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Protected areas in the world's ecoregions: How well connected are they?

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A B S T R A C T

Protected areas (PAs) are the main instrument for biodiversity conservation, which has triggered the development of numerous indicators and assessments on their coverage, performance and efficiency. The connectivity of the PA networks at a global scale has however been much less explored; previous studies have either focused on particular regions of the world or have only considered some types of PAs.

Here we present, and globally assess, ProtConn, an indicator of PA connectivity that (i) quantifies the percentage of a study region covered by protected connected lands, (ii) can be partitioned in several components depicting different categories of land (unprotected, protected or transboundary) through which movement between protected locations may occur, (iii) is easy to communicate, to compare with PA coverage and to use in the assessment of global targets for PA systems.

We apply ProtConn to evaluate the connectivity of the PA networks in all terrestrial ecoregions of the world as of June 2016, considering a range of median dispersal distances (1–100 km) encompassing the dispersal abilities of the large majority of terrestrial vertebrates.

We found that 9.3% of the world is covered by protected connected lands (average for all the world's ecoregions) for a reference dispersal distance of 10 km, increasing up to 11.7% for the largest dispersal distance considered of 100 km. These percentages are considerably smaller than the global PA coverage of 14.7%, indicating that the spatial arrangement of PAs is only partially successful in ensuring connectivity of protected lands. The connectivity of PAs largely differed across ecoregions. Only about a third of the world's ecoregions currently meet the Aichi Target of having 17% of the terrestrial realm covered by well-connected systems of PAs. Finally, our findings suggest that PAs with less strict management objectives (allowing the sustainable use of resources) may play a fundamental role in upholding the connectivity of the PA systems.

Our analyses and indicator make it possible to identify where on the globe additional efforts are most needed in expanding or reinforcing the connectivity of PA systems, and can be also used to assess whether newly designated sites provide effective connectivity gains in the PA system by acting as corridors or stepping stones between other PAs. The results of the ProtConn indicator are available, together with a suite of other global PA indicators, in the Digital Observatory for Protected Areas of the Joint Research Centre of the European Commission.

1. Introduction

Protected areas (PAs) are essential for biodiversity conservation. The fate of many endangered species, the preservation of healthy ecosystems with high species and genetic richness, and the delivery of ecosystem services from natural habitats strongly depend on PA systems that are well designed and managed. For this reason, many studies have presented and delivered indicators on the coverage, land cover trends, pressures, performance, and management efficiency of PAs (e.g. Joppa et al., 2008; Nelson and Chomitz, 2011; Joppa and Pfaff, 2011; Laurance et al., 2012; Geldmann et al., 2013; Nolte et al., 2013; Coetzee et al., 2014; Marino et al., 2015; Gray et al., 2016). These studies and indicators provide very valuable information on different aspects of PAs, but they have not explicitly considered the PA system as a network of sites potentially linked through spatial and temporal interactions. Because of these links and interactions, it may not be possible to evaluate the functioning of the network as a whole as the sum of its individual parts (PA) separately considered.

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There is indeed a growing recognition that PAs cannot be conceived and managed as "islands" isolated from other PAs and from the rest of the landscape context (Laurance et al., 2012). Even if a given area is designated as protected because of the local biodiversity values it presents, such as high species richness and presence of endangered or endemic species, and even when all the appropriate conservation measures are taken inside that PA, declines in biodiversity within the PA may still occur as a result of the extinction debts produced by the lack of connectivity with other (ideally protected) populations and natural habitats (Kuussaari et al., 2009; Pressey et al., 2015). In addition, it is projected that climate change will make some PAs inhospitable for many of the species they currently harbor, requiring species to move to new locations matching their environmental requirements, typically at higher latitudes or altitudes (Thomas et al., 2012; Beale et al., 2013). In the absence of connectivity in the PA systems, individual PAs may turn into climatic traps under warming, hampering their ability to meet their long-term conservation goals. Therefore, the connectivity of PAs, defined as the ease of species movements and other ecological flows among protected locations, is at the forefront of the concerns for biodiversity conservation.

The scientific evidence on the importance of PA connectivity has already translated into global commitments at the political level. In the 10th meeting of the Convention on Biological Diversity (CBD) around 200 parties to the CBD (i.e. most of the world's governments) adopted a Strategic Plan for Biodiversity for the 2011–2020 period including twenty Aichi Biodiversity Targets (CBD, 2010). In Aichi Target 11 the international community agreed to increase by 2020 the terrestrial area under protection to at least 17% in 'effectively and equitably managed, ecologically representative and well connected systems of protected areas' (CBD, 2010). Despite the importance of these global goals for PAs, the definition and supporting material of Aichi Target 11 (CBD, 2011) does not specify a quantitative criterion or indicator to be used to track progress towards the connectivity element of this target. This lack of available indicators and of quantifiable aspects has prevented consistent interpretation by signatories, and has made it difficult to stimulate and quantify progress towards the Aichi Target 11 element on well-connected PA systems, as is also the case for other Aichi Targets (Butchart et al., 2016). On the other hand, there are very few studies that have quantified the connectivity of the terrestrial PA networks, particularly at a global scale. To our knowledge, none of the existing studies has provided information that can be used to report against the connectivity component of the global Aichi Target 11, because they have only covered some countries, regions or continents (e.g. Minor and Lookingbill, 2010; Gurrutxaga et al., 2011; Opermanis et al., 2012; Mazaris et al., 2013; Wegmann et al., 2014; Maiorano et al., 2015; Belote et al., 2016), because they have mapped connectivity patterns or priority areas but have not provided an indicator that can be used to assess PA connectivity targets (e.g. Gurrutxaga et al., 2011; Wegmann et al., 2014; Belote et al., 2016), and/or because, even if they are global, they have only considered some types of PAs (Santini et al., 2016), omitting a large part of the protected lands that may contribute to connectivity and related Aichi Targets.

Here we present Protected Connected (ProtConn), an indicator of the connectivity of PA systems that improves the detail and comprehensiveness of previous related assessments mainly by depicting different categories of land through which movement between protected locations may occur, including the assessment of the contribution of transboundary PAs to connectivity (i.e. how PAs outside a study region help to connect those PAs inside). ProtConn is based on graph theory (network analysis) and accounts for both the land area that can be reached within PAs and that reachable through the connections between different PAs. We assess this indicator globally for all the world's terrestrial ecoregions, as large units of land with similar environmental conditions and distinctive species composition, using the information on PAs as of June 2016. In our assessment, we do not consider the heterogeneity of the landscape matrix in between PAs, because the resistance to species movement by different land covers has been shown to be highly variable among and within species (Goosem, 2001; Rytwinski and Fahrig, 2012; Gastón et al., 2016). Rather, we provide a more general analysis at the global level that is not attached to the details of particular species but focuses on the connectivity of PA systems as given by the coverage and spatial arrangement of PAs and by the range of dispersal distances that have been observed for the majority of terrestrial vertebrates.

By doing so, we aim to provide an indicator of PA connectivity which can be directly used by the CBD and its parties to assess progress towards Aichi Target 11 and other future targets, as well as by the European Union (EU) to support its Green Infrastructure Strategy where PAs such as Natura 2000 sites form the backbone of a broader EU Biodiversity Strategy to 2020. For this purpose, the ProtConn indicator has been developed to support and further enrich the Digital Observatory for Protected Areas (DOPA) of the Joint Research Centre of the European Commission (Dubois et al., 2013, 2015), which can be accessed at http://dopa.jrc.ec.europa.eu/ . DOPA is a set of web services and applications that, using global reference datasets, provides a broad range of consistent and comparable indicators on the state of and pressures on PAs worldwide (Dubois et al., 2016). The information provided by the ProtConn indicator, together with other global indicators on PAs available in DOPA, can be used, for example, to support spatial planning, resource allocation, strategies for improving the PA networks, and national and international reporting.

2. Methods

2.1. Spatial layers: sources and processing

2.1.1. Protected areas

We downloaded the public version of the World Database on Protected Areas (WDPA) for June 2016 as a file geodatabase from Protected Planet (http://www.protectedplanet.net/). 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 (IUCN and UNEP-WCMC, 2016). WDPA includes all sites designated at a national level (e.g. national parks), under regional agreements (e.g. the Natura 2000 network in the European Union) and under international conventions and agreements (e.g. natural World Heritage sites), which for June 2016 gives about 200,000 terrestrial PAs. As in other global PA assessments (e.g. UNEP-WCMC and IUCN, 2016), we excluded from subsequent analysis those PAs with a "proposed" or "not reported" status, sites reported as points without an associated reported area, and UNESCO Man and the Biosphere Reserves (as their buffer areas and transition zones may not meet the IUCN protected area definition, and because most of their core areas overlap with other protected areas); these excluded sites were about 3% of the total number of terrestrial PAs reported in the WDPA. We considered all PA types, including PAs with not reported or not assigned IUCN category in the WDPA, in consistency with other analyses of global targets for PAs (e.g. UNEP-WCMC and IUCN, 2016). For PAs reported in the WDPA as points with unknown boundaries but including a reported area, a geodesic circular buffer with an area equal to the reported value was created and used in the analysis, similarly to previous studies (e.g. Gray et al., 2016; UNEP-WCMC and IUCN, 2016). The PA polygons (including the buffered points) were dissolved to remove all overlaps between different designation types and avoid double counting (e.g. where the same area is designated both as a National Park and as a World Heritage site). The PA polygons in the dissolved layer could hence correspond to several overlapping or adjacent PAs. For computational feasibility of the connectivity calculations, we removed PA polygons with an area (calculated in Mollweide projection) smaller than 1 km^2, which is consistent with other previous analysis on PAs at global or European scales (Leroux et al., 2010; Opermanis et al., 2012; Santini et al., 2016) and retained 99.9% of the total land area covered by PAs globally.

