the human modification and human footprint indices within each lake, I used the zonal statistics tool in ArcMap (version 10.2). Human modification values were mainly used to assess the current levels of human pressure within the world's lakes, while the human footprint values were used to assess the changes in human pressure within the lakes during the 16-year period for which the index is available, i.e., between 1993 and 2009 (Venter et al., 2016a). Note that because the most recent human footprint index dates back to approximately 10 years ago, I also used the data on human population densities, on which the index is based (Venter et al., 2016b)—and which are now available for the years 2000 to 2020 (Gridded Population of the Worlds, v4; CIESIN, 2018)—to assess the

Table 1
Indicative impacts on lakes caused by each of the pressures included in the human modification and human footprint indices.

Human pressure	Indicative impact on lakes	Reference
Human settlements (population density, built-up areas)	• Land drainage and reclamation for human settlements leading to: (i) lake degradation and habitat loss, (ii) disruption of hydrological and other processes (e.g., nutrient cycling), (iii) loss of ecosystem functioning and services, (iii) loss of biodiversity. • Pollution resulting from domestic and commercial discharges. • Overexploitation of aquatic resources (e.g., fish). • Water abstraction for domestic and commercial uses leading to disruption of hydrological and other processes. • Introduction of non-native species resulting in loss of biodiversity.	Beeton, 2002; Carpenter et al., 2011; Cui et al., 2016; Dudgeon et al., 2006; Jia et al., 2018; Porst et al., 2019; Saunders et al., 2002
Agriculture (croplands, pastures)	• Land drainage and reclamation for agriculture. • Pollution resulting from nutrient enriched runoff (e.g., from manure use and fertilizers). • Water abstraction for crop irrigation and livestock production.	Beeton, 2002; Sievers et al., 2018
Transportation (roads, railways, waterways†)	• Land drainage and reclamation for road and railway construction. • Pollution resulting from stormwater runoff due to impervious surfaces. • Noise pollution caused by traffic leading to negative impacts on biodiversity (e.g., affecting the fitness and survival of birds, amphibians, and other taxa). • Increased access to lakes leading to further increases in human presence and disturbance.	Reid et al., 2019; Sievers et al., 2018; Søndergaard and Jeppesen, 2007
Mining and energy production (mining‡, oil wells‡, wind turbines‡)	• Lake degradation and habitat loss. • Pollution caused by heavy metals and other toxic substances leading to: (i) reduced water quality, and (ii) loss of biodiversity (e.g., loss of birds, fish, amphibians, macroinvertebrates, and macrophytes).	Dudgeon et al., 2006; Sievers et al., 2018
Electrical infrastructure (powerlines‡, nighttime lights)	• Lake degradation and habitat loss. • Light pollution leading to negative impacts on biodiversity (e.g., affecting the fitness and survival of birds, fish, amphibians, and other taxa)	Reid et al., 2019

† Included only in human footprint index only.
‡ Included only in human modification index.

extent to which the patterns in changes in human pressure are still applicable today. To achieve this, I followed a three-step approach. First, I measured the correlation between the human footprint index in 2009 and the human population densities in 2010 within each lake. This way I was able to confirm that the human population densities are a suitable proxy for the human footprint within the lakes. Then, I measured the change in human population densities within each lake between the years 2000 and 2010. This was necessary in order to verify that the changes in human population densities reflected the changes in human pressure found when using the human footprint index. Lastly, I measured the changes in human population densities between the years 2010 and 2020, to assess if those patterns have remained the same. In accordance with the methods of Venter et al., (2016b), I converted human population densities into a score ranging from 1 to 10, using the following formula: score = 3.333 x log (inhabitants/km^2+1). As in Venter et al. (2016b), I assigned a score of 10 to all pixels with more than 1000 inhabitants/km^2.

To avoid inaccuracies related to the resolution of the data used (i.e., 1 km^2), and in consistency with the methods of other studies (e.g., Anderson and Mammides, 2020; Jones et al., 2018), I excluded from the analysis all lakes < 5 km^2. When using the human modification index (Kennedy et al., 2019), I considered lakes to be under "considerable human pressure" if they had a mean value larger than 0.1. Kennedy et al. (2019) defined values between 0 and 0.1 as "low" human pressure and values above that as "moderate" to "very high", using the following scale: $0.1 < HMI \leq 0.4$ moderate, $0.4 < HMI \leq 0.7$ high, $0.7 < HMI \leq 1.0$ very high. When using the human footprint index, I calculated the number of lakes under "considerable human pressure" using the definition of Jones et al. (2018), who considered values ≥ 4 as representing "intense human pressure". It should be clarified here that what constitutes "considerable human pressure" is likely to vary from lake to lake—at least to a certain extent. For example, similar levels of agricultural intensity may affect lakes dissimilarly if different agricultural practices and regulations are followed (Zhang et al., 2017). However, the emerging findings from the related literature suggest that the threshold values used in previous studies to define human pressure are appropriate for such global analysis (Di Marco et al., 2019, 2018; Tucker et al., 2018). For example, Di Marco et al. (2018) found that human footprint values as low as 3 can increase significantly the extinction risk of mammals across the globe.

Parts of many of the lakes did not have a human modification or human footprint value (on average 20% and 6% of the lakes' surface area respectively). Therefore, those parts were not included in the calculations of the mean human footprint and modification indices. They mostly represented the deep limnetic zones of large lakes (as opposed to their littoral zones, which are the most biodiverse; Vadeboncoeur et al., 2011). Although the lack of these data does not affect in any way the calculations regarding the change in human footprint from 1993 to 2009, it could potentially affect the percentage of lakes under human pressure, if one assumes that the missing data could represent no human footprint or no modification (i.e., a value of 0). However, this assumption would be invalid, since lakes with a high human pressure within their littoral zones are unlikely to be free of human influence within their limnetic zones. On a related note, one could argue that even if the human pressure within the boundaries of the lakes is relatively low, lakes could still be under considerable human pressure if their surrounding areas are highly threatened by anthropogenic activities. To address this possibility, I calculated also the mean human footprint and modification values within a distance of 1 km from each lake.

