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LETTER

Persistent Disparities between Recent Rates of Habitat Conversion and Protection and Implications for Future Global Conservation Targets

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Abstract

Anthropogenic conversion of natural habitats is the greatest threat to biodiversity and one of the primary reasons for establishing protected areas (PAs). Here, we show that PA establishment outpaced habitat conversion between 1993 and 2009 across all biomes and the majority ($n = 567$, 71.4%) of ecoregions globally. However, high historic rates of conversion meant that 447 (56.2%) ecoregions still exhibit a high ratio of conversion to protection, and of these, 127 (15.9%) experienced further increases in this ratio between 1993 and 2009. We identify 41 "crisis ecoregions" in 45 countries where recent habitat conversion is severe and PA coverage remains extremely low. While the recent growth in PAs is a notable conservation achievement, international conventions and associated finance mechanisms should prioritize areas where habitat is being lost rapidly relative to protection, such as the crisis ecoregions identified here.

Introduction

Humans have reshaped patterns and processes in ecosystems across the terrestrial biosphere, both intentionally and unintentionally, for millennia (Ellis *et al.* 2010; Dirzo *et al.* 2014). This reshaping has accelerated over time (Steffen *et al.* 2015), with a human footprint now obvious in most parts of the terrestrial realm (Sanderson *et al.* 2002). One of the more severe impacts of this anthropogenic transformation of the biosphere is the loss of natural habitats. Three decades of conservation science have extensively documented the impacts of habitat transformation on genetic diversity, species survival, and ecosystem function (Fischer & Lindenmayer 2007). In many cases, these impacts have proved insurmountable, making habitat loss the greatest driver of postindustrial species endangerment and extinctions (Venter *et al.* 2006; Hoffmann *et al.* 2010).

Protected areas (PAs) spearhead global efforts to conserve nature, and when properly managed they are particularly effective for combating habitat loss (Bruner *et al.* 2001; Gaston *et al.* 2008). Since 1992, the Convention on Biological Diversity (CBD) has catalyzed a global proliferation of PAs, including through a commitment in 2010 to protect 17% of terrestrial and 10% of marine environments globally by 2020, especially "areas of particular importance for biodiversity and ecosystem services" through "ecologically representative" PA systems or other

"area-based conservation measures" (CBD 2011). Some nations have set national PA commitments even greater than the global target (Butchart *et al.* 2015), and there has been a pronounced expansion of the global PA estate over the past two decades (Juffe-Bignoli *et al.* 2014).

Yet, many nations are also expanding their use of natural resources as a primary means of achieving economic development targets (Brunnschweiler 2008). Consequently, rates of anthropogenic habitat conversion are climbing alongside PA growth (Hansen *et al.* 2013). This situation has led to the establishment of a dedicated CBD Aichi target (Target 5) under which nations committed to halve and, where feasible, bring close to zero the rate of habitats loss (CBD 2011). To be effective at slowing habitat conversion, it is widely recognized that PAs need to be placed in areas at risk of loss in the absence of protection (Pressey *et al.* 2015; Visconti *et al.* 2015). However, despite increasing recognition by nations of the importance of PAs in abating habitat loss (Watson *et al.* 2014), there has been no assessment of which areas have experienced the greatest rates of recent anthropogenic habitat conversion, nor whether the recent growth in the PA estate is located in high conversion areas. This is critical baseline information that will not only allow nations to report on their progress toward achieving CBD targets (CBD 2011), but also inform the priorities of financial mechanisms (e.g., the Global Environment Facility) that fund PA establishment (Watson *et al.* 2016).

Here, we examine the extent of habitat conversion across the world's biomes and ecoregions in 1993 and 2009 using a novel and temporally explicit cumulative threat map (Venter *et al.* 2016). We compare the relationship between habitat conversion and PA establishment during this period and identify those ecoregions (and the nations that contain them) that need urgent attention if the 2020 CBD's strategic goal to "improve the status of biodiversity by safeguarding ecosystems, species and genetic diversity" is to be achieved.