2.1.2. Ecoregions

The connectivity analyses were performed for each of the 827 terrestrial ecoregions of the world delineated by Olson et al. (2001) as a biogeographic regionalization of the global terrestrial biodiversity that can serve to support the development of large-scale conservation strategies. The ecoregions are large units of land, each containing a distinct composition of natural communities which share similar environmental conditions, with boundaries that approximate the original extent of these natural communities prior to major land-use change. The Terrestrial Ecoregions of the World data set (TEOW, 2001) was used for the spatial analyses. Ecoregions are classified in TEOW into 14 biomes and 8 realms (7 if Antarctica is excluded), which were also considered in the analysis (see Section 2.3.4 below).

The TEOW layer was intersected with the dissolved PA layer and the resultant features were converted to single parts, which gave the individual PA polygons falling within each ecoregion, hereafter referred to simply as PAs for brevity. Their area was calculated in Mollweide projection. In order to facilitate computation of the inter-PA distance calculations on the dissolved vector layer (see next Section 2.2.1) we reduced the number of vertices in the polygons using the Simplify Geometries tool in QGIS 2.12 with a tolerance of 100 m. All subsequent processing and indicator calculations were done using this vector layer unless explicitly noted.

2.2. Inter-PA distances, dispersal kernels, and transboundary PAs

2.2.1. Calculating inter-PA distances and accounting for transboundary PAs

We selected all PAs within each ecoregion, calculated the centroid of these PAs (one centroid for all PAs in an ecoregion), and projected the PA layer to an azimuthal equidistant projection centered in the coordinates of that centroid for subsequent accurate distance calculation (including PA buffering) in each ecoregion. PAs within the ecoregion were then buffered by a distance of 500 km. All PAs outside the ecoregion falling (entirely or partially) within this buffer were considered as transboundary areas potentially contributing to connectivity between the PAs within the ecoregions, i.e. the connectivity of two PAs within the ecoregion could be enhanced by a different PA located outside the ecoregion that functioned as a connecting element or stepping stone between them. The distance of 500 km was selected because it covered all the PAs to which movement was likely given the set of dispersal distances considered (see Section 2.2.2 below). Both the PAs within the ecoregion and the transboundary PAs were included in the ecoregion layers for the distance and connectivity processing, although they were treated differently in the calculation of the connectivity indicators (see Section 2.3.2). We calculated the distances between the edges of the PAs in the azimuthal equidistant projection for each ecoregion using the Conefor Inputs plugin in QGIS 2.12.

2.2.2. Dispersal distances and kernel

We considered four median dispersal distances (d) of 1, 10, 30 and 100 km, which covered values up to the median dispersal abilities of the large majority of terrestrial species. Of the 44 bird and more than 65 mammal species with reported median dispersal distances in Sutherland et al. (2000), Whitmee and Orme (2013) and Santini et al. (2013), no bird species and only five mammal species had some cases in which d exceeded 100 km. All the 75 terrestrial bird species reported in Paradis et al. (1998) had their mean natal dispersal distances within the 1–100 km range. A very similar range of d values from 0.177 to 99.58 km was used by Santini et al. (2016) as it encompassed the variability in dispersal distances observed in terrestrial vertebrates, and the same range of 1–100 km was used by Minor and Lookingbill (2010). The central value of the log-transformed range of dispersal distances considered (1–100 km) is d = 10 km; we therefore selected 10 km as the reference d for which we preferentially show several of the results of the connectivity analysis (although the indicators are calculated and provided for the other d values as well). There are species with dispersal abilities below d = 1 km, such as many small rodents (Sutherland et al., 2000; Whitmee and Orme, 2013; Santini et al., 2013), most amphibians (Smith and Green, 2005) and most butterflies (Stevens et al., 2013). Although our indicators could be calculated for any d value, here we decided not to analyze the range of d below 1 km mainly because of the limited spatial precision and accuracy of the PA boundaries in the WDPA for many countries, and because such small distances are unlikely to provide significant levels of inter-PA connectivity at an ecoregion or global scale.

The probability of direct dispersal (p_{ij}) between two PAs i and j was calculated through a negative exponential function of the distance separating the PAs, in which p_{ij} = 0.5 for those PAs separated by a distance equal to the species median dispersal distance (d). This exponential dispersal kernel is widely used in connectivity analyses (e.g. Saura and Pascual-Hortal, 2007; Gurrutxaga et al., 2011).

Note that the maximum dispersal distances that can be reached by a species are much larger than the median d, and this is compatible with the modelling here adopted. For example, a distance between PAs equal to 5d can be traversed with a probability of 0.03 (i.e. 3% of the dispersing individuals of a species could reach that distance). A buffer of 500 km was hence considered sufficient to account for the potential contribution of transnational PAs (Section 2.2.1) even for the largest considered d = 100 km.

2.3. Protected area connectivity indicators

2.3.1. The Probability of Connectivity and Equivalent Connected Area metrics

Two related graph-based metrics underlie the PA connectivity indicators presented in this study: the Probability of Connectivity (PC) (Saura and Pascual-Hortal, 2007; Saura and Rubio, 2010) and the Equivalent Connected Area (ECA) (Saura et al., 2011; Saura and de la Fuente, 2017). PC and ECA measure the reachable habitat resources in a landscape or region, accounting for both the resources that can be reached within the habitat patches (intrapatch connectivity) and those made available by (reachable through) the connections with other habitat patches (interpatch connectivity). In this way, the metrics acknowledge that species may be able to reach a larger amount of habitat resources either through bigger patches (patches are assumed to be internally connected) or through more numerous or stronger connections among different patches.

For calculating PC and ECA, we represented the PA systems in each ecoregion (including transboundary PAs) as a weighted probabilistic graph (network). In this graph, nodes (patches) corresponded to PAs, weighted by a certain attribute as described below (Section 2.3.2). Links represented the possibility for movement between nodes (PAs) and were weighted by the probability of direct dispersal between them (p_{ij}). Given this graph representation, PC is defined as the probability that two randomly selected locations within an ecoregion fall into protected locations that are connected to each other. The Equivalent Connected Area (ECA) is defined as the size (area) that a single PA should have to provide the same amount (area) of reachable protected land as the network of PAs in an ecoregion.

2.3.2. The Protected Connected indicator

We defined and calculated a set of indicators to assess the connectivity of PA systems (Table 1). These connectivity indicators are based on PC and ECA and have the Protected Connected land (ProtConn) as the main indicator, but are here newly presented and partitioned into several fractions that provide a more insightful and complete view of the connectivity of the PA systems. In this way, the new set of indicators improves the detail and accuracy of previous PA connectivity assessments that used similar PC and ECA metrics (Gurrutxaga et al., 2011; Mazaris et al., 2013; Santini et al., 2016).

The first three indicators considered in the analyses (see Table 1 for a text description) are expressed as a percentage of the total area of the study region (here ecoregion) and are given by the following equations:

$$ProtConn = 100 \times \frac{ECA}{A_L} = 100 \times \frac{\sqrt{\sum_{i=1}^{n+t}\sum_{j=1}^{n+t} a_i a_j p^*_{ij}}}{A_L} \quad (1)$$

$$Prot = 100 \times \frac{\sum_{i=1}^{n} a_i}{A_L} \quad (2)$$

$$ProtUnconn = Prot - ProtConn \quad (3)$$

where n is the number of PAs within the ecoregion, t is the number of PAs in the transboundary buffer (here of 500 km) outside the ecoregion, a_i and a_j are the attribute of PAs i and j, A_L is the maximum landscape attribute (here total ecoregion area), and p^*_{ij} is the maximum product probability of all paths connecting nodes i and j. Both direct and indirect (stepping-stone) movements between PAs are accounted for by p^*_{ij}. By definition $p^*_{ij} \geq p_{ij}$, since p_{ij} only accounts for direct dispersal movements; p^*_{ij} will be higher than p_{ij} when some intermediate stepping-stone PAs make dispersal between i and j more likely than what a direct movement (not using any stepping stone) would do (Saura and Pascual-Hortal, 2007; Saura and Rubio, 2010; Saura, 2015). The attribute of the nodes is here made equal to the area of the PAs for those PAs within the ecoregion, and equal to 0 for the transboundary PAs outside the ecoregion. In this way, we analyze a network in which the sources and destinations of the dispersal fluxes are only those PAs within the ecoregion (those with $a_i > 0$), but in which the potential role of PAs outside the ecoregion as connectors or stepping stones between PAs within the ecoregion is considered; in the details of the underlying metrics, this means that for the transboundary PAs only the connector fraction of the PC metric is considered (Saura and Rubio, 2010; Baranyi et al., 2011).