2.3. Measuring human pressure within lakes in Key Biodiversity Areas and protected areas

To identify which lakes were located within Key Biodiversity Areas (KBA), I used the spatial boundaries of KBAs (Langhammer et al., 2018), obtained from Birdlife International following a request. To assess whether the increase in human footprint was lower within lakes in protected areas compared to lakes outside protected areas, I used the Word Database of Protected Areas (October 2018 version) available at

Table 2
Distribution of the world's lakes within each geographical region. The percentage of lakes in which the human footprint index had increased, remained unchanged, and decreased between the years 1993 and 2009 is also shown, along with the percentage of lakes under considerable human pressure, measured using the human footprint (HF) and the human modification (HM) indices.

Geographical region	Number of lakes	Increase in HF (%)	No change in HF (%)	Decrease in HF (%)	Under human pressure HF 1993 (%)	Under human pressure HF 2009 (%)	Under human pressure HM (%)
Africa	870	66.8	15.2	18.0	77.5	84.0	87.9
Asia	8,286	23.0	53.9	23.1	43.3	43.1	42.5
Europe	3,644	18.5	26.9	54.6	61.7	56.9	62.4
North America	18,734	7.0	83.9	9.1	11.6	10.6	12.3
Oceania	868	19.6	72.0	8.4	21.9	21.5	21.7
South America	1,938	47.8	37.0	15.2	45.3	46.2	60.3

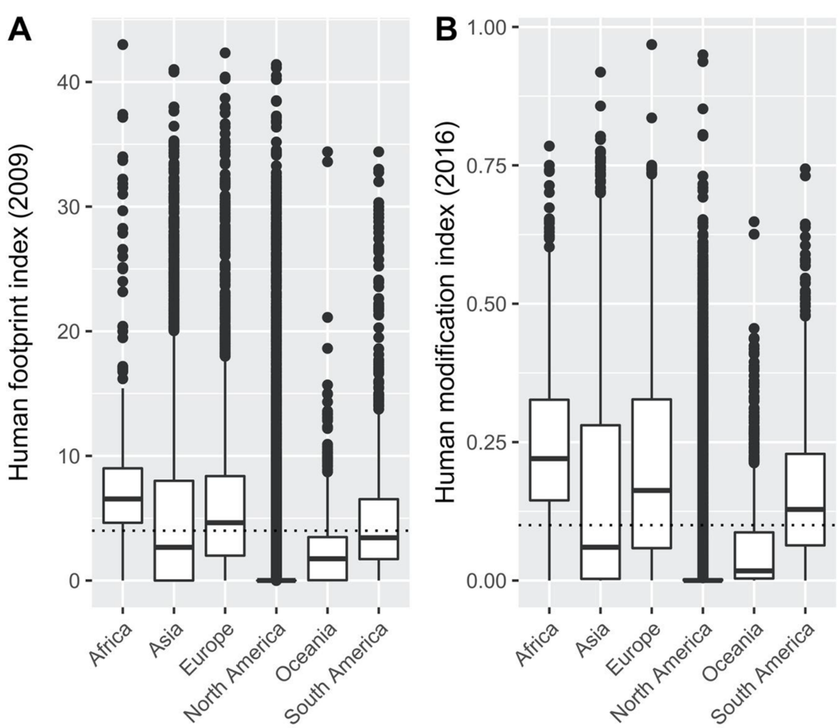

Fig. 1. Human pressure within the lakes in each geographical region measured using (A) the human footprint index, and (B) the human modification index. The dotted horizontal lines indicate the thresholds used to define “considerable human pressure” (i.e., mean human modification value > 0.1 and mean human footprint value ≥ 4).

https://protectedplanet.net/. I only kept in the analysis protected areas established before 1993 to avoid biasing the results by including areas established after the first year for which the human footprint was measured. Approximately 10% of the protected areas in the global database lacked a date of establishment. Following previous studies, I assigned to those areas a random year of establishment (Anderson and Mammides, 2020; Jones et al., 2018), by drawing from the list of establishment years of the rest of the protected areas in that country. I categorized protected areas according to their protection level as follows: (a) strictly protected (IUCN categories I–II), (b) non-strictly protected (IUCN categories III–VI), and (c) areas with no IUCN category reported (Jones et al., 2018; Mammides, 2020).

2.4. Quasi-experimental matching analysis

When evaluating the effectiveness of protected areas, it is important to control for confounding factors that may be driving the observed differences between protected areas and areas outside (Andam et al., 2008; Joppa and Pfaff, 2011; Nelson and Chomitz, 2011). For instance, areas located in isolated regions, at higher elevations, and steeper slopes are less likely to be affected by human activities regardless of whether they are situated within a protected area or not (Joppa and Pfaff, 2009). One can effectively control for such confounding variables using the quasi-experimental matching approach (Andam et al., 2008; Ho et al., 2011; Nelson and Chomitz, 2011).

To create a matched dataset, I first generated a series of randomly placed points within each lake. Specifically, I generated one random point per 5 km^2 of lake area, resulting in total in 330,987 points. Then, for each point, I recorded: (1) its human footprint in 1993 and 2009, (2) its country, geographical region, and biome, and (3) whether it was located inside or outside a protected area (established before 1993). Using the “MatchIt” package (Ho et al., 2011) in R, and the “nearest neighbour” approach (Ho et al., 2011), I matched points within lakes located in protected areas to points in lakes outside protected areas, controlling for elevation, slope, country, and human footprint in 1993 (Anderson and Mammides, 2020). I used the resulting matched dataset, and the Wilcoxon rank test, to compare the change in mean human footprint inside vs. outside protected areas. I ran the analysis separately for each biome (Anderson and Mammides, 2020).

3. Results

Overall, there were 34,469 lakes ≥ 5 km^2 covering a total area of 2,281,609 km^2. Of those, 129 were found outside the range covered by the human footprint and the human modification indices and therefore were excluded from further analysis. The majority of the lakes were located in North America and Asia (54.6% and 24.1% respectively), while 10.6% were located in Europe and 5.6% in South America. The rest were located in Africa and Oceania, 2.5% respectively. Of the total number of lakes, 86.2% were located outside protected areas in 1993,

Table 3
Distribution of the world's lakes within each biome. The percentage of lakes in which the human footprint index had increased, remained unchanged, and decreased between the years 1993 and 2009 is also shown, along with the percentage of lakes under considerable human pressure, measured using the human footprint (HF) and the human modification (HM) indices.