Methods

Biome and ecoregion classification

Biomes and, at a finer spatial scale, ecoregions, represent relevant environmentally and ecologically distinct spatial units at the global scale and are used by international funding institutions and conservation organizations to guide broad-scale global conservation investments and action (Olson & Dinerstein 2002; Funk & Fa 2010). Following previous global analyses (Hoekstra *et al.* 2005; Segan *et al.* 2016), we used the global biomes ($n = 14$) and ecoregions ($n = 825$) identified by Olson *et al.* (2001) as the basis for our analysis.

Measures of habitat modification

We used the revised Human Footprint map (Venter *et al.* 2016) to measure habitat conversion. The revision takes advantage of recently available datasets to provide a cumulative score of eight in-situ anthropogenic pressures. These pressures include urban centers, intensive agriculture, pasture lands, human population density, night-time lights, roads, railways, and navigable waterways. Following Sanderson *et al.* (2002), individual pressures were placed on a 0–10 scale and then summed to create the cumulative measure of the Human Footprint. We note that the presence of a human pressure and its actual impact on biodiversity is assumed, but these pressures are considered among the greatest threats to biodiversity (Maxwell *et al.* 2016), and previous analyses have shown the Human Footprint is an important predictor of extinction risk (Di Marco *et al.* 2013).

For our purposes, a threshold criterion for habitat conversion was set at a Human Footprint value of 4 or greater. This value equates to a human pressure score equal to pasture lands, representing a reasonable approximation of when anthropogenic land conversion has occurred to an extent that the land can be considered human dominated and can no longer be considered "natural." Previous analyses show that this threshold is where species are far more likely to be threatened by habitat loss (Di Marco *et al.* 2013).

We note that there is no universal threshold for habitat conversion, because there is no single level at which the environmental values we associate with habitat "intactness" are suddenly lost (Tulloch *et al.* 2016). We therefore explore the sensitivity of our results using different thresholds (see Supplementary Materials). Here, we present only the results using the threshold of "4 or greater," as the sensitivity analysis revealed only minor variation in the results.

Protected areas

We estimated temporal trends in PA coverage using data on the year of PA establishment recorded in the 2014 version of the World Database on Protected Areas (UNEP-WCMC 2014). As this was unknown for 15% of the area of the terrestrial PA estate, we followed Butchart *et al.* (2012) and assigned a year by randomly selecting a year (with replacement) from all PAs within the same country with a known date of establishment. For countries with fewer than five PAs with known year of establishment, a year was randomly selected from all terrestrial PAs with a known date of establishment. The random assignment was repeated 1,000 times to identify the median and 95% confidence intervals.

