Contributed Paper

Effects of Errors and Gaps in Spatial Data Sets on Assessment of Conservation Progress

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Abstract: *Data on the location and extent of protected areas, ecosystems, and species' distributions are essential for determining gaps in biodiversity protection and identifying future conservation priorities. However, these data sets always come with errors in the maps and associated metadata. Errors are often overlooked in conservation studies, despite their potential negative effects on the reported extent of protection of species and ecosystems. We used 3 case studies to illustrate the implications of 3 sources of errors in reporting progress toward conservation objectives: protected areas with unknown boundaries that are replaced by buffered centroids, propagation of multiple errors in spatial data, and incomplete protected-area data sets. As of 2010, the frequency of protected areas with unknown boundaries in the World Database on Protected Areas (WDPA) caused the estimated extent of protection of 37.1% of the terrestrial Neotropical mammals to be overestimated by an average 402.8% and of 62.6% of species to be underestimated by an average 10.9%. Estimated level of protection of the world's coral reefs was 25% higher when using recent finer-resolution data on coral reefs as opposed to globally available coarse-resolution data. Accounting for additional data sets not yet incorporated into WDPA contributed up to 6.7% of additional protection to marine ecosystems in the Philippines. We suggest ways for data providers to reduce the errors in spatial and ancillary data and ways for data users to mitigate the effects of these errors on biodiversity assessments.*

Keywords: gap analysis, priority setting, protected area, spatial analyses, spatial error, WDPA

Efectos de Errores y Vacíos en Conjuntos de Datos Espaciales sobre la Evaluación del Progreso de la Conservación

Resumen: *Los datos sobre la localización y extensión de áreas protegidas, ecosistemas y distribución de especies son esenciales para la determinación de brechas en la conservación de la biodiversidad y la identificación de prioridades de conservación futuras. Sin embargo, estos conjuntos de datos siempre tienen errores en los mapas y metadatos asociados. Los errores a menudo son soslayados en los estudios de conservación, no obstante sus efectos negativos potenciales sobre la extensión reportada de la protección de especies y ecosistemas. Utilizamos 3 estudios de caso para ilustrar las implicaciones de 3 fuentes de error en los reportes de progreso hacia los objetivos de conservación: áreas protegidas con límites desconocidos que son reemplazados por centroides amortiguadores, propagación de múltiples errores en los datos espaciales y conjuntos incompletos de datos de áreas protegidas. Hasta 2010, la frecuencia de áreas protegidas con límites desconocidos en la Base de Datos Mundial de Áreas Protegidas (BDMAP) provocó que la extensión de protección estimada de 37.1% de los mamíferos Neotropicales terrestres fuera sobreestimada en 402.8% en promedio y 62.6% de las especies fue subestimada en 10.9% en promedio. El nivel estimado de protección de los arrecifes de coral del mundo fue 25% mayor cuando se utilizaron datos recientes de resolución más fina, contrariamente a los datos de resolución gruesa disponibles globalmente. La inclusión de conjuntos de datos adicionales aun no incorporados a BDMAP contribuyó hasta en 6.7% a la protección adicional en los ecosistemas marinos de las Filipinas. Sugerimos formas para que los proveedores de datos reduzcan los*

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errores en datos espaciales y ancilares y formas para que los usuarios de datos mitiguen los efectos de estos errores sobre las evaluaciones de biodiversidad.

Palabras Clave: análisis de brechas, análisis espaciales, BDMAP, definición de prioridades, error espacial

Introduction

Data on the location and extent of protected areas (PAs), ecosystems, and species' distributions are essential for determining gaps in protection of biodiversity and identifying future conservation priorities. The quality of gap analyses (Scott et al. 1993) and conservation prioritization exercises depends on the accuracy and resolution of the underlying spatial data (Chape et al. 2005). However, good-quality data sets are scarce (Boitani et al. 2011), and gap analyses are confounded by errors of omission (false absences of species and ecosystems in PAs) and commission (false presence of species and ecosystems in PAs) (Rondinini et al. 2006). Commission and omission errors can partially balance each other, if summed, and can reduce the under- or overestimation of protection, but they can nevertheless mislead conservation decisions. Omission errors may reduce opportunities for management of species or ecosystems of conservation concern in PAs. Commission errors may result in wasteful expenditure on areas incorrectly presumed to contain species or ecosystems of conservation interest (Rondinini et al. 2006). Errors in the spatial and ancillary (textual) components of data sets of global extent, such as the World Database on Protected Areas (WDPA) (IUCN & UNEP-WCMC 2010), used for gap analyses and conservation planning are inevitable. Such errors are generally related to the spatial resolution of these data sets (Chape et al. 2005) and to mismatch in resolution and spatial projection in the mosaic of data sets from which they are derived. Neglecting these errors could have serious implications for the assessment of progress toward conservation goals such as those determined by the Convention on Biological Diversity (2010).

The spatial and ancillary errors associated with data sets used for gap analyses and their implications have been discussed (e.g., Gaston et al. 2008; Halpern et al. 2009), but quantitative assessments of these errors are few (but see, e.g., Spalding et al. 2008; Joppa & Pfaff 2009; Leroux et al. 2010). Jenkins and Joppa (2009) evaluated the implications of using buffered centroids of PAs when their boundaries were missing in WDPA, and found that centroid buffering had little effect on the estimated protection of the world's ecoregions but a much larger effect on the amount of forest cover within PAs. Overestimation of PA coverage derived from double-counting areas protected under different national or international legislation can be minimized (Chape et al. 2005; Spalding et al. 2008). Sometimes this minimization introduces additional errors due to differences in spatial resolution or geographic references (i.e., coordinate system and projection) of PA data sets used to assemble WDPA.

