Contributed Paper

Global protected-area coverage and human pressure on tidal flats

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Abstract: Tidal flats are a globally distributed coastal ecosystem important for supporting biodiversity and ecosystem services. Local to continental-scale studies have documented rapid loss of tidal habitat driven by human impacts, but assessments of progress in their conservation are lacking. With an internally consistent estimate of distribution and change, based on Landsat satellite imagery, now available for the world's tidal flats, we examined tidal flat representation in protected areas (PAs) and human pressure on tidal flats. We determined tidal flat representation and its net change in PAs by spatially overlaying tidal flat maps with the World Database of Protected Areas. Similarly, we overlaid the most recent distribution map of tidal flats (2014–2016) with the human modification map (HM_c) (range from 0, no human pressure, to 1, very high human pressure) to estimate the human pressure exerted on this ecosystem. Sixty-eight percent of the current extent of tidal flats is subject to moderate to very high human pressure ($HM_c > 0.1$), but 31% of tidal flat extent occurred in PAs, far exceeding PA coverage of the marine (6%) and terrestrial (13%) realms. Net change of tidal flat extent inside PAs was similar to tidal flat net change outside PAs from 1999 to 2016. Substantial shortfalls in protection of tidal flats occurred across Asia, where large intertidal extents coincided with high to very high human pressure ($HM_c > 0.4$–1.0) and net tidal flat losses up to 86.4 km^2 (95% CI 83.9–89.0) occurred inside individual PAs in the study period. Taken together, our results show substantial progress in PA designation for tidal flats globally, but that PA status alone does not prevent all habitat loss. Safeguarding the world's tidal flats will thus require deeper understanding of the factors that govern their dynamics and effective policy that promotes holistic coastal and catchment management strategies.

Keywords: Aichi Biodiversity Target 11, coastal management, habitat loss, human modification map, spatial bias

Cobertura Mundial de Áreas Protegidas y la Presión Humana sobre las Planicies Mareales

Resumen: Las planicies mareales son un ecosistema costero con distribución global e importancia para el mantenimiento de la biodiversidad y los servicios ambientales. Existen estudios, desde locales hasta continentales, que han documentado la pérdida acelerada del hábitat mareal causado por el impacto humano, aunque las evaluaciones sobre el progreso en su conservación son muy pocas. Ahora que está disponible una estimación internamente coherente de la distribución y el cambio, basado en las imágenes satelitales de Landsat, de las planicies mareales del mundo, examinamos la representación de estas planicies dentro de las áreas protegidas (APs) y la presión humana sobre las mismas. Determinamos la representación de las planicies mareales y su cambio neto dentro de las APs mediante la superposición espacial de los mapas de las planicies mareales y la Base de Datos Mundial de Áreas Protegidas. De manera similar, superpusimos el mapa más reciente de la distribución de las planicies mareales (2014-2016) en el mapa de modificaciones humanas (MH) (abarca desde 0, ninguna presión humana, hasta 1, presión humana muy alta) para estimar la presión humana ejercida sobre este ecosistema. El

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68% de la extensión actual de las planicies mareales está sujeta a una presión humana desde moderada hasta muy alta (MH > 0.1), aunque el 31% de la extensión de las planicies mareales se encuentra dentro de las APs, lo que excede por mucho el porcentaje de protección de los dominios marino (6%) y terrestre (13%). El cambio neto de la extensión de las planicies mareales dentro de las APs fue similar al cambio neto de las planicies fuera de las APs entre 1999 y 2016. La insuficiencia sustancial de la protección de las planicies mareales ocurrió en Asia, en donde grandes extensiones intermareales coincidieron con una presión humana alta y muy alta (MH > 0.4-1.0) y la pérdida neta de planicies mareales de hasta 86.4 km^2 (95% IC 83.9-89.0) ocurrió dentro de una sola AP durante el periodo de estudio. Si se consideran en conjunto, nuestros resultados muestran un progreso importante en la designación de AP para las planicies mareales a nivel mundial, aunque el solo estado de AP no previene la pérdida de hábitat. Salvaguardar las planicies mareales del planeta por lo tanto requerirá de un entendimiento más profundo de los factores que rigen sobre sus dinámicas y de políticas efectivas que promuevan estrategias holísticas de manejo costero y de captación.

Palabras Clave: manejo costero, mapa de modificaciones humanas, Objetivo 11 de Biodiversidad de Aichi, pérdida de hábitat, sesgo espacial

【摘要】: 滩涂是分布在全球的海岸带生态系统, 对支持生物多样性和生态系统服务十分重要。从局部到大陆尺度的研究报道了人类影响导致滩涂栖息地的快速丧失, 但是对它们保护进展的评估还较为有限。本研究基于目前全球滩涂已有的 Landsat 卫星图像, 获得对分布和变化内部一致的估计, 进而分析了保护区中滩涂的代表情况及人类对滩涂的压力。我们通过将滩涂分布图和全球保护区数据库进行空间叠加, 确定了保护区中滩涂的代表情况及其净变化。同样地, 我们将最近的滩涂分布图 (2014–2016年) 与人类改造地图 (human modification map, HM_c, 无人类压力为 0, 非常高的人类压力为1) 相叠加, 以估计人类对该生态系统施加的压力。现有滩涂有68%受到中等至非常高的人类压力 (HM_c > 0.1) , 但有31%的滩涂位于保护区内, 远远超过海洋 (6%) 和陆地 (13%) 受保护的范围。从1999年到2016年, 保护区内外滩涂范围的净变化情况相似。在我们的研究期间, 整个亚洲的滩涂都严重缺乏保护, 这些地区有大量潮间带受到高至非常高的人类压力 (HM_c> 0.4–1.0) , 且在个别保护区内, 滩涂净损失高达 86.4 平方千米 (95% CI 83.9–89.0) 。综合而言, 我们的结果表明全球保护区对滩涂的覆盖取得了重大进展, 但受到保护区覆盖本身并不能完全防止栖息地丧失。因此, 全球滩涂保护需要更深入地了解影响其动态变化的因素以及可以促进海岸和流域整体管理策略的有效政策。**【翻译: 胡怡思; 审校: 聂永刚】**