Biome	Number of lakes	Increase in HF (%)	No change in HF (%)	Decrease in HF (%)	Under human pressure HF 1993 (%)	Under human pressure HF 2009 (%)	Under human pressure HM (%)
Tropical and subtropical moist broadleaf forests	1,815	51.7	19.8	28.4	64.8	67.8	75.7
Tropical and subtropical dry broadleaf forests	472	46.6	8.1	45.3	91.5	92.6	96.2
Tropical and subtropical coniferous forests	57	42.1	10.5	47.4	77.2	75.4	71.9
Temperate broadleaf and mixed forests	4,162	32.2	31.4	36.4	64.8	64.2	68.3
Temperate coniferous forests	842	24.6	47.1	28.3	43.6	42.0	41.1
Boreal forests	13,307	5.4	82.1	12.5	9.4	8.3	9.4
Tropical and subtropical grasslands, savannas, and shrublands	897	46.3	34.9	18.8	55.0	56.1	64.0
Temperate grasslands, savannas, and shrublands	2,289	25.2	25.9	48.9	70.6	62.4	75.9
Flooded grasslands and savannas	350	54.0	16.6	29.4	74.0	75.7	84.3
Montane grasslands and shrublands	677	23.6	68.6	7.8	23.2	24.5	21.7
Tundra	7,383	1.8	96.9	1.4	1.9	1.9	1.8
Mediterranean forests, woodlands, and scrub	520	35.2	28.1	36.7	70.2	66.9	73.3
Deserts and xeric shrublands	1,380	29.3	56.9	13.8	47.0	47.4	39.1
Mangroves	130	40.8	32.3	26.9	74.6	73.1	80.8

* 43 lakes were located within the 'rock and ice' biome and another 16 lakes in areas outside those covered by the spatial layer depicting the biomes.

while 13.8% (n = 4,736) were located (either fully or partially) within one or more protected areas. 4.5% of the lakes were located within strictly protected areas, i.e., IUCN categories I and II, 6.2% in non-strictly protected areas (III–VI), and 3.1% in areas with no IUCN category assigned. 710 lakes were located within Key Biodiversity Areas (KBAs).

3.1. Human footprint and human modification values within the world's lakes

In 1993, the mean human footprint within the world's lakes ranged from 0 to 42 (mean = 3.2), with about one-third of the lakes (n = 9,748) being under considerable human pressure (i.e., mean human footprint $\geq$ 4). The corresponding number in 2009 was 9,450 (i.e., smaller by 298). Overall, during the 16-year period examined, the mean human footprint had increased in 16.2% of the world's lakes (n = 5,571), remained unchanged in 65.9% (n = 22,639), and decreased in 17.9% (n = 6,130). The human modification value within the world's lakes ranged from 0 to 0.97 (mean = 0.01), confirming that indeed approximately one-third of the lakes (n = 10,226) are still under considerable human pressure (i.e., mean human modification value > 0.1). The human footprint and modification values within the lakes correlated strongly with the corresponding values within the surrounding areas of the lakes ($\leq$ 1 km), essentially producing the same patterns (r > 0.96; Table A1).

In 1993, the mean human footprint within lakes in KBAs ranged from 0 to 41.5 (mean = 8.7), with 585 of the lakes (i.e., 82.4%) being under considerable human pressure. Human footprint increased in almost half of the lakes in KBAs (47.5%), while it remained unchanged in 16.6% of the lakes and decreased in 35.9% in 2009. The mean human modification value within the lakes in KBAs ranged from 0 to 0.77 (mean = 0.26), with 603 of them (i.e., 84.9% being under considerable human pressure in 2016).

3.2. Human footprint and human modification values within the various geographical regions

The change in mean human footprint varied considerably across the various geographical regions (Table 2). In North America, the human footprint had increased in only 7% of the lakes, while it remained unchanged in 83.9%. Likewise, in Europe and Oceania it had only increased in 18.5% and 19.6% of the lakes respectively (Table 2). In fact, in Europe the human footprint had decreased in 54.6% of the lakes (the highest percentage of reduction across all geographical regions). In contrast, the human footprint increased in two-thirds of the lakes in Africa (66.8%). The corresponding percentages in South America and Asia were 47.8% and 23.0% respectively (Table 2).

Similar patterns were found when examining the changes in human population densities within the lakes (Table A2). First, the correlation between human population densities within the lakes in 2010 and human footprint in 2009 was 0.81—confirming that human population densities are indeed an appropriate proxy for the human footprint within the lakes. Second, the correlation between the percentage of lakes in the six geographical regions in which the human footprint had increased and the percentage of lakes in which the human population densities had increased (between the years 2000 and 2010) was 0.97. The corresponding values for the lakes in which the human footprint had decreased or remain unchanged were 0.99 and 0.95 respectively. Third, the changes in human population densities within the lakes between the years 2010 and 2020 mirrored those found earlier (r > 0.99; Table A2). These findings suggest that the reported patterns regarding the changes in human pressure within the world's lakes between 1993 and 2009 remain the same until today. For instance, the human population densities within most of the lakes in Africa (74.4%) continue to rise (Table A2). In contrast, in North America, the human population densities are increasing in only 4.7% of the lakes. As with the changes

Table 4
Results of the Wilcoxon rank tests comparing the change in mean human footprint (HF) within lakes inside and outside protected areas between the years 1993 and 2009. A positive number indicates that human footprint had increased during the 16-year period examined while a negative number indicates the opposite. The results are based on the matched dataset, generated using the quasi-experimental matching technique, controlling for differences in elevation, slope, country, and mean human footprint in 1993. The number of matched points within each biome is also presented.

