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Original Research Article

Built-up areas within and around protected areas: Global patterns and 40-year trends

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A R T I C L E I N F O

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A B S T R A C T

Protected areas (PAs) are a key strategy in global efforts to conserve biodiversity and ecosystem services that are critical for human well-being. Most PAs have some built-up structures within their boundaries or in surrounding areas, ranging from individual buildings to villages, towns and cities. These structures, and the associated human activities, can exert direct and indirect pressures on PAs. Here we present the first global analysis of current patterns and observed long-term trends in built-up areas within terrestrial PAs and their immediate surroundings. We calculate for each PA larger than 5 km^2 and for its 10-km unprotected buffer zone the percentage of land area covered by built-up areas in 1975, 1990, 2000 and 2014. We find that globally built-up areas cover only 0.12% of PA extent and a much higher 2.71% of the unprotected buffers as of 2014, compared to 0.6% of all land (protected or unprotected). Built-up extent in and around PAs is highest in Europe and Asia, and lowest in Africa and Oceania. Built-up area percentage is higher in coastal and small PAs, and lower in older PAs and in PAs with stricter management categories. From 1975 to 2014, the increase in built-up area was 23 times larger in the 10-km unprotected buffers than within PAs. Our findings show that the development of built-up structures remains limited within the boundaries of PAs but highlight the need to carefully manage the considerable pressure that PAs face from their immediate surroundings.

1. Introduction

Protected areas (PAs) are a key strategy in global efforts to conserve biodiversity and ecosystem services that are critical for human well-being (Watson et al., 2014; UNEP-WCMC et al., 2018). PAs are established and managed to achieve the long-term conservation of nature with associated ecosystem services and cultural values (Dudley, 2008). They play a fundamental role in the *in situ* conservation of genetic, species and ecosystem diversity, and in the delivery of economic, social and cultural

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benefits from nature to people (Mulongoy and Gidda, 2008; UNEP-WCMC et al., 2018). The critical importance of PAs is recognized in several international agreements and targets for biodiversity conservation and sustainable development. In Aichi Target 11 of the Strategic Plan for Biodiversity 2011–2020 of the Convention on Biological Diversity (CBD), the international community agreed to conserve at least 17% of terrestrial and inland water areas through effectively and equitably managed, ecologically representative and well-connected systems of PAs by 2020 (CBD, 2010). Terrestrial PAs also contribute to the UN Sustainable Development Goal (SDG) 15 that seeks to "protect, restore and promote sustainable use of terrestrial ecosystems" (UNGA, 2015).

As of May 2019, terrestrial PAs cover almost 12.8% of the Earth's land area, compared to around 10% in 1992 when the CBD was signed (UNEP-WCMC et al., 2018). Depending on their primary management objectives, PAs are commonly classified into different management categories, ranging from strict nature reserves to sustainable use areas (Dudley, 2008). Most PAs are not free from human habitation and use: PAs constitute the homeland of millions of people (including many indigenous peoples; Stevens, 2014; Garnett et al., 2018), support hundreds of millions of livelihoods, and are used by billions of people for recreation and tourism. For example, forest PAs alone have been estimated to support a significant part of the livelihoods of nearly 1.1 billion people worldwide (Mulongoy and Gidda, 2008), and the world's terrestrial PAs receive over 8 billion visits per year (Balmford et al., 2015).

Human habitation and use usually requires some built infrastructure, including settlements, roads and visitor facilities. Hence, the majority of the more than 200,000 terrestrial PAs around the world include built-up structures within their boundaries or immediate surroundings. These man-made structures range from individual buildings (e.g. visitor centres, museums, hotels, lodges, or religious buildings) to villages, towns and even cities (Dudley, 2008; SCBD, 2012; Elmqvist et al., 2013; Worboys et al., 2015). Effective PA planning, establishment and management therefore require careful balance of human needs with the needs of the species and ecosystems to be conserved.

PAs around the world face widespread - and often increasing - human pressures and threats that have profound impacts on biodiversity and ecosystem services (Geldmann et al., 2014; Watson et al., 2014; Jones et al., 2018; Schulze et al., 2018). These pressures include overexploitation of wildlife resources (e.g. through fishing, hunting and poaching), development and encroachment resulting in habitat degradation and fragmentation, extractive activities such as logging and mining, transportation infrastructure such as roads and railroads, pollution and the spread of wildlife diseases, pests and invasive alien species. Depending on their location, extent, type and trend, built-up structures and areas can also exert direct and indirect pressures on PAs, often by interacting with and/or intensifying other pressures and threats (McDonald et al., 2009).

The extent and evolution of built-up areas within and around PAs are important indicators of the level of land consumption and potential habitat transformation and fragmentation, and thus the effectiveness of PAs for biodiversity conservation. Several global analyses in the past have assessed current and potential future impacts of urban growth on nearby PAs by combining relatively coarse data (c. 1 km^2) on urban extent around the year 1995 from the Global Rural/Urban Mapping Project (GRUMP) with modelling approaches (McDonald et al., 2008; McDonald et al., 2009; Güneralp and Seto, 2013). For example, McDonald et al. (2009) noted that the distance between urban areas and protected areas will generally decrease as a result of rapid global urban growth, and Güneralp and Seto (2013) projected that the amount of urban land within 50 km of PAs will triple between 2000 and 2030. However, so far, a detailed global assessment of the current and historic extent of built-up areas within and around PAs has been missing.

Recent advances in the global mapping and monitoring of built-up areas using earth observation through satellite sensors allow, for the first time, an assessment of global patterns and 40-year trends in built-up areas at an unprecedented spatial and temporal resolution (Pesaresi et al., 2016a). The Global Human Settlement Layer (GHSL) developed by the Joint Research Centre (JRC) of the European Commission makes it possible to analyse in a complete, consistent and detailed manner the trajectory of built-up areas for the whole planet over the past 40 years. In the GHSL, built-up areas are defined as areas where buildings can be found, ranging from individual buildings to whole settlements (Pesaresi et al., 2013). However, this definition does not include other types of man-made structures such as roads, railroads and bridges. The GHSL has shown that, over the past 40 years, built-up areas increased by more than twice globally, with major regional differences.