RelConn is expressed as a percentage of PA coverage in the region (Prot), as given by:

$$RelConn = 100 \times \frac{ProtConn}{Prot} \quad (4)$$

Note that while all indicators provide useful and complementary information, the meaningful connectivity indicator is ProtConn, and not RelConn, as illustrated in Fig. A1 in Appendix A; it is preferable, from a conservation and PA design point of view, to have a higher ProtConn with a lower RelConn than a high RelConn at the expense of a low ProtConn (Fig. A1). ProtConn is similar to the normalized ECA used by Saura and Bodin (2014) or Santini et al. (2016), but is here improved and enriched to depict different categories of land through which movement between protected locations may occur as well as to account for transboundary connectivity in the ecoregion-level indicator, as described next.

2.3.3. Fractions of the Protected Connected indicator

The Protected Connected (ProtConn) land indicator can be partitioned into three fractions (Table 1) that are expressed as a percentage of the total ProtConn value, hence summing up to 100:

$$ProtConn[Prot] + ProtConn[Unprot] + ProtConn[Trans] = 100 \quad (5)$$

Or, by further partitioning ProtConn[Prot] into two more detailed fractions, ProtConn[Within] and ProtConn[Contig], we get the final set of four ProtConn fractions (Table 1):

$$ProtConn[Within] + ProtConn[Contig] + ProtConn[Unprot] + ProtConn[Trans] = 100 \quad (6)$$

The ProtConn fractions are calculated using the following equations:

$$ProtConn[Prot] = 100 \times \frac{100 \times \frac{\sqrt{\sum_{i=1}^{n} a_i^2}}{A_L}}{ProtConn} \quad (7)$$

$$ProtConn[Within] = 100 \times \frac{100 \times \frac{\sqrt{\sum_{i=1}^{r} a'^2_i}}{A_L} \times \sqrt{\frac{\sum_{i=1}^{n} a_i}{\sum_{i=1}^{r} a'_i}}}{ProtConn} \quad (8)$$

$$ProtConn[Contig] = ProtConn[Prot] - ProtConn[Within] \quad (9)$$

$$ProtConn[Trans] = 100 \times \frac{100 \times \frac{\sqrt{\sum_{i=1}^{n+t}\sum_{j=1}^{n+t} a_i a_j p^*_{ij}} - \sqrt{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i a_j p^*_{ij}}}{A_L}}{ProtConn} \quad (10)$$

$$ProtConn[Unprot] = ProtConn - ProtConn[Prot] - ProtConn[Trans] \quad (11)$$

where r is the number of single-part PA polygons in the intersection of the TEOW ecoregion layer with the non-dissolved WDPA layer (hence including individual PAs with overlaps for multiple designations), a'_i is the area of the single-part PA polygon i in such intersected non-dissolved layer, and the rest is the same as described above. There are overlaps in the PA polygons in such a non-dissolved layer because the same location may be covered by several PAs of different types (e.g. same area designated as a National Park and as a World Heritage site), which would lead to an overestimate (double counting) of the actual area protected in the ecoregion, hence biasing the value of ProtConn[Within]. This area overestimate is accounted for in the ProtConn[Within] formula through the correction factor $\sqrt{\sum_{i=1}^{n} a_i / \sum_{i=1}^{r} a'_i}$.

The ProtConn fractions may be alternatively expressed as a percentage of the total land area in the study region, rather than as a percentage of the total ProtConn value, simply by multiplying by ProtConn/100 in Eqs. (5)–(11), case in which the sum of the fractions would equal the ProtConn value, rather than 100 as in Eqs. (5) and (6). All the values of these fractions shown in the results of this paper are expressed, however, as the percentage of the total ProtConn value as given by Eqs. (5)–(11).

All the connectivity indicators were calculated using the command line version of the software package Conefor 2.6 (Saura and Torné, 2009), updated at www.conefor.org.

2.3.4. Averages at the global, realm and biome levels

The indicator values were aggregated at the global, realm and biome level by calculating the average of the ecoregion-level indicator values weighted by the area of each ecoregion. In the

Table 1
Indicators on protected area (PA) connectivity in this study. All the indicators are expressed as percentages. The main and most important connectivity indicator is Protected Connected (ProtConn). ProtConn can be further partitioned in several fractions (see second part of the table) giving additional details and insights on PA connectivity (see methods for equations and related details). PA coverage is not a connectivity indicator but it is included because of its wide use in assessing PA systems and because it is a key benchmark for the described connectivity indicators. Although in this table and throughout the manuscript we refer to connected lands, the set of described indicators could also be applied to water bodies or to other specific ecosystems such as forests or grasslands.

Indicator name (acronym)	Description
Indicators referring to the entire connectivity or coverage of PAs in a region	
Protected Connected land (ProtConn)	Percentage of the study region covered by connected protected lands. It is calculated as the value of the Equivalent Connected Area metric divided by the total area of the study region.
PA Coverage/Protected land (Prot)	Percentage of the study region covered by PAs.
Protected Not Connected land (ProtUnconn)	Percentage of the study region covered by protected lands that are isolated. It is simply the difference between Prot and ProtConn.
Relative Connectivity of PAs (RelConn)	Percentage of the protected lands within the study region that are connected. It is calculated as the ratio between ProtConn and the PA coverage (Prot), multiplied by 100.
Protected Connected by moving... (fractions of ProtConn referring to specific components of PA connectivity)	
...through Protected lands (ProtConn[Prot])	Percentage of the Protected Connected land (ProtConn) that can be reached by moving only through protected lands, without traversing unprotected lands. This indicator can be partitioned in two subindicators, ProtConn[Prot] = ProtConn[Within] + ProtConn[Contig], which are described next.
...within Individual PAs (ProtConn[Within])	Percentage of the Protected Connected land (ProtConn) that can be reached by moving only within individual PAs, i.e. how much land can be accessed by species if they move only within the limits of individual PAs.
...through Contiguous PAs (ProtConn[Contig])	Percentage of the Protected Connected land (ProtConn) that can be reached by moving through sets of immediately adjacent (contiguous) PAs, without traversing any unprotected lands. This percentage excludes the protected land that can be reached by moving within a single PA, which is given by ProtConn[Within].
...through Unprotected lands (ProtConn[Unprot])	Percentage of the Protected Connected land (ProtConn) that can be reached by moving through unprotected areas. It includes movements between PAs that entirely happen through unprotected lands and others that traverse unprotected lands in the initial and final stretches but that may use some protected land in between. The value of this fraction will be lower when PAs are separated by larger tracts of unprotected lands, making inter-PA movements less likely, particularly when the distances that need to be traversed through unprotected lands are large compared to the species dispersal distance.
...through Transboundary Protected lands (ProtConn[Trans])	Percentage of the Protected Connected land within the study region (ProtConn) that can be reached by moving through PAs located outside the region boundaries. It includes the effect of both transboundary PAs in the strict sense (i.e. individual PAs that extend across region boundaries) as well as of other PAs that, located outside the region, promote the connectivity between PAs within the region by acting as stepping stones between them.

calculation of these averages we excluded Antarctica and lakes as mapped in the TEOW layer. The individual indicator values for the four Antarctic ecoregions were, however, also calculated.

3. Results

3.1. World averages of the protected area connectivity indicators

In average, Protected Connected lands (ProtConn) only covered 9.3% of the area of the world's terrestrial ecoregions for a median dispersal distance $d = 10$ km (Fig. 1). ProtConn ranged from 8.5% to 11.7% for the minimum and maximum considered d of 1 and 100 km, respectively (Figs. 2 and A2 in Appendix A).

Protected Connected land was, for all considered d, noticeably smaller than the global PA coverage of 14.7% (i.e., land covered by PAs, either connected or not), as shown in Figs. 1 and 2. The spatial arrangement of PAs was therefore only partially successful in ensuring connectivity of protected lands, considering the dispersal ranges of the large majority of terrestrial vertebrates. For instance, for $d = 10$ km, only 63% of the total protected land was connected (RelConn = 63 = 100*9.3/14.7).

Further partitioning the ProtConn indicator showed that species could reach most of the protected connected land by moving only through PAs within the ecoregion (ProtConn[Prot]), as shown in Fig. 1. This could happen in two ways. First, by accessing the resources that are available within an individual PA (more protected connected land reachable within a PA the larger the PA is); this possibility (ProtConn[Within]) accounted for 58.1% of the total Protected Connected land for $d = 10$ km, with a decreasing relative contribution for larger d (Figs. 1 and A2). Second, species could traverse multiple adjacent PAs when they were spatially arranged as to allow for continuity of movement through protected lands; this possibility (ProtConn[Contig]) accounted for 22.5% of ProtConn for $d = 10$ km, again with a decreasing relative contribution for more mobile species (Figs. 1 and A2).

Other movement possibilities between protected locations in the ecoregion involved either unprotected land or protected land outside the ecoregion boundaries (Fig. 1). Movement through unprotected lands (ProtConn[Unprot]) clearly increased with species dispersal abilities and accounted for a maximum of 30.7% of the total ProtConn value for the largest considered d of 100 km (Figs. 1 and A2). The lowest ProtConn[Unprot] value (only 3.9% of total ProtConn) was found for the shortest dispersal distance considered ($d = 1$ km), as shown in Fig. A2 ; note, however, that if species with even lower dispersal abilities through unprotected landscapes would be considered, ProtConn[Unprot] would further decrease, eventually getting very close to zero for species with d well below 1 km. Transboundary connectivity (i.e., how PAs outside an ecoregion help to connect the PAs within that ecoregion) had, in average, a noticeable contribution: for $d = 10$ km, 8.2% of the protected connected land was due to the contribution of transboundary PAs (ProtConn[Trans]) promoting connectivity between PAs within the ecoregion (Fig. 1). ProtConn[Trans] decreased with species dispersal abilities, ranging from 8.5% to 5.7% for d of 1 km and 100 km respectively (Fig. A2).