Biome	Random points	Matched points	HF change inside	HF change outside	Result	p-value	
Tropical and subtropical moist broadleaf forests	14,354	3,674	−0.18	0.08	0.616	0.538	
Tropical and subtropical dry broadleaf forests	3,274	516	−0.67	0.34	1.536	0.125	
Tropical and subtropical coniferous forests	244	136	0.57	0.32	−1.736	0.083	
Temperate broadleaf and mixed forests	29,262	6,404	−0.37	−0.06	3.692	< 0.001	***
Temperate coniferous forests	5827	1,902	−0.17	−0.05	2.704	0.007	**
Boreal forests	78,329	6,574	−0.09	−0.15	−1.220	0.223	
Tropical and subtropical grasslands, savannas, and shrublands	16,124	2,810	0.10	−0.02	−3.637	< 0.001	***
Temperate grasslands, savannas, and shrublands	22,947	6,024	−0.60	−0.15	2.970	0.003	**
Flooded grasslands and savannas	5360	1,458	0.11	0.16	4.800	< 0.001	***
Montane grasslands and shrublands	10,199	1,098	0.02	−0.02	5.440	< 0.001	***
Tundra	32,995	9,208	−0.01	0.01	−0.235	0.815	
Mediterranean forests, woodlands, and scrub	3047	908	−0.59	−0.28	0.711	0.477	
Deserts and xeric shrublands	26,250	5,020	0.06	−0.04	−1.213	0.225	
Mangroves	749	280	0.63	0.50	−2.556	0.011	*

Table A1
Changes in human footprint within a distance of 1km from each lake between the years 1993 and 2009. Also shown, the percentage of lakes with surrounding areas under considerable human pressure as measured using the human footprint (HF) and the human modification (HM) indices.

Geographical region	Increase in HF (%)	No change in HF (%)	Decrease in HF (%)	Under human pressure HF 1993 (%)	Under human pressure HF 2009 (%)	Under human pressure HM (%)
Africa	70.2	10.7	19.1	82.5	87.9	90.5
Asia	37.2	47.1	15.7	46.9	48.0	45.0
Europe	25.5	19.8	54.7	68.4	64.5	65.5
North America	8.3	81.4	10.3	12.5	11.9	13.2
Oceania	29.4	62.8	7.8	29.1	31.0	24.0
South America	61.4	24.4	14.3	48.6	51.3	68.8

in human footprint (Table 2), Europe has the highest percentage of lakes in which the human population densities are actually decreasing (29%; Table A2).

Regardless of which index was used to measure human pressure (i.e., human footprint vs. human modification), Africa had the highest percentage of lakes—as well as highest proportion of lake area (in km^2)—under considerable human pressure (Fig. 1; Table A3). Europe and South America had the second and third largest percentages, both in terms of the number of lakes and the total area (Table 2 and Table A3). Interestingly, though, the human footprint within each of the six geographical regions was driven by different pressures (Figs. A1 and A2). For example, while high human population densities and dense road networks appeared to be a widespread issue within most of the world's lakes (except perhaps North America; Figs. A1 and A2), other pressures were for the most part restricted to only some of the regions. Pastures were on average higher in Africa, Oceania, and South America (Fig. A1). In contrast, nighttime lights were on average higher in Europe (Fig. A2). Pressures from railways, built-up areas, and croplands, were on average low across all regions, albeit there were plentiful of exceptions within each region (Figs. A1 and A2).

The percentage of lakes within KBAs in which human footprint had increased was consistently higher that the corresponding overall percentage within each region (Table A4). Although this was true for all six regions, the percentage of lakes within KBAs in which human footprint had increased was especially high for Africa (> 70%; Table A4). Similar patterns were found when examining the number of lakes in KBAs under considerable pressure. In all but one of the regions, more than half of the lakes in KBAs were under considerable pressure—with the percentages in Africa, Asia, and Europe nearing or exceeding 90% (Table A4). Analogous patterns were found when examining the changes in human population densities within the lakes in KBAs (Table A5). As with the increases in human footprint, the increases in human densities were consistently higher within lakes in KBAs (compared to lakes outside KBAs), even within the regions in which the overall increases were moderate to low (Table A5).

3.4. Human footprint and human modification values within the various biomes

The change in mean human footprint varied considerably across the various biomes (Table 3). In some biomes, such in tundra and boreal forests, the human footprint had increased in only a small percentage of the lakes (1.8% and 5.4% respectively; Table 3). However, in other biomes, especially in tropical and subtropical regions, the human footprint had increased in more than 40% of the lakes (Table 3). Interestingly, in some of those biomes (e.g., the tropical and subtropical dry broadleaf forests and coniferous forests), the human footprint had also decreased in a large percentage of the lakes (45.3% and 47.4% respectively; Table 3). Likewise, the human footprint had decreased in many of the lakes in temperate grasslands, savannas, and shrublands (48.9%). The percentage of lakes within each biome that was under considerable human pressure in 2009 ranged from 1.9%, in tundra, to 91.5% in tropical and subtropical dry broadleaf forests (mean = 54.2%, sd = 26.6%). The same patterns were found when human pressure was measured using the human modification index (Table 3). Overall, biomes in the tropical regions tended to have a larger percentage of lakes under considerable human pressure compared to biomes in the temperate region (Table 3). The same was also true in terms of the total lake area (Table A6). Moreover, as in the case of the geographical regions, the changes in human footprint within the biomes were mirrored by the changes in human population densities between the years 2010 and 2010 and 2010 and 2020 (Table A7). Lakes within tropical and subtropical subregions experienced on average the largest increases in human population densities (Table A7), while lakes within temperate

