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Creation of a high spatio-temporal resolution global database of continuous mangrove forest cover for the 21st century (CGMFC-21)

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ABSTRACT

Aim To provide high-resolution local, regional, national and global estimates of annual mangrove forest area from 2000 through to 2012 with the goal of driving mangrove research questions pertaining to biodiversity, carbon stocks, climate change, functionality, food security, livelihoods, fisheries support and conservation that have been impeded until now by a lack of suitable data.

Location Global, covering 99% of all mangrove forests.

Methods We synthesized the Global Forest Change database, the Terrestrial Ecosystems of the World database and the Mangrove Forests of the World database to extract mangrove forest cover at high spatial and temporal resolutions. We then used the new database to monitor mangrove cover at the global, national and protected area scales.

Results Countries showing relatively high amounts of mangrove loss include Myanmar, Malaysia, Cambodia, Indonesia and Guatemala. Indonesia remains by far the largest mangrove-holding nation, containing between 26% and 29% of the global mangrove inventory with a deforestation rate of between 0.26% and 0.66% per year. We have made our new database, CGMFC-21, freely available.

Main conclusions Global mangrove deforestation continues but at a much reduced rate of between 0.16% and 0.39% per year. Southeast Asia is a region of concern with mangrove deforestation rates between 3.58% and 8.08%, this in a region containing half of the entire global mangrove forest inventory. The global mangrove deforestation pattern from 2000 to 2012 is one of decreasing rates of deforestation, with many nations essentially stable, with the exception of the largest mangrove-holding region of Southeast Asia. We provide a standardized spatial dataset that monitors mangrove deforestation globally at high spatio-temporal resolutions. These data can be used to drive the mangrove research agenda, particularly as it pertains to monitoring of mangrove carbon stocks and the establishment of baseline local mangrove forest inventories required for payment for ecosystem service initiatives.

Keywords
Blue carbon, carbon emissions, GIS, mangrove deforestation, payments for ecosystem services, remote sensing

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INTRODUCTION

A systematic global mangrove database with high spatio-temporal resolution is lacking. Without such a database, research into mangrove functionality is on a weak empirical footing. The majority of historical estimates of mangrove cover are snapshots that used aggregated data from regional or national studies. For example, the Food and Agriculture Organization of the United Nations (FAO) regularly compiles snapshots of mangrove cover at the national scale. Many of the data in these reports are single estimates of national mangrove cover that propagate through each subsequent report and across reports. Such reports have proven important to the mangrove research community in depicting historical mangrove cover and loss but do not meet the requirements of the current mangrove research agenda, which requires a global mangrove database with high spatio-temporal granularity. For example, when conducting a literature search of historical estimates of mangrove cover in Malaysia, Friess & Webb (2011) noted that the mangrove data estimates were highly variable, resulting in high amounts of uncertainty when compiling trends of mangrove loss over time. The three major issues causing this uncertainty are stated as being: a lack of reporting of the actual method of calculating mangrove cover, particularly in the grey literature in which mangrove cover analyses often reside; a lack of traceability of data points that comprise a study; and problematic data assumptions often due to sampling of mangroves or assumptions on the unverifiable temporal axis of a study (Friess & Webb, 2011).

Mangrove atlases provide an additional source of information on global mangrove cover (e.g. Spalding *et al.*, 1997, 2010) and generally provide information on mangrove cover at the national scale. Such atlases provide important informa-

tion on mangroves, particularly mangrove species information and the local situation of mangrove forests. Other mangrove estimates often refine either these atlas datasets or the FAO data. Using FAO and other national estimates it is notable that conflicting trends in mangrove change can exist across different data sources, within the same data sources and across such significant mangrove-holding nations as Indonesia, Brazil and the Philippines (Friess & Webb, 2014) as well as in Mexico (Ruiz-Luna *et al.*, 2008). Studies into mangrove biodiversity, mangrove functionality, mangrove carbon stocks and mangrove conservation are hindered by the conflicting trends found across these datasets (Friess & Webb, 2014). Indeed, such conflicting information hampers policy decisions not only for issues related to mangroves (Friess & Webb, 2011) but also for other forest types globally. Table 1 depicts this problematic variability within global mangrove estimates (Lanly, 1982; FAO, 1995, 1997, 2000, 2003, 2005, 2007, 2010). Depending on the datasets used, global mangrove forest cover can be represented as an increasing trend from 1980 to 2005, a decreasing trend from 1980 to 2005 or a variable trend.

Global remotely sensed products overcome many of the caveats of national estimates from government organizations by utilizing a systematic approach to mangrove mapping of all nations. Despite this, all pre-existing remotely sensed products are lacking either the spatial resolution, temporal resolution or the required mangrove classification to adequately fill the identified data gap. For example, global land-cover products such as GlobCover are at a resolution of 300 m, lack a mangrove classification and have only two coverage dates post-2000. The MODIS land-cover classification products are annual but also at a coarse 250-m resolution with no mangrove classification. GLC 2000 does contain a 'tree cover, regularly flooded, saline water' classification, but the resolution is a coarse 1-km grid and again offers a single snapshot. The

Table 1 Global mangrove area estimates in km^2 by year and author. The mangrove area estimates within each decade are highly variable