Here we combine the multi-temporal GHSL built-up area with the World Database on Protected Areas (WDPA; UNEP-WCMC and IUCN, 2019) to conduct the first global analysis of current patterns and observed long-term trends in built-up areas within PAs and their immediate surroundings. We calculate for each PA larger than 5 km^2 and its 10-km unprotected buffer zone the percentage of land area covered by built-up areas for 1975, 1990, 2000, and 2014 to answer the following questions: How much land within and around PAs is covered by built-up structures? How has built-up area within and around PAs changed over the past 40 years? How do the patterns and trends differ between continents, regions and countries, and between different types of PAs (e.g. depending on their management category, size, age and location)? By doing so, we aim to provide novel insights on one of the most important but less-studied sources of human pressure on PAs, with implications for the global assessment of the condition, management and governance of PAs and the broader landscape context in which they are embedded.

2. Materials and methods

2.1. Protected areas and 10 km buffer zones

We downloaded the public version of the World Database on Protected Areas (WDPA) for May 2019 from Protected Planet (UNEP-WCMC and IUCN, 2019). The WDPA is managed by the World Conservation Monitoring Centre (WCMC) of the United Nations Environment Programme (UNEP) in collaboration with the International Union for Conservation of Nature (IUCN), and is collated from national and regional datasets (UNEP-WCMC, 2019). This dataset consists of 232,323 protected areas (PAs), of which those of 10 km^2 or larger are documented in detail in the Digital Observatory for Protected Areas (DOPA) developed by the Joint Research Centre of the European Commission (Dubois et al., 2016) and those of 5 km^2 or larger are considered in this study. The DOPA, accessible at http://dopa.jrc.ec.europa.eu, provides a broad range of consistent and comparable indicators on PAs at country, ecoregion and protected area level (Dubois et al., 2016, Bastin et al., 2017). These indicators are particularly relevant for Aichi Biodiversity Target 11 (Protected Areas) of the CBD, and the UN Sustainable Development Goal 15 (Life on Land).

In this study, we excluded, in addition to PAs with an area below 5 km^2, the following PAs. First, all PAs with undefined boundaries, so-called point PAs that are reported by national authorities with only a single geographic reference for the centre of the PA. Second, we excluded all marine PAs, i.e. we only considered terrestrial PAs and coastal PAs. Coastal areas represented about 10% of the total number of PAs. For the coastal PAs, defined as those that comprised both terrestrial and marine portions (as opposed to entirely terrestrial PAs), we only considered their land portion for all analyses. The land portion was determined by excluding from calculations the class ‘1 = water surface’ of the Built-up layer, described in the next paragraph, so that marine parts or other inland water bodies are not considered in computation of surfaces. Third, we excluded PAs with a “proposed” or “not reported” status in the WDPA, in line with common practice for global PA analyses (e.g., UNEP-WCMC and IUCN, 2016; Saura et al., 2018). Fourth, we excluded UNESCO Man and the Biosphere Reserves, as their buffer areas and transition zones may not meet the IUCN protected area definition (Dudley, 2008), and because most of their core areas overlap with other protected areas (UNEP-WCMC and IUCN, 2016). Fifth, we excluded all PAs that had not been already designated before 2014 (as well as those that had no designation year reported in the WDPA), given that the spatial data on built-up areas used in this study were only available up to 2014 (see next section). Applying all these selection criteria produced a final dataset of 52,447 PAs whose accumulated land area represented 92.8% of the accumulated land area for the full set of terrestrial PAs before any exclusion or PA size threshold.

Finally, in order to compare changes within and around the PAs, we considered, around each PA, a 10 km unprotected buffer zone. This zone covered the land around each PA that did not overlap with any other PA, hereafter referred to as the unprotected 10-km buffer.

2.2. Built-up areas

The dataset used for the analysis of built-up areas is the Global Human Settlement Layer (GHSL) BUILT product updated in 2017 (Corbane et al., 2017). The GHSL is based on 32,808 individual images collected by different Landsat satellite sensors in the past 40 years (Pesaresi et al., 2016a). It is developed by processing Landsat images organised in four collections, namely GLS1975, GLS1990, GLS2000 and an ad-hoc collection of Landsat-8 imagery centred at 2014. The resulted GHSL BUILT grid provides multitemporal information (1975, 1990, 2000 and 2014) on the presence of built-up areas globally. At the most basic level, the GHSL maps the observable presence of built-up structures (or buildings), which are defined as “enclosed constructions above ground which are intended or used for the shelter of humans, animals, things or for the production of economic goods” (Pesaresi et al., 2013). The GHSL defines built-up area class as “the union of all the spatial units collected by the specific sensor and containing a building or part of it” (Pesaresi et al., 2013). The information extraction workflow used to produce the GHSL BUILT grid relies on a Symbolic Machine Learning classifier designed for processing large volumes of image data (Pesaresi et al., 2016b). The dataset is distributed as a classification grid at a spatial resolution of 30 m, used in this study, and a set of derived aggregated layers at 250 m and 1 km resolution grids. The dataset used in this work (GHS_BUILT_LDSMT_GLOBE_R2018A_3857_30_V_1_0) was released in 2018 as a part of the Community Release (Florczyk et al., 2018) for research purpose in support to the GEO Human Planet Initiative community.

2.3. Administrative boundaries

Global Administrative Unit Layers (GAUL, 2015) for year 2015, developed by the Food and Agricultural Organization (FAO) of the United Nations,[1] were used to display the country boundaries in the global maps shown in this paper. When producing global maps at the country level, we labelled as “No data” the countries that have less than 1000 km^2 of protected land, which was the minimum area here considered as a threshold to provide reliable estimates of the built-up area indicator for individual countries.

[1] http://www.fao.org/geonetwork/srv/en/metadata.show?id=12691.

2.4. Built-up area calculation

For each PA and its unprotected buffer we calculated, the percentage of the land area covered by built-up areas in each of the four years in which the GHSL was available (1975, 1990, 2000 and 2014). In calculating the built-up percentage in each of the years, we excluded all PAs that had not been already designated before that year (as well as those that had no designation year reported in the WDPA). In this and all other related analyses, we used the spatial resolution of 30 × 30 m of the GHSL; all PAs and their unprotected buffers were rasterized to this resolution. In addition, we calculated the percentage of all land (either protected or unprotected) covered by built-up areas globally and in each country, as a reference for comparison of the built-up area values obtained in the PAs and their buffers. Antarctica was excluded in all calculations.