关键词: 海岸管理, 人类改造地图, 栖息地丧失, 空间偏差, 爱知生物多样性目标11

Introduction

Tidal flats are a productive coastal ecosystem that supports unique biological assemblages, along with economically and recreationally valuable ecosystem services (Millennium Ecosystem Assessment 2005; Murray et al. 2014). The high productivity, unique biological assemblages, and important ecological services provided by tidal flats are due in part to their position at the boundary of the terrestrial and marine realms, where they are periodically inundated by the ocean and exposed according to the tides. However, because tidal flats are subject to interaction between the terrestrial and marine realms, they are vulnerable to threatening processes occurring on land, in rivers, and at sea (MacKinnon et al. 2012). There is an urgent need to better understand threats to tidal flat extent and their ability to deliver ecosystem services, as well as safeguard the biodiversity they support (Millennium Ecosystem Assessment 2005; Murray et al. 2019).

Numerous studies document the rapid loss of local tidal flats (e.g., MacKinnon et al. 2012; Miththapala 2013; Murray et al. 2014, 2019). Tidal flat loss and degradation occur from a range of threatening processes that act on multiple scales, including those originating from human actions, such as reclamation, sea-level rise, vegetation loss, reduced sediment flow, nutrient runoff, and coastal hardening (Stoms et al. 2005; MacKinnon et al. 2012; Murray et al. 2014). For example, from the early 1980s to the late 2000s, tidal flats in the Yellow Sea disappeared at a rate of >1% per year, primarily due to reclamation (Murray et al. 2014). The Wadden Sea—the largest transboundary Ramsar site in the world—is estimated to have lost one-third of its tidal flat extent since the 16th century due to reclamation and coastal retreat (Reise 2005). In contrast, tidal flat gain can occur when deposition patterns and coastal processes are altered by anthropogenic impacts, thereby resulting in a complex suite of drivers that can result in both positive and negative net change in extent (MacKinnon et al. 2012; Murray et al. 2019).

Protected areas (PAs) are the primary management tool to stem biodiversity and habitat loss (CBD 2010; Barr et al. 2011), and PA coverage is used as a measure of global conservation progress, success, and goal setting (CBD 2010; Watson et al. 2014). For instance, Aichi Biodiversity Target 11 calls for "at least 17 per cent of terrestrial and inland water areas and 10 per cent of coastal and marine areas … are conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas" (CBD 2010). Although there is debate surrounding the adequacy of these targets to ensure habitat persistence, there is at least general agreement that more protection is beneficial (Pressey et al. 2003; Barr et al. 2011). Consequently, gap analyses are integral to track progress toward targets, highlight areas to focus future work due to low coverage or representativeness, and help formulate new global targets (Brooks et al. 2004; Schmitt et al. 2009; CBD 2010).

The placement of PAs in relation to threatening processes, and not just PA coverage, is vital for effective conservation (Sanderson et al. 2002; Joppa & Pfaff 2009). Yet, PAs are often placed in regions of low human pressure and hence low economic value (Pressey & Tully 1994; Joppa & Pfaff 2009). Tidal flats are subject to strong human pressure due to their proximity to coastal regions, which are hubs for human populations, intensive human activities, and high economic value (Murray et al. 2019). Consequently, tidal flat PAs can be affected by natural processes (e.g., erosion and sedimentation) and human activities (e.g., land claim, downsizing, and degazettement of PAs), as has been demonstrated in the Yellow Sea region (Ma et al. 2019). However, there has been no global study of the extent to which tidal flats are represented in the PA network.

Murray et al. (2019) produced the first high-resolution maps (30 × 30 m) of global tidal flat extent, which covered the period 1984–2016. Change analyses revealed that 16.0% of tidal flats were lost from 1984 to 2016; 3.1% was lost from 1999 to 2016 (17.1% and 61.3% of coastline analyzed, respectively) (Murray et al. 2019). These declines indicate an urgent need to assess how PAs are being used to conserve tidal flats.

We conducted the first global analysis of the PA coverage of tidal flats (2014–2016), human pressure on tidal flats (2014–2016), and change in tidal flat extent inside and outside PAs from 1999 to 2016. We assessed PA coverage with reference to Aichi Biodiversity Target 11, coverage of marine and terrestrial realms, country-level governance effectiveness (world governance indicators) (Kauffman et al. 2010), and jurisdiction (marine, coastal, and terrestrial PA) and designation (national, international, and regional PA), to provide insight into the actors responsible for tidal flat stewardship. We examined the distribution of protected and unprotected tidal flats across a global composite map of terrestrial human pressures (human modification map, hereafter HM_C) to assess bias in placement of tidal flat PAs. Finally, we empirically assessed net change of tidal flat extent inside and outside PAs from 1999 to 2016. Although PA coverage for other ecosystems (e.g., forests and mangroves) has long been available to decision makers, PA coverage for the world's tidal flats remains entirely unknown.