ID no.	Source	Reference year	No. of countries	Mangrove area (km^2)
1	FAO (2007, p. 9)	1980	Global	187,940
2	Lanly (1982, p. 43)	1980	76	154,620
3	Saenger *et al.* (1983, pp. 11–12)	1983	66	162,210
4	FAO (2004, Table 2.3)	1980–85	56	165,300
	1980s mean (sources 1–4)			167,518
5	FAO (2007, p. 9)	1990	Global	169,250
6	Groombridge (1992, pp. 325–6)	1992	87	198,478
7	ITTO & ISME (1993, p. 6)	1993	Global	141,973
8	Fisher & Spalding (1993, p. 11)	1993	91	198,817
9	Spalding *et al.* (1997, p. 23)	1997	112	181,077
	1990s mean (sources 5–9)			177,919
10	Spalding *et al.* (2010, p. 6)	2000–01	123	152,361
11	FAO (2007, p. 9)	2000	Global	157,400
12	Aizpuru *et al.* (2000; secondary source)	2000	112	170,756
13	Giri *et al.* (2011, p. 156)	2000	Global	137,600
14	FAO (2007, p. 9)	2005	Global	152,310
	2000s mean (sources 10–14)			154,085

Mangrove Forests of the Word (MFW) Landsat-based mangrove database overcomes many of these obstacles, creating what the authors state is, 'the most comprehensive, globally consistent and highest resolution (30 m) global mangrove database ever created' (Giri et al., 2011 p. 154).

MFW advanced mangrove mapping by providing a systematic approach to mapping mangrove cover across all nations, thus allowing for local, regional, national and global analysis of mangroves in the year 2000. Despite this, MFW and similar global mangrove measurement models have two major limiting factors. Firstly, they lack a systematic temporal mangrove measure, as they are one-time snapshots of historical mangrove cover. Secondly, the actual measurement of mangrove at the mapping unit is presence or absence and does not report the actual amount of mangrove cover at each location. This may be important, as mangrove forests are often fringe forests located at the terrestrial–water interface with a high likelihood that not all of the pixel area classified as mangrove may be mangrove forest. Indeed, although a mangrove stand may consistently exist over time at the pixel scale, it has been noted that the quality of the mangroves may be degraded due to pollution, grazing or oil spills, and a presence or absence approach to mangrove mapping is unlikely to capture such degradation (FAO, 2007).

Although categorical presence and absence data are the most common form of remotely sensed forest mapping (DeFries et al., 1995; Bennett, 2001), it is noted such data may not represent the forest heterogeneity that may be present (DeFries et al., 1995) and additionally may not accurately represent true forest canopy cover (Asner et al., 2005). The continuous measure approach used in this paper probably has its highest utility when used in forest-based payment for ecosystem services (PES) programmes, such as those targeted to reduce emissions from deforestation and forest degradation (REDD) which often only use forest presence or absence measures without accounting for forest degradation over time. Indeed, it is notable that current remote sensing products are not adequate to capture the spatial variability required to produce accurate forest carbon maps (Asner et al., 2010). In addition to systematic and annual mapping of mangrove forest, we use a percentage tree-cover approach to mangrove mapping as opposed to mapping based on presence or absence. That is, we report the likely amount of mangrove present at the minimum mapping unit as opposed to presence or absence of mangrove. By doing this we can capture measures of mangrove degradation and adjust for mangrove area in fringe pixel situations. The percentage cover approach is more relevant than categorical mapping methods when the mangrove analysis is concerned with measurements of standing biomass or carbon stocks as opposed to measuring of biodiversity or habitat when the actual amount of pixel cover may be less important.

Despite the lack of a robust post-2000 mangrove change database, concern over mangrove deforestation is well elucidated in the recent literature, with numerous mangrove change studies at the global, national and local scales (e.g.

Satapathy et al., 2007; Hamilton, 2013). Knowledge of the economic value of mangroves to ecosystem services has existed for some time (e.g. Barbier & Cox, 2004; Barbier, 2006), with much of the literature concerned with how mangroves support fisheries (e,g, Chong, 2007; Lugendo et al., 2007). Despite the important ecological services role of mangrove forest, it is in the realm of climate change that mangrove research has come to the forefront of the land-use change literature in recent years. Mangrove forests have been shown to contain some of the largest forest carbon sinks per hectare of any forest type globally (Bouillon et al., 2008; Donato et al., 2011), including substantial carbon stored below ground in mangrove soil (Donato et al., 2011; Murdiyarso et al., 2015). Therefore, mangrove deforestation probably releases more CO_2 per hectare than deforestation of any other forest type. Indeed, work is under way on placing economic value on the carbon stored in mangrove forests (Siikamäki et al., 2012), adding substantially to the potential economic value of preserved mangroves.

An emerging issue in the mangrove and wider forest research community is the inability of current forest databases to set baseline reference scenarios for PES schemes such as national-scale REDDS projects (Angelsen et al., 2012). As Table 1 indicates, utilizing FAO estimates as the baseline for REDD forest programmes could result in highly unsatisfactory mangrove monitoring and evaluation. Yet, it is FAO data that are most often used in studies concerned with the establishment of REDD baselines (e,g, Griscom et al., 2009a,b; Huettner et al., 2009) and compatibility with FAO data is often viewed as a prerequisite of any potential REDD measure (Huettner et al., 2009). A realization that the degradation portion of REDD is omitted within the FAO data does exist within the literature (Griscom et al., 2009b). Yet, the suitability of such datasets for PES analysis appears to be mostly unaddressed, despite the realization that such data have profound implications, up to and including the mechanisms for national participation in future climate change treaties (Angelsen, 2008).