We highlight 3 important additional issues that have been overlooked in the application of existing global data sets: errors in fine-scale gap analyses when PA boundaries are unknown; propagation of multiple spatial errors in data used for gap analyses; and incomplete protected-area data sets.

In the WDPA 2010, there were 28,303 PAs with an associated International Union for Conservation of Nature category (IUCN) (IUCN & WCMC 1994) that were represented only by point locations with associated extent (IUCN & UNEP-WCMC 2010). These PA records without boundaries constituted 28.09% of the global number of protected sites (27.58%, $n = 37{,}860$, when accounting for all PAs, including those without IUCN category. They also represented an unquantifiable proportion of the total extent of PAs, given common errors in reporting the extent of these PAs, often due to the misuse of hectares instead of square kilometers (P.V. & M.D.M., unpublished data). Users of WDPA typically transform these points into circles with sizes equivalent to the reported extent. The resulting circles only roughly overlap with the actual, but unknown, protected-area polygons. Nonetheless, they are commonly used in gap analyses (e.g., Rodrigues et al. 2004; Spalding et al. 2008). Jenkins and Joppa (2009) showed that estimates of protection of the world's ecoregions change by <1% in 70% of cases when boundaries of PAs are replaced with buffers around point locations. However, we hypothesize that when biodiversity features are considered at a finer spatial resolution, the use of buffered points instead of actual PA polygons lead to much larger discrepancies in estimated extent of protection.

Errors related to PA and biodiversity distribution maps may interact. In combining any 2 spatial layers, inaccuracies may accrue due to various types of mismatches between them. Coastal ecosystems, due to their narrow width and occurrence across the land-sea interface, are particularly prone to these errors. For instance, different spatial definitions of coastline can strongly affect the assessment of conservation status by decreasing or increasing extent and coverage of these ecosystems by PAs (Christian & Mazzilli 2007; Spalding et al. 2008). Specifically, although IUCN defines the boundary between the marine and terrestrial portions of PAs as the line of high tide, most coastlines are defined as the line of medium tide. Therefore, using the mid-tide line as a reference can result in portions of some marine protected areas

(MPAs) falling inland and thus being excluded when delimiting analyses by using the mid-tide coastline. Unfortunately, it is not always clear, due to missing or incorrect ancillary data, whether the terrestrial portion of an MPA or the marine portion of an otherwise terrestrial PA are real and deliberate or an artifact of spatial errors. The estimated extent of protection is also affected by the use of maps at different spatial resolutions (Wabnitz et al. 2010) and by the spatial location of coastal ecosystems associated with the fractal nature of coastlines (McNeill 1994). We hypothesize that near-shore ecosystems such as coral reefs, seagrass beds, and mangrove forests have highly variable apparent protection, depending on the coastline map used and on the spatial resolution and accuracy of PA and ecosystem maps.

Incomplete protected-area data sets are used in the monitoring of conservation objectives. For example, throughout the Coral Triangle (Indonesia, Malaysia, Papua New Guinea, Philippines, Solomon Islands, and Timor-Leste) and Pacific regions, community-based approaches to spatial management and protection of marine and coastal ecosystems are more common than nationally designated PAs. However, these areas are frequently omitted from the WDPA—although they are similar by definition to IUCN management categories V and VI (Dudley 2009). These locally managed marine areas (LMMAs) often emerge as a synthesis of local tradition and scientific knowledge and comprise a multitude of management strategies (Mills et al. 2011). The role of LMMAs in achieving conservation objectives has often been overlooked because they are small, lack legal recognition by national governments, and do not fit the definitions of the IUCN protected-area categories (Mora et al. 2006). An LMMA typically benefits from high levels of local community support and compliance, and thus has conservation value, even if conservation is not the primary objective (Weeks et al. 2010). We hypothesize that including LMMAs, currently absent from WDPA, results in more realistic estimations of the proportion of marine ecosystems that are under some level of protection, especially where socioeconomic conditions favor more localized forms of protection.

We used case studies to illustrate the implications of the problems associated with PAs with unknown boundaries, propagation of multiple spatial errors, and incomplete protected-area data sets on conservation progress. We sought to demonstrate that the limitations of global data sets highlighted here merit attention because they strongly affect assessments of conservation objectives. We suggest ways for data providers to reduce errors associated with spatial and ancillary data and provide suggestions for data users to mitigate the effects of these errors on broad-scale biodiversity assessments.

Methods

World Database on Protected Areas

For all of the analyses described below, we used the 2010 version of the World Database on Protected Areas (IUCN & UNEP-WCMC 2010), which provides the most comprehensive data set on PAs globally (Chape et al. 2005). The WDPA merges national PA data sets and is widely used for gap analyses at scales ranging from local (e.g., Brandon et al. 2005; Struebig et al. 2010) to global (e.g., Rodrigues et al. 2004; Wood et al. 2008). This database is also used by the United Nations Environmental Program World Conservation Monitoring Centre (UNEP-WCMC) to periodically assess the protection afforded to species and ecosystems globally and to report progress toward the UN Millennium Development Goals.