Methods

Global Tidal Flat Data Set

The global map time series of tidal flats extends from 1984 to 2016 in 3-year intervals (Murray et al. 2019). It was developed by collating Landsat 4, 5, 7, and 8 satellite images (n = 707,528; 30-m resolution) that intersected within 1 km of the global coastline between 60° south and 60° north (Murray et al. 2019). Only pixels within 50 km of the coast in marine environments, 5 km of the coast in terrestrial environments, and 100 m elevation and depth were assessed; all others were masked from further analysis. A random forest machine learning classifier was used to identify pixels corresponding to tidal flat based on 10,701 globally distributed training points and 56 covariate layers with global extent. We define *tidal flat systems* as sandflats (unconsolidated coarse-grain sediments), mudflats (fine-grain sediments), and wide tidal rock platforms (consolidated sediments, organic material, or rocks). We excluded ecosystems dominated by vegetation (mangroves, vegetated marshes, etc.) (Murray et al. 2019). We used the 2014–2016 map to assess current tidal flat extent (100% of coastline assessed) because it is the most recent map available. For analyses of areal changes of tidal flats, we compared the 1999–2001 and 2014–2016 tidal flat maps because they best resolved the trade-off between length of time series and spatial coverage (61.3% of coastline assessed) of the map data. Only pixels that were classified with ≥10 satellite images according to the quality assurance bands within each of these periods were used in this analysis to ensure the 2 maps were spatially consistent. We projected all data to World Geodetic System 84 reference system and calculated tidal flat extents by converting each pixel to area (square kilometers) and applying weighted sums—allowing pixel snippets at a resolution of one-hundredth of the original pixel size to be included in analysis—for all extent calculations.

Protected-Area Coverage of Tidal Flats

The World Database of Protected Areas (WDPA) is the most comprehensive PA database (UNEP-WCMC & IUCN 2018). We assessed tidal flat protection with the WDPA polygons data set, which excludes broken, point, and null geometries (UNEP-WCMC & IUCN 2018). Excluding these geometries ensured that only PAs with clearly defined boundaries were analyzed and that estimates of protected tidal flat were conservative (Appendix S1). We selected PAs implemented before 2017 from the WDPA to ensure the best temporal match between the PA network and current tidal flat data (2014–2016). For PAs with unknown establishment dates, we assigned the median known establishment year of PAs within the same country based on random sampling with replacement (n = 1000). For countries with <5 PAs with known establishment years, the assigned establishment year was based on the random sampling of all available PAs. Overlapping PAs were dissolved to prevent overestimating protected-area coverage. We then calculated the percentage of total tidal flat extent that fell within PA boundaries and summed the values over exclusive economic zones for country and global-level assessments. Based on the first and third quartiles, we defined low- and high-extent countries as those with ≤12.4 and ≥562.6 km^2 of tidal flat, respectively.

To compare the coverage of tidal flats with that of the marine and terrestrial realms, we summed all nontidal flat pixels and categorized them as marine or terrestrial according to coastline data from the Large Scale International Boundary Polygons data set (United States Department of State 2013). We then determined PA coverage for both realms.

The world governance indicators (Kauffman et al. 2010) were used to assess whether the coverage of country-level tidal flats was related to governance. The world governance indicators assess 6 aspects of each country: regulatory quality, rule of law, control of corruption, absence of violence, voice and accountability, and political stability and scores each aspect from −2.5 (poor governance) to +2.5 (high governance) (Kauffman et al. 2010). We calculated the 2016 mean of these indicators for each country with tidal flats ($n = 151$), following the methods of Amano et al. (2017). Because high governance is considered the primary driver of PA designation (Amano et al. 2017), we fitted a beta regression model with governance as the single predictor of country-level coverage of tidal flats (betareg R package) (Cribari-Neto & Zeileis 2010). All values (y) were adjusted using the following equation to account for 0 and 1 inflation:

$$\frac{\left(y\left(n-1\right)+0.5\right)}{n}, \tag{1}$$

where n is the sample size (Cribari-Neto & Zeileis 2010).

To provide insight into the actors responsible for tidal flat stewardship, we investigated tidal flat coverage according to PA designations (international, national, and regional) and jurisdictions (marine, coastal, and terrestrial). Designatory and jurisdictional coverage of tidal flats was calculated for each unique combination of overlapping PA types (Appendix S2). Additionally, we calculated tidal flat coverage according to IUCN (International Union for Conservation of Nature) management categories (Appendix S2).

Human Pressure

The HM_c quantifies human disturbances to the terrestrial environment at 1-km^2 resolution based on remotely sensed measures of population density, built-up areas, cropland, livestock, major roads, minor roads, two-tracks, railroads, oil wells, wind turbines, powerlines, and nighttime lights (Kennedy et al. 2019). The HM_c is based on a continuous metric from 0 to 1 with meaningful scaling (e.g., a pressure of 0.5 has twice as much impact as a pressure of 0.25 and half as much impact as a pressure of 1). We followed Kennedy et al.'s (2019) categorization of HM_c values as no human pressure ($HM_c = 0$), low ($HM_c > 0-0.1$), moderate ($HM_c > 0.1-0.4$), high ($HM_c > 0.4-0.7$), and very high ($HM_c > 0.7-1$) pressure, with an HM_c value of 0.4 approximating the transition to human-dominated environments.

Because most threats to tidal flats originate on land (MacKinnon et al. 2012; Miththapala 2013), we considered the HM_c (Kennedy et al. 2019) to be a broad indicator of human pressure on this ecosystem. However, we acknowledge that some disturbances represented in the HM_c may not correspond to direct threats to tidal flats and that other potentially important environmental (e.g., sediment flow), ecological (e.g., *Spartina* [Strong & Ayres 2013]), and off-site pressures (e.g., dams) were not incorporated into our analyses.