The recently released Global Forest Cover (GFC) database (Hansen et al., 2013) has the potential to overcome many of the limitations of traditional mangrove estimates. It contains annual data from 2000 to 2012, as well as containing percentage tree cover at the minimum mapping unit. Unfortunately, this dataset does not distinguish between forest types (Tropek et al., 2014). To overcome this issue, synthesis with other datasets that define land cover at similar spatial resolutions is required. We propose synthesizing MFW with the GFC and Terrestrial Ecosystems of the World (TEOW) databases to monitor the change in mangrove forest since 2000 at a high spatial resolution.

Global forest cover

The GFC dataset provides the best highest resolution map of forest cover yet produced (Hansen et al., 2013). It uses over 650,000 Landsat images to map the change in global forest

cover at yearly intervals from 2000 to 2012. The dataset allows forest loss and forest gain to be measured against a baseline of year 2000 forest cover. The dataset estimates total forest loss between 2000 and 2012 to be approximately 2.3 million km^2, with gains offsetting approximately 800,000 km^2 of these losses (Hansen et al., 2013). Although not explicitly defined in the data, almost all mangrove forest cover apart from juvenile mangrove forests and forests consisting wholly of mangrove scrub is probably captured.

The GFC database and methodology have been criticized for not differentiating between native forest and forest plantations and ignoring the ecological role of forests. For example, it has been noted that plantation forests that displace indigenous or other more diverse forest types (such as oil palm in Ecuador, soybean in Brazil or banana in the Philippines) are given the same weight as traditional forest cover in the non-discriminatory GFC analysis (Tropek et al., 2014). This critique, although valid from an ecological perspective, is unlikely to alter the mangrove data implicitly embedded in the database unless other forest types that reach a height of 5 m within the analysis period have displaced mangrove. Although displacement by forest plantations may be possible in drainage situations or at the terrestrial interface of mangrove forest, such displacement by plantation or other forests has not been documented in the global mangrove deforestation literature that mostly attributes mangrove deforestation to displacement by aquaculture or urban expansion (Hamilton, 2013). Indeed, the integration of data with other sources is proposed as a means of overcoming the critique noted above (Hansen et al., 2014) and this is the approach taken in this paper. This dataset provides the primary database used to delineate mangrove forest area.

Mangrove forests of the world

MFW delineates mangrove forest cover globally for the year 2000 at the same resolution as GFC. MFW processes over 1000 Landsat scenes using a hybrid unsupervised and supervised classification approach (Giri et al., 2011). It does not attempt to depict forest change over time but does provide a one-time global snapshot of mangrove forest cover in the year 2000. As opposed to the continuous tree-cover approach, MFW provides mangrove presence or absence data at the minimum mapping unit of 1 ha. This dataset is most suitable for mangrove analysis concerned with actual tree cover such as calculations of above- and below-ground biomass and estimations of carbon stocks. When combined with GFC, this database potentially provides a solution to the inherent issues related to establishing forest baselines for PES programmes such as REDD. This dataset provides the second database to help delineate mangrove forest cover in this paper.

Terrestrial ecoregions of the world

TEOW is an integrated map product developed over 10 years that delineates 825 global ecoregions, nesting them within 14 biomes and 8 biogeographical realms (Olson et al., 2001).

Olson et al. (2001, p. 933) defined ecoregions as follows: "Ecoregions are relatively large units of land containing distinct assemblages of natural communities and species, with boundaries that approximate the original extent of natural communities prior to major land-use change". The ecoregion framework presented has become one of the foundational geospatial layers used in biodiversity and conservation. As opposed to other land-cover/land-use designations, this dataset explicitly delineates the mangrove ecosystem as a unique biome in their dataset. Although the mangrove biome does not necessarily mean mangrove is present, in combination with other datasets the depiction of whole-system mangrove biome forest transition can be analysed for changes in canopy cover. This dataset provides the third database for delineating mangrove forest area, including tree loss and gain within the entire mangrove biome.

The database produced in this paper is a combination of GFC, MF and TEOW. The resolution of the mangrove data presented in this analysis is 0.00027777°, or approximately 30 m, with a measure of mangrove forest cover provided at each minimum mapping unit. Our presented dataset probably has the highest spatial resolution, the highest temporal resolution and the highest attribute resolution of all global mangrove datasets and allows for systematic mangrove analysis at global, continental, country, region, estuary or even individual study area scales. Despite the importance of establishing trends of mangrove loss, it is not in the analysis of mangrove change that these data provide the most utility but in driving research into questions related to mangroves – biomass, carbon stocks, functionality, food security, biodiversity, livelihoods and fisheries support – that have been hindered until now by a lack of suitable data.

MATERIALS AND METHODS

To create our Global Database of Continuous Mangrove Forest Cover for the 21st Century (CGMFC-21) we synthesized the GFC database (Hansen et al., 2013), the MFW database (Giri et al., 2011) and the TEOW database (Olson et al., 2001) in conjunction with other ancillary datasets to produce global mangrove forest cover measures for 2000 to 2012, and estimates for 2013 and 2014.