Fine-Scale Gap Analyses with Unknown Protected-Area Boundaries

To explore the implications of using buffered protected-area centroids when the actual shape of PAs is unknown, we followed a similar approach to that of Jenkins and Joppa (2009). We replaced protected-area polygons with their buffered centroids (circles equivalent in size to the actual polygon and centered on the polygon centroid) to assess the protection of habitat for Neotropical terrestrial mammals ($n = 1558$), derived from Rondinini et al.'s (2011) habitat suitability models. In contrast to the ecoregional analysis of Jenkins and Joppa (2009), our biodiversity data were at a much finer spatial resolution (300 m).

We used all WDPA polygons in the Neotropical realm of IUCN categories I–IV ($n = 1045$) and created dummy protected-area data sets that represented PAs with varying percentages of actual polygons and buffered centroids. We increased the balance between area protected within buffered centroids and actual PA polygons by increments of 10% of the total PA extent (i.e., 10%, 20%, . . . , 100%). We replicated each partial increment in percentage (i.e., 10–90%) of buffered centroids 10 times. Each replicate data set contained a different randomly selected combination of polygons and buffered centroids, thereby accounting for the effects of replacing particular PAs. In total, we had 91 dummy data sets, 10 replicates for each of the 9 increments in percentage of PA extent represented within buffered centroids, plus the data set with 100% of the PAs buffered. We then measured the percent difference in protection for each mammal species when using the dummy data sets compared with true protection of the species (obtained by using the original WDPA map containing polygons only). For this purpose, we excluded 301 species with distributions that did not overlap PAs in the polygon data set. For each increment in percentage of centroids and for each species, we averaged the percent difference in protection with the original data set across the 10 replicates. The dummy data sets were created with a custom code in Matlab (The MathWorks 2011).

We assumed an acceptable level of error in the estimated extent of species protection relative to the true extent was 20% for either under- or overestimates of the area protected. For each increment in extent of area protected within buffered centroids, we calculated how many species would surpass this percent error in estimated protection. Because 20% is a subjective threshold, we performed sensitivity analyses by varying the acceptable level of error from 0% to 100%.

The error resulting from the use of PAs with unknown boundaries (i.e., buffered centroids) can result in omission and commission errors. We estimated the amount of these 2 types of errors separately for each species and for each increment in the proportion of buffered centroids within the dummy data sets. These errors were calculated for each buffered PA and summed together to yield the total area of false presences and absences within PAs in the dummy data set and the relative percent error. For these analyses, we also averaged the results across the 10 replicates and applied a 20% omission–commission error as an arbitrary acceptable level of false absence or presence in PAs. Finally, we calculated how many species would exceed this threshold for either omission or commission error. All the spatial analyses were performed in a Mollweide equal-area projection (300-m resolution with GRASS GIS 6.4) (Neteler et al. 2012).

Propagation of Multiple Spatial Errors in Gap-Analyses Data

For our second case study, we used spatial data depicting the global distribution of coastal ecosystems (i.e., coral reefs, seagrass, and mangroves) and the WDPA to assess variation in the estimated extent of protection resulting from the use of data sets with different spatial resolutions and qualities. We used the World Atlas of Coral Reefs (WACR) (UNEP-WCMC 2003) as an example of a coarse-resolution map (1-km raster). Until recently, this was the only map available for global assessments. We used Coral Reefs of the World (CRW) (UNEP-WCMC 2010) as an example of a fine-resolution map (30-m resolution for 80% of the data set). This is an interim global coral reef data set that supersedes WACR, except for about 20% of the data that still derive from WACR. For each of these data sets, we calculated the total extent of the world's coral reefs and assessed their extent of protection.

In some instances, due to the poor resolution of the maps, marine ecosystems and MPAs fall inland of the line of mid-tide and appear to be terrestrial. To explore this problem, we used the CRW data set, the Global Distribution of Mangroves (version 3.0) (UNEP-WCMC 1997), and Global Distribution of Seagrasses (version 2.0) (UNEP-WCMC 2005). All 3 data sets are readily available, of global extent, and are commonly used for gap analyses at different scales. We assessed the differences in protection provided to each of the 3 ecosystems by the marine portion of PAs and the terrestrial portion of MPAs. For reference, we used Global Self-Consistent Hierarchical High-Resolution Shoreline (version 2, 2009), (Wessel & Smith 1996) to identify marine and terrestrial portions of PAs and ecosystems. We also measured the percent change in total area of each ecosystem protected when we included PAs that were listed in the WDPA as terrestrial only or PAs with a marine component but listed in WDPA as having terrestrial portions. All spatial analyses for this case study and the following were performed in a Mollweide equal-area projection with ArcGis 10 (Environmental Systems Research Institute 2011).

Accounting for Locally Managed Marine Areas

We assessed the benefit of including LMMAs on the apparent extent of protection afforded to coastal ecosystems. To do this, we compared the results of a gap analysis for seagrass, mangrove, and coral reef ecosystems in the Philippines that was based on WDPA data alone with a more comprehensive analysis that included both WDPA polygons and LMMAs from the Philippine national protected-area database (Weeks et al. 2010).

Using the spatial data sets described in the second case study, we measured the area of seagrass, mangrove, and coral reef (with CRW) ecosystems protected when accounting for WDPA protected-area polygons; buffered centroids of PAs with unknown boundaries (as calculated in our first case study); and LMMAs (Weeks et al. 2010). In the Philippine LMMA database, protected-area polygons were unavailable and the point data were buffered; therefore, this database had the same problem highlighted in the first case study. However, because of the small size of LMMAs, it is likely that inaccuracies in habitat representation were minimal.