3.2. Protected area connectivity indicators for individual ecoregions

The connectivity of PAs largely differed across ecoregions (Fig. 3). The Protected Connected land indicator for individual ecoregions encompassed the full possible range of variation (Fig. 4), from 0% (for those ecoregions with no designated PAs, and hence with no protected connected land) to 100% (for ecoregions fully

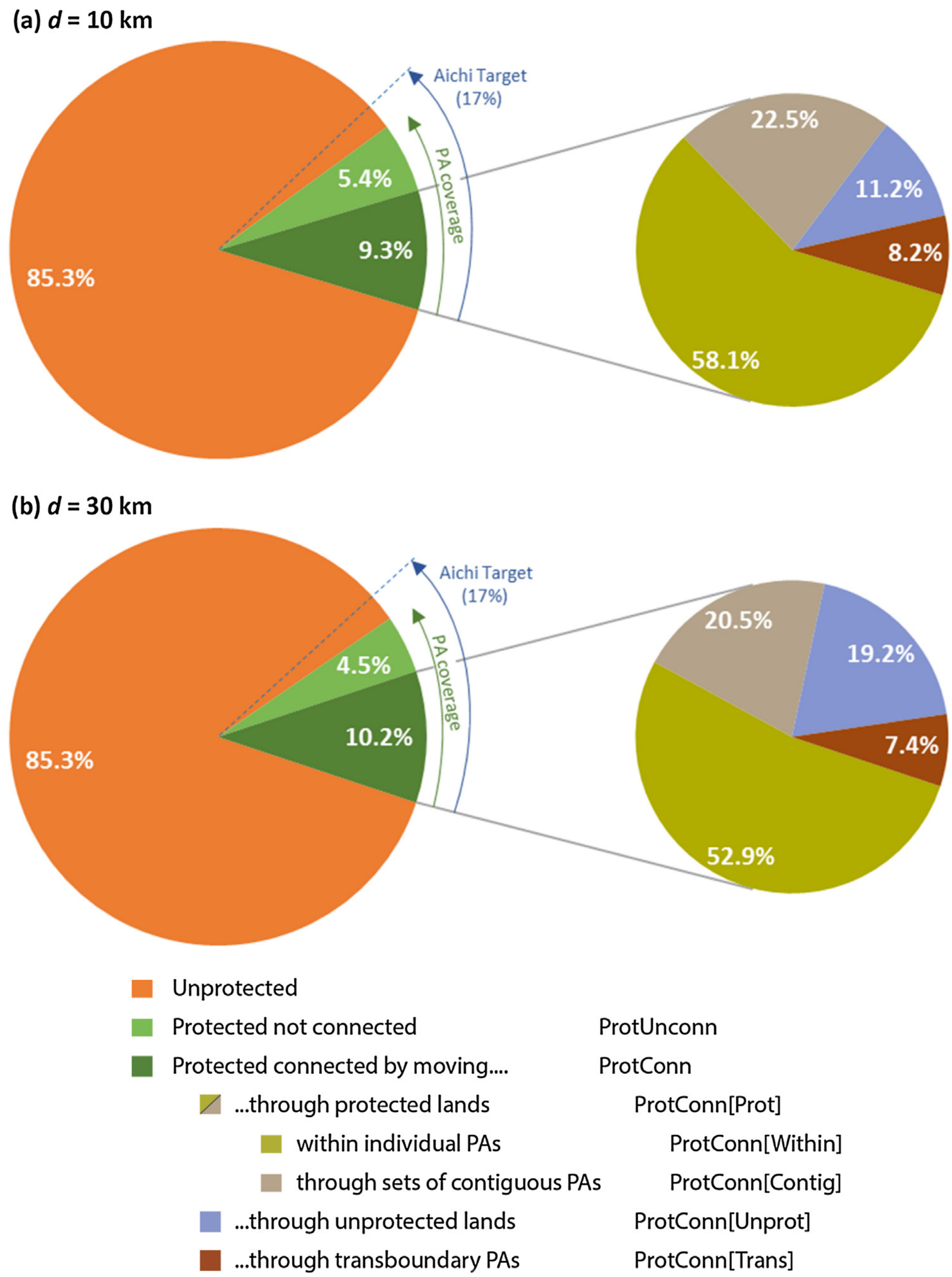

Fig. 1. Global average of the Protected Connected land indicator (dark green slice in the left pie chart) and of its fractions (right pie chart) for all the world's terrestrial ecoregions and a median species dispersal distance *d* of (a) 10 km and (b) 30 km. Global PA coverage (sum of protected connected and protected not connected land: 14.7%) and the Aichi Target 11 for year 2020 are also indicated next to the left pie charts. The indicator values for *d* of 1 km and 100 km are provided as pie charts in Fig. A2 in Appendix A.

covered by one or several adjacent PAs, which ensured the continuity of protected land all throughout the ecoregion). Large ecoregions with well-connected PA networks, as given by high ProtConn values, were found in the tundra and taiga ecoregions of Alaska, in the Amazonian and Orinoco moist forests (most notably in Brazil and Venezuela), in Europe, in Greenland, in the Tibetan plateau in China, in most of the Central American ecoregions adjacent to the Caribbean Sea, and in several ecoregions in Southern Africa and in Western-Central and tropical Australia, among others (Fig. 3). Large ecoregions with low Protected Connected land values were found in most of North America, in the southern half of South America, in Northern Africa, and in the large majority of Asia, among others (Fig. 3). A considerable variability in ProtConn values was also found at the realm and biome level (Appendix B).

The Protected Connected land indicator, by definition, cannot be higher than the PA coverage (it is not possible to have more protected connected land than the total protected land in an ecoregion). However, the Relative Connectivity indicator, which quantifies how much smaller ProtConn is compared to the total PA coverage, largely varied across ecoregions (Fig. 4). While in the global average a little less than two thirds of protected lands (RelConn = 63%) were actually connected for d = 10 km (see Figs. 1–2 and previous Section 3.1), RelConn could be much higher or lower than 63% for particular ecoregions. Some illustrative examples of ecoregions where the Protected Connected land indicator is almost

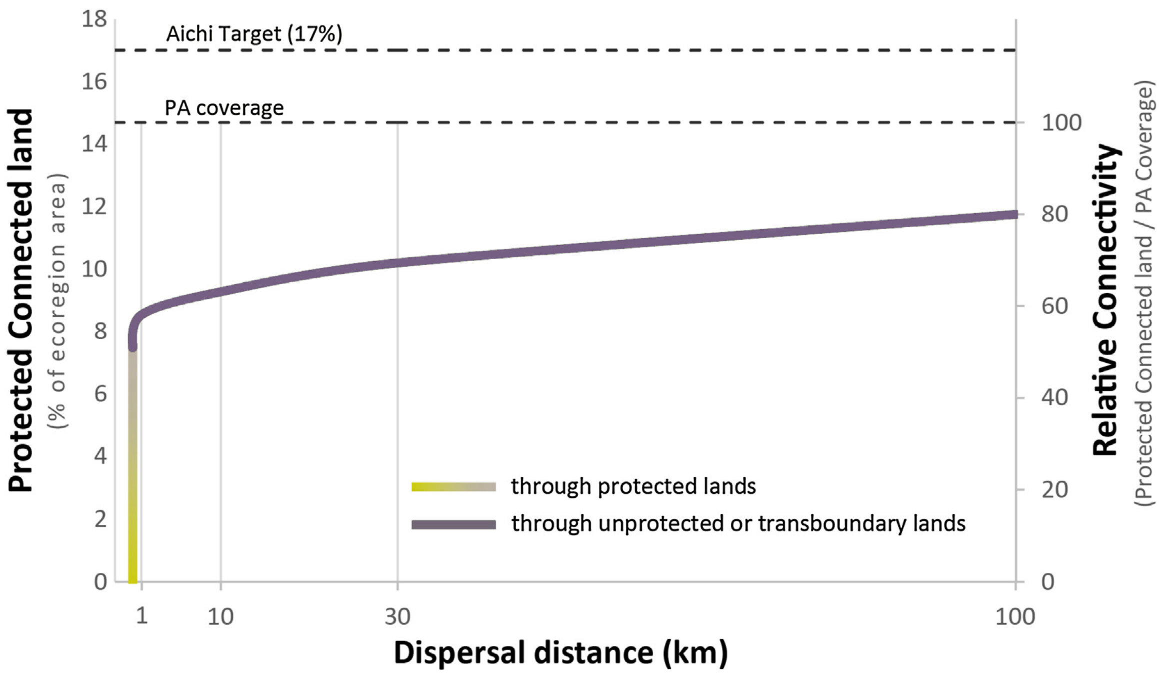

Fig. 2. Protected Connected land (left *y* axis) and Relative Connectivity (right *y* axis) in the world's terrestrial ecoregions (global average) as a function of species median dispersal distance (km) outside PAs. The plot differentiates between the protected connected land that is reachable by moving through protected lands within the ecoregion and that which is reachable through unprotected or transboundary lands. The dashed lines indicate the current global PA coverage and the Aichi Target 11 for 2020.

as high as the PA coverage are shown in Fig. 5. Fig. 6 gives examples of ecoregions in which a large part of the protected land is unconnected (Protected Connected land considerably lower than PA coverage, i.e. low RelConn); this can happen either for ecoregions below (Fig. 6a) or above (Fig. 6b) the 17% Aichi Target.