The first step in the process was to calculate year 2000 mangrove cover globally. To achieve this vector MFW was converted back into its native resolution of 0.00027777° for all locations; this resulted in a raster layer of year 2000 mangrove cover with an attribute of presence or absence. During this process, pixel alignment was enforced with GFC. Both MFW and GFC use the same native pixel size so no resampling was required. We then extracted all of the year-2000 tree-cover pixels that overlaid the year 2000 mangrove defined area. This resulted in only pixels that had been determined to have mangrove in the year 2000. After pixel extraction, each pixel was given an additional attribute of area in metres squared based on the percentage tree cover present. This area calculation was achieved by applying a latitudinal correction

to each pixel based on the spherical law of cosines. This was preferable to other methods as it avoided computationally expensive reprojection and the data maintain their original coordinate system. Additionally, it avoided the pixel averaging and estimating that would have resulted during data reprojection. The final step was to apply the percentage tree-cover value to each pixel. For example, if the pixel was determined to be 900 m^2 in size and it had 50% mangrove tree cover then the pixel was given a mangrove value of 450 m^2.

Once year 2000 mangrove cover was established, GFC was queried for loss in 2001, and each loss pixel was converted into area using the methods outlined above. Pixels that had been deforested during 2001 were then integrated into the 2000 mangrove dataset to produce the 2001 dataset. This was repeated for all years from 2001 to 2012, with the preceding year becoming the baseline mangrove cover layer for establishing loss for the following year. This resulted in 13 mangrove datasets (one for each year) at 0.00027777° resolution (approximately 30 m in the tropics) for all areas that had mangrove present in the year 2000. The 0.00027777° global data for each year were then aggregated to the national scale with any mangrove falling outside of national boundaries being allotted to the closest nation while remaining in its actual location.

The second measure of forest change focuses on forest cover in the entire mangrove biome, as opposed to a stricter definition of verified year 2000 mangrove forests. TEOW was rasterized to 0.00027777° for all locations; this resulted in a raster layer depicting the entire mangrove biome in addition to locations with mangrove known to exist during the year 2000. During this rasterization process, pixel alignment was again enforced to comply with GFC. We then extracted all of the year 2000 GFC tree-cover pixels that overlaid the mangrove biome pixels. This resulted in only pixels that are located within the mangrove biome or had mangrove in 2000. Again, the continuous pixel value was converted into area using a latitude adjustment grid and mangrove loss was burned into each pixel for subsequent years. As opposed to MFW, areas within the TEOW mangrove biome that had experienced a gain of mangrove forest were additionally added to the dataset. This mangrove measure is best described as monitoring forest change that has occurred in all areas of the mangrove biome, even those outside delineated mangrove forests. This layer allows for monitoring of mangrove growth that may have occurred outside areas that had no historical mangrove cover. This dataset is most suitable for mangrove analysis concerned with biome characteristics such as habitat fragmentation and biodiversity analyses.

After compiling both the mangrove measures above and establishing the linearity of the mangrove change a simple ordinary least squares regression was performed on the national data to predict the mangrove areas for 2013 and 2014 and to bring the datasets to the present. In addition to the global mangrove areas reported by country we extracted the data for the mangrove-dominated Ramsar sites of Everglades National Park in North America, Cobourg Peninsula in northern Australia, Sundarbans National Park on the border of India and Bangladesh, Douala Edéa National Park in Cameroon on the west coast of Africa and Cayapas-Mataje on the west coast of Ecuador bordering Colombia. We additionally calculated the mangrove deforestation trend for all protected areas globally.

To test the representativeness and accuracy of the findings presented we utilized the only other approximately 0.00027777° measure of continuous forest cover available for one of the regions analysed. The USGS National Land Cover Dataset (NLCD) provides intermittent continuous tree-cover measures for the contiguous United States (Homer *et al.*, 2012). From the 2011 NLCD data, we extracted the 2,037,420 pixels within Florida that are coincident with our 2011 mangrove data. We then converted the NLCD dataset into square metres and compared the two mangrove measures for Florida. Our dataset estimates 1341 km^2 of mangrove forest cover in Florida during 2011, whereas NLCD, combined with MFW, estimates 1391 km^2 of mangrove forest cover. The 3.6% difference between the two estimates of Florida mangrove increases confidence that the data presented here are an accurate and representative depiction of continuous mangrove cover that is comparable to other remote sensing-derived continuous forest datasets. Additionally, a portion of the 3.6% disagreement is probably due to slightly differing sensor acquisition dates during 2011.

Measures of potential error are provided in Appendix S1 in the Supporting Information and a comparison between continuous and binary measures of mangrove cover are provided in Appendix S2.

RESULTS

Mangroves are located in 105 countries (Appendix S3), as well as in the special administrative areas of China (Hong Kong and Macau), the four French overseas provinces of Martinique, Guiana, Guadeloupe and Mayotte and the contested area of Somaliland. For reporting purposes Hong Kong and Macau are aggregated into China, the French provinces are aggregated into France and Somaliland is aggregated into Somalia. Omitted forests constitute less than 0.01% of the global mangrove total and are discussed in detail in Appendix S1 The top 20 mangrove-holding nations contain between 80% and 85% of global mangrove stocks and are presented in Table 2, continued to include all nations in Appendix S3.