Results

Fine-Scale Gap Analyses with Unknown Protected-Area Boundaries

We found up to 100% underestimation and 900% overestimation of protection for some Neotropical mammal species, even with small percentages of PAs represented as buffered centroids (Fig. 1a). Replacing 20% of PAs in the Neotropical realm with buffered centroids (i.e., a value similar to the 22% found in WDPA for Neotropical PAs in IUCN categories I–IV) resulted in 16% of all Neotropical mammals surpassing a threshold in error of

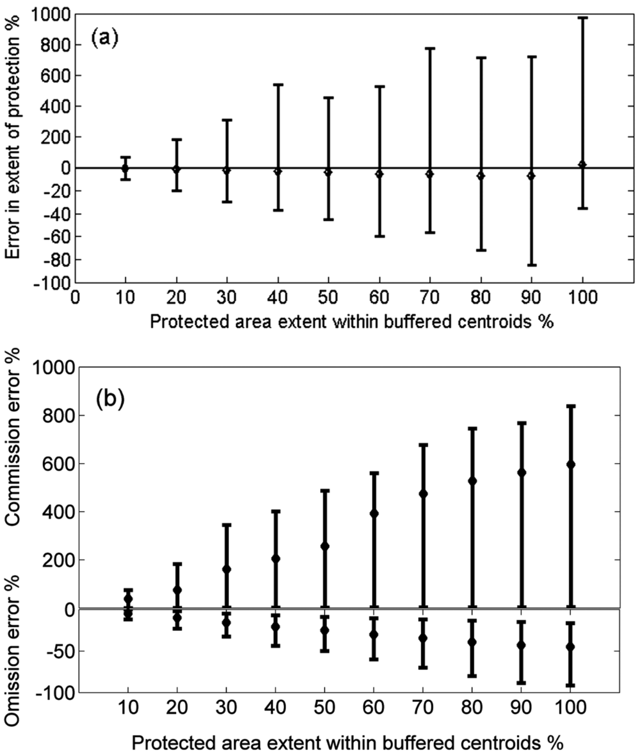

Figure 1. (a) Percent error in the estimated extent of protection of Neotropical terrestrial mammal habitat with increasing percentages of total protected area extent in buffered centroids (diamonds, median error across all species; bars, 5th and 95th percentiles of error distributions across all species; negative values on the y-axis have a different scale than positive values). (b) Separate values of commission and omission errors in protection for each species of terrestrial Neotropical mammal (x-axis as in panel [a]).

20% (including under- and overestimates of the correct value [Supporting Information]). Increasing buffered centroids to 30% (i.e., a value similar to the observed 28% of PAs globally) resulted in 21% of Neotropical mammals surpassing the error threshold. Results of sensitivity analyses of threshold errors considered acceptable are in Supporting Information.

Despite the median error being close to zero for all increments of PA extent within buffered centroids, the tails of the distribution of errors were extremely wide and right skewed (Fig. 1a) because there was no upper bound in overestimation, whereas the underestimation was bounded between 0 and 100%. When representing 30% of the PA extent within buffered centroids, 37% of the terrestrial Neotropical mammals had their extent of protection overestimated. The average overestimation across these species was 402.8%. About 63% of the species had their extent of protection underestimated; the average underestimation among these species was 10.9%.

Twenty percent of species had an unacceptable error of either commission or omission (i.e., ≥20% error) with 20% of PA extent within buffered centroids. This percentage increased to 36% when we used the reference level of 30% of PA extent in buffered centroids (Supporting Information).

The median and confidence intervals of the error in extent of protection for a given percentage of buffered centroids were closer to zero (Fig. 1a) than the median commission and omission error of protection across PAs (Fig. 1b). As percentages of PA extent within buffered PAs centroids increased, both commission and omission errors tended to increase linearly (Fig. 1b) and roughly balanced one another in terms of overall error in the measured extent of protection (Fig. 1a).

Propagation of Multiple Spatial Errors in Gap-Analyses Data

The spatial resolution of ecosystem data sets affected the amount of coral reef that was perceived as protected. Approximately 22% of the world's coral reefs appeared to be protected with the 1-km WACR data set. This percentage increased to 28% with the CRW data set. Across regions, the finer-resolution coral reef data set consistently resulted in greater extent of protection for marine ecosystems, although the difference was more notable for some regions (e.g., Central Indo-Pacific and Eastern Indo-Pacific) (Fig. 2). A small percentage of the world's coral reefs were protected by the "terrestrial" portions of PAs (1.4% and 1.0% for the low- and high-resolution data sets, respectively) (Fig. 2) as defined by the mid-tide coastline. Although the extent of coral reef protected by the terrestrial portion was relatively small, it summed to 3750 km^2 and 1520 km^2 (i.e., 6.3% and 3.7% of the total coral reef protected) for the WACR and CRW data sets, respectively. The effect of this error was most notable for the Tropical Eastern Pacific ecoregion but also for the Temperate Northern Pacific, Tropical Atlantic, and Western Indo-Pacific ecoregions (Fig. 2b).

Sixteen percent of the world's seagrass was estimated to be protected. Similar to coral reefs (Figs. 2 & 3a), only a small percentage of the worlds' seagrass was represented in the "terrestrial" component of MPAs and terrestrial PAs (0.9 and 0.2% respectively), although these numbers combined represented approximately 7% of the total protected extent of seagrass (Fig. 3a).