Each PA, as well as its unprotected buffer, was considered to belong to the country reported in the ISO3 field of the WDPA, through which country-level summaries were produced. Note that the ISO3 codes from the WDPA include cases of territories under the sovereignty of other nations. Examples are Reunion Island, a French overseas territory located in the Indian Ocean, and Greenland, a self-governing territory that is part of the Kingdom of Denmark. The use of these ISO3 codes in the WDPA for the countries or territories does not imply any endorsement by the authors, nor any official position by the European Commission, on the sovereignty of these lands. Country-level results were aggregated at the level of continents and regions using the country groupings of the M49 standard of the Statistics Division of the United Nations Secretariat, available at https://unstats.un.org/unsd/methodology/m49/ (accessed March 2019). We used the classification fields “region name” (here referred to as continents) and “sub-region name” (here referred to as regions) in this standard, which classified the world into 6 and 18 country groups respectively. Regional and continental values are, therefore, influenced by these country groupings, such as the Russian Federation being included in Europe (continent) and Eastern Europe (region), or Greenland being included within America (continent) and Northern America (region), among other examples. We also considered the aggregated built-up area values for the European Union (EU), considering the 28 countries within the EU when this analysis was conducted (EU-28). In calculating EU values, we excluded the PAs in territories whose reported ISO3 in the WDPA was different from those 28 countries, even if under the sovereignty of a EU member state, as in the case of Greenland or Réunion Island.

We also considered, for each PA, the information available in the WDPA regarding the management category (as defined in Dudley, 2008), the type (coastal or terrestrial), and the year of the enactment of the PA status (Inscribed or Designated), hereafter referred to as designation year for brevity. We summarized the built-up area values separately for each of the PA management categories, for coastal and terrestrial PAs, and for different years of PA designation.

3. Results

3.1. Built-up structures in protected areas and their buffers at the continental, regional and country levels

Built-up areas cover globally 0.12% of the land area within terrestrial and coastal PAs larger than 5 km^2 as of 2014 (Fig. 1), which is about five times lower than the 0.57% of all global land (either unprotected or protected) that is built up. The

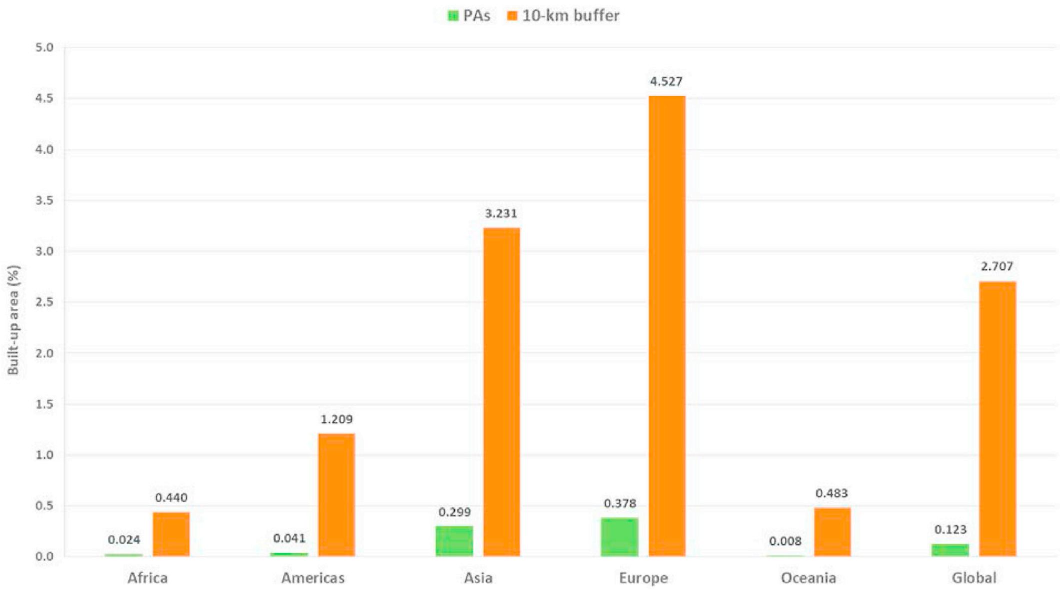


Fig. 1. Percentage of built-up areas in the protected areas (PAs) and in their unprotected 10-km buffers for each continent as of 2014.