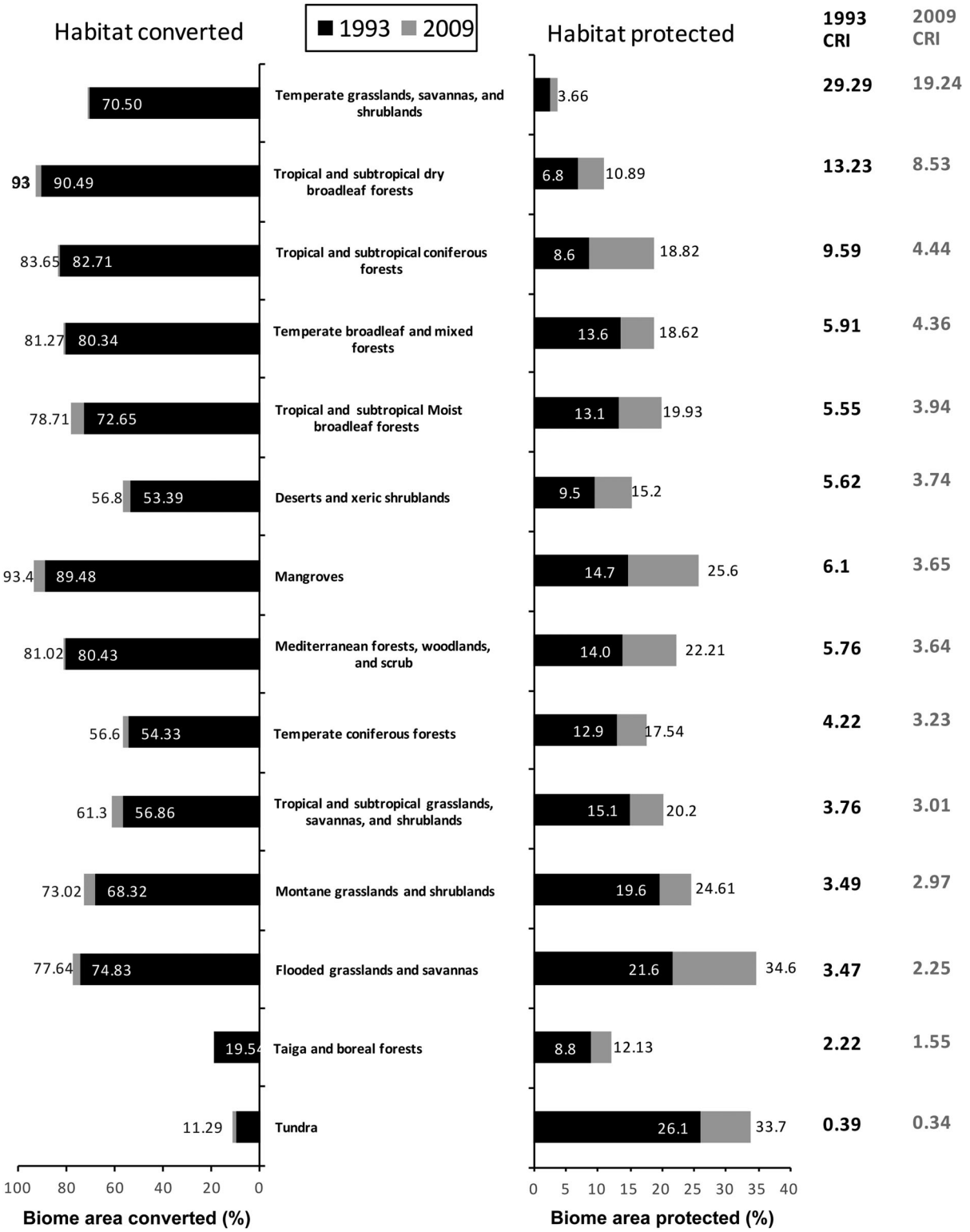

Figure 1 Percentage of habitat conversion and PA coverage among the world's 14 terrestrial biomes in 1993 (black bars) and 2009 (gray bars). The baseline assumption is full habitat extent across all biomes. Numbers inside the black bars show the value as of 1993, while numbers at the end of the bars show the value as of 2009. Biomes are ordered by their conservation risk index (CRI) for 2009 (which was calculated as the ratio of percentage area converted to percentage area covered by PAs, following Hoekstra *et al.* 2005).

We followed the methods of previous global assessments (Rodrigues *et al.* 2004; Jenkins & Joppa 2009; Venter *et al.* 2014) and included only PAs with a national designation, excluding areas protected only by international agreements and all PAs with a status other than "designated." For PAs that met the above criteria, but for which only central coordinates and total area were available ($n = 15{,}404$), a circular buffer of the appropriate area was generated around the central coordinates to depict the spatial extent of the PA. PAs that lacked polygonal representation or a specified areal extent were excluded from the analysis ($n = 7{,}311$).

Analysis of spatial data

All spatial data were processed in vector format using ESRI ArcGIS v10 and Mollweide equal-area projection. For all terrestrial coverage statistics, we followed established practice (Juffe-Bignoli *et al.* 2014; Venter *et al.* 2014) by excluding terrestrial Antarctic ecoregions, "Rock and Ice" and "Lakes." We also excluded ecoregions that had an area < 5,000 km^2, because of discrepancies in spatially referenced information across datasets over small areas, which left 794 ecoregions out of a possible 825.