For mangroves, considering the terrestrial component of PAs increased the global extent of protection from 2.1% (marine portion only) to 27.4% (Fig. 3a). This meant that 92.3% of the world's protected mangrove ecosystem area was not accounted for when considering only the marine component of PAs. Higher percentages of mangrove ecosystem area were found in MPAs of particular

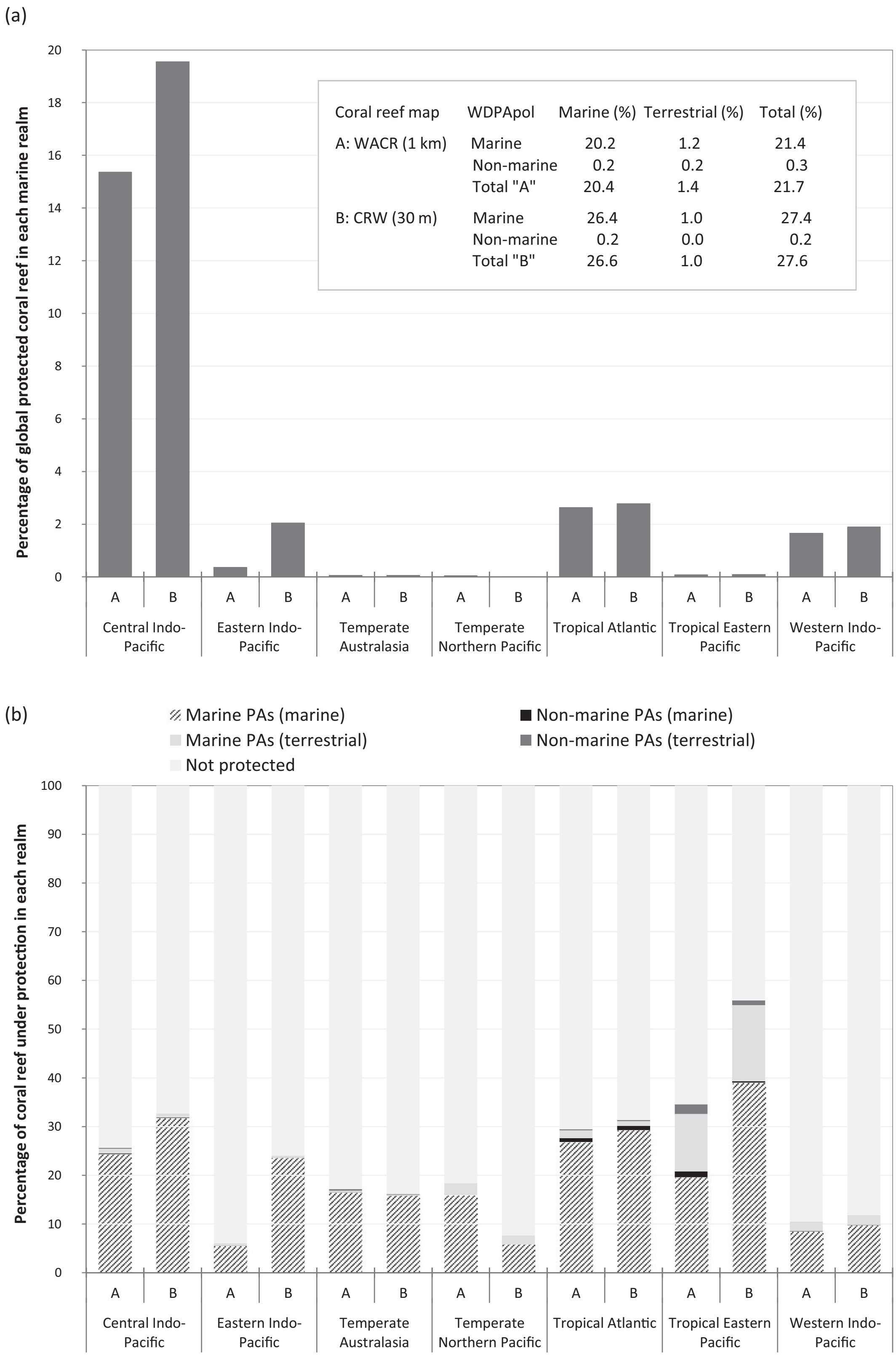

Figure 2. (a) Percentages of global protected coral reefs within each marine realm and (b) percentages of coral reef ecosystem area occurring in each marine realm protected by different types of protected areas (PAs). Representation of coral reefs in PAs across marine realms are based on maps with different spatial resolutions. Two sets of values are given for each realm on the basis of (A) the World Atlas of Coral Reefs data set, and (B) Coral Reefs of the World (CRW) data set.