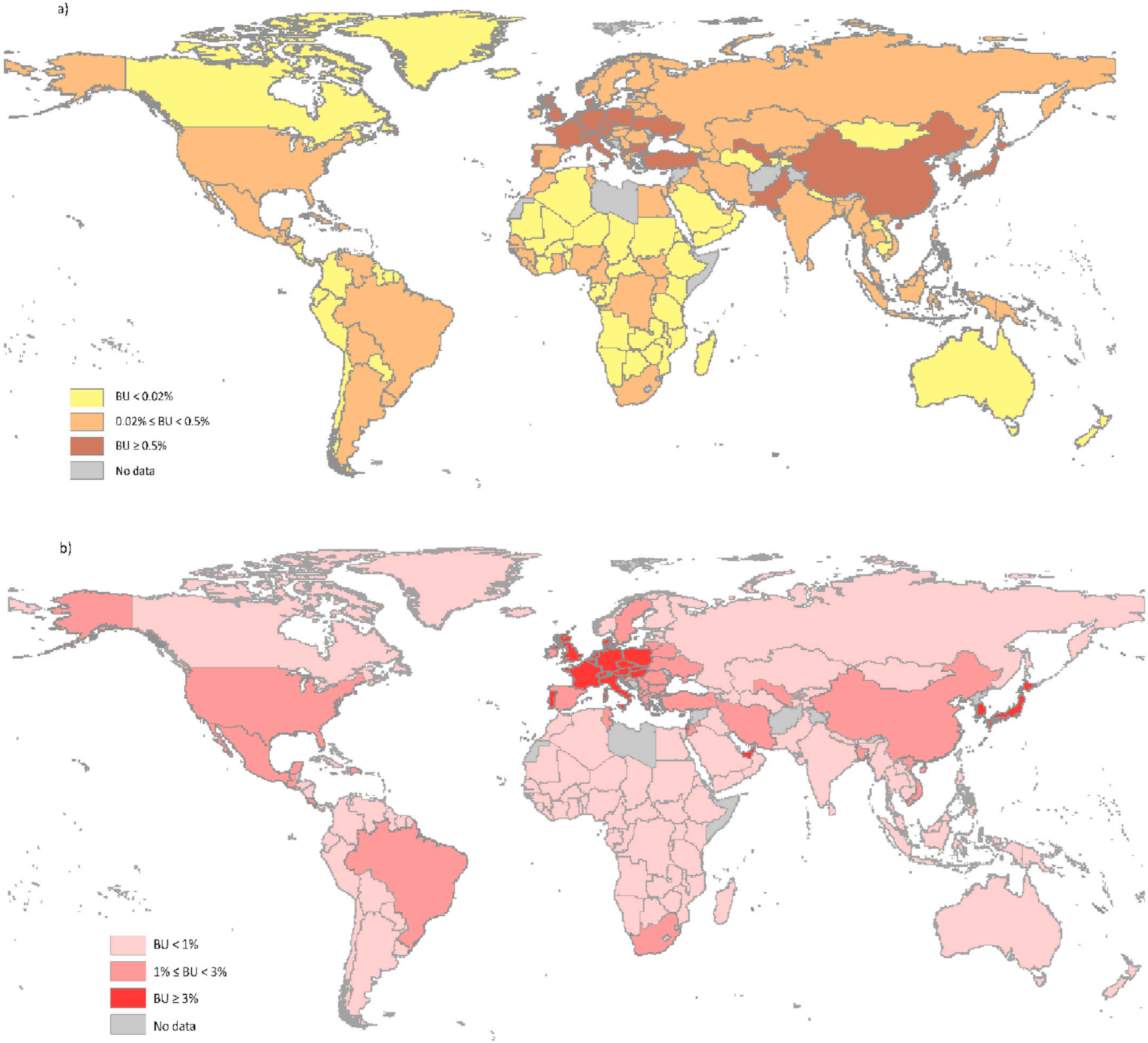


Fig. 2. Percentage of the protected areas (a) and of their unprotected 10-km buffers (b) in each country covered by built-up areas (BU) as of 2014. Countries or territories labelled as "No data" have less than 1000 km^2 of protected land, which was the minimum area here considered as a threshold to provide reliable estimates of the built-up area indicator.

percentage of built-up areas in the 10 km unprotected buffers surrounding the PAs is 2.71% (Fig. 1), which is much higher (about 23 times larger) than within the PAs and also considerably higher (about five times larger) than the value for all land.

Built-up areas within PAs are, however, very unevenly distributed across continents and countries (Figs. 1 and 2a). In Europe, 0.378% of the PA network is built up (Fig. 1), which increases up to 0.616% if Russia is excluded from the statistics for Europe. This latter value is very similar to that for the European Union (0.633%), and is about five times larger than the global average. Asia is the second continent by this indicator. The lowest presence of built-up structures within PAs is found, at the continental level, in Oceania, Africa and America. At the regional level (Supplemental Fig. 1), the highest percentages of built-up areas within PAs are found in the PAs of Western Europe (1.196%), Southern Europe (0.475%) and Eastern Asia (0.712%), which contrasts with the much lower values in Australia and New Zealand (0.007%), Sub-Saharan Africa (0.016%) and Northern America (0.032%). The variability in built-up areas within PAs at the country level (Fig. 2a) ranges from cases such as Belgium (2.87%) to others like Greenland, Iceland, Belize, Central African Republic, Niger, Mongolia, or Suriname, all of which have less than 0.001% of their PA land covered by built-up areas. Of the ten largest countries of the world, China (0.861%) and India (0.167%) have a percentage of built-up area within PAs above the global average of 0.118%. The remainder of these ten largest countries are below the global average, in increasing order as follows: Canada (0.003%), Australia (0.007%), Algeria (0.009%), Brazil (0.036%), Argentina (0.039%), Russia (0.055%), USA (0.063%) and Kazakhstan (0.073%). More than one third (38%) of the analysed PAs are completely free of built-up areas as mapped in the GHSL. These PAs with no constructions occur mainly in remote and largely intact tropical, desert or boreal areas of countries such as Brazil, Russia, Australia, USA and Canada. The PAs with no built-up structure within them have a total area of more than 0.7 Mkm^2 in each of these countries, and even above 1 Mkm^2 in the case of Brazil.

In all continents, the percentage of built-up area is higher in the 10 km unprotected buffers around the PAs than within the PAs (Fig. 1). Wide variation can be seen in the difference between the percentage of built-up area in the buffers and in the PAs. This difference is highest, at the continental level, in Europe, followed by Asia (Fig. 1). At the country level, the highest built-up percentage in unprotected buffers, as well as the highest difference from the values within the PAs, is found in densely populated European countries (Fig. 2b): Belgium, the Netherlands, and Germany have, respectively, 18.9%, 15.6% and 11.6% of their unprotected 10-km buffers covered by built-up areas. Globally, the percentage of built-up areas in the unprotected areas around PAs is 2.71% (Fig. 1), which is five times larger than the 0.57% of all global land (either unprotected or protected) that is built up. On Europe, Asia and the Americas, the built-up density in the unprotected 10-km buffers around PAs is higher than the average for all land (either unprotected or protected).

This difference in built-up area between PAs and their unprotected buffers occurs from the moment in which PAs are designated. If we consider only those PAs that were designated in years 1975, 1990, 2000 and 2014, and assess the built-up area distribution with the GHSL information for those same years, we find that, in the year they were designated, PAs had a

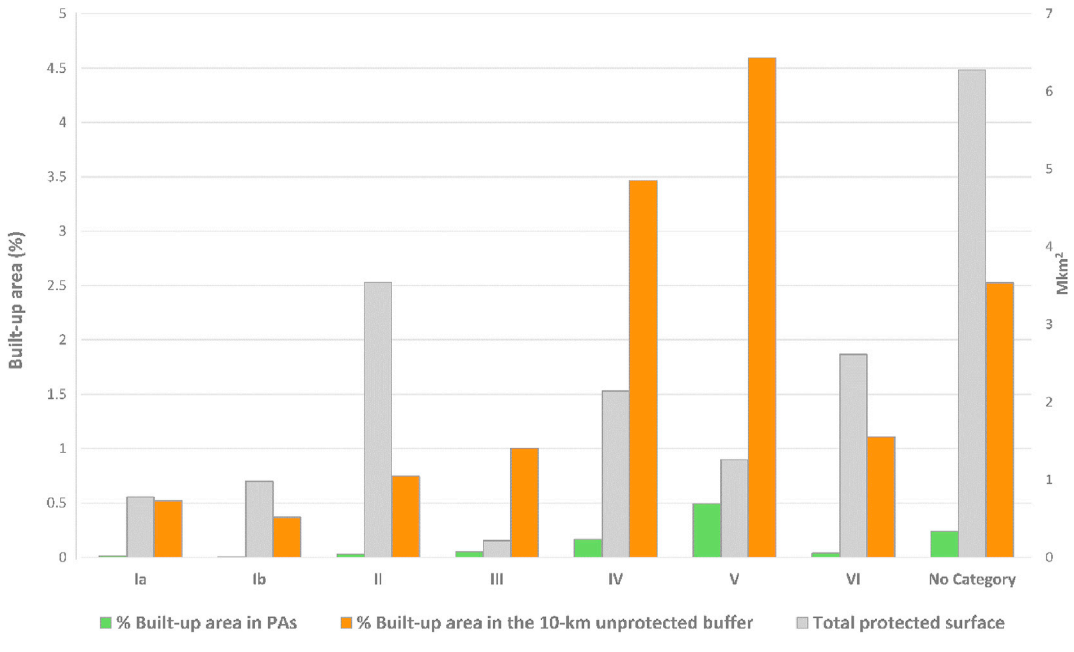


Fig. 3. Percentage of built-up areas inside the protected areas (PAs) and in their unprotected 10-km buffers for each IUCN management category as of 2014 (percentage values in the left vertical axis). The grey bars show the total area under protection (area values in the right vertical axis) for each IUCN category for the set of PAs considered in this study. The values for "No Category" in the chart include all PAs with IUCN Category "Not reported", "Not assigned" and "Not applicable" as reported in the WDPA.