In June 2016, 43% of the world's ecoregions already meet the Aichi Target 11 of providing a terrestrial coverage of PAs of at least 17% by 2020. In comparison, however, only 28% of the world's ecoregions have a Protected Connected land of at least 17% for $d = 10$ km (with such percentage ranging from 25% to 37% for d of 1–100 km respectively). The progress towards Aichi Target 11 is slowest for the largest ecoregions; if we focus on the half of the world's ecoregions with the largest area, only 35% of them meet the 17% target for PA coverage and only 19% of them meet the 17% target for Protected Connected land for $d = 10$ km. Similarly, only one of the seven world's realm and three of the fourteen world's biomes had ProtConn $\geq$ 17% for $d = 10$ km (Appendix B). It therefore follows that a significant number of ecoregions already meet in June 2016 the 17% target in terms of PA coverage but not in terms of PA connectivity (Fig. 7). In summary, the work required to improve the network of protected areas is much larger if the target of well-connected PA systems is to be achieved than if the target needs to be addressed purely in terms of the coverage (amount) of land protected.

In many ecoregions the connectivity of the PAs was not benefited, or was only slightly benefited, by protected areas located beyond the ecoregion boundaries. In half of the world's ecoregions, the percentage of Protected Connected land due to PAs outside ecoregion boundaries (ProtConn[Trans]) was smaller than 1% for $d = 10$ km, compared to the 8.2% world average (Fig. 1). However, transboundary connectivity played a much more prominent role in some other ecoregions, as in the example illustrated in Fig. 5b. In this example, riparian PAs and other PAs located outside the ecoregion were able to provide linkages between several of the PAs in different sectors of the ecoregion that would be otherwise isolated or much more weakly connected (Fig. 5b).

4. Discussion

4.1. Have protected area networks been well designed in order to ensure connectivity?

Ideally, the coverage of a protected area network should be accompanied by comparable levels of Protected Connected land, as in the examples in Fig. 5. Our results have shown, however, that the spatial arrangement of PAs is only partially successful in ensuring the connectivity of protected lands. The PA networks only seem to achieve intermediate levels of connectivity for most of the terrestrial species, as given by an average relative connectivity of 63% for a reference median dispersal distance $d = 10$ km (Fig. 2). This probably reflects that PAs have been often established “opportunistically”, in remote areas with low productivity where there is little conflict with human land uses (Scott et al., 2001; Joppa and Pfaff, 2009), or based on the values within the individual areas that are designated as protected (local species diversity, presence of unique habitats, endangered or endemic species, scenic attributes, etc.). Much less attention has been paid, in the PA designation process, to their connecting role in a wide PA network context or to the likelihood of species movements (and of other ecological flows) to and from other PAs.

4.2. How far are we from the Aichi Target for protected area connectivity?

The international community, represented by the Parties to the CBD, committed, in Aichi Target 11, to increase by 2020 the terrestrial area under protection to at least 17% in well-connected systems of protected areas (CBD, 2010). Tittensor et al. (2014) projected, through statistical models, the PA trends up to 2020 and concluded that this 17% Aichi Target was likely to be met for PA coverage. Even when the current PA coverage as of June 2016 (14.7%) is below the value projected to such date by Tittensor et al. (2014), there may still be opportunities for this target to be met by 2020.

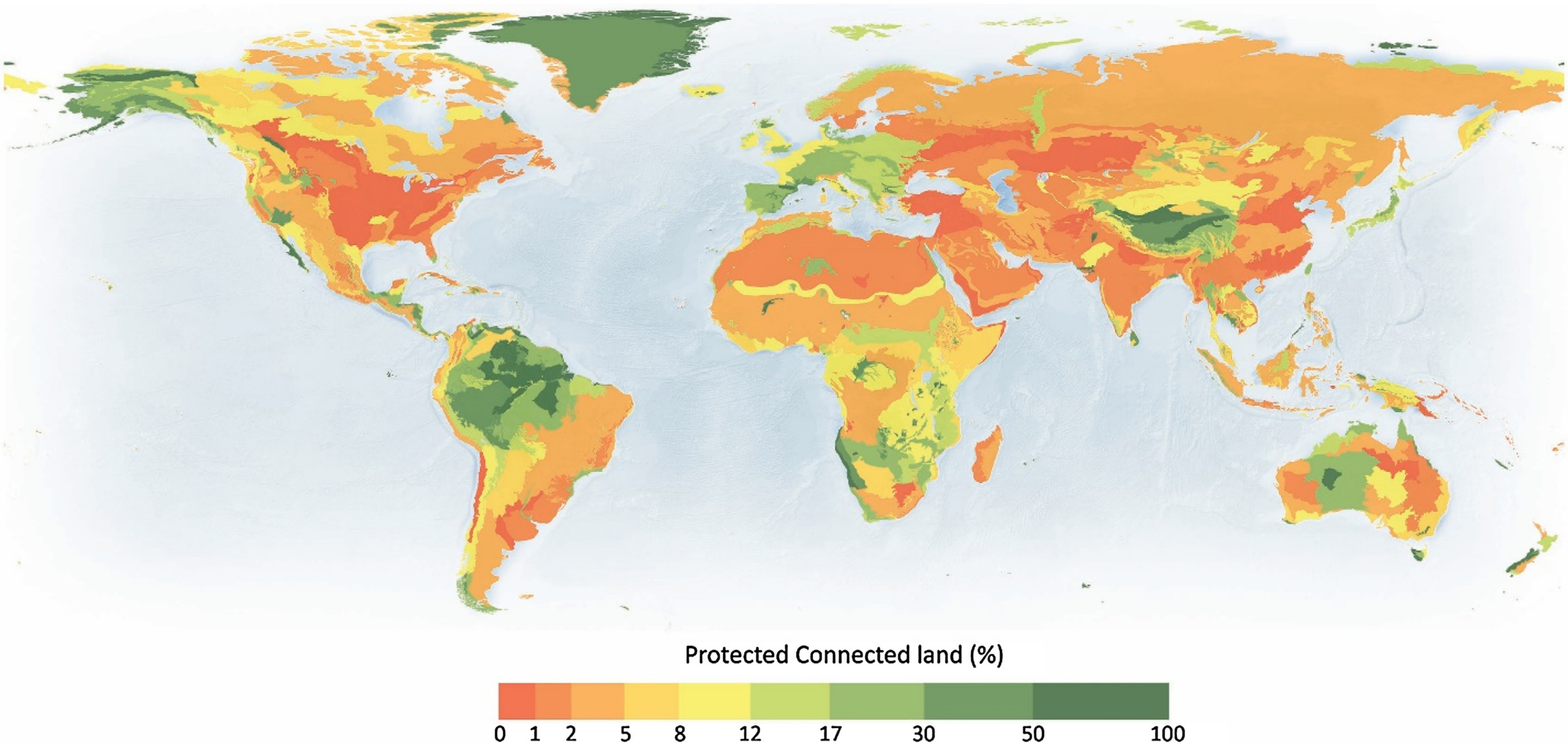

Fig. 3. Protected Connected land (% of ecoregion area) for all the world's terrestrial ecoregions for a reference median dispersal distance of $d = 10$ km.

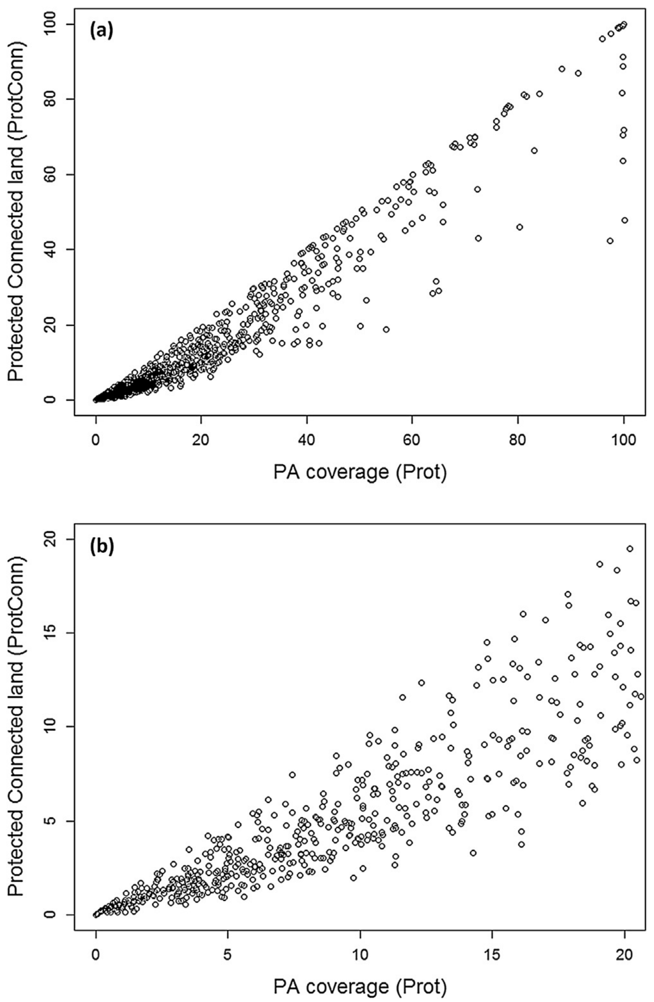

Fig. 4. Protected Connected land for d = 10 km (y axis) against PA Coverage (x axis) (a) for all the terrestrial ecoregions of the world and (b) as a more detailed view for the subset of ecoregions with PA coverage up to about 20%, which is the ProtConn range within which most of the ecoregions lie.