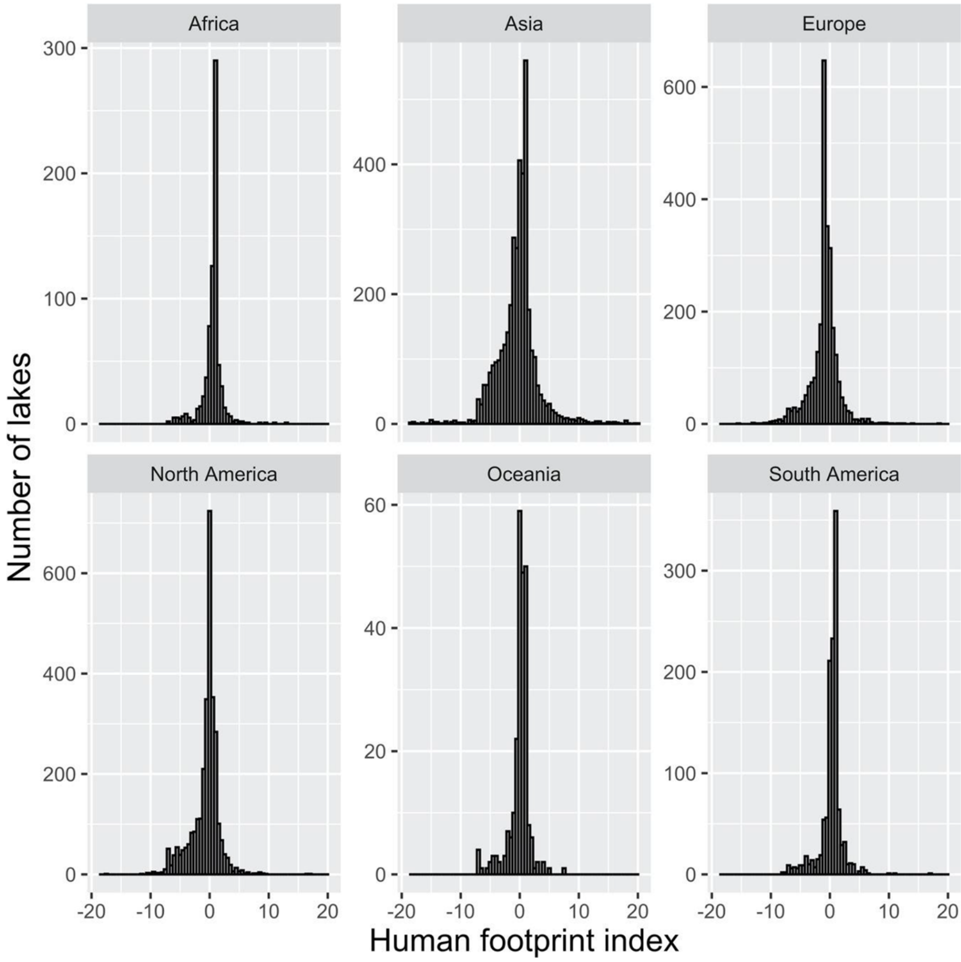

Fig. 2. Changes in mean human footprint between the years 1993 and 2009 within the world's 11,701 lakes in which the human footprint had either increased or decreased. A positive number indicates an increase in human footprint while a negative number indicates a decrease.

Table A2
Changes in human population densities within the lakes in each geographical region during the years 2000–2010 and 2010–2020.

Geographical region	2000–2010 Increase (%)	No change (%)	Decrease (%)	2010–2020 Increase (%)	No change (%)	Decrease (%)
Africa	78.5	18.5	3.0	74.4	19.4	6.2
Asia	22.2	66.7	11.1	19.5	68.4	12.2
Europe	15.5	55.2	29.3	15.0	55.9	29.0
North America	6.1	92.5	1.4	4.7	92.9	2.4
Oceania	7.0	93.0	0.0	6.1	93.8	0.1
South America	40.1	55.7	4.3	34.4	57.3	8.3

Table A3
Area covered by the lakes in each geographical region along with the percentage of area under low and considerable human pressure in 1993 and 2009 (i.e., mean human footprint (HF) < 4 and ≥ 4 respectively).

Geographical region	Area (km^2)	HF 1993 < 4 (%)	≥ 4 (%)	HF 2009 < 4 (%)	≥ 4 (%)
Africa	257,679	42.5	57.2	35.6	64.3
Asia	790,731	61.8	38.0	63.3	36.3
Europe	172,356	45.2	54.7	49.5	50.3
North America	898,169	86.1	13.6	86.1	13.9
Oceania	49,711	89.7	10.0	89.5	10.4
South America	111,422	60.3	39.4	59.2	41.0

regions, such as tundra and boreal forests, experienced the lowest (Table A7).

3.3. *Effectiveness of protected areas in mitigating human pressure within the world's lakes*

The human footprint had increased in 15.4% of the lakes situated outside protected areas. In the rest of the lakes, outside protected areas, there was either no change (68.0%) or the human footprint had decreased (16.6%). Regarding lakes within protected areas, the human footprint had increased in 21.5%, remained unchanged in 52.6%, and decreased in 25.9%. The percentage of lakes within protected areas in which human footprint had increased was higher in those with no IUCN category (24.4%) or a non-strict protection level (i.e., IUCN categories III–VI; 22.9%). Of those under strict protection (i.e., IUCN categories I–II), the human footprint had increased in 17.4% of them, remain

Table A4
Distribution of the world's lakes in Key Biodiversity Areas within each geographical region. The percentage of lakes in which the human footprint index (HF) had increased, remained unchanged, and decreased between the years 1993 and 2009 is also shown, along with the percentage of lakes under considerable human pressure, measured using the human footprint (HF) and the human modification (HM) indices.

Geographical region	Number of lakes	Increase in HF (%)	No change in HF (%)	Decrease in HF (%)	Under human pressure HF 1993 (%)	Under human pressure HF 2009 (%)	Under human pressure HM (%)
Africa	151	70.9	10.6	18.5	85.4	88.7	94.0
Asia	236	39.8	13.6	46.6	88.1	87.7	89.4
Europe	177	36.7	13.6	49.7	93.8	91.0	95.5
North America	51	33.3	29.4	37.3	60.8	52.9	45.1
Oceania	6	66.7	16.7	16.7	50.0	66.7	50.0
South America	89	56.2	33.7	10.1	53.9	58.4	61.8

Table A5
Changes in human population densities within lakes in Key Biodiversity Areas in each geographical region during the years 2000–2010 and 2010–2020.

Geographical region	2000–2010			2010–2020		
	Increase (%)	No change (%)	Decrease (%)	Increase (%)	No change (%)	Decrease (%)
Africa	82.3	14.3	3.4	76.9	16.3	6.8
Asia	55.9	19.5	24.6	47.0	17.8	35.2
Europe	50.3	40.7	9.0	36.7	27.7	35.6
North America	39.2	58.8	2.0	25.5	60.8	13.7
Oceania	50.0	50.0	0.0	50.0	50.0	0.0
South America	47.2	37.1	15.7	44.9	36.0	19.1

Table A6
Area covered by the lakes in each biome along with the percentage of area under low and considerable human pressure in 1993 and 2009 (i.e., mean human footprint (HF) < 4 and ≥ 4 respectively).