To assess the distribution of tidal flat PA coverage across the human pressure gradient, we overlaid the HM_c onto the 2014–2016 tidal flat map. Tidal flat pixels without an HM_c value (38.1%) were assigned the same level of pressure as the nearest pixel via Euclidean allocation (mean distance to nearest pixel 1.9 km, range > 0.01−56.9 km). Following Kennedy et al. (2019), we scored human pressure in intervals of 0.1, following absolute 0 (e.g., 0, >0–0.1, > 0.1–0.2). We then calculated proportional difference between protected and unprotected tidal flat extent for each HM_c interval following Joppa and Pfaff (2009):

$$\left(\frac{protected\ tidal\ flat\ extent\ - unprotected\ tidal\ flat\ extent}{total\ tidal\ flat\ extent}\right). \tag{2}$$

Proportional differences were bound between −1 (0% protection) and +1 (100% protection) at each HM_c interval. Proportional differences were compared against null expectations of 50% tidal flat coverage (in line with Half Earth expectations, proportional difference of 0) and our global estimate of tidal flat coverage (Wilson 2016). Deviations from the expected proportional difference of global tidal flat coverage were interpreted as spatial bias in PA placement.

Tidal Flat Loss Within Protected Areas

Net tidal flat change between 1999–2001 and 2014–2016 was quantified and compared inside and outside of the PA network and for individual PAs. Only PAs established before 1999 ($n = 5927$) were considered to ensure that observed changes in tidal flat extent could not occur prior to PA implementation (Appendix S1). We used the 95% CIs from Murray et al. (2019) to represent uncertainty in area estimates (Lyons et al. 2018).

Map data were processed in Google Earth Engine (Gorelick et al. 2017), and data were summarized and visualized in R 3.4.2 (R Core Team 2017).