percentage of built-up area in their unprotected surroundings that was globally 25 times higher than within their boundaries (average for the four years considered).

3.2. Built-up area for different protected area types

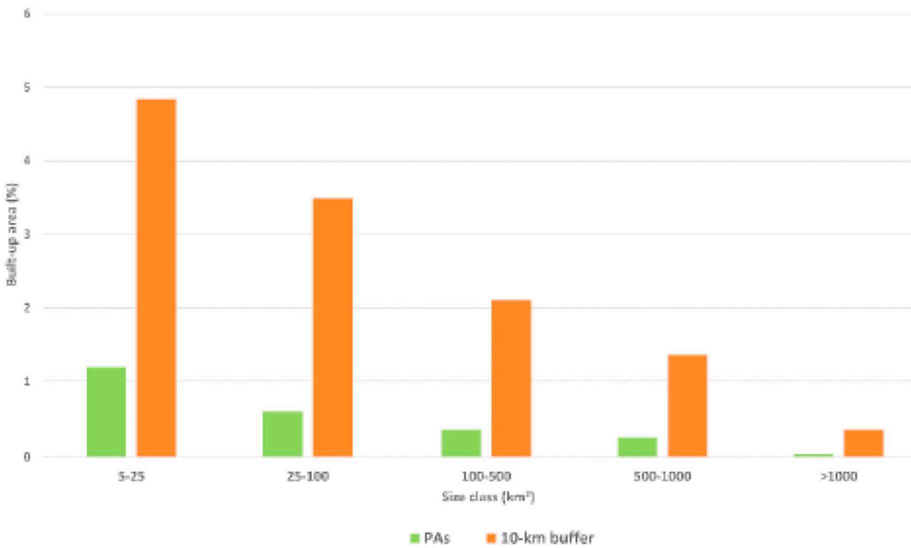
Strict nature reserves and wilderness areas (IUCN PA category I) have the lowest percentage of built-up area (0.008%), while the opposite is found for PAs with IUCN category V (protected landscapes), as shown in Fig. 3. PAs of IUCN category V are also those where built-up areas were highest in the 10-km unprotected buffers compared to within the PAs. Readers should however be aware that, because PAs can overlap for many reasons, around 25% of the areas have multiple designations (Deguignet et al., 2017). In Fig. 3, each protected area has been analysed independently when exploring the links between the management categories and the amount of built up areas.

Small PAs have, on average, higher percentages of built-up area than larger ones (Fig. 4). The average built-up percentage is 30 times larger in terrestrial PAs with sizes ranging from 5 to 25 km^2 (1.20%) than in the terrestrial PAs larger than 1000 km^2 (0.04%) and more than 13 times larger when considering their 10 km unprotected surrounding areas, as shown in Fig. 4.

Built-up area is globally more than double in the land of PAs classified as coastal in the WDPA (0.26% covered by built-up areas) than in those PAs classified as entirely terrestrial (0.11%). Built-up area percentage is also higher for coastal than for terrestrial PAs when considering the land around the entire PA extent: buildings cover 5.66% and 2.53% of the land in the 10-km buffers surrounding the PAs classified as coastal and terrestrial, respectively.

3.3. Trends in built-up areas in protected areas from 1975 to 2014

PAs that were designated several decades ago have considerably fewer built-up structures than more recently designated PAs. This is true when considering both the percentage of built-up area at the time when different PAs were designated (built-up values in 1975, 1990 and 2000), and the current (2014) built-up percentage for PAs designated before and after 1975, as shown in Fig. 5a.



Size of protected areas (in km^2)	Built up area in protected areas (in %)	Built up area in 10-km buffer (in %)	Total protected surface (km^2)
5-25	1.20	4.84	245,224
25-100	0.62	3.49	551,719
100-500	0.37	2.11	1,712,468
500-1000	0.26	1.36	1,198,143
>1000	0.04	0.37	14,080,972

Fig. 4. Percentage of built-up areas inside the protected areas (PAs) and in their unprotected 10-km buffers for four different PA size ranges (5–25 km^2, 25–100 km^2, 100–500 km^2, 500–1000 km^2, >1000 km^2) as of 2014. The table provides the numbers underpinning the histogram and the total protected surface in km^2 for the different sizes of protected areas.