Mangrove forests of the world (MFW) results

Our new estimate of mangrove area, within the area identified by MFW, revised for percentage cover as opposed to presence or absence, for the year 2000 is 83,495 km^2 (Appendix S3). This is a decrease of 54,360 km^2 from the 137,760 km^2 total reported by Giri *et al.* (2011). This decrease of 39% from MFW is primarily due to a differing definition of mangrove used in the two analyses and does not evidence a substantial loss of mangrove or any error by either set of authors. Such a substantial difference in area

Table 2 The top 20 mangrove-holding nations as of 2000 and their change in mangrove area from 2000 to 2014 in km^2 and percentage of the global total. The top four countries contain almost 50% of the world's mangrove forests. The full table for all nations and both methods is provided in Appendix S3.

| 2000 MFW rank | Country name | 2000 | | | | 2014 | | | |
| | | MFW | | Biome | | MFW | | BIOME | |
		km^2	Percentage	km^2	Percentage	km^2	Percentage	km^2	Percentage
1	Indonesia	24,073	28.83	46,642	26.95	23,143	28.40	42,278	25.79
2	Brazil	7721	9.25	18,168	10.50	7663	9.40	17,287	10.55
3	Malaysia	4969	5.95	8738	5.05	4691	5.76	7616	4.65
4	Papua New Guinea	4190	5.02	5982	3.46	4169	5.12	6236	3.80
5	Australia	3327	3.98	3359	1.94	3315	4.07	3314	2.02
6	Mexico	3021	3.62	6240	3.61	2985	3.66	6036	3.68
7	Myanmar	2793	3.34	4205	2.43	2508	3.08	3783	2.31
8	Nigeria	2657	3.18	6944	4.01	2653	3.26	6908	4.21
9	Venezuela	2416	2.89	7579	4.38	2401	2.95	7516	4.59
10	Philippines	2091	2.50	2115	1.22	2060	2.53	2084	1.27
11	Thailand	1933	2.32	4362	2.52	1876	2.30	3936	2.40
12	Bangladesh	1774	2.12	2317	1.34	1773	2.18	2314	1.41
13	Colombia	1674	2.01	6313	3.65	1672	2.05	6236	3.80
14	Cuba	1660	1.99	2471	1.43	1624	1.99	2407	1.47
15	United States	1612	1.93	1616	0.93	1553	1.91	1554	0.95
16	Panama	1328	1.59	2768	1.60	1323	1.62	2673	1.63
17	Mozambique	1226	1.47	2716	1.57	1223	1.50	2658	1.62
18	Cameroon	1119	1.34	1344	0.78	1113	1.37	1323	0.81
19	Gabon	1087	1.30	3929	2.27	1081	1.33	3864	2.36
20	Ecuador	938	1.12	1971	1.14	935	1.15	1906	1.16
	Total	71,608	85.76	139,777	80.76	69,761	85.61	131,931	80.48

MFW, Mangrove Forests of the Word (Landsat-based mangrove database).

between the two methods does suggest that binary pixel measures may indeed be inadequate for many mangrove analyses, such as establishing mangrove carbon stocks for REDD programmes. The difference between CGMFC-21 and nationally reported statistics compiled by the FAO (Table 1) is closer to a 50% reduction in mangrove forest cover. This is consistent with wider forest findings outside the mangrove biome in Latin America that report areas 50% smaller when using continuous remote sensing data as opposed to national estimates without remotely sensed data (DeFries et al., 2002).

Mangrove forests that existed in 2000 have decreased by 1646 km^2 globally between 2000 and 2012 (Fig. 1). This corresponds to a total loss over the analysis period of 1.97% from the year 2000 baseline. This equates to a global loss during this period of 137 km^2, or 0.16% per year. The losses appear generally consistent across the period analysed with an almost linear relationship ($r^2 = 0.99$) between year and loss.* This consistent trend with little deviation allows future trends to be reliably extrapolated from the dataset with a high amount of certainty. Extrapolated to 2014, global mangroves are estimated to cover 81,484 km^2 (Appendix S3) of the earth's surface.

Myanmar appears to represent the current hotspot for mangrove deforestation, with a rate of deforestation more than four times higher than the global average (Appendix S3). Although Myanmar has the highest rate of loss, Indonesia has by far the largest area loss. The 3.11% mangrove loss in Indonesia equates to 749 km^2 of mangrove loss and constitutes almost half of all global mangrove deforestation. The majority of this loss is occurring in the provinces of Kalimantan Timur and Kalimantan Selatan, with a distinct deforestation hotspot visible along the eastern coast of Kalimantan. Southeast Asia has experienced relatively high amounts of loss and this is of importance as this these nations contain almost half of the global mangrove area. Other countries outside Southeast Asia that have sustained significant mangrove losses as a percentage of their 2000 total include India and Guatemala. Within the Americas, Africa and Australia the deforestation of mangrove is approaching zero, with nominal rates in many countries.

Mangrove biome (TEOW) results

Mangrove loss patterns in the entire mangrove biome exhibit mostly similar patterns to the MFW loss patterns described above, but with some important differences. Mangrove biome tree cover declined from 173,067 km^2 in 2000 to