Assessing relationship between habitat conversion and protection

Habitat conversion rates over time are related both to the availability of unconverted land and to the rates of land protection. We explored the role of these two factors by building a generalized linear model in which conversion rates were predicted as a function of "original proportion of converted land" and "current proportion of Pas." We also calculated the habitat conversion-to-protection ratio between percentage area converted and percentage area covered by PAs (following Hoekstra *et al.* 2005) for 1993 and 2009. We call this ratio the "conversion risk index" (CRI) because it relates to the risk of conversion of remaining intact habitat for ecoregions and biomes (Hoekstra *et al.* 2005). We categorized the threat risk of ecoregions based on their CRI using the following criteria. First, any ecoregion that met the 17% PA target outlined in the 2010 CBD strategic plan was considered not at risk, albeit only in the sense that it meets the current globally accepted target for PA extent (CBD 2011). Second, for all those ecoregions with <17% PA coverage, we identified "at-risk" ecoregions: *moderate,* those ecoregions having CRI > 2 or total areal habitat conversion > 20%; *high,* those with CRI >10 or total areal habitat conversion >40%; and *very high,* those with CRI >25 or total areal habitat conversion > 50%. Finally, of the ecoregions at very high risk in 2009, a further subset of "*crisis* ecoregions" that have also experienced high rates (>10%) of recent habitat conversion since 1993 was identified. We labeled all ecoregions that do not meet any of these "at-risk" categories as "*low risk,*" recognizing that biodiversity in these areas is of course not free from threat and that PAs are just one form of conservation response.

Results

Habitat loss across biomes and ecoregions

Globally, over half (51.4%) of the world's land area was converted to human-dominated land-uses in 2009, of which 9.3% (4,406,769 km^2) was converted between 1993 and 2009. Two biomes (mangroves and tropical and subtropical broadleaf forests) were > 90% converted by 2009 (Figure 1). During the period 1993–2009, all biomes experienced some degree of habitat conversion, with *tropical and subtropical moist broadleaf forests*, *montane grasslands and shrublands*, *tropical and subtropical grasslands, savannas and shrublands*, and *mangroves* experiencing the most change (Figure 1). Within biomes, there was considerable variation in habitat conversion across ecoregions. The extent of habitat conversion in 2009 ranged from <1% in 13 ecoregions (1.6%) to > 75% in 426 ecoregions (53.7%) (Figure 2a). Our assessment of habitat conversion since 1993 shows that 91 ecoregions (11.6%) underwent >10% habitat loss during the 16-year period, but the majority (52.5%) underwent relatively small losses (<1%).

Rates of PA growth across biomes and ecoregions

The terrestrial PA network almost doubled between 1993 and 2009, growing by 7,004,035 km^2 (9.0% of land) to cover 18,874,488 km^2 (14.2%). This has led to substantial increases in protection levels at the biome scale, with 10 of the 14 biomes achieving >17% protection in 2009 (Figure 1). Two biomes (*temperate grasslands, savannahs and shrublands*, and *tropical and subtropical dry broadleaf forests*) stand out as still having relatively low levels of protection (Figure 1). Habitat protection exceeded > 17% coverage in 314 (39.5%) ecoregions in 2009, a large increase with respect to 1993 ($n = 184$, 23.2%; Figure 2).

PAs are not necessarily immune to habitat conversion (or indeed other important threatening processes such as overharvesting, invasive species, and climate change); however, we found on average, very little habitat conversion has occurred within PAs during the study period, with an increase in average Human Footprint values of just 0.15.