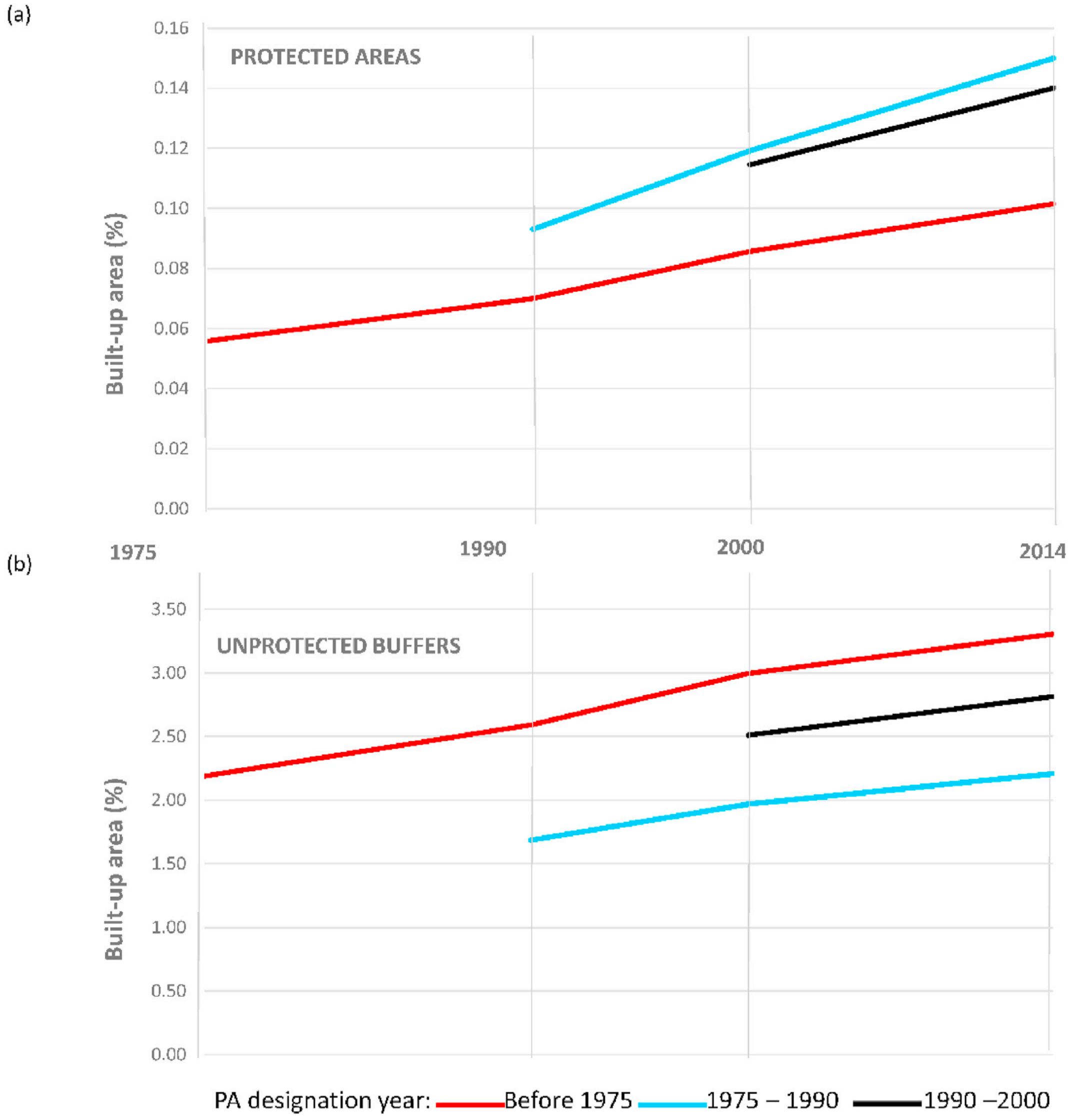


Fig. 5. Trends in the percentage of built-up areas inside protected areas (PAs) (a) and in the 10-km unprotected buffers (b) for those PAs designated before year 1975 (red line), designated before year 1990 and after 1975 (blue line) and designated before year 2000 and after 1990 (black line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

In 1975, the built-up areas only covered 0.056% of the PAs that had been designated before that year (Fig. 5a). This figure increased up to 0.093% when considering the built-up extent in 1990 and the PAs that had been designated before 1990 but after 1975, but was still less than the 0.115% of built-up area as of 2000 in the PAs designated before 2000 and after 1990.

The increase in the area occupied by built-up areas within the PAs that had been designated before 1975 was more rapid in the period from 1990 to 2000 than in 1975–1990 and in 2000–2014, as shown in Fig. 6. The rates of annual increase in built-up areas increased noticeably when more recent PAs were incorporated in the analysis (Figs. 5 and 6); for the PAs designated before 1990 but after 1975, the annual increase was also highest in 1990–2000. These results show that the older PAs (those designated before 1975) were not only freer from this form of human pressure when they were designated, but that they have also experienced lower rates of increase in built-up areas than more recent PAs for comparable periods (Figs. 5 and 6). Older PAs withstand greater pressure outside their borders (10 km unprotected surrounding) than more recently designated PAs, but experience less pressure within their borders compared to more recent PAs.

The annual increase in the extent of built-up areas in the 10-km unprotected buffers surrounding the PAs was of at least 0.017% for all considered periods and PA designation dates, which is a much higher rate than within the PAs (see above and in Fig. 6). For those PAs that had already been designated before 1975, the increase in built-up area in the period 1974–2015 was 22 times larger in the 10-km unprotected buffers than within the PAs (Fig. 6). The increase in built-up area from 1975 to 2014

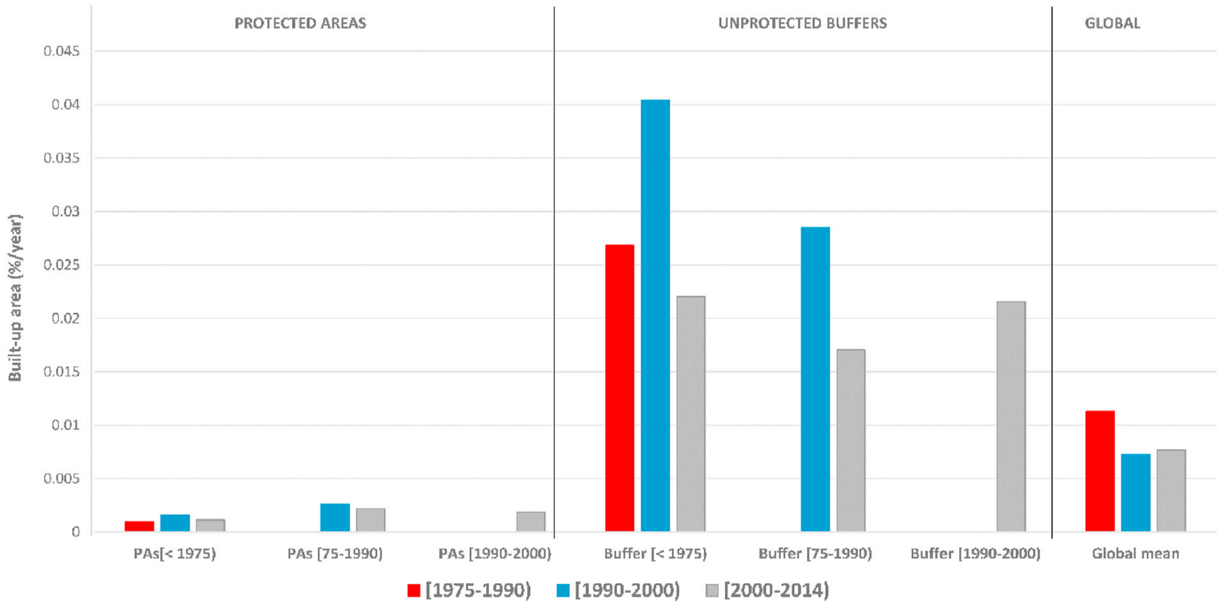


Fig. 6. Absolute annual increase in the percentage of land covered by built-up areas in protected areas (PAs), in the 10-km unprotected buffers around PAs and in all land (protected or unprotected, near or far from PAs) for different time periods. Time periods are defined by the dates for which the Global Human Settlement Layer (GHSL) is available. For the PAs and their buffers, the values are reported separately by different PA designation years.

in all world's land, either unprotected or protected, was 0.35%, i.e. nearly seven times larger than within the PAs (0.046%) and significantly lower than the value for the unprotected PA buffers (1.11%). The built-up area expansion in the unprotected buffers was fastest, just as within the PAs, in the period 1990–2000 (Figs. 5 and 6).