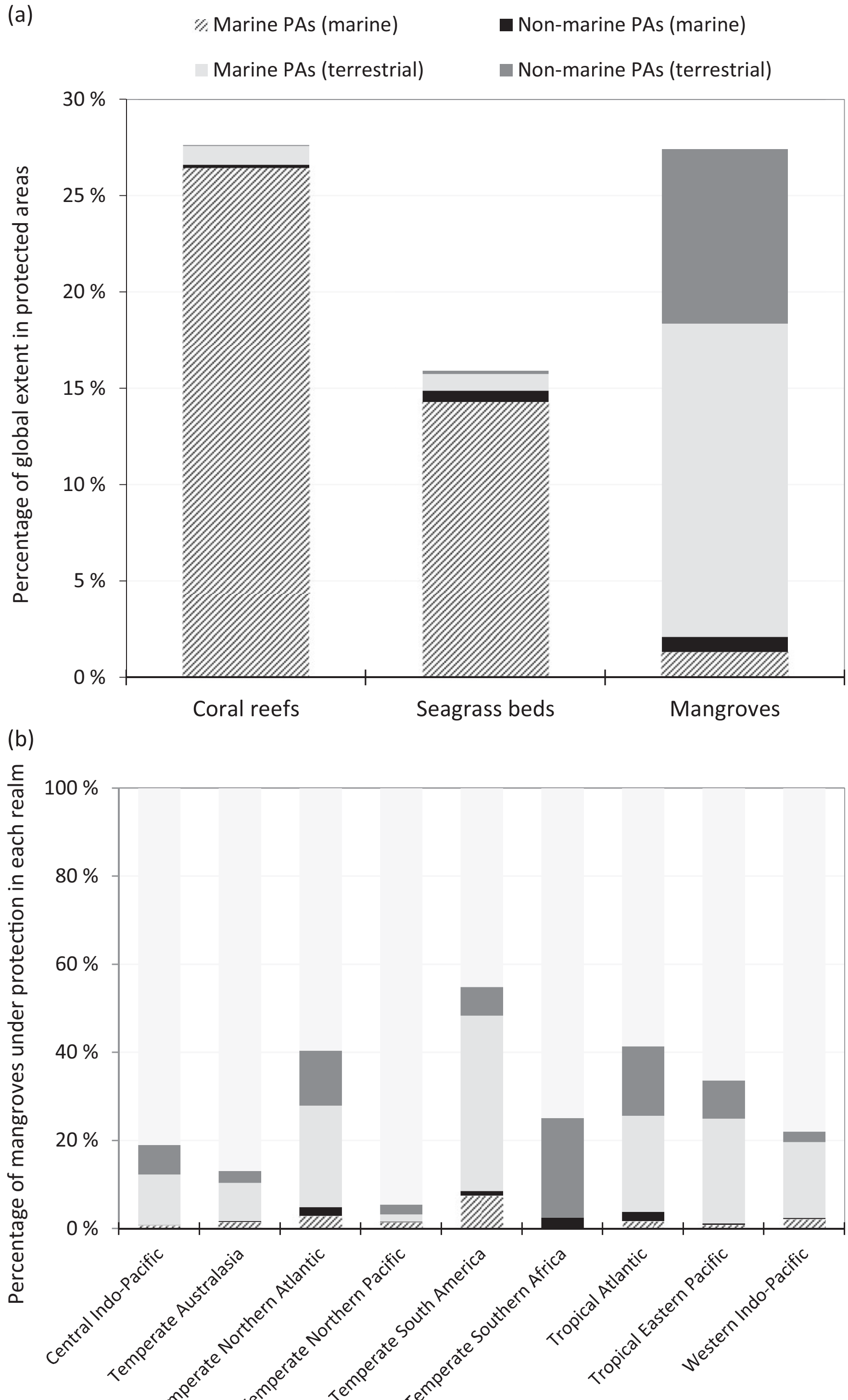

Figure 3. Representation of selected marine ecosystems in PAs: (a) global extent of coral reefs (on the basis of CRW data set), seagrass beds, and mangroves in PAs and (b) global mangrove ecosystem area in each marine realm protected by different types of PAs.

regions such as the Western Indo-Pacific and Tropical Atlantic realms (Fig. 3b).

Accounting for Locally Managed Marine Protected Areas

The WDPA polygons contributed most to the total area protected for each of the 3 marine ecosystems in the Philippines, respectively 2946 km^2 of seagrass (19.6% of the total extent of seagrass in the Philippines), 721 km^2 of mangroves (44.8%), and 768 km^2 of coral reefs (6.3%) (Fig. 4). However, including LMMAs added an additional 536 km^2 of seagrass protection (3.6% of total extent), 108 km^2 of mangrove protection (6.7%), and 401 km^2 of coral reef protection (3.3%). The WDPA buffered points contributed the least protection (<1% for all ecosystems).