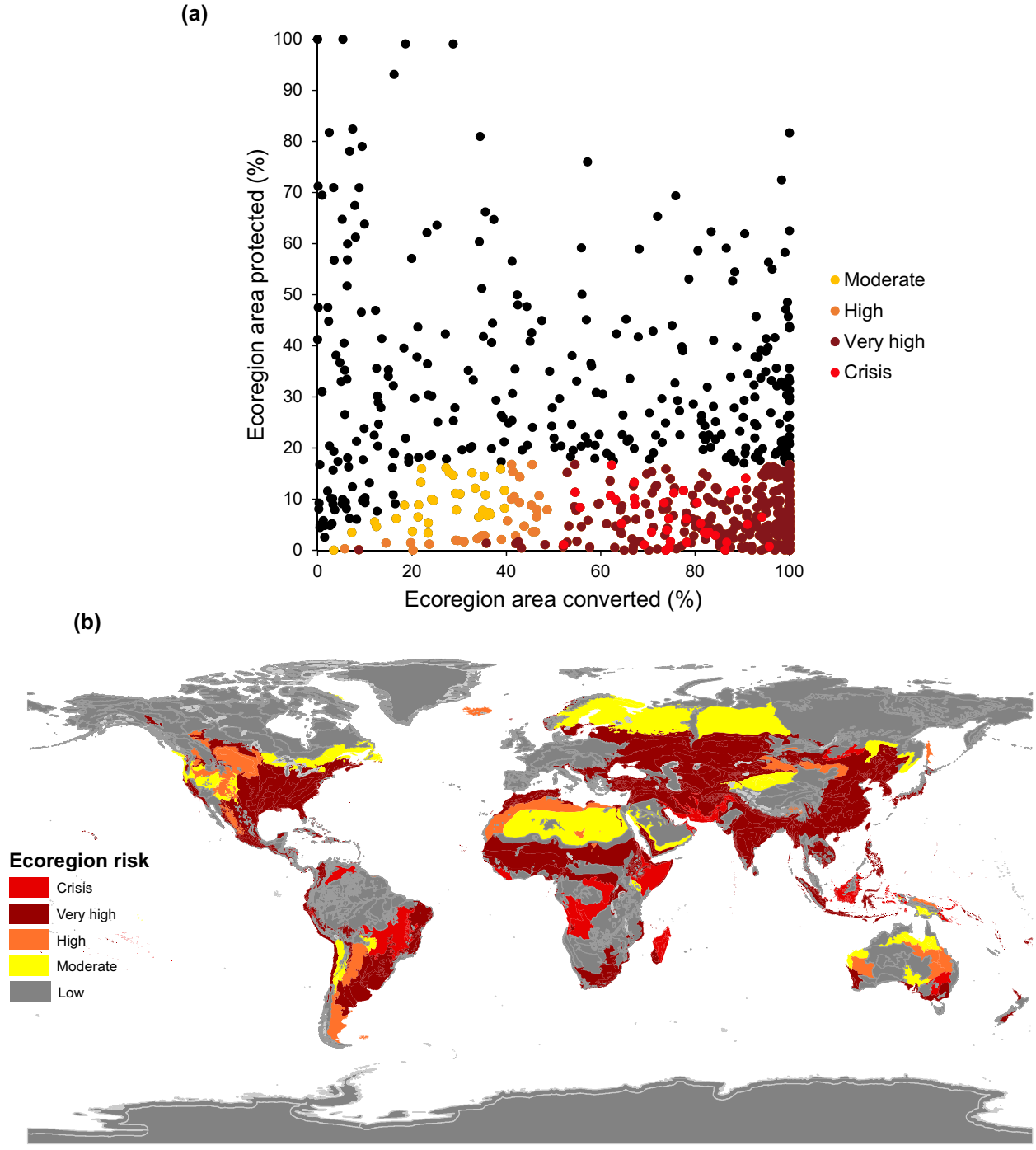

Figure 2 The relationship between degree of habitat conversion and PA coverage across the world's terrestrial ecoregions in 2009 as a scatterplot (a) and their locations (b). Ecoregions with > 50% habitat conversion or conservation risk index (CRI) > 25, and with >10% change in habitat conversion from 1993 to 2009, are classified as crisis ecoregions (red); ecoregions with > 50% habitat conversion or CRI > 25 are classified as very highly at risk (maroon); ecoregions with > 40% conversion or CRI > 10 are classified as highly at risk (orange); and those ecoregions with > 20% conversion or CRI > 2 are classified as moderately at risk (yellow). CRI for each ecoregion was calculated as the ratio of % area converted to % area covered by PAs.