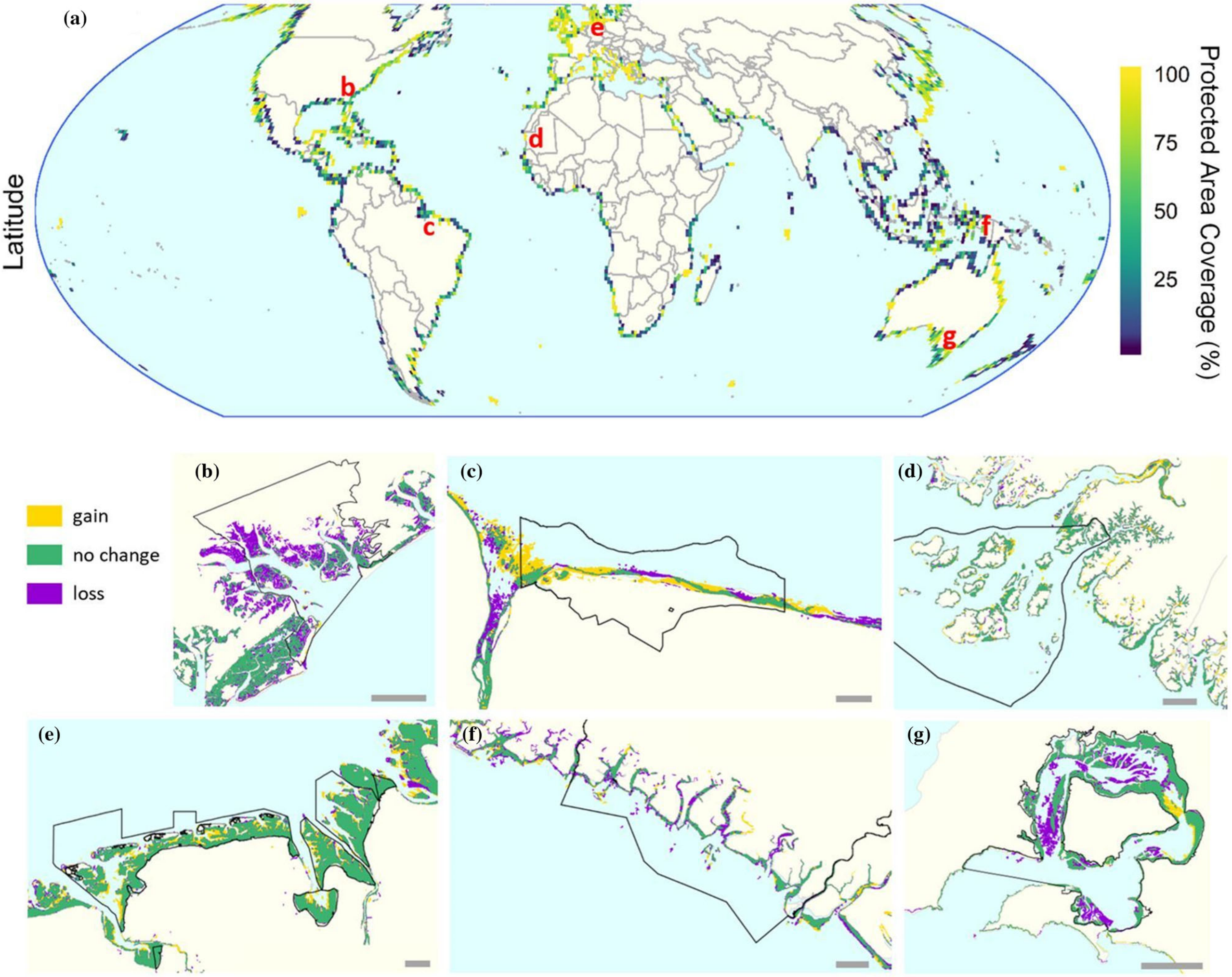

Figure 1. Global distribution of protected-area (PA) coverage of tidal extent (2014–2016) and net change in tidal extent (1999–2016) in protected areas: (a) PA coverage of tidal flats (0–100%) per 1° pixel (from purple, low, to yellow, high coverage; 1 ° resolution), (b) loss of inland tidal flats (net loss 62 km^2) in Ashepoo-Combahee-Edisto Basin PA, South Carolina (U.S.A.), (c) increase in tidal flat extent (net 80 km^2) across the river mouth and coastline in the Bigi Pan Multiple Use Management Area, Suriname, (d) increase in tidal flat extent (net 115 km^2) around the islands of the nationally and internationally protected Bijago Archipelago, Guinea Bissau, (e) increase in tidal flat extent in Lower Saxon Wadden Sea National Park, Germany (net 234 km^2, largest increase in any PA from 1999 to 2016), (f) loss of tidal flat extent (net 60 km^2) in Taman National Park, Indonesia, (g) tidal flat extent loss (net 60 km^2) in the Ramsar Wetland of International Importance, Western Port, Australia (purple, loss; yellow, gain; green, no change from 1999 to 2016; gray bar is scale, 10 km).

Results

Protected-Area Coverage of Tidal Flats

Our study extent contained 89.7% of the global PA estate and contained or intersected 196,507 of the 217,632 PAs implemented before 2017, with 10,582 of these PAs intersecting the 2014–2016 tidal extent. Current PA coverage of tidal flats was 31.4%, far surpassing the terrestrial (13.3%) and marine (5.7%) realms (Figs. 1a & 2a). Despite high coverage of tidal flats globally, 52 of 178 countries had inadequate coverage based on the Aichi targets (<10%) (Fig. 3; Appendices S3 & S4). These countries ranged from those with low tidal flat extent (min. Syria 0.32 km^2, 0% protection) to those with extensive tidal flats (max. Myanmar 3316 km^2, 0.64% protection) (Fig. 3; Appendices S3 & S4). Shortfalls in coverage were also evident across broader regions, such as East and Southeast Asia, central and eastern Africa, parts of South America, the Gulf of Aden, and numerous small Pacific island nations (Figs. 1a & 3). Countries,

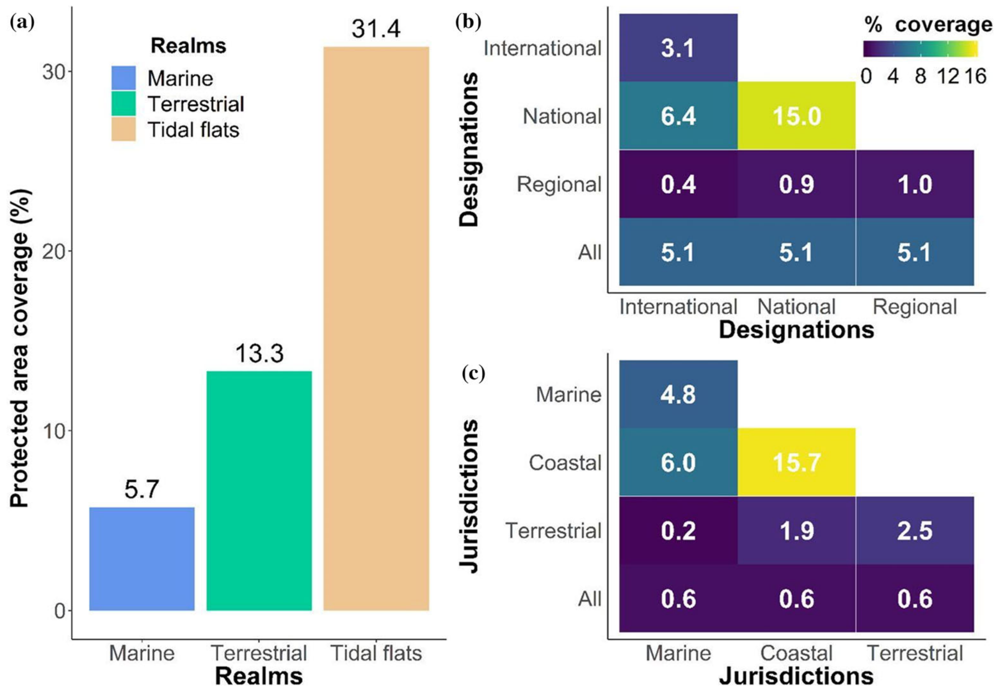

Figure 2. (a) Total percent protection of tidal flats across 3 realms between 60° north and 60° south, (b) percent protection of global tidal flats accounting for overlap within protected-area (PA) designation types, and (c) percent protection of global tidal flats by jurisdiction. In (b) and (c), colors represent percent protection (low, purple, to high, yellow). Summing all values for a single PA type in a matrix (e.g., all international values) gives the total percentage of global tidal flats covered by that PA type (e.g., international PAs cover 15.0% of global tidal flat area).