Figure 1 Global mangrove change from 2000 to 2012 with extrapolated data for 2014. Grey represents all locations with known mangrove existing in 2000 and black represents all locations in the wider mangrove biome. The x-axis is year and the y-axis is km².
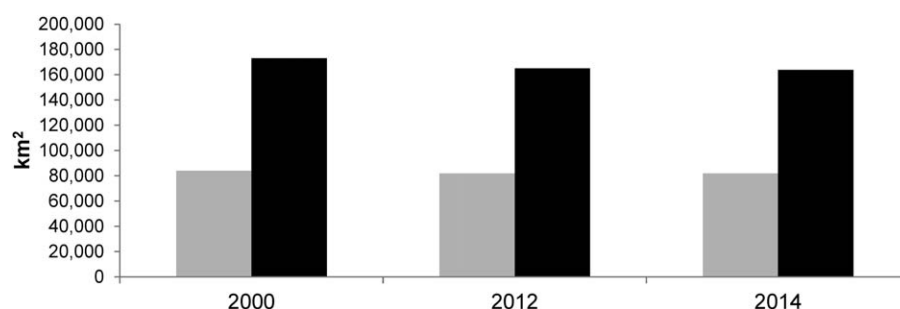
167,387 km² in 2012 (Appendix S3). We extrapolate these numbers to estimate a tree cover of 163,925 km² in 2014. The global deforestation rate in the mangrove biome from 2000 to 2012 was 4.73%, with an annual rate of loss of 0.39% (Appendix S3). This indicates that the wider mangrove biome may be under more stress than the actual trees delineated as mangrove in year 2000 by MFW. Myanmar, Indonesia, Malaysia, Cambodia and Guatemala (Appendix S3) all have relatively high levels of tree loss within the mangrove biome. Again, Southeast Asia is the region of most concern, with an average mangrove loss of 8.08% during the analysis period. Significant mangrove-holding nations such as Nigeria, Venezuela, Bangladesh and Fiji have established stable forest cover in the mangrove biome with loss rates close to zero during the analysis period.

Ramsar and protected sites

Ramsar sites and protected areas are included in the results to demonstrate the capability of our dataset to provide subnational estuarine-specific data from 2000 to present as well as important insights into the role of protected areas in conserving mangrove forests. Table 2 represents the almost negligible loss in the selected Ramsar areas, apart from the Everglades. The percentage of mangrove loss within the selected Ramsar sites is 50% lower than the global average mangrove loss (Table 3), with a mangrove loss rate of 0.08% per year between 2000 and 2012. The percentage of mangrove loss within all global protected areas as defined by the World Database on Protected Areas (IUCN & UNEP, 2013),

Table 3 Mangrove loss by Ramsar site. Mangrove loss from 2000 to 2012 in km² and percentage of 2000 mangrove area, for specific Ramsar wetlands on each continent in areas with mangrove present in 2000.

Site	2000 area (km²)	2012 area (km²)	Percentage loss
Sundarbans	197,994	197,961	0.02
Everglades	93,090	89,945	3.38
Douala Edéa	24,648	24,532	0.47
Cayapas-Mataje	14,807	14,748	0.40
Garig Gunak Barlu	11,360	11,296	0.56
Total	341,899	338,482	1.00

using the TEOW biome method, is again almost 50% lower than the global average, with annual losses of 0.21% between 2000 and 2012.

DISCUSSION

This paper has presented a systematic data synthesis approach to providing continuous measures of mangrove cover, using the highest spatio-temporal resolutions available. The designed methodology can be applied to other forest types globally, enabling relatively rapid forest change metrics at high spatio-temporal resolutions. The use of continuous data has reduced the mangrove area by approximately 40% from earlier estimates. This is not a cause for concern, as the difference is due to an enhanced measure of mangrove cover as opposed to a substantial loss in mangrove forest. Indeed, if we convert these data back to presence or absence the mangrove area is in very close agreement with other mangrove datasets at the country scale. The continuous mangrove variable used in this paper should provide an improved measure of mangrove when the concern is woody biomass, carbon storage and habitat degradation.

The post-2000 mangrove deforestation trend of between 0.16% and 0.39% per year represents a significant decrease in annual rates of mangrove loss in comparison with the proceeding decades. For example, using a synthesis of FAO data the best estimate for annual losses during the 1980s is 0.99% per year (FAO, 2007) and for the 1990s it is 0.70% per year (FAO, 2007). While still suffering a substantial decline, the reported decrease in the mangrove deforestation since 2000 doe not support the idea that gained traction in the mid-2000s that the world could be without functional mangroves within 100 years (Duke et al., 2007). Such concerns were based on extrapolated data from estimates of mangrove deforestation obtained from the 1980s and 1990s; the trends in these datasets do not appear to have continued into the 21st century.

The data presented here address the well-documented problems of establishing consistent PES baselines and provide much needed information on degradation as well as deforestation. Estimates of mangrove carbon stock, as well as the economic value placed on such carbon holdings, are enhanced by providing systematic measures of mangrove holdings at annual intervals as opposed to using latitudinal

estimates of carbon from single snapshots of mangrove cover from presence or absence data. These data provide systematic global estimates of mangrove cover as well as providing both the temporal and spatial resolution required for high-fidelity analyses of mangrove change. Additionally, the methodology provided allows researchers to develop PES baseline and degradation products at high spatio-temporal resolutions for other forest types globally.

Although global mangrove losses have slowed considerably, and can be considered static in many nations (including internationally important internationally important Ramsar sites and protected areas), this condition is not universal; Southeast Asia remains a region of concern and the discovery of Myanmar as a frontier for mangrove deforestation since 2000 requires further research. Aquaculture has expanded substantially in Myanmar since 1999 (Hishamunda et al., 2009) and this may be the driving force behind the deforestation, although rice cultivation is additionally noted as a major driver of mangrove loss in the Ayerwaddy Delta region of Myanmar (Webb et al., 2014). Indonesia remains a country of concern, with annual mangrove deforestation approximately double the global average; this equates to almost half of all global mangrove losses (Appendix S3). These data do not elucidate the cause of deforestation, and a regional analysis is required to fully account for these losses.