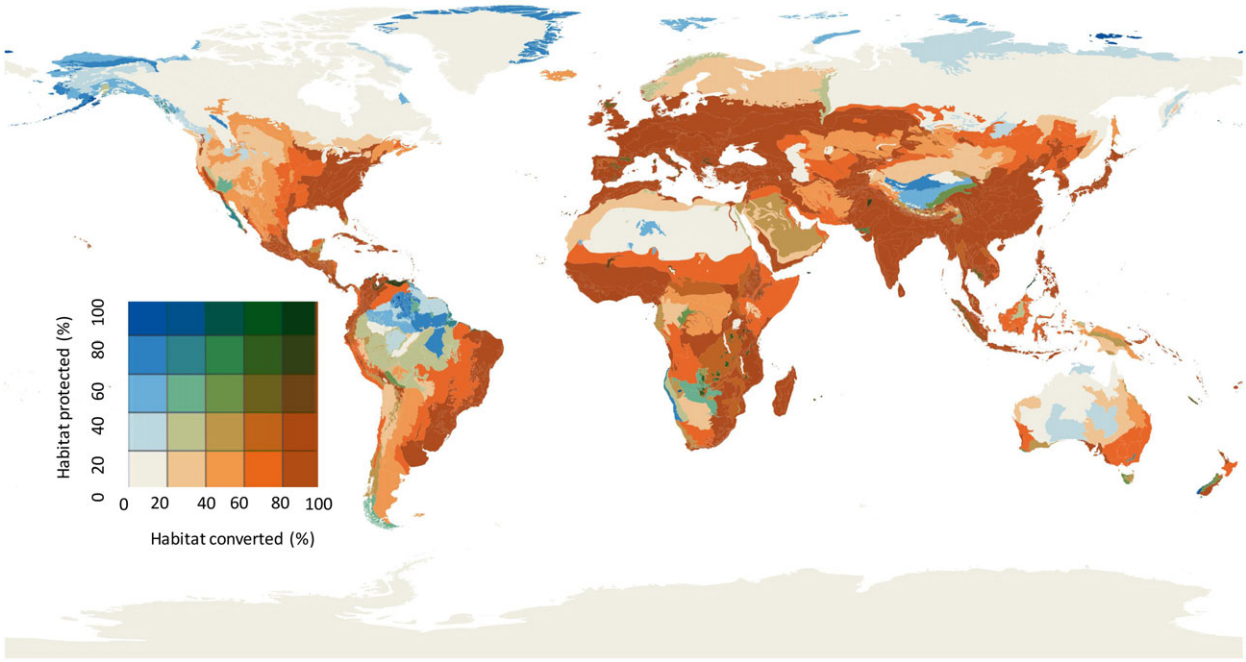

Figure 3 The spatial relationship between degree of habitat conversion versus PA coverage in terrestrial ecoregions in 2009.

Relationship between habitat loss and protection

The vast majority of ecoregions have very high levels of habitat conversion compared to their overall areal protection (Figures 1 and 3). These highly converted and poorly protected ecoregions occur across all continents and dominate Europe, south and south-east Asia, western South and North America, western Africa, and Madagascar. The small number of ecoregions that contain high levels of protection and low levels of conversion are primarily located in the Arctic, the northern Amazon, North Asia, and central Australia (Figure 3).

Encouragingly, all biomes had a lower CRI in 2009, indicating that the rate of new protection exceeded the rate of habitat conversion at the biome level during the period (Figure 1). At a finer scale, 567 (71.4%) ecoregions also showed a lower CRI in 2009 than in 1993 (Figure 4). On the other hand, 203 (25.3%) ecoregions showed a higher CRI in 2009 than in 1993, indicating that habitat conversion outpaced protection. These latter ecoregions occurred in all biomes and on all continents, but were concentrated in eastern and western Africa, north-western Madagascar, northern and southern South America, north Asia, Indonesia, Papua New Guinea, and in many parts of Australia, United States, and New Zealand (Figure 4).

Conversion over the 16-year time period was negatively and significantly correlated with the extent of converted land in 1993 ($r = -0.06$, $P < 0.05$), but there was no significant relationship between the extent of PA coverage in 1993 and in 2009 ($r = -0.02$, $P = 0.11$).