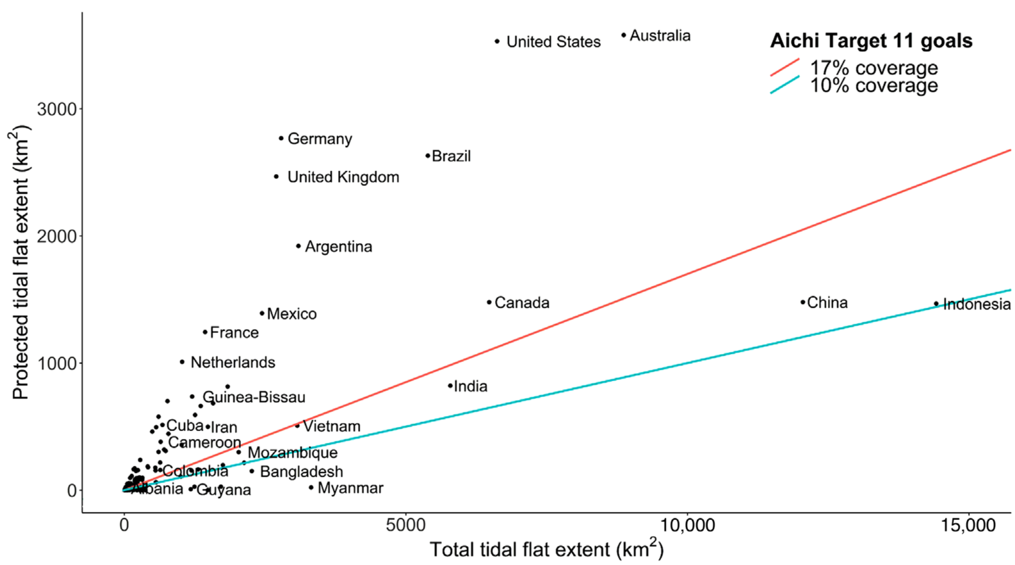

Figure 3. Total area and protected area (PA) (2014–2016) of tidal flats by country (lines, PA coverage goals specified by Aichi Biodiversity Target 11; blue, 10% coverage goal for marine and coastal areas; red, 17% coverage goal for terrestrial and inland water areas).

such as Vietnam, India, China, Russia, and Indonesia, had > 10% of mapped tidal flats within PAs, but this coverage was lower than most other high-extent countries (Figs. 1a & 3; Appendices S3 & S4). Overall, countries with strong governance (such as Australia, Japan, western European countries, Canada, and the United States) (Figs. 1a & 3) had higher coverage as evidenced by the positive correlation between country-level PA coverage and governance ($\beta = 0.429$ [SE 0.001], $p < 0.0001$) (Appendix S5).

All PA designations and jurisdictions contributed to tidal flat coverage (Figs. 2b & 2c), but most coverage was provided solely under national designation (15.0% of total tidal flat extent) and coastal jurisdiction (15.7%) (Figs. 2b & 2c). Individual contributions by international (3.1%), regional (0.4%), marine (4.8%), and terrestrial (0.2%) PAs contributed relatively little to the coverage of tidal flats (Figs. 2b & 2c). There was substantial overlap among PA types (Figs. 2b & 2c): 12.5% overlap between designations and 8.5% between jurisdictions (Figs. 2b & 2c). Although national and coastal PAs principally contributed to tidal flat coverage in nonoverlapping regions, all other PA types contributed most of their coverage in regions of overlap (Figs. 2b & 2c). The IUCN management category IV provided the highest coverage (6.7%) followed by VI (5.7%), II (5.3%), and V (4.2%) (Appendix S6). Internationally protected and other PAs contributed more coverage (4.9% and 3.5%, respectively) than categories Ia (0.9%), Ib (0.6%), and III (0.2%) (see Appendix S7 for further discussion).

Human Pressure

Less than 9% of tidal flats were free from human pressure ($HM_c = 0$) and were mostly restricted to remote areas in Canada (Supporting information). More than two-thirds of tidal flats were exposed to low ($HM_c > 0$–0.1) to moderate ($HM_c > 0.1$–0.4) human pressure, 24% and 48%, respectively (Appendix S8). We found that some of the world's largest deltas—including the Wadden Sea in Germany, Nemunas Delta in Lithuania, and the Mekong Delta in Vietnam—exist in close proximity to moderate human pressure (Appendix S9). The remaining 21% of tidal flats faced high ($HM_c > 0.4$–0.7; 18%) and very high ($HM_c > 0.7$–1; 3%) human pressure, primarily concentrated in Europe, the Yellow Sea, and from Cote D'Ivoire east to Nigeria (Appendix S9). Coverage of tidal flats exceeded the global average of 31.4% in areas facing low ($HM_c > 0$–0.1, 40.3%) and the lowest interval of moderate ($HM_c > 0.1$–0.2, 32.4%) human pressure (Fig. 4a). All other HM_c intervals, representing more than half of the world's tidal flats (56.2%), fell below the global average (Figs. 4a & 4b); the HM_c intervals with the lowest coverage were > 0.7–0.8 and > 0.8–0.9 (19.7% and 16.8%, respectively). Countries with expansive tidal flats and relatively low coverage (e.g., Myanmar and Bangladesh) often contained tidal flats in moderate to very high human pressure areas (Fig. 1a & Appendix S9).

Tidal Flat Loss Within Protected Areas

From 1999 to 2016, tidal flat extent did not significantly differ within the PA network (3.2%, 95% CI −2.7% to 9.5%) compared with outside the PA network (−1.3%, 95% CI −7.0% to 4.7%). Our analysis of individual PAs showed that the percentage of PAs that experienced net loss (e.g., Figs. 1b, 1f, & 1g) and net gain (e.g., Figs. 1c–e) were similar (51.6% and 48.4% respectively), but that average gains of 1.8 km^2 (1.78−1.89 km^2, 95% CI <0.01–240.6 km^2) were greater than average losses of 0.9 km^2 (0.85–0.91 km^2, 95% CI < 0.01–89.0) (Appendix S10). Furthermore, a greater number of PAs experienced large-scale (> 50 km^2) net gain than loss ($n = 24$ [95% CI 24] and $n = 8$ [95% CI 7, 8], respectively) (Figs. 1b–g & Appendix S10).