The situation is, however, considerably less optimistic regarding the part of the target which relates to "well connected systems of protected areas". Although the Aichi Target 11 does not specify itself how the connectivity of PAs should be measured, it is reasonable to assume that the target would be met if the Protected Connected land indicator reached 17% by 2020. However, the current global average for Protected Connected land is only slightly above the half of that target (9.3% for d = 10 km). Even if the projections by Tittensor et al. (2014) for PA coverage, which today may look overoptimistic, were met by 2020, our results suggest that the Protected Connected land would still fall clearly below the 17% level. How much of the total protected land (PA coverage) would be effectively connected by 2020 is hard to say, since this will depend on how efficiently new PAs are designated in order to promote connectivity between the rest of previously existing PAs, e.g. whether networks like those in the examples in Fig. 5 can be achieved through newly designated sites. If we assume a "business as usual" scenario in PA designation, we have to conclude that, by 2020, relative connectivity would remain quite similar to its current levels (RelConn = 63% for d = 10 km). Under such relative connectivity levels, a 17% in PA coverage would translate into only 10.7% of Protected Connected land for a median dispersal distance of d = 10 km. In fact, to reach 17% of Protected Connected land for that d, a PA coverage of around 27% would need to be attained; a coverage which is far beyond the projected values by Tittensor et al. (2014) or any other reasonable expectation. Even for median dispersal distances of 30 km and 100 km, which are above the movement abilities of the very large majority of terrestrial species, a PA coverage of 24.5% and 21.3% would need to be attained, and this is still far from what may reasonably be expected to be achieved by 2020.

4.3. The importance of management effectiveness

Our connectivity indicator relies on the assumption that PAs are effectively conserved and managed in order to ensure sufficient connectivity levels that allow the successful movement of species through protected lands. There is however, in many cases, a gap between the formal protection of an area and the actual implementation of appropriate conservation and management measures in that area. Several studies have shown that PAs are able to reduce, but not to stop, deforestation, land use change and other pressures on biodiversity (such as poaching) as compared to unprotected sites (Joppa and Pfaff, 2011; Geldmann et al., 2013; Barber et al., 2014; Gray et al., 2016; Vačkář et al., 2016). These changes and pressures may significantly reduce functional connectivity, either because species may directly avoid moving through highly modified landscapes (behavioral aversion) or because of an increase in the mortality of animals dispersing through those landscapes (for example due to poaching or road kills). Even when these changes and pressures are lower within PAs than in unprotected landscapes, it is clear that 'paper parks' without adequate governmental and financial support are unlikely to meet the conservation objectives for which they are designated (Watson et al., 2014; Marino et al., 2015). Assessment of progress towards management effectiveness is therefore of crucial importance to ensure that PAs are able to play their full role as functional connectivity providers in a wider network of protected sites.

4.4. Connected protected area systems to halt biodiversity losses

Protected areas have been reported to have, and to retain through time, higher species richness and abundance than unprotected sites (Laurance et al., 2012; Geldmann et al., 2013; Coetzee et al., 2014; Gray et al., 2016), but still biodiversity losses or declines in species abundance continue to occur within protected lands (Craigie et al., 2010; Laurance et al., 2012). Recently, Gray et al. (2016) estimated that the global system of PAs is 41% effective at retaining species richness and 54% effective at retaining local species abundance. The extent to which the biodiversity loss that PAs are experiencing is due to the potential lack of connectivity with other protected sites (or with other natural habitats available in unprotected areas) is a subject of ongoing debate that would require further research, and is outside the scope of this study. However, Laurance et al. (2012) found that biodiversity losses in tropical PAs during the last 20–30 years were strongly determined by changes outside reserves such as deforestation, which may increase the isolation of PAs. Such change processes may ultimately lead to poorer connectivity levels of the broader PA networks, and to subsequent additional biodiversity losses, as long as no form of protection is given to the stretches of land that have the potential to provide linkages between the PAs. This evidence, in combination with our finding that most of the world's PA networks do not currently feature high levels of Protected Connected lands, suggest that improving the connectivity of the PA systems is possibly the most necessary and challenging task ahead, together with ensuring PA conservation management effectiveness.

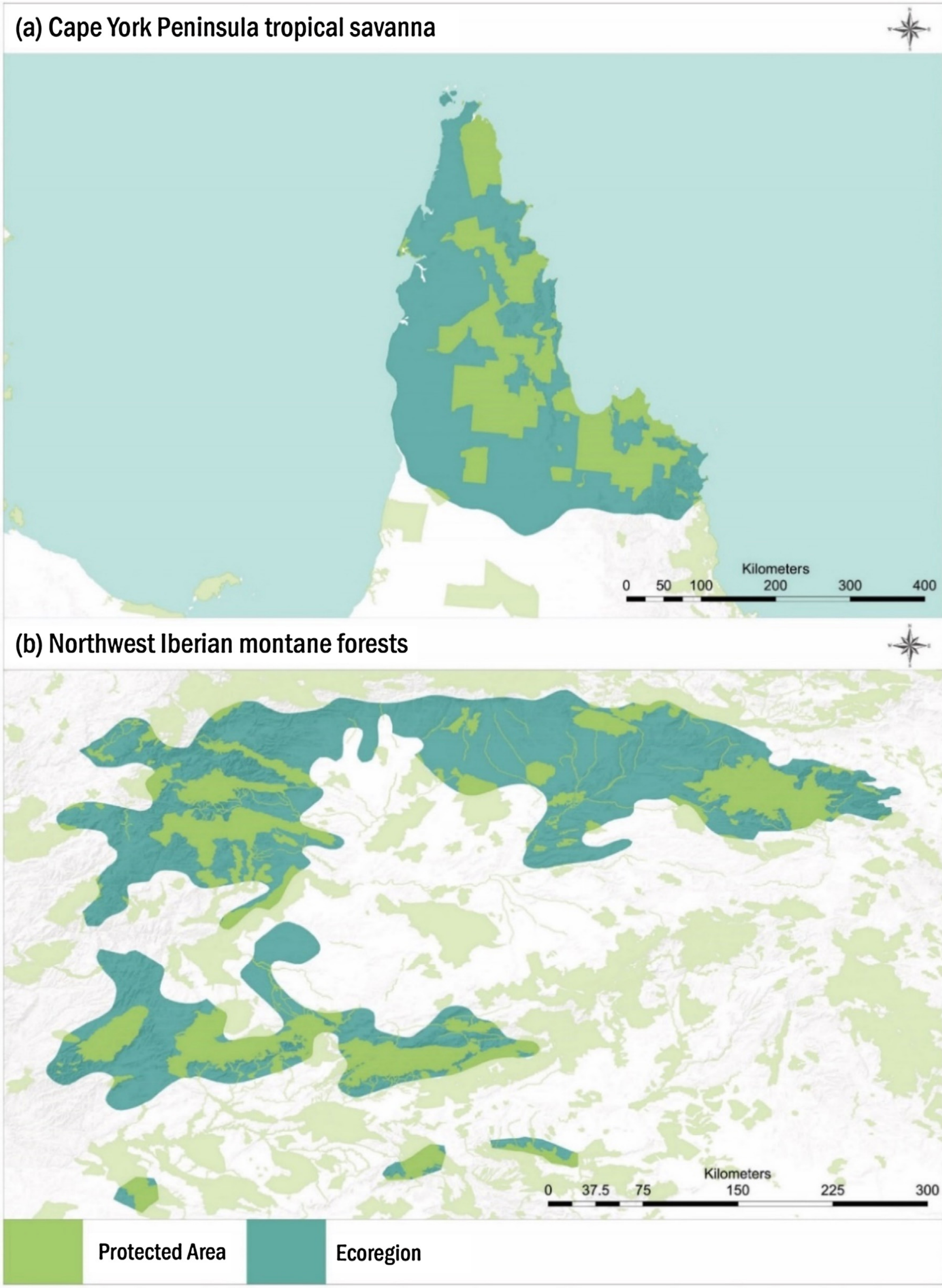

Fig. 5. Two ecoregions in which the Protected Connected land is quite close to the total amount of protected land (PA coverage): (a) Cape York Peninsula tropical savanna, in Australia and (b) Northwest Iberian montane forests, in Spain and Portugal. In (a) the PA coverage is 31.0%, and the Protected Connected land is 24.9% for $d = 10$ km (reaching up to 30.0% for $d = 100$ km); RelConn = 80% for $d = 10$ km. In (b) the PA coverage is 27.2% and the Protected Connected land is 23.7% for $d = 10$ km (increasing up to 26.7% for $d = 100$ km); RelConn = 87% for $d = 10$ km. In (b) there is a very large contribution from transboundary PAs to the connectivity of PAs within the ecoregion; 46.5% of the total ProtConn in the ecoregion for $d = 10$ km is thanks to transboundary connectivity, compared to the global average of 8.2% for the same dispersal distance (Fig. 1). See Fig. A3 in Appendix A for the indicator pie charts for these two ecoregions for $d = 10$ km.