Biome	Area (km^2)	HF 1993		HF 2009	
		< 4 (%)	≥ 4 (%)	< 4 (%)	≥ 4(%)
Tropical and subtropical moist broadleaf forests	145,191	38.6	61.4	35.6	64.4
Tropical and subtropical dry broadleaf forests	18,957	15.1	84.9	17.5	82.5
Tropical and subtropical coniferous forests	1,797	24.1	75.9	28.0	72.0
Temperate broadleaf and mixed forests	816,819	41.7	58.3	43.8	56.2
Temperate coniferous forests	67,881	63.0	37.0	62.5	37.5
Boreal forests	494,687	89.0	11.0	89.5	10.5
Tropical and subtropical grasslands, savannas, and shrublands	201,621	49.1	50.9	45.3	54.7
Temperate grasslands, savannas, and shrublands	115,797	51.2	48.8	55.1	44.9
Flooded grasslands and savannas	22,196	56.4	43.6	54.4	45.6
Montane grasslands and shrublands	57,360	84.1	15.9	84.7	15.3
Tundra	157,061	98.3	1.7	98.2	1.8
Mediterranean forests, woodlands, and scrub	15,045	41.6	58.4	45.0	55.0
Deserts and xeric shrublands	162,050	79.9	20.1	79.0	21.0
Mangroves	2,850	22.6	77.4	28.7	71.3

*43 lakes were located within the 'rock and ice' biome and another 16 lakes in areas outside those covered by the spatial layer depicting the biomes.

unchanged in 64.1% and decreased in 18.5%. 22.6% of the lakes within strictly protected areas were under considerable human pressure in 2009 (as measured using the human footprint index). The corresponding percentages for the lakes within areas with no IUCN status or IUCN III-VI were 42.8% and 42.4% respectively. Similar patterns were found when the human modification index was used to measure human pressure (22.8, 44% and 48.% respectively)

The matching analysis showed that in six of the fourteen biomes the change in human footprint was higher within lakes in protected areas than lakes outside. However, the difference was statistically significant for only two of those (Table 4). Overall, the human footprint within the lakes in protected areas had reduced in eight of the biomes. It is worth noting, though, that in five of those biomes the human footprint had actually decreased in most of the lakes regardless of the protection status (Table 4). In fact, in boreal forests the reduction was higher outside protected areas (Table 4). In the other three biomes the human footprint had decreased in lakes within protected areas but increased in those outside (Table 4). Finally, in six of the biomes, the human footprint had increased in the lakes within protected areas. In five of those, the increases were higher in protected areas than areas outside, although the results were statistically significant for only three of them (Table 4).

4. Discussion

Multiple important messages can be extracted from the above results. First, it appears that one-third of the world's lakes are under considerable human pressure as measured using the human footprint and the human modification indices (Kennedy et al., 2019; Venter et al., 2016b). However, most of the world's lakes experienced no increase in human footprint during the 16-year period examined. In fact, human footprint had decreased in many of the lakes and only increased in a small percentage of them (Table 2); a pattern that was also reflected in the changes in human population densities within the lakes. However, this pattern was not uniform across the globe. Lakes within temperate regions, especially in North America, experienced less increase in human footprint and overall appear to be on average under lower human pressure—irrespective of the index used to measure human pressure (Fig. 1). In Europe, the human footprint had decreased in more than half of the lakes (Fig. 2), suggesting that it may be overall decreasing (although note that half of the European lakes are still under considerable human pressure; Table 2).

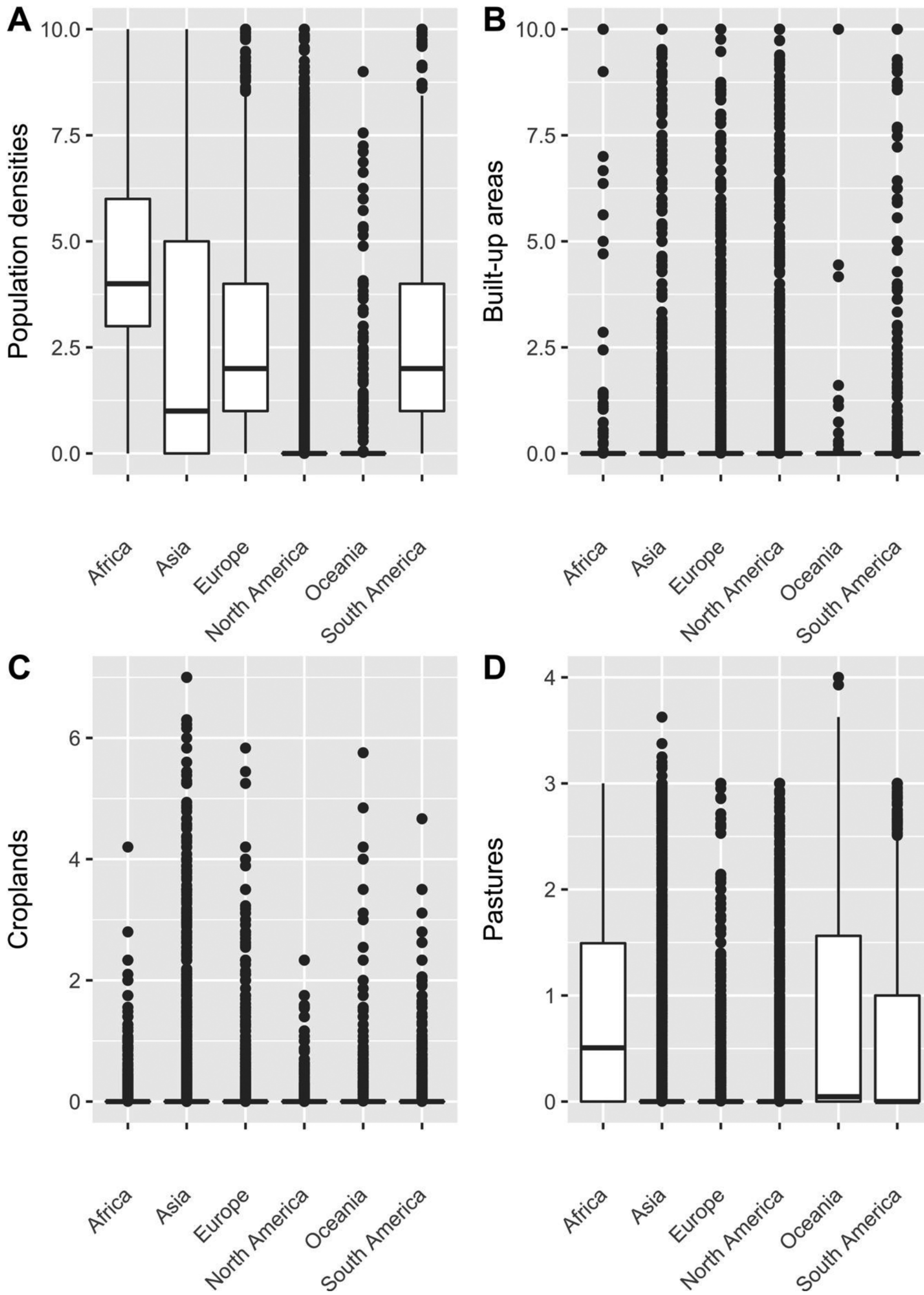

Fig. A1. Box-plots illustrating the pressure exerted on the lakes, within each geographical region, by human population densities, built-up areas, croplands, and pastures. The data are based on the human footprint index from 2009.