In summary, the global pattern of mangrove deforestation during since 2000 is one of a decreasing rate of deforestation; many nations are essentially stable, with the exception of the largest mangrove-holding nations of Southeast Asia. Although the global, national and regional mangrove holdings reported in this paper are significant to the wider research community, including those interested in climate change, it is with the presentation of a global, systematic, continuous, annual, high-resolution mangrove dataset that this research has the most utility. Researchers studying such important mangrove-related issues as fisheries, conservation, CO_2 emissions, carbon sequestration and livelihoods now have access to the data required to undertake robust analyses into these important mangrove research questions.

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REFERENCES

Aizpuru, M., Achard, F. & Blasco, F. (2000) Global assessment of cover change of the mangrove forests using satellite imagery at medium to high resolution. EEC Research Project no. 15017-1999-05 FIED ISP FR. Joint Research Center, Ispra, Italy.

Angelsen, A. (2008) REDD models and baselines. International Forestry Review, 10, 465–475.

Angelsen, A., Brockhaus, M., Sunderlin, W.D. & Verchot, L.V. (2012) Analysing REDD+: challenges and choices. Center for International Forestry Research (CIFOR), Bogor, Indonesia.

Asner, G.P., Knapp, D.E., Broadbent, E.N., Oliveira, P.J., Keller, M. & Silva, J.N. (2005) Selective logging in the Brazilian Amazon. Science, 310, 480–482.

Asner, G.P., Powell, G.V., Mascaro, J., Knapp, D.E., Clark, J.K., Jacobson, J., Kennedy-Bowdoin, T., Balaji, A., Paez-Acosta, G. & Victoria, E. (2010) High-resolution forest carbon stocks and emissions in the Amazon. Proceedings of the National Academy of Sciences USA, 107, 16738–16742.

Barbier, E.B. (2006) Mangrove dependency and the livelihoods of coastal communities in Thailand. Environment and livelihoods in tropical coastal zones: managing agriculture–fishery–aquaculture conflicts (ed. by C.T. Hoanh, T.P. Tuong, J.W. Gowing and B. Hardy), Comprehensive assessment of water management in agriculture series. Oxford University Press, London.

Barbier, E.B. & Cox, M. (2004) An economic analysis of shrimp farm expansion and mangrove conversion in Thailand. Land Economics, 80, 389–407.

Bennett, B. (2001) What is a forest? On the vagueness of certain geographic concepts. Topoi, 20, 189–201.

Bouillon, S., Borges, A.V., Castañeda-Moya, E., Diele, K., Dittmar, T., Duke, N.C., Kristensen, E., Lee, S.Y., Marchand, C., Middelburg, J.J., Rivera-Monroy, V.H., Smith, T.J. & Twilley, R.R. (2008) Mangrove production and carbon sinks: a revision of global budget estimates. Global Biogeochemical Cycles, 22, GB2013.

Chong, V.C. (2007) Mangroves–fisheries linkages in the Malaysian perspective. Bulletin of Marine Science, 80, 755–772.

DeFries, R.S., Field, C.B., Fung, I., Justice, C.O., Los, S., Matson, P.A., Matthews, E., Mooney, H.A., Potter, C.S. & Prentice, K. (1995) Mapping the land surface for global atmosphere–biosphere models: toward continuous distributions of vegetation's functional properties. Journal of Geophysical Research: Atmospheres (1984–2012), 100, 20867–20882.

DeFries, R.S., Houghton, R.A., Hansen, M.C., Field, C.B., Skole, D. & Townshend, J. (2002) Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s. Proceedings of the National Academy of Sciences USA, 99, 14256–14261.

Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Stidham, M. & Kanninen, M. (2011) Mangroves among the most carbon-rich forests in the tropics. Nature Geoscience, 4, 293–297.

Duke, N.C., Meynecke, J.O., Dittmann, S., Ellison, A.M., Anger, K., Berger, U., Cannicci, S., Diele, K., Ewel, K.C., Field, C.D., Koedam, N., Lee, S.Y., Marchand, C., Nordhaus, I. & Dahdouh-Guebas, F. (2007) A world without mangroves? Science Magazine, 317, 41–42.

FAO (1995) Forest resources assessment 1990. FAO, Rome, Italy.

FAO (1997) *State of the world's forests, 1997*. Words and Publications, Oxford, UK.

FAO (2000) *Global forest resources assessment*. FAO, Rome, Italy.

FAO (2003) Status and trends in mangrove area extent worldwide. *Forest resources assessment programme* (ed. by M.L. Wilkie and S. Fortuna). Working Paper 63. FAO, Rome, Italy.

FAO (2005) *Global forest resources assessment 2005*. FAO, Rome, Italy, http://www.fao.org/docrep/008/a0400e/a0400e00.HTM.

FAO (2007) *The world's mangroves 1980–2005*. FAO Forestry Paper. FAO, Rome, Italy.

FAO (2010) *Global forest resources assessment 2010*. FAO, Rome, Italy.

FAO Fisheries and Aquaculture Department (2004) *Mangrove forest management guidelines*, FAO Forestry Paper 117. FAO Fisheries and Aquaculture Department, Rome.

Fisher, P. & Spalding, M. (1993) *Protected areas with mangrove habitat*. World Conservation Centre, Cambridge, UK.

Friess, D. & Webb, E. (2011) Bad data equals bad policy: how to trust estimates of ecosystem loss when there is so much uncertainty? *Environmental Conservation*, **38**, 1–5.

Friess, D.A. & Webb, E.L. (2014) Variability in mangrove change estimates and implications for the assessment of ecosystem service provision. *Global Ecology and Biogeography*, **23**, 715–725.