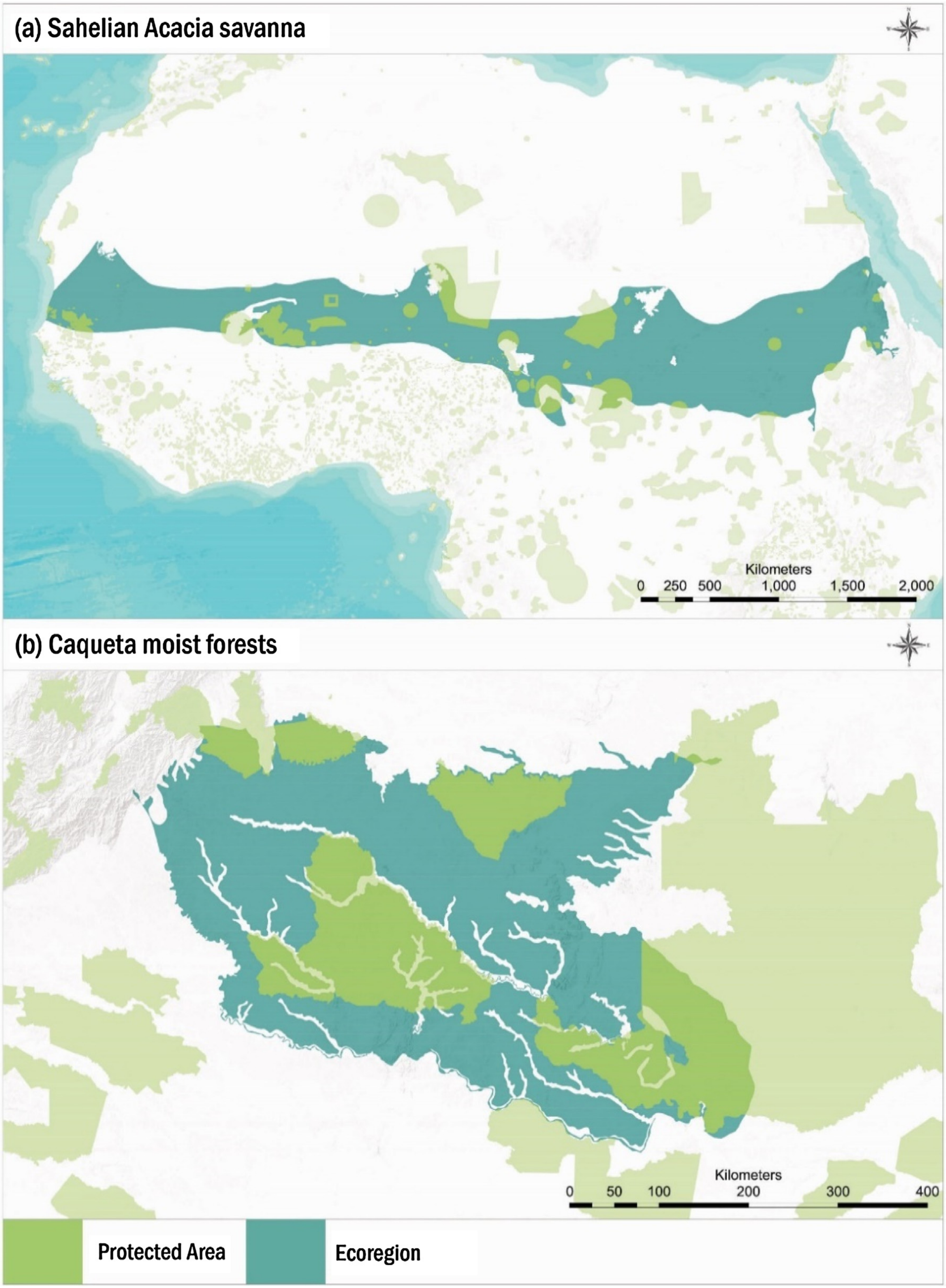

Fig. 6. Two ecoregions in which the Protected Connected land is considerably lower than the amount of protected land (PA coverage): (a) Sahelian Acacia savanna, in Africa and (b) Caqueta moist forests, in Colombia and Brazil. In (a) the PA coverage is 10.8% but the Protected Connected land is only 3.7% for $d = 10$ km (reaching only up to 5.0% for $d = 100$ km); RelConn = 34% for $d = 10$ km. In (b) the PA coverage is 33.4% and the Protected Connected land is 19.1% for $d = 10$ km; therefore, both PA coverage and ProtConn are already in June 2016 well above the 17% Aichi Target. ProtConn is however significantly below PA coverage, with RelConn = 57% for $d = 10$ km, below the global average of 63%. This relatively low RelConn is due to the lack of any protected linkage between the large PAs in the ecoregion, which are in addition quite far from each other. This result means that the large effort made in protecting a large amount of land (PA coverage) has not efficiently translated into a commensurable level of connectivity of the PA network for many of the species inhabiting these PAs (those with d from 1 to 30 km, for which Protected Connected land ranges from 18.9% to 22.4%). For $d = 100$ km there is however a very remarkable increase in the connectivity level, yielding ProtConn = 28.3% for that d. See Fig. A4 in Appendix A for the indicator pie charts for these two ecoregions for $d = 10$ km.

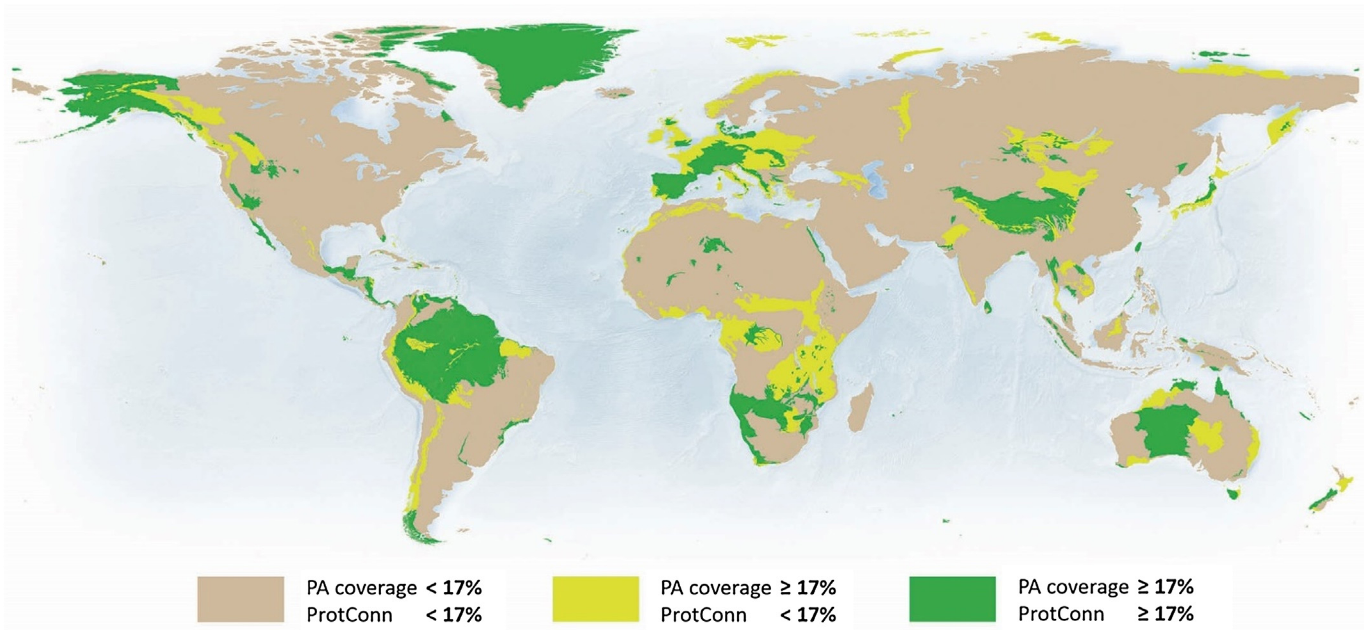

Fig. 7. World's terrestrial ecoregions classified according to whether the 17% Aichi Target has been or not achieved in June 2016 for PA coverage and/or for Protected Connected land (ProtConn) for a reference dispersal distance d = 10 km.

4.5. Which types of protected areas are able to promote connectivity?

The International Union for Conservation of Nature (IUCN) has defined several categories of PAs according to their management objectives and restrictions (Dudley, 2008), from strict nature reserves (category I) to PAs with sustainable use of natural resources (categories V and VI). We have here considered all PA categories together and, therefore, our analysis is in principle not able to assess the specific contribution to PA network connectivity of different PA categories. However, we can provide some insights on this matter by comparing our results with those of a recent analysis of the connectivity of the global PA network by Santini et al. (2016), which only considered PAs with IUCN categories I–IV. Because their assessment did not include PAs of categories V and VI, nor those PAs with not reported or not assigned category in the WDPA, Santini et al. (2016) obtained a global PA coverage of 5.6%, less than half of the 14.7% global PA coverage in this study. More interestingly, Santini et al. (2016) found, using a similar connectivity indicator based on the Probability of Connectivity and Equivalent Connected Area metrics as in our study, that less than 50% of the protected land was connected; the Relative Connectivity ranged from 28% to 50% for d from 0.177 to 99.58 km. This percentage is considerably lower than the Relative Connectivity we here found for the entire PA network, which ranges from 58% to 80% for almost the same d values of 1 and 100 km (Fig. 2). Taken together, these numbers imply that the amount of protected connected land (PA coverage multiplied by RelConn) in Santini et al. (2016) would be about 4–5 times lower than the comparable figure reported in this study considering all PAs. The magnitude of this underestimate suggests, despite the differences between the analysis in Santini et al. (2016) and in this study, that PAs with categories other than I–IV (or with no reported category) do not merely increase the global PA coverage, which is obvious. More importantly, they are able to effectively increase the connectivity of the entire network of PAs by acting as connecting elements between PAs of categories I–IV and between the rest of PAs, either by providing physical continuity of protected lands or by functioning as stepping stones promoting movement between PAs. It is interesting to note that, in line with our conclusion, a study in the Brazilian Atlantic forest by Crouzeilles et al. (2013) found that the key connectors between forest patches were better covered by sustainable use PAs (category V) than by strictly protected PAs (categories I–IV).