Discussion

This study provides the first assessment of PA coverage of tidal flats globally. We discovered that 92% of the world's tidal flats are proximal to human pressure ($HM_c > 0.0$), with over two-thirds proximal to moderate or higher pressure. However, PA coverage of tidal flats far exceeded that of marine and terrestrial realms and more than met Aichi Biodiversity Target 11, being similar to the coverage of coral reefs (32%) and mangroves (36%) (Millennium Ecosystem Assessment 2005; Spalding et al. 2014). Protected-area coverage was unevenly distributed across the human pressure gradient. Coverage of tidal flats in moderate to very high pressured areas ($HM_c = > 0.2$–1.0, range = 16.8–29.2%) fell below the global average (31.4%) and was particularly low in East and Southeast Asia (12.3% tidal extent in PAs of $HM_c = 0.0$, > 0.2–1.0), where the recent rapid loss of tidal flats has occurred (MacKinnon et al. 2012; Murray et al. 2014). Collectively, our results highlight encouraging progress, but also a suite of factors that may impact effective, coordinated management of the coastal zone and the capacity of PAs to prevent tidal flat loss.

Spatial Biases in Global Protected-Area Coverage

Protected areas are frequently placed in locations of low human pressure because they hold lower economic value (e.g., Pressey & Tully 1994; Joppa & Pfaff 2009), and it appears that tidal flats are not exempt from this bias. Tidal flats in areas of high and very high human pressure that had high PA coverage were typically in developed countries with high governance scores where extensive historic losses had already occurred (e.g., Japan [Akiko & Okamoto 2008] and England [Foster et al. 2014]), whereas countries with lower governance scores, such as India (> 0.05%) and Nigeria (> 0.05%), had minimal to no coverage of tidal flats exposed to high and very high pressure. Tidal flats subject to upper-moderate human pressure ($HM_c > 0.2$–0.4) were also relatively poorly protected and comprised more than one-quarter of the total global extent of tidal flats. These findings highlight the shortcomings of uniform percentage targets that do not account for representation of human pressure, biodiversity, or other factors (Pressey & Tully 1994; Joppa & Pfaff 2009; Ma et al. 2019).

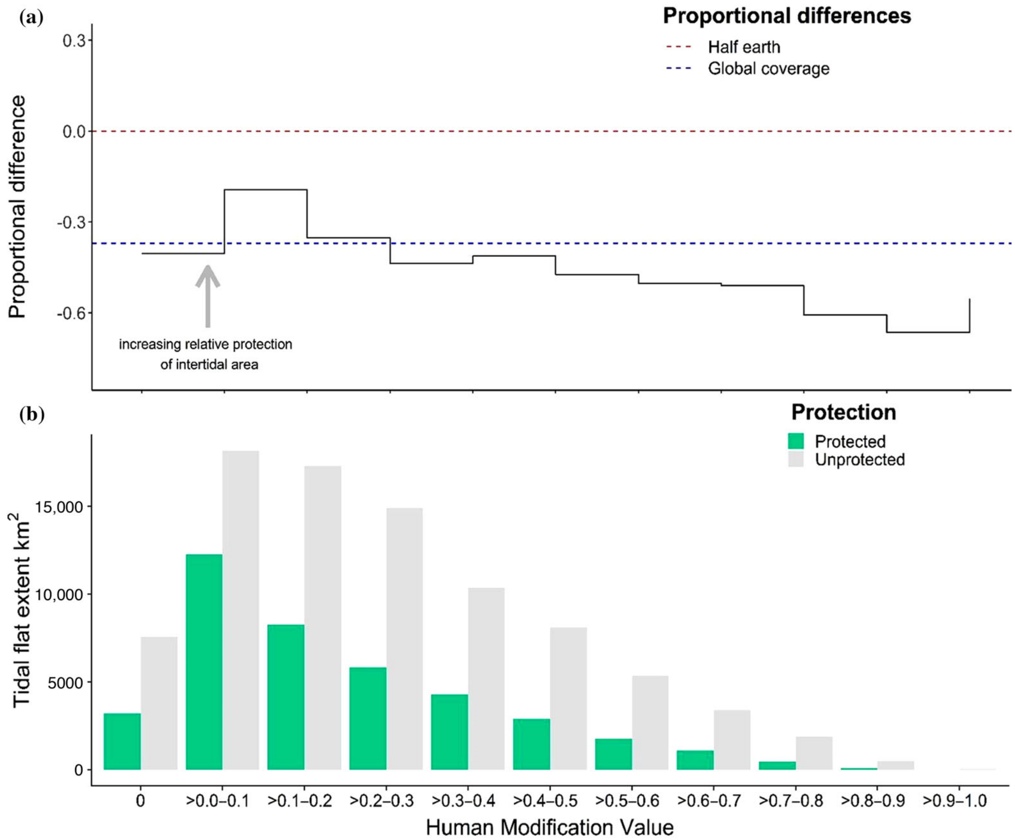

Figure 4. Global tidal flat protected-area (PA) coverage across the human pressure gradient for 2014–2016 (a) proportional differences (see methods for calculations) in tidal flat protected-area (PA) coverage across the human pressure gradient (i.e., values of human modification index that range from no human pressure [0.0] to very high human pressure [1.0]) (above dashed blue line, higher levels of coverage compared with global percent tidal flat coverage [> 31.4%]; values below blue line, lower levels of coverage [<31.4%]; dashed red line, 50% PA coverage of tidal flats; gray arrow, direction of increasing relative coverage of tidal flats) and (b) distribution of tidal flats across the human pressure gradient as represented by human modification index values (gray bars, unprotected tidal flat; green bars, protected tidal flat).

Consequently, the overall high coverage of tidal flats may be a misleading indicator of the PA network's ability to protect tidal flats from contemporary human pressures.