Giri, C., Ochieng, E., Tieszen, L.L., Zhu, Z., Singh, A., Loveland, T., Masek, J. & Duke, N. (2011) Status and distribution of mangrove forests of the world using earth observation satellite data. *Global Ecology and Biogeography*, **20**, 154–159.

Griscom, B., Shoch, D., Stanley, B., Cortez, R. & Virgilio, N. (2009a) Sensitivity of amounts and distribution of tropical forest carbon credits depending on baseline rules. *Environmental Science and Policy*, **12**, 897–911.

Griscom, B., Shoch, D., Stanley, B., Cortez, R. & Virgilio, N. (2009b) *Implications of REDD baseline methods for different country circumstances during an initial performance period*. The Nature Conservancy, Arlington, VA.

Groombridge, B. (ed.) (1992) *Global biodiversity: status of the earth's living resources*. Chapman & Hall, London.

Hamilton, S. (2013) Assessing the role of commercial aquaculture in displacing mangrove forest. *Bulletin of Marine Science*, **89**, 585–601.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O. & Townshend, J.R.G. (2013) High-resolution global maps of 21st-century forest cover change. *Science*, **342**, 850–853.

Hansen, M.C., Potapov, P.V., Margono, B., Stehman, S., Turubanova, S.A. & Tyukavina, A. (2014) Response to comment on high-resolution global maps of 21st-century forest cover change. *Science*, **344**, 981

Hishamunda, N., Bueno, P.B., Ridler, N. & Yap, W.G. (2009) *Analysis of aquaculture development in Southeast Asia*. FAO, Rome, Italy.

Homer, C.H., Fry, J.A. & Barnes, C.A. (2012) The national land cover database. *US Geological Survey Fact Sheet*, **3020**, 1–4.

Huettner, M., Leemans, R., Kok, K. & Ebeling, J. (2009) A comparison of baseline methodologies for 'reducing emissions from deforestation and degradation'. *Carbon Balance and Management*, **4**, 4.

ITTO & ISME (1993) *Mangrove ecosystems: technical reports*. ITTO/ISME/JIAM Project PD71/8. International Society for Mangrove Ecosystems (ISME), International Tropical Timber Organization (ITTO) and Japan International Association for Mangroves (JIAM), Nishihara, Japan.

IUCN & UNEP (2013) *The world database on protected areas – WDPA*. UNEP, Cambridge, UK.

Lanly, J.P. (1982) *Tropical forest resources assesment*. Global forest resources assessment. FAO, Rome, Italy.

Lugendo, B.R., Nagelkerken, I., Kruitwagen, G., van der Velde, G. & Mgaya, Y.D. (2007) Relative importance of mangroves as feeding habitats for fishes: a comparison between mangrove habitats with different settings. *Bulletin of Marine Science*, **80**, 497–512.

Murdiyarso, D., Purbopuspito, J., Kauffman, J.B., Warren, M.W., Sasmito, S.D., Donato, D.C., Manuri, S., Krisnawati, H., Taberima, S. & Kurnianto, S. (2015) The potential of Indonesian mangrove forests for global climate change mitigation. *Nature Climate Change*, **5**, 1089–1092.

Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., Underwood, E.C., D'amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C., Loucks, C.J., Allnutt, T.F., Ricketts, T.H., Kura, Y., Lamoreux, J.F., Wettengel, W.W., Hedao, P. & Kassem, K.R. (2001) Terrestrial ecoregions of the world: a new map of life on earth: a new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity. *BioScience*, **51**, 933–938.

Ruiz-Luna, A., Acosta-Velázquez, J. & Berlanga-Robles, C.A. (2008) On the reliability of the data of the extent of mangroves: a case study in Mexico. *Ocean and Coastal Management*, **51**, 342–351.

Saenger, P., Hegerl, E.J. & Davie, J.D.S. (1983) *Global status of mangrove ecosystems*. Commission on Ecology Papers no. 3. World Conservation Union (IUCN), Gland, Switzerland.

Satapathy, D.R., Krupadam, R.J., Kumar, L.P. & Wate, S.R. (2007) The application of satellite data for the quantification of mangrove loss and coastal management in the Godavari estuary, east coast of India. *Environmental Monitoring and Assessment*, **134**, 453–469.

Siikamäki, J., Sanchirico, J.N. & Jardine, S.L. (2012) Global economic potential for reducing carbon dioxide emissions from mangrove loss. *Proceedings of the National Academy of Sciences USA*, **109**, 14369–14374.

Spalding, M., Blasco, F. & Field, C. (1997) *World mangrove atlas*. International Society for Mangrove Ecosystems, Okinawa, Japan.

Spalding, M., Kainuma, M. & Collins, L. (2010) *World atlas of mangroves*. Earthscan, London.

Tropek, R., Sedláček, O., Beck, J., Keil, P., Musilová, Z., Šímová, I. & Storch, D. (2014) Comment on "high-resolution global maps of 21st-century forest cover change". *Science*, **344**, 981.

Webb, E.L., Jachowski, N.R.A., Phelps, J., Friess, D.A., Than, M.M. & Ziegler, A.D. (2014) Deforestation in the Ayeyarwady Delta and the conservation implications of an internationally-engaged Myanmar. *Global Environmental Change*, **24**, 321–333.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix S1 Supplemental methods.
Appendix S2 Differing mangrove measures.
Appendix S3 Table S1 (in Excel format): mangrove loss by year and country utilizing both methods presented in this paper.

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