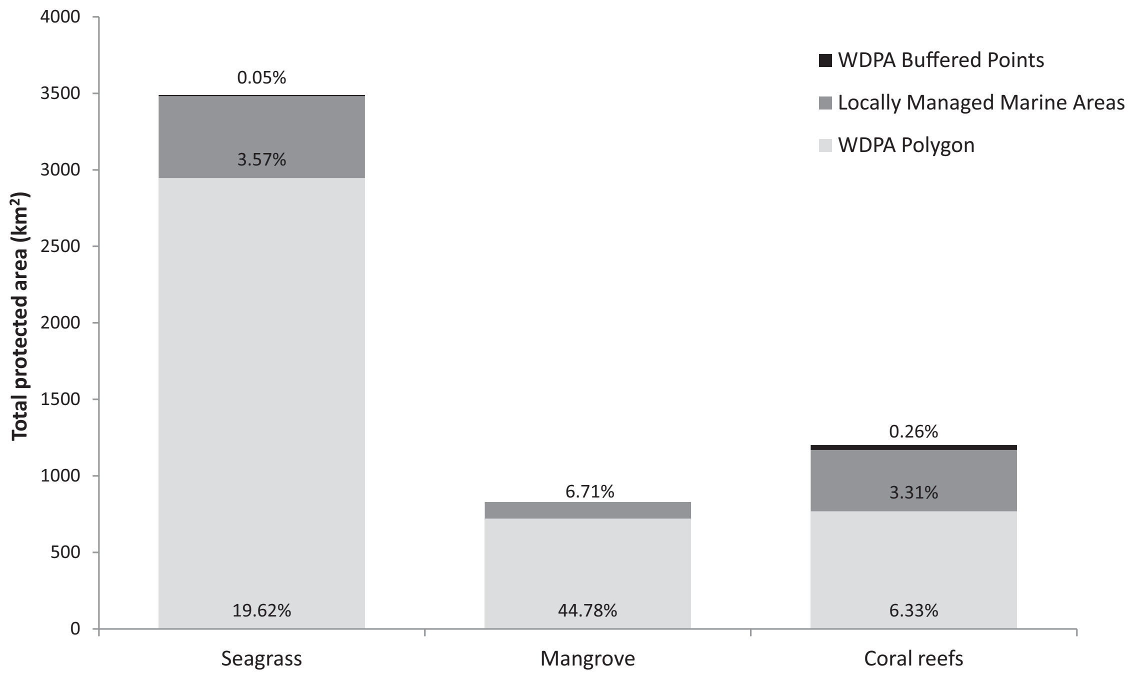

Figure 4. Percentages of seagrass, mangrove, and coral reef area afforded protection by the World Database on Protected Areas (WDPA). On the y-axis, the stacked histograms indicate the area of seagrass, mangrove, and coral reefs (based on the CRW data set) protected by WDPA polygons, locally managed marine areas, and WDPA buffered centroids for the Philippines. No WDPA buffered centroids protect mangroves. The percentages associated with areas in bars are of total ecosystem area.

Discussion

Effect of Buffered Centroids on Gap Analyses

Replacing 30% of Neotropical PAs with buffered centroids (a figure similar to the actual percentage of missing-boundary entries in WDPA globally) caused errors in the extent of protection estimated for Neotropical Terrestrial mammals that were up to 3 orders of magnitude larger than those estimated on the basis of ecoregions (Jenkins & Joppa 2009). We chose the Neotropical realm because it has the highest mammal species richness, yet we see no reason why these results would not be representative of other regions or biodiversity features (e.g., taxa, vegetation types) mapped at fine resolution. Our findings illustrate that even a relatively small percentage of PAs with missing boundaries can result in very large over- or underestimation of biodiversity protection. Considering a portion of a species range protected, when it is not, could affect the perceived conservation status of the species. In particular, when evaluating a species status against a given representation target (e.g., species' range size [Rodrigues et al. 2004]), having a high overestimate would result in a false sense of protection for the species. However, a high underestimate could result in overallocation of conservation funds toward species that are already well protected, which reduces the amount of money available for species with a real protection gap. Errors of omission and commission in individual PAs had much more serious implications. For example, replacing 30% of PAs with buffered centroids resulted in mean commission error of 161% (95% CI = 1–345%) and a mean omission error of 16% (95% CI = 5–32%). Therefore, even when the overall extent of protection was correctly estimated with buffered centroid data sets, individual commission errors could direct efforts toward areas in which the species is absent, and omission errors would result in missed opportunities to protect species in PAs where the species is present. Species with irregularly shaped distributions have even higher omission and commission error than the averages reported here (Supporting Information).

Propagation of Multiple Spatial Errors in Gap-Analyses Data

The global extent of coral reef area measured with the most up-to-date and fine-resolution coral reef map (CRW) was approximately 46% lower than the extent measured with the lower-resolution map (WACR). This finding is consistent with Wabnitz et al. (2010), who reported a 50% overestimate of coral reef ecosystem by WACR in selected regions. As expected, the difference in coral reef extent also yielded a very different estimate of the percentage of coral reefs under protection. Use of the CRW data set increased the global percentage of coral reef area protected by almost one-third.

The artificial protection afforded to coral reefs by application of the line of high tide to separate terrestrial and marine PAs was also likely associated with spatial errors of ecosystem maps, PA boundaries, and the resolution of the coastline. Despite the overall small contribution of the "terrestrial" component of PAs to coral reef protection, some regions, such as the Tropical Eastern Pacific, need a detailed assessment because of the large relative contribution of the terrestrial component to coral reef protection. This large terrestrial contribution could be due to the large number of small islands in the Tropical Eastern Pacific; their relative proportion of coastline per unit area likely inflated this estimate due to inaccuracies in the coastline map.

Previous estimates of the extent of coral reef protection differ: 21% by Chape et al. (2005) using WACR 2001 (Spalding et al. 2001), 14% by Wood et al. (2008) using WACR 2003, and 27% by Burke et al. (2011) and using CRW. The increase in protection reported by the latest assessment can be partially explained by the recent addition of very large MPAs (e.g., Chagos Archipelago). However, our findings indicate that an important portion of this estimated increase is an artifact of the use of maps of different resolution. This difference arises because many MPAs in the tropics follow the outline of coral reef patches; therefore, although the total extent of coral reefs is reduced when more accurate maps are used, the extent of PA does not decrease as much. Because CRW contains elements from the original 1-km data set, its future completion will likely result in further apparent improvement in estimated coral reef protection.