4. Discussion

4.1. Limited development of built-up areas within PA boundaries

Given that protected areas are declared and managed to conserve natural values, it is expected that built-up structures have a limited extent within PAs; an extent that is compatible with the conservation objectives and, where applicable, with the sustainable use of resources in the less strict PAs. This expectation is broadly in agreement with our findings, given that, globally, the percentage of built-up areas is about five times lower within PAs than the average for all land globally (unprotected and protected). It is also expected that, once a given area is declared as protected, built-up structures do not expand significantly with time (Jones et al., 2018). Our results show that this is generally the case; for instance, in the period 1975–2014 the increase in the area covered by built-up structures was eight times larger in all land globally than in the PAs that were already designated by 1975.

These findings are of importance because, in many cases, there are a number of direct and indirect pressures to biodiversity that are associated with buildings, settlements, urbanization and other forms of human-made infrastructures (McDonald et al., 2008; McDonald et al., 2009; Laurance et al., 2015), which might reduce biodiversity conservation success (Knapp et al., 2008; Alberti, 2005). These associated pressures may include poaching or overexploitation (fishing, hunting, logging, wildlife trade, etc.), extractive activities (e.g. mining), pollution (sound, light, air and water), the development of other infrastructures such as roads or railroads, or an increased spread of wildlife diseases, pests, of invasive alien species.

On the other hand, well-planned and controlled increases in built-up structures within PAs are not necessarily in conflict with conservation objectives. They may even be beneficial to PA success by supporting the infrastructures required for adequate management of the PAs and of the threats to their conservation values. Buildings used as ranger facilities, PA visitor or nature interpretation centres or wildfire extinction infrastructure, for example, are part of the integrated management of PAs and are necessary for their effective conservation management. In addition, local communities and settlements often form part of the socioecological systems designated as PAs (Palomo et al., 2014; Worboys et al., 2015). Local and indigenous communities have frequently managed and used land in ways that have maintained biodiversity; therefore, their constructions and infrastructures should not be viewed as a negative pressure which necessarily conflicts with the conservation objectives of PAs (Borrini-Feyerabend et al., 2004; Worboys et al., 2015; Garnett et al., 2018). Many studies have shown that PAs work best if they are supported by local communities (e.g. Andrade and Rhodes, 2012; Oldekop et al., 2016).

4.2. PAs face considerable built-up densities in their surroundings

Although the extent of built-up structures within PAs is limited, we found high built-up percentages in the unprotected 10 km buffers around PAs. This percentage is, globally, five times higher in unprotected buffers than the average for all land globally (unprotected and protected). This result is mainly driven by Europe, where both the PA coverage and the building density in the unprotected buffers is the highest of all continents, but it also happens, to a lesser degree, in the other continents, which all have a higher percentage of buildings in the unprotected surroundings of their PAs than in all land on the continent. This remarkable built-up density in PA surroundings may be because of several reasons. First, historically, many PAs have been designated in areas with low human influence (Joppa and Pfaff, 2009); and when PAs are designated, their boundaries are often delineated in such a way that human settlements are mostly kept outside PAs but frequently in close vicinity to them. Our results show that this is the strongest reason: in the year in which PAs were designated, PAs had a percentage of built-up area in their unprotected surroundings that was about 27 times higher than within their boundaries. Second, once PAs are established in a given area, and thereby further constructions are limited within their boundaries, they may displace any new built-up structures to their immediate surroundings. Third, PAs may have an attraction effect, so that new residential areas, such as second homes or holiday facilities, are constructed nearby PAs to enjoy the benefits and ecosystem services that PAs conserve and deliver, such as recreation, aesthetic values or air quality (Radeloff et al., 2010; Brambilla and Ronchi, 2016). Our findings are consistent with these displacement and attraction effects, although they cannot directly distinguish between the two: the increase in the built-up area has been, for all the considered periods, three times larger in the unprotected PA buffers than in all land globally.

The considerable density of built-up structures in the proximity of PAs here reported may have significant effect on the ecological processes and biodiversity within PAs (Hansen and DeFries, 2007). In addition to the direct pressures from human activities outlined in the previous section, the expansion of constructions around PAs may have a barrier effect that limits the dispersal of species, leading to reduced landscape connectivity and increased PA isolation (Bierwagen, 2007; Ewers and Rodrigues, 2008; Renwick et al., 2015), which in turn may hamper the ability of species to shift their ranges to adapt to climate change. Several studies have demonstrated an increasing isolation of species assemblages and PAs due to urbanization processes (Wade and Theobald, 2010; Radeloff et al., 2010; Knapp et al., 2008; Ricketts, 2001). These findings highlight the need to adequately manage urbanization and human settlements in the wider landscape context in which PAs are embedded, including the conservation or restoration of corridors of suitable habitat in the PA surroundings. These corridors may, in addition, enhance the provision of ecosystem services from PAs into nearby landscapes and urban areas.

4.3. High variability in built-up extent in PAs across regions

Our study shows a very high variability in the percentage of built-up areas within and around PAs across continents, regions and countries. This variability is intimately linked to human population density, socioeconomic development, PA coverage (percent of land designated as protected) and the related proximity between PAs and cities or other forms of human settlements (McDonald et al., 2009). At one extreme, we find many European countries and some Asian countries like Japan or China in which the extent of built-up areas is, even within PAs, higher than the global average for all land (either unprotected or protected). At the other extreme, we find that about a third of the PAs analysed are completely free of built-up structures within their boundaries; these PAs are concentrated in tropical, desert and boreal ecoregions in countries like Brazil, Russia, Australia or Canada. These country and regional differences broadly agree with studies that have examined the degree of human footprint in PAs or of human modification of the land worldwide as a result of multiple sources of human pressure or human stressors (Jones et al., 2018; Kennedy et al., 2019), although our analysis provides a more detailed and specific view on one of the most durable and intensive changes on land cover by humans.