At-risk ecoregions

We identified 447 "at-risk" ecoregions based on their CRI and high levels of conversion in 2009, of which 341 were "very high" (Figure 2). These very high-risk ecoregions were found on every continent and biome, and were represented in 67 nations (Figure 2b). In addition, 41 *crisis* ecoregions were identified, as they had experienced >10% conversion between 1993 and 2009 (Figure 2b). These crisis ecoregions are located in 45 nations, but are especially concentrated in Indonesia (8), Papua New Guinea (6), Madagascar (5), Angola, DR Congo, and Pakistan (4 each).

While the majority of ecoregions remained in the same risk category in both 1993 and 2009, 79 ecoregions were downgraded from either very high or high risk to low risk (Table 1). The ecoregions that moved from imperiled categories to low-risk categories were generally located in Europe and Africa (Table 1; Figure S2). Of the "at-risk" ecoregions identified in 2009, 121 (27%) had a CRI ratio that worsened from 1993 to 2009 (Figure S1; Table S1),

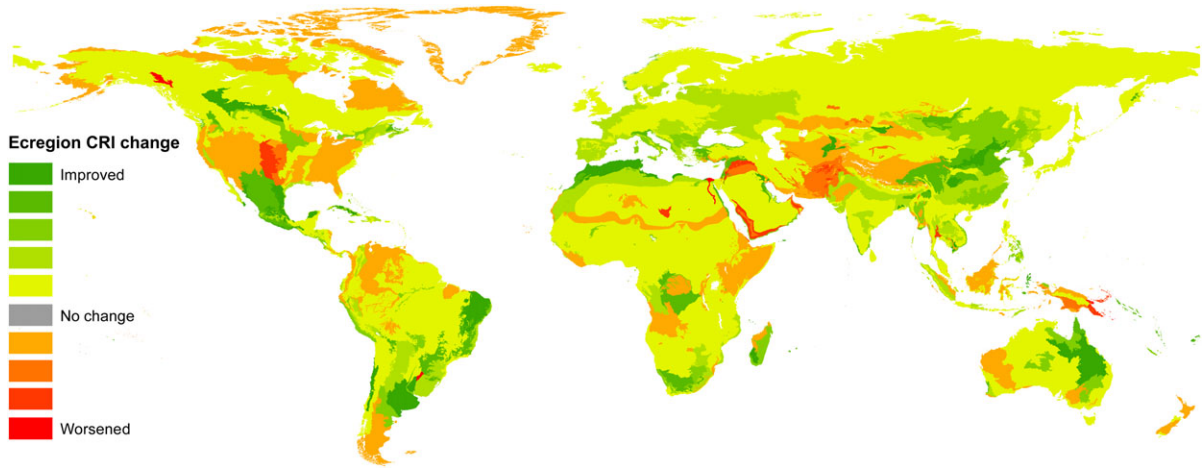

Figure 4 The spatial patterns of the changing ratios between habitat conversion and protected area coverage in 1993 and 2009 across the world's ecoregions. Ecoregions that experienced worsening ratios are shown in red and those in which the ratio improved (i.e., slower habitat conversion and/or greater PA expansion) are shown in green. Those in which there was zero change are shown in gray.

Table 1 Ecoregion status in 1993 and 2009, based on ratios between habitat conversion and PA coverage, and the degree of total habitat conversion (see methods for how ecoregions were categorized)

		2009 Risk level					
		Low	Moderate	High	Very high	Crisis	Total
1993 Risk level	Low	246	1	0	0	0	247
	Moderate	22	34	8	0	1	65
	High	9	1	18	4	6	38
	Very High	70	0	3	337	34	444
	Total	347	36	29	341	41	

Note: There were a total of 688 "at-risk ecoregions" (those not categorized as low risk) in 1993, and 447 in 2009.

of which 66 (54.5%) were considered very highly at risk and 22 (18%) were identified as crisis ecoregions.

Discussion

The past two decades have seen alarming rates of global habitat conversion (Bianchi & Haig 2013; Parr *et al.* 2014). This is particularly concerning considering that habitat loss is the largest driver of biodiversity loss globally (Hoffmann *et al.* 2010). Our results reveal a significant continued disparity between the overall amount of habitat converted versus the amount protected at both the biome and ecoregional scales over the past two decades. In 2005, Hoekstra and colleagues argued that a global habitat crisis was upon us based on the ratio of habitat lost versus protected (Hoekstra *et al.* 2005). While direct comparison between the studies is limited by differences in the data used, our temporal analyses support the argument presented by Hoekstra *et al.* (2005) and show that the crisis is not yet averted. The vast majority of terrestrial ecoregions still have dangerously high levels of habitat conversion relative to their levels of protection (Figures 1 and 3).