We estimated that 27.4% of the world's mangroves are included in PAs of IUCN categories I–IV. Wood et al. (2008) reported protection of 18% of the world's mangroves, whereas Spalding (2010) reported a value of 25%. Differences in values between these studies were attributed to the genuine increase in PA coverage in the intervening 2 years (Spalding et al. 2010). However, the information provided by these reports is insufficient to exclude the possibility that the observed increase is partially (or perhaps largely) due to differences in the coastline layers used or the use of updated data sets. Aside from these differences in data sets, regional gaps in maps of mangrove ecosystems also add to the uncertainty in the estimated extent of protection (Spalding et al. 2010). Moreover, habitat loss and habitat dynamics of mangrove forests and the other marine ecosystems we examined should be accounted for to detect genuine changes in protection (Supporting Information).

Approximately 90% of the protected mangrove ecosystem globally lies above the line of medium tide (i.e., within the terrestrial portion of PAs). This denotes the importance of terrestrial PAs in the protection of coastal and marine ecosystems. Terrestrial PAs, however, are typically disregarded when assessing the extent of protection of coastal and marine ecosystems.

Our estimate of current protection of seagrass (16%) was much higher than the other global estimate available, which reported 10% protection (Spalding et al. 2010). The inclusion of "terrestrial" protection of seagrass and a more recent WDPA data set contributed to these differences.

Accounting for Locally Managed Marine Protected Areas

The LMMAs contributed much to the total area protected for the 3 marine ecosystem investigated in the Philippines. The number of LMMAs increased rapidly following the devolution of responsibility for managing coastal and marine resources from national to municipal governments (Alcala & Russ 2006). This trend toward decentralized management has also occurred in Indonesia (Siry 2006) and island nations across the Pacific. Because LMMAs represent an increasing percentage of PAs globally, the problems associated with their omission in gap analyses will become more acute. When the WDPA is the only database used to assess progress toward international conservation commitments, such as the CBD targets, the conservation efforts of these countries are likely to be underestimated.

Recent attempts have been made to better estimate the contribution of LMMAs to conservation. In Fiji the differential contributions to national conservation objectives were estimated for various types of closures and other management within LMMAs (Mills et al. 2011) and provided more accurate reporting than either ignoring LMMAs or treating them as equivalent to complete protection. Similar to LMMAs, community managed forests on average more effectively reduce rates of deforestation than PAs officially recognized by IUCN (Porter-Bolland et al. 2012). The WDPA database has recently started incorporating LMMAs. Nevertheless, when performing gap analyses in regions with locally managed marine or terrestrial areas in place, we recommend seeking out sources of information additional to the WDPA that better capture the full range of conservation initiatives.

Recommendations for Data Providers and Users

On the basis of our findings, we recommend ways in which data providers might improve the accuracy of national and international databases on biodiversity and PAs. (1) Establish a priority list of PAs currently lacking actual boundaries in spatial databases and define their boundaries to avoid the use of buffered centroids, starting with the largest, most biodiversity rich and irregularly shaped PAs. (2) Periodically verify the boundaries of old PAs to account for downgrading, downsizing, and degazettment of PAs (Mascia & Pailler 2011). (3) Ensure that metadata and mapping methods for national databases of PAs are standardized (e.g., compliant to ISO metadata standards) to facilitate the integration in WDPA.

Use of an accurate standard coastline would reduce error associated with estimates of protection afforded to coastal ecosystems. (4) Conduct quality checks of ancillary data (e.g., check mistakes in PA size due to the use of hectares instead of square kilometers and verify information on terrestrial and marine components of PAs). (5) Assess community-managed PAs and their inclusion in WDPA.

The implications of spatial and nonspatial errors in the national and international data sets used for conservation monitoring can be somewhat mitigated with some preprocessing of the data and careful evaluation of the assumptions behind data treatment (e.g., implications of filtering out certain IUCN management categories). We recommend end users (1) clip the portion of buffered centroids of PAs known to be only terrestrial or marine to their respective realm; (2) clip the portion of buffered centroids of PAs known only from one country to the country borders; (3) in regions with local or community-based management, seek out sources of protected-area data additional to the WDPA and work with stakeholders to estimate the relative contributions of different kinds of community-based spatial management to national and international conservation objectives; (4) when available, use newer and finer-resolution biodiversity maps to report on the extent of protection and use these maps to reassess previous estimates of protection to measure genuine changes in protection over time; (5) state and quantify data errors and inadequacies.

Spatial errors and their effects on results of conservation studies can be measured with the methods presented here and elsewhere (e.g., Jenkins & Joppa 2009). Application of these methods can help identify data gaps, improve monitoring of conservation progress, and result in more-informed and probably more effective conservation actions.

Inaccurate Data and Biodiversity Targets

In 2010, the world's nations pledged ambitious targets for biodiversity conservation by 2020 (Normile 2010). Our results show that efforts to monitor progress toward such targets rely largely on inaccurate data that can mislead reporting and prioritization of conservation efforts. This problem need to be addressed now because biodiversity monitoring needs correct baseline levels of protection to track genuine improvement or decline of conservation status of species and ecosystems if appropriate responses are to be devised (Butchart et al. 2007).

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Supporting Information

Percentage of species surpassing a 20% error in estimated extent of protection for increasing percentage of protected area within buffered centroids (Appendix S1), results of sensitivity analyses of threshold error in estimated extent of protection (Appendix S2), percentage of species surpassing 20% in either commission or omission error for increasing percentage of protected area within buffered centroids (Appendix S3), additional discussion on the effects of buffered centroids (Appendix S4), and information on habitat loss, ecosystem dynamics, and gap analyses (Appendix S5) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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