The same patterns were found when examining the changes in human population densities within lakes between the years 2000 and 2010 and 2010 and 2020 (Table A2). Moreover, similar patterns were also reported in a recent metanalysis that was based on 189 studies and in which the authors examined the loss of wetlands within various geographical regions (Davidson, 2014). They found that wetland loss in North America was low and that it was decreasing in Europe (Davidson, 2014). In another global metanalysis, researchers found that aquatic vegetation within several of the lakes in North America and Europe was recovering but it was deteriorating within lakes in Asia, especially China (Zhang et al., 2017). These patterns appear to be broadly consistent with the Environmental Kuznets Curve theory, which predicts decreasing environmental degradation in developed regions (Carson, 2009).

The theory also predicts increased environmental degradation in developing regions (Carson, 2009), a pattern that was also seen in the results presented here. Lakes in tropical and subtropical regions, especially in Africa and South America, experienced considerable increases in human footprint. Additionally, the human population densities within the lakes in those regions appear to be increasing further (Table A7). These trends are alarming because these regions tend to support many of the planet's most biodiverse areas (Gaston, 2000; Laurance et al., 2012; Lewis, 2000). Consequently, it is probable that although the human footprint had not increased in most of the world's lakes, the benefits to biodiversity are disproportionately low because biodiverse lakes have been nevertheless impacted considerably. This possibility is further supported by the fact that more than 80% of the lakes in Key Biodiversity Areas are under considerable pressure.

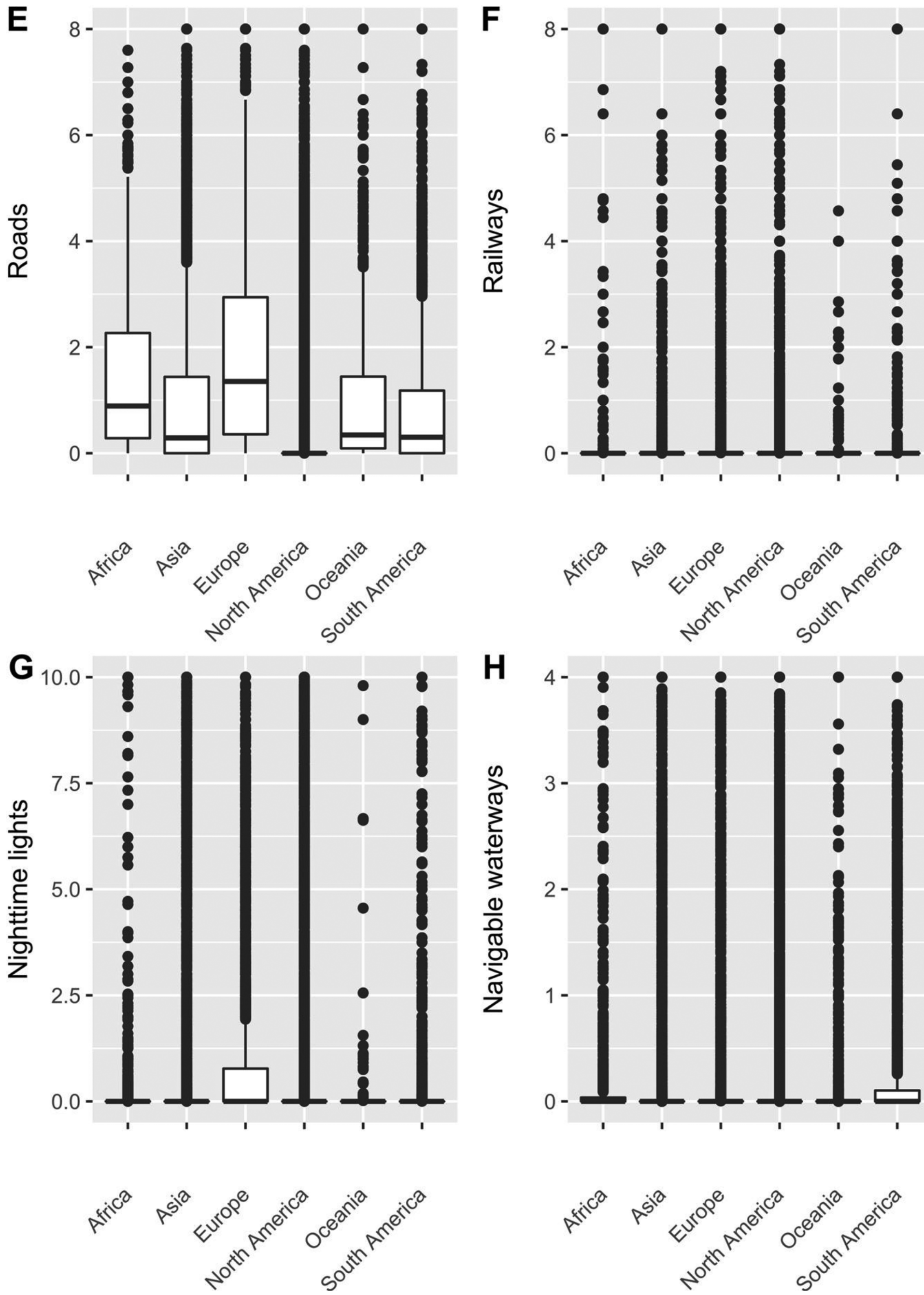

Fig. A2. Box-plots illustrating the pressure exerted on the lakes, within each geographical region, by roads, railways, nighttime lights, and navigable waterways. The data are based on the human footprint index from 2009.