Protected Area Composition and Implications for Management

High national and coastal PA coverage suggests that countries act as the primary stewards of tidal flats. However, not all countries performed equally when it came to tidal flat coverage. Our results suggest that countries with strong governance may be more likely to progress toward coverage targets, although options for achieving such progress will vary. For instance, Syria could protect 100% of its tidal flats (0.32 km^2) through 2 small PAs, whereas a country, such as Bangladesh (2262 km^2), would require multiple PAs and complex strategic planning to attain even a representative 10%. Although countries act as the primary stewards of tidal flats, the relatively high international PA coverage (14.9%) highlights the transboundary significance of tidal flat ecosystems and suggests that increased coverage could also be achieved through alternative forms of habitat protection, such as special management zones.

Overlap between PA designation and jurisdiction types suggests the potential for conflicting management goals (Margules & Pressey 2000; Dhanjal-Adams et al. 2016). Overlapping PAs of different jurisdictions or designations may compete for funding, undertake conflicting management actions, or inefficiently use their resources (Deguignet et al. 2017). Furthermore, the narrowness and position of the coastal zone between realms presents the situation that neither marine nor terrestrial PAs were developed to prioritize tidal flat conservation (Dhanjal-Adams et al. 2016). Alternatively, jurisdictional overlap affords the opportunity for coordinated landscape-level management and could provide additional benefits to tidal flat protection if all jurisdictions make a concerted effort to protect these areas (Stoms et al. 2005; Dhanjal-Adams et al. 2016).

Suitability of Protected Areas for Tidal Flat Ecosystems

Despite a net loss (Murray et al. 2019), we found no significant difference between tidal flat net change inside compared with outside the PA network from 1999 to 2016. Because the complex dynamics of tidal flats can result in large distributional shifts over relatively short times, net tidal flat loss could be due to movement outside of PA boundaries driven by natural coastal dynamics (Murray et al. 2019). Additional explanations for tidal flat loss inside PAs include that implementation alone does not necessarily lead to effective management (e.g., Carranza et al. 2014); PAs may not be sufficient to manage off-site threats, such as reduced sediment flow from upstream damming (Stoms et al. 2005; Pressey et al. 2007); PAs may slow, rather than stop, loss of tidal flats (e.g., Selig & Bruno 2010); and some protected areas may not be designed for habitat protection (e.g. cultural world heritage; UNESCO 2019).

Given that tidal flats span diverse ecological and sociopolitical contexts (Leverington et al. 2010; Ma et al. 2019), it is likely that all of these factors contribute to losses inside PAs. This raises the question of whether PAs are equipped to preserve the extent of such dynamic habitats, where drivers of change may often originate outside the PA (e.g., Pressey et al. 2007). Protected area implementation affects the function as well as the extent of habitat, so an assessment of tidal flat health and the ecosystem services they provide, both inside and outside of PAs, is needed to fully understand drivers of tidal flat change and to identify and prioritize methods for their protection.

Limitations

Due to inconsistent collection and consolidation of Landsat imagery, our results for change in tidal flat extent in PAs are limited to assessable areas (North America and Europe). Nonassessable regions include primarily South America, Asia, Africa, and Oceania, where losses of tidal flats within PAs are known to be ongoing (e.g., Appendix S11; Geldmann et al. 2019; Anderson & Mammides 2020). Although our work presents a snapshot of tidal extent net change inside and outside of PAs, analysis of PA effectiveness (with appropriate counterfactuals) and trends in tidal flat extent in individual PAs—based on the full suite of global tidal flat maps available—would provide a more detailed picture of how tidal flats are influenced by PAs. Lastly, a global pressure map for coastal ecosystems is needed. Although the human modification map (Kennedy et al. 2019) and Halpern et al.'s (2008) global map of human impact on marine ecosystems—a composite map of remotely sensed pressures on the world's oceans—together provide global pressure coverage, their composite scales are incompatible and neither fully encompasses coastal ecosystems, which are susceptible to both terrestrial and marine pressures. For this reason, there is a need for a global assessment of coastal pressures, especially because these ecosystems are highly valued and protected yet continue to be degraded and lost (Millennium Ecosystem Assessment 2005; Spalding et al. 2014).

Beyond Protected Areas

Although tidal flats have high PA coverage, our results suggest that PAs alone are unlikely to be enough to prevent ongoing losses within their boundaries. Although shifting or replacing underperforming PAs to match changing tidal flat extents could improve performance, this would likely conflict with other management goals and be expensive to maintain (Fuller et al. 2010; Alagador et al. 2014). Additionally, implementing PAs large enough to encompass entire tidal flat systems could yield positive conservation outcomes, but requires significant funding and strategic planning (Bruner et al. 2004; Watson et al. 2014). Targeting PAs to key habitats and processes that result in tidal flat increases as well as areas at greatest risk of loss could be worthwhile, but a greater understanding of natural tidal flat dynamics is needed before this approach could be put into action (Duarte et al. 2008). Another approach is to implement integrated coastal zone and catchment management across interacting components of the marine, coastal, and terrestrial realms (Salm et al. 2000; Millenium Ecosystem Assessment 2005; Stoms et al. 2005). Integrated management focuses on the preservation of ecosystem processes, rather than piecemeal approaches that treat PAs as closed ecological systems, and explicitly aims to address off-site threats (MacKinnon et al. 2012; Miththapala 2013). When implemented effectively, integrated coastal zone management can achieve better outcomes than nonintegrative approaches (Zagonari 2008; Day et al. 2015), and landscape-scale conservation can increase the benefits and resources provided by ecosystems (Hodder et al. 2014).

Our results provide a starting point to help direct conservation efforts toward forming a more comprehensive PA network for tidal flats. Individual countries, as the primary stewards of this ecosystem, will need to lead the way in evaluating current management actions, employing innovative and integrative management strategies, addressing spatial biases in PA placement, and enacting protective policy to effectively preserve tidal flats.

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Supporting Information

Additional information is available online in the Supporting Information section at the end of the online article. 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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