In addition, we report a considerably higher pressure of built-up areas on coastal PAs than on exclusively terrestrial PAs. This high pressure on the protected coastal land is linked to the concentration of human population, extractive activities (e.g. fishing) and transportation facilities (e.g. ports) near the sea. A successful management of built-up areas may be particularly important in coastal PAs, given the fragility of and threats to many coastal habitats such as mangroves or salt marshes, the intimate links to the marine areas under protection, and the vulnerability of these coastal PAs and habitats to climate change (Gilman et al., 2008; Sandilyan and Kathiresan, 2012; Romañach et al., 2018).

More detailed information on built-up area within individual PAs is available in the DOPA Explorer of the Digital Observatory for Protected Areas (DOPA) of the Joint Research Centre of the European Commission, which can be accessed at: https://dopa-explorer.jrc.ec.europa.eu/

4.4. Trends in PA designation are associated with higher built-up densities in recent PAs

Historically, terrestrial PA establishment preferentially targeted designation of large PAs in remote locations with low anthropogenic influence or pressure (Joppa and Pfaff, 2009; Venter et al., 2018). Although this helped conserving some of the most intact portions of the Earth, it also raised some concerns as to whether sufficient protection and representation was given to species and habitats that persisted in more humanized contexts. The latter may suffer from far larger threats and human pressures, thereby benefiting more from the designation of a PA (Joppa and Pfaff, 2009). In addition, enlargement of PA systems inevitably implies protecting landscapes with a higher human influence than those covered at the earlier stages of PA designation. The combination of these factors has led to a significant shift in three important characteristics of the PAs being designated through time. Firstly, in regions like Western Europe or Northern America, more recently designated PAs are generally smaller, to cover the relatively small patches of natural or semi-natural land interspersed in intensively modified landscapes. Second, the more recent PAs have been more frequently designated under less strict management categories that allow for sustainable use of resources, to accommodate multiple uses of the landscape in these more humanized settings. Third, newer PAs typically contain higher percentages of built-up area within their boundaries as well as in their immediate surroundings, as clearly shown in our study. These trends are particularly noticeable in regions where a high percentage of the land is covered by PAs and/or with high or relatively high human population densities; for example in several European or Asian countries. These trends accentuate the need for adequate management and governance of PAs, as outlined above, in a context of increasing pressure from built-up areas within, and particularly around, PAs. These trends may only intensify in the future, both because of the projections of human population growth and because of the additional expansion of the PA systems required to meet Aichi Target 11 and other likely post-2020 PA targets. According to MacDonald et al. (2008), most PAs (88%) likely to be impacted by new urban growth are in countries whose low to moderate income and emerging economies potentially limit institutional capacity to adapt to new anthropogenic stresses on PAs.

4.5. Limitations and further research

Although we have provided the most detailed and accurate assessment of built-up areas and their trends in and around PAs worldwide, some limitations need to be taken into account, which most likely lead to some underestimate of the actual extent of built-up areas here reported, particularly in rural or sparsely populated areas (Freire et al., 2016). First, the Global Human Settlement Layer (GHSL) does not detect traditional settlement patterns composed of natural materials (e.g. wood) and/or located below a vegetation canopy. Second, the built-up area information for 1975 and 1990 should be interpreted with more caution because comparatively fewer satellite images were available for the corresponding years, resulting in important no data areas over northern South America and northern Asia, respectively, and over many islands of the Pacific (Gutman et al., 2013; Corbane et al., 2017). Third, the 30 m resolution of the GHSL may be insufficient to detect some small and isolated buildings. Additionally, the images from GLS1975 collection were gathered by Landsat MSS sensor with spatial resolution lower than 30 m (used by the further Landsat missions), which may influence the built-up classification results for the epoch 1975 especially in low density areas.

In addition, we have used a 10 km distance to assess built-up patterns within the immediate surroundings of the PAs. This 10 km distance is appropriate because the median distance from a PA to an urban area is already less than 50 km in many regions and 15% of the global urban land is within 10 km of a PA (McDonald et al., 2009). However, some built-up pressures on PAs may well extend beyond 10 km (McDonald et al., 2009), and would not be captured by our assessment. Similarly, we have used a 5 km^2 size threshold in the studied PAs; if smaller PA were considered they may, as suggested by our results on the built-up pressure for PAs of different sizes, have an even higher built-up pressure. The effect of these smaller PAs may be however limited in the global or continental results because those PAs above 5 km^2 already cover more than 90% of the total land under protection.

Although we have evaluated the trends over several decades in the presence of built-up structures in PAs globally, our analysis and conclusions are not intended to specifically address the effectiveness of PAs in preventing built-up area expansion. Further research may consider matching methods that control for observable covariates correlated with both protection and built-up area expansion (Andam et al., 2008). This would allow accounting for the non-random location of PAs and for potential spill over effects, thereby more accurately measuring the effectiveness of PAs in this regard (Andam et al., 2008). Finally, we have provided an in-depth assessment of the presence of human structures in PAs and their proximity globally, but we have not assessed the driving factors of built-up expansion nor measured the actual impacts that these structures have on the species and ecosystems under protection. Further work may explore the interactions between pressures on and changes within PAs through a combination of correlative and mechanistic approaches considering a wider range of human activities affecting PAs. This would allow providing a more comprehensive picture on where to preferentially target conservation measures and possible alternatives for socioeconomic development and urban area expansion in the broader landscape context in which PAs are embedded.

Last but not least, two anonymous reviewers raised a number of questions which go beyond the scope of this paper but give interesting research directions. We will briefly highlight here a few of these questions which should be further addressed to fill important knowledge gaps. The uncertainties regarding the positive or negative impacts of new built-up areas underline the need for improved guidelines and recommendations for better cost-benefit analyses. Similarly, one might consider the need from managing bodies to report in detail on the use of the built-up areas and to incorporate such information in the certification process for protected areas that is underpinning the IUCN Green List of Protected and Conserved Areas. Other analyses which could help refine our conclusions could address the evolution of built-up areas in different sub regions as well as in the different ecoregions, as well as explicitly addressing the driving factors or explanatory variables for built-up patterns and trends at this regional or ecoregion level. Finally, the suitability of each area could be further assessed in terms of exposure to further human developments. This last aspect could be an interesting work to be done with the help of artificial intelligence.

Readers are invited to consult regularly the DOPA website as our analyses and methods are updated at least every year.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2020.e01291.

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