Moreover, the percentage of lakes in which the human footprint had increased was much higher in lakes within Key Biodiversity Areas than lakes outside (47.2% vs 16.2% respectively). This was true in all geographical regions, even those in the temperate zone (Table A4). This pattern was reflected also in the increases in human population densities within the lakes in KBAs (Table A5). For instance, while only a fifth of the lakes in Asia experienced an increase in human population densities between the years 2010 and 2020, the corresponding percentage for lakes within KBAs in Asia was 47%. Similarly, in North America the percentages were 4.7% and 25.5% respectively (Table A5)

It is evident from the above results that conservation measures must be taken to tackle the increasing human pressure within the world's lakes, especially biodiverse lakes. Often such measures involve the establishment of protected areas. However, the results of the matching analysis presented here and the results of other studies (Anderson and Mammides, 2020; Jones et al., 2018; Laurance et al., 2012), suggest that protected areas are not always effective in mitigating human pressure (Anderson and Mammides, 2020; Bruner et al., 2001; Geldmann et al., 2019; Mammides, 2020). Although protected areas had been successful in reducing the human pressure within the lakes in several of the biomes, in others (e.g., in tropical and subtropical coniferous forests and in mangroves) the pressure was higher in lakes within protected areas than lakes outside. Similar patterns were found when looking at the role of protected areas in reducing human pressure within the word's last wild regions (Anderson and Mammides, 2020).

This suggests that conservation actions in regions affected the most need to go beyond the designation of new protected areas (Anderson and Mammides, 2020; Chazdon et al., 2009; Laurance et al.,

Table A7
Changes in human population densities within the lakes in each biome during the years 2000–2010 and 2010–2020.

Biome	2000–2010 Increase (%)	No change (%)	Decrease (%)	2010–2020 Increase (%)	No change (%)	Decrease (%)
Tropical and subtropical moist broadleaf forests	63.9	27.7	8.4%	53.1	31.8	15.2
Tropical and subtropical dry broadleaf forests	71.6	14.6	13.8%	66.1	15.9	18.0
Tropical and subtropical coniferous forests	70.2	26.3	3.5%	57.9	29.8	12.3
Temperate broadleaf and mixed forests	30.3	47.3	22.4%	23.7	49.4	26.9
Temperate coniferous forests	24.6	72.0	3.4%	21.6	72.2	6.2
Boreal forests	1.9	94.3	3.9%	1.9	94.4	3.6
Tropical and subtropical grasslands, savannas, and shrublands	43.6	55.1	1.3%	42.9	53.6	3.5
Temperate grasslands, savannas, and shrublands	17.3	61.3	21.4%	15.9	65.1	19.1
Flooded grasslands and savannas	71.4	24.3	4.3%	64.6	28.9	6.6
Montane grasslands and shrublands	15.2	82.2	2.5%	13.6	82.4	4.0
Tundra	0.2	99.5	0.4%	0.4	99.5	0.1
Mediterranean forests, woodlands, and scrub	36.0	55.2	8.8%	24.8	51.5	23.7
Deserts and xeric shrublands	27.6	69.2	3.3%	27.1	70.3	2.6
Mangroves	70.8	22.3	6.9%	61.5	24.6	13.8

*43 lakes were located within the 'rock and ice' biome and another 16 lakes in areas outside those covered by the spatial layer depicting the biomes.

2012). First, the governance of the existing areas needs to be improved in order for them to be as effective as possible (Bruner et al., 2001; Lockwood, 2010). Second, the socioeconomic factors driving the increases in human pressure must be addressed (Chazdon et al., 2009; Mammides, 2020). High human population densities appear to be a major threat to many of the world's lakes (Fig. A1). Importantly, in many of those lakes, the human population densities continue to increase, especially in tropical and subtropical regions (Table A7), which tend to be the most biodiverse. Consequently, efforts to address the increasing human population densities within the lakes are likely to play a major role in reducing the human pressure currently exerted on them. Road densities are also a significant threat to the world's lakes, which needs to be addressed (Fig. A1). Numerous studies have shown that roads can have a range of negative effects on waterbodies and their biodiversity (Findlay and Bourdages, 2000; Giosa et al., 2018; Riffell, 2018; Roe et al., 2006). Lastly, pastures appear to be also threatening many of the lakes, especially in Africa, Oceania, and Asia (Fig. A1). As the demand for livestock products continues to increase, the associated pressures on the lakes in those regions will intensify. It is thus essential to take the required measures to prevent the further encroachment of pastures on lakes.

It is important to clarify here that the results of this study are based only on relatively large lakes (i.e., ≥ 5 km^2) for which such analysis could be performed reliably. Also, the results are based only on the types of threats incorporated in the human footprint and the human modification indices (Kennedy et al., 2019; Venter et al., 2016a). Other important threats such pollution, e.g., eutrophication and acidification (Borre et al., 2001), overexploitation, invasive species (Hulme, 2018), and climate change are also affecting the world's lakes (Carpenter et al., 2011; Dudgeon, 2014). Although many of those threats correlate strongly with the human pressures included in this analysis (Jones et al., 2018; Kennedy et al., 2019; Table 1), the results presented here are likely to be an underestimation of the true human pressure on the lakes globally.

5. Conclusions

The human pressure on the world's lakes varies considerably across biomes and geographical regions. Although lakes in temperate regions, particularly in North America, appear to be on average relatively free from human pressure, the opposite is true for lakes in tropical regions, especially in Africa (but also in South America and Asia). This pattern is alarming because these regions are the most biodiverse (Butchart et al., 2010; Gaston, 2000). Moreover, the high human pressure on the lakes located within Key Biodiversity Areas (Langhammer et al., 2018), confirms further the need to protect better biodiverse lakes. Expanding the network of protected areas may not always sufficiently mitigate the pressure exerted by human activities (Laurance et al., 2012; Watson et al., 2014), especially in regions where human population densities and activities are increasing rapidly. It is therefore important to improve environmental governance (Bruner et al., 2001) and to address the socioeconomic drivers responsible for the increases in human pressure (Rands et al., 2010).

CRediT authorship contribution statement

Christos Mammides: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

I declare I have no conflict of interest associated with this study.

Acknowledgements

I am grateful to all the researchers who have developed and made available the datasets used in this study. I am also thankful to the editors of the journal and the three anonymous reviewers for their exceptionally constructive feedback.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2020.102084.

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