Interestingly, available research has not found a consistent pattern between IUCN category and the actual efficiency of PAs; PAs of categories with more restrictive management objectives do not seem to necessarily experience less deforestation or loss of intact ecosystems (Joppa et al., 2008; Leroux et al., 2010; Nelson and Chomitz, 2011; Ferraro et al., 2013; Nolte et al., 2013; Coetzee et al., 2014; Pfaff et al., 2014; Blackman et al., 2015; Brun et al., 2015; Pfaff et al., 2015; Dudley et al., 2016). Even if some PA categories may suffer moderate land use change, their role as connectivity providers is likely to be less affected than their habitat suitability for resident individuals, given the species dispersal plasticity that recent research has reported. According to this research, species are able to use a wider set of land covers, and to tolerate higher degrees of human modification, when selecting areas for dispersal movements than when establishing home ranges and permanent populations (Elliot et al., 2014; Mateo-Sánchez et al., 2015; Gastón et al., 2016). Therefore, some increase in suboptimal habitats is likely to affect the potential of a PA to host large, permanent reproductive populations of a given species, while having comparatively less effect on the likelihood of species movements happening through that PA. Interestingly, Gray et al. (2016) found, when comparing protected and unprotected sites, that PAs were more effective in retaining biodiversity in human-dominated land uses (plantation and cropland) than in primary and secondary vegetation. These findings further suggest that the role of PAs with some degree of sustainable resource use in maintaining diversity and functional connectivity should not be undervalued, provided that they complement rather than offset PAs with stricter conservation objectives.

Taken together, these evidences advocate for considering all PA categories (as well as PAs with no reported category) when assessing the connectivity of PA systems. In addition, Aichi Target 11 may be achieved not only through PAs but also through "other effective area-based conservation measures". This creates opportunities to recognize the potential contribution to connectivity of other areas, beyond the current definition of PAs, through which species movements and other ecological flows are effectively happening, and in which there is a commitment to maintain or enhance their connecting role through appropriate conservation management measures. For example, Bergsten et al. (2013) found, in an analysis for northern Sweden, that non-formally protected sites such as those classified as Woodland Key Habitats were able to significantly increase the connectivity levels for mature pine forests compared to what was provided by fully designated PAs alone.

4.6. The relevance of the ecoregion level for global assessments of protected area connectivity

Several assessments have evaluated the connectivity of PAs at the country level or using other administratively-defined units of analysis (e.g. provinces), in one case globally (Santini et al., 2016) and in most others in particular continents or regions (Gurrutxaga et al., 2011; Opermanis et al., 2012; Mazaris et al., 2013; Maiorano et al., 2015; Belote et al., 2016). Although such analyses match the boundaries in which political and management decisions are taken, species distributions and movements do not follow or adhere to administrative boundaries. An ecoregion-level analysis may provide a better characterization of the connectivity of PAs, by focusing on sites with potentially more similar ecological conditions and species composition than those grouped at the country level. On the other hand, we have found highly contrasting levels in the PA connectivity of different ecoregions within the same country. In such cases, an intermediate value of PA connectivity derived at the country level may mask, and leave unreported, ecoregions within the country where connectivity is actually well above the policy targets and others in which PAs are largely isolated and where, therefore, further efforts should be concentrated. This is particularly the case for large countries like Brazil, reported with an intermediate connectivity in Santini et al. (2016), but with a high PA connectivity for the moist forests in the Amazon and a much lower ProtConn for the Atlantic forests and other ecoregions like the Cerrado savannas or the Caatinga shrublands, according to our analyses. Similar examples are China, with high ProtConn in the Tibetan plateau but much lower PA connectivity in almost all other ecoregions (particularly in the Eastern half of the country), and Australia (Figs. 3 and 7). The ecoregion-level assessment may therefore provide more finely-tuned, ecologically relevant results in these cases. However, given that political decisions on PAs are mostly taken at the national level, assessments at the country level will remain necessary. Probably, a combination of indicators at the country and ecoregion level can provide the most useful picture in order to track progress towards national and global biodiversity targets.

4.7. Limitations and further research

We believe that our study provides the most accurate and detailed characterization of the connectivity of the global network of protected areas so far. At the same time, we acknowledge that there is room for further improving or enriching the indicator, and this is part of our planned future work, particularly by considering landscape composition and matrix resistance to species movements within and between PAs. Doing so would allow us to relax the implicit assumption that there are no human-caused limitations to connectivity within PAs because their composition is all sufficiently favorable to species movements and because they are managed properly in order to maintain connectivity in the short and long term. In fact, this may not be the case, given the heterogeneity of land uses that is found in some PAs and the different degree of support to and pressures on different PAs. A significant step in this direction could be made by incorporating information from remote sensing observations in order to characterize the conditions within PAs globally, as well as other databases that might be available on PA management effectiveness. Similarly, a further enriched version of the indicator could account for the degree of resistance that different land cover types offer to species movements, thereby capturing the impacts on connectivity of the heterogeneity of the landscape matrix in between PAs. One challenge in this direction is quantifying landscape matrix resistance in a way that is relevant for a broad array of species, as needed in a global PA assessment, rather than relying on fine-tuned resistance surfaces parameterized for a particular species and study area. An interesting and sufficiently generic proxy for landscape resistance could be the degree of human modification of the terrestrial environment compared to natural conditions, which has been used in some studies focused in Mexico and the USA (Correa Ayram et al., 2017; Belote et al., 2016) and could be characterized globally using the recently updated human footprint indicator (Venter et al., 2016).

Regarding the scale of species movements, in this work we have considered a range of dispersal distances that covers the movement abilities of most terrestrial vertebrates, but there are other species that would need a separate, specifically-tailored analysis beyond the scope of this study. For example, migratory bird species are equipped with extraordinary navigating and flight abilities and can traverse thousands of kilometers in their migrations. At the same time, however, they are largely dependent on the availability, along their migratory routes, of suitable and interconnected stopover sites, which have been recently reported to be particularly poorly covered by PAs globally (Runge et al., 2015). On the other hand, because of the global scope of our assessment and of the spatially accuracy of the PA delineation in some regions, we intentionally left out of the analysis median species dispersal distances below 1 km. The same proposed indicator could be however used to assess the connectivity levels for these less mobile species, though this would be best tackled at more local scales, using more spatially accurate datasets that better capture the fine-scale information important for this type of species.

Future development of the indicator may include an assessment of the contribution of each individual PA to the total ProtConn value, identifying those PAs that are most valuable in upholding the connectivity of the PA system and others that, by contrast, are largely isolated; such development could build from the node-level connectivity fractions described in Saura and Rubio (2010). Future ProtConn assessments may also account for the connectivity contribution of other area-based conservation measures as distinct from PAs, as long as the required information on these areas is available in a comparable manner worldwide. Finally, we have here focused on the protected land in terrestrial ecoregions, but the proposed indicator could be also applied to other units of analysis (e.g. countries), to specific terrestrial habitat types (e.g. forests) or to freshwater or marine ecosystems, with some adaptations particularly in the latter case.

4.8. Conclusions

We have presented the Protected Connected (ProtConn) indicator, which captures, but also separately reports, several important aspects of the connectivity of PA systems and of the types of land through which PA connectivity may be supported. ProtConn is the result of the combination, through network analysis, of the sizes, coverage and spatial arrangement of PAs with the species dispersal distances considered. Despite the underlying complexity and multiple fractions involved, the indicator is, in its proposed visualization (Fig. 1), easy to communicate to end users and to compare against national and global targets for PA coverage and connectivity.

Our application of the indicator to the terrestrial realm has evidenced highly uneven levels of PA connectivity across the world's ecoregions, and the need for targeted actions to improve the connectivity of PA systems. We suggest that the work ahead for PA system design and improvement is substantial, and that efforts should focus much more on reinforcing the connectivity of PA systems than on simply increasing the PA coverage.

The results of the ProtConn indicator could be updated in the future as PA networks are expanded through newly designated sites or modifications of the currently existing sites, and may also be calculated at other scales of analysis other than the ecoregion level here considered (e.g. countries). The ProtConn values will be freely accessible, together with other global indicators on PAs, in the Digital Observatory for Protected Areas of the European Commission. In this way, we hope to contribute to the assessment of current and future progress towards PA targets from the national to the global level, and particularly the Aichi Target 11 for the year 2020.

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Appendices A and B Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2016.12.047.

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