Encouragingly, we discovered that recent increases in protection are substantially outpacing rates of habitat conversion over the past two decades in all biomes and in >70% of ecoregions (Figures 1 and 4). This has led to a decreasing number of "at-risk" ecoregions between the two time periods, down 35% from 569 in 1993 to 431 in 2009 (Table 1). These results support studies reporting recent positive progress toward achieving a more representative PA system by at least some nations (Juffe-Bignoli *et al.* 2014; Di Marco *et al.* 2015). However, we also found that the availability of unconverted land played a major role in predicting habitat conversion rates when compared with PA extent over the time period. If this trend continues, those ecoregions with large proportions of remaining habitat are more likely to suffer future high conversion rates. This result speaks to the need for an expansion of PAs in ecoregions with relatively high availability of natural habitats, even if they are currently undergoing low rates of conversion.

While some ecoregions have shown recent improvements in PA coverage relative to habitat conversion, the fact that the majority of all ecoregions are still considered "at risk" owing to high habitat conversion relative to protection highlights the scale of the issue. Nearly, 30% ($n = 127$) of ecoregions that were "at-risk" in 1993 experienced a further worsening in their ratio of habitat conversion to PA coverage. Of these, 69 were considered at very high risk in 2009 and two were classified as crisis ecoregions. Clearly, strategic protection is urgently needed in these highly converted and underprotected ecoregions, especially those we classify as "very high" risk and "crisis" (Figure 2b). Achieving this protection will be complicated by the fact that many ecoregions, which are defined by biophysical characteristics, cross international boundaries, and the fact that there can be considerable spatial variation within ecoregions in habitat conversion rates. We identify 45 nations that contain all the crisis ecoregions and 67 nations that contain very high-risk ecoregions; coordinated implementation of new PAs across these countries is needed. To avert further biodiversity losses, global and regional PA finance mechanisms should be directed toward these nations as a priority, to catalyze PA establishment where it is needed most (Pressey *et al.* 2015; Visconti *et al.* 2015).

Ecoregions represent biophysically and climatically distinct units, and are often used in assessments of the representativeness of PAs for biodiversity targets (Jenkins & Joppa 2009). However, a focus on ecoregions may hide nuanced but important conservation implications of habitat clearance. In particular, as ecoregions vary in their size across six orders of magnitude, even small percentage conversion rates in large ecoregions, such as Africa's Sahelian Acacia Savanna or the Brazilian Cerrado, can have major implications for species loss and the disruption of ecosystem services. Species loss can occur in areas where there have been only relatively small amounts of habitat loss (He & Hubbell 2011), and this can have significant impacts on important ecosystem processes, such as net primary production (Cardinale *et al.* 2012). Significant scope exists for subsequent analyses aimed at quantifying the biodiversity and ecosystem service implications of the habitat conversion mapped in this study.

When targeting future protection, we urge that nations move beyond simply improving ecological representation, and attempt to capture those specific sites and locations that are important for imperiled biodiversity and at high risk of future clearance (Butchart *et al.* 2012; Venter *et al.* 2014). This will not only necessitate nuanced planning techniques (Groves & Game 2015), but also a substantial change in direction in how the global community next sets PA targets in international conventions.

Acknowledgments

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Main document. Sensitivity analysis around habitat conversion thresholds

Figure S1. The location of ecoregions that have improved habitat conversion/protection ratios from 1993 to 2009, but are still categorized as at risk ecoregions.

Figure S2. The location of the ecoregions that changed their "at risk" status from 1993 to 2009, based on changes in habitat conversion to protection ratios, and the level of habitat conversion.

Table S1. The number of "at-risk" ecoregions that have decreased habitat conversion/protection ratios from 1993 to 2009.

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