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The Mangroves of the Zambezi Delta: Increase in Extent Observed via Satellite from 1994 to 2013

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Abstract: Mangroves are recognized for their valued ecosystem services provision while having the highest carbon density among forested ecosystems. Yet they are increasingly threatened by deforestation, conversion to agriculture and development, reducing the benefits they provide for local livelihoods, coastal protection and climate change mitigation. Accordingly, accurate estimates of mangrove area and change are fundamental for developing strategies for sustainable use, conservation and Reducing Emissions from Deforestation and Degradation (REDD+). The Zambezi River Delta in Mozambique contains one of the largest mangrove forests in Africa, and deforestation has been reported to be substantial, however these estimates vary widely. We used Landsat imagery from 1994, 2000 and 2013, to estimate a total current mangrove area of 37,034 ha, which is a net increase of 3723 ha over 19 years. The land cover change assessment was also used to provide perspective on ecosystem carbon stocks, showing that the Zambezi Delta mangrove ecosystem acts as a large carbon sink. Our findings reinforce the importance of conducting land cover change assessments using coherent data and analytical models, coupled with field validation. Broader application of our approach could help quantify the rates of natural change from erosion and land aggradation contrasted with anthropogenic causes.

Keywords: mangrove mapping; Landsat; monitoring; deforestation; land use change detection; REDD+; blue carbon; remote sensing

1. Introduction

The Zambezi River Delta contains one of the largest mangrove forests in eastern Africa, comprising a large portion of the country's total mangrove area, which is greater than 2% of global mangrove extent [1,2]. These mangrove forests are recognized for supporting terrestrial and marine biodiversity [3], containing large carbon stocks [4] and providing essential ecosystem services to local communities, which equate to significant economic value [5]. Accordingly, the reported deforestation of mangroves in the Zambezi River Delta has important ramifications for ecosystem goods, services and values that are derived from the area [6,7]. Reducing deforestation is a major contribution to mitigating climate change, and international programs such as Reducing Emissions from Deforestation and Forest Degradation (REDD+) are designed to incentivize conservation of forested lands in developing countries. One premise of REDD+ and other programs is the accurate estimation of a baseline forest cover and deforestation rate due to anthropogenic causes.

Estimates of mangrove extent in the Zambezi delta range widely, and many report substantial decreases in mangrove [1,6,8,9]. However, these estimates are summarized over different spatial extents of the delta area, and are more often based on a comparison of data from disparate methods and sources rather than a consistent analysis of a single dataset. Those estimates also very often lack essential targeted field verification. Access into the interior of dense mangroves stands is difficult and time consuming, therefore, satellite imagery is a useful complement to map large areas of mangrove at a consistent time scale.

Optical satellite imagery is being employed more and more to map mangroves efficiently because of mangrove species' unique multispectral signature, improving upon previous manual and field based methods or interpretation of aerial photography [10,11]. Owing to its long-term record of consistent moderate resolution imagery with varied spectral bands, the Landsat sensor in particular can be used for accurate change analyses, particularly in mangroves [2,10]. Viewing these ecosystems from space offers the advantage of a consistent view over a larger scale, and rapid, cost effective monitoring. However, results can vary, even when using similar data sources. Therefore, to provide consistent monitoring over the long term, a repeatable, user-independent or semi-automated approach is recommended to produce comparable results over time. Unsupervised classification was thus selected for this analysis to ensure consistency, using radiometrically corrected imagery, along with band ratios and enhancements of spectral bands which have been proven to discern mangroves from other forest types [12].

Our objectives were to assess mangrove area and measure the rate of change within the Zambezi River Delta utilizing Landsat data over a nearly two decade period, and to determine the effects of change on mangrove carbon stocks. We analyzed a 19-year Landsat time series to assess mangrove extent from 1994 to 2013, using band ratio and unsupervised classification methods. Very high resolution (VHR) data were used to validate the Landsat analysis, as well as provide a more detailed mangrove map for comparison. This assessment was part of an effort to establish baseline conditions of carbon stocks within the Delta so that it may be considered for inclusion in a REDD+ or other payment for ecosystem services program. The effort also included an objectively designed inventory of carbon stocks within the mangrove forest [4]. Here, we report on the land cover change assessment that is supported by the inventory, an independent land cover validation dataset, and low altitude aerial survey data to assess areal change and estimate potential carbon loss.

2. Study Area

The Zambezi River Delta

The Zambezi River Delta is a flat alluvial plain located in central Mozambique, spanning the boundary of Sofala and Zambezia provinces along 200 km of coastline from Quelimane to the Zuni River. The boundary of this analysis was defined according to the strict definition of the delta, from Chinde in the north to Mupa River in the southern end of the Marromeu Reserve (Figure 1). The vegetation of the Zambezi River Delta is a mixture of woodlands, savanna, grasslands, mangroves, and coastal dunes [6]. The mangrove forest is composed of all eight mangrove species found in Mozambique: *Avicennia marina*, *Bruguiera gymnorhiza*, *Ceriops tagal*, *Heritiera littoralis*, *Lumnitzera racemosa*, *Rhizophora mucronata*, *Sonneratia alba* and *Xylocarpus granatum* [13], reaching heights of up to 30 m [4,6], supporting a variety of terrestrial and aquatic biodiversity [14]. The Marromeu Buffalo Special Reserve is a protected area located on the southern bank, and a vibrant fishing industry and small villages exist throughout the Delta.

The extent of mangroves has been derived from aerial photo and satellite imagery, resulting in estimates ranging from less than 50,000 ha [6,15,16] to more than 150,000 ha [1,15] and many reports in between [8,9,13]. The distribution of mangrove forests within the Delta is recognized to be dynamic; however, the effects of the Kariba and Cahora Bassa dams built in 1959 and 1974, respectively, have affected water flow and flooding regimes throughout the Delta have not been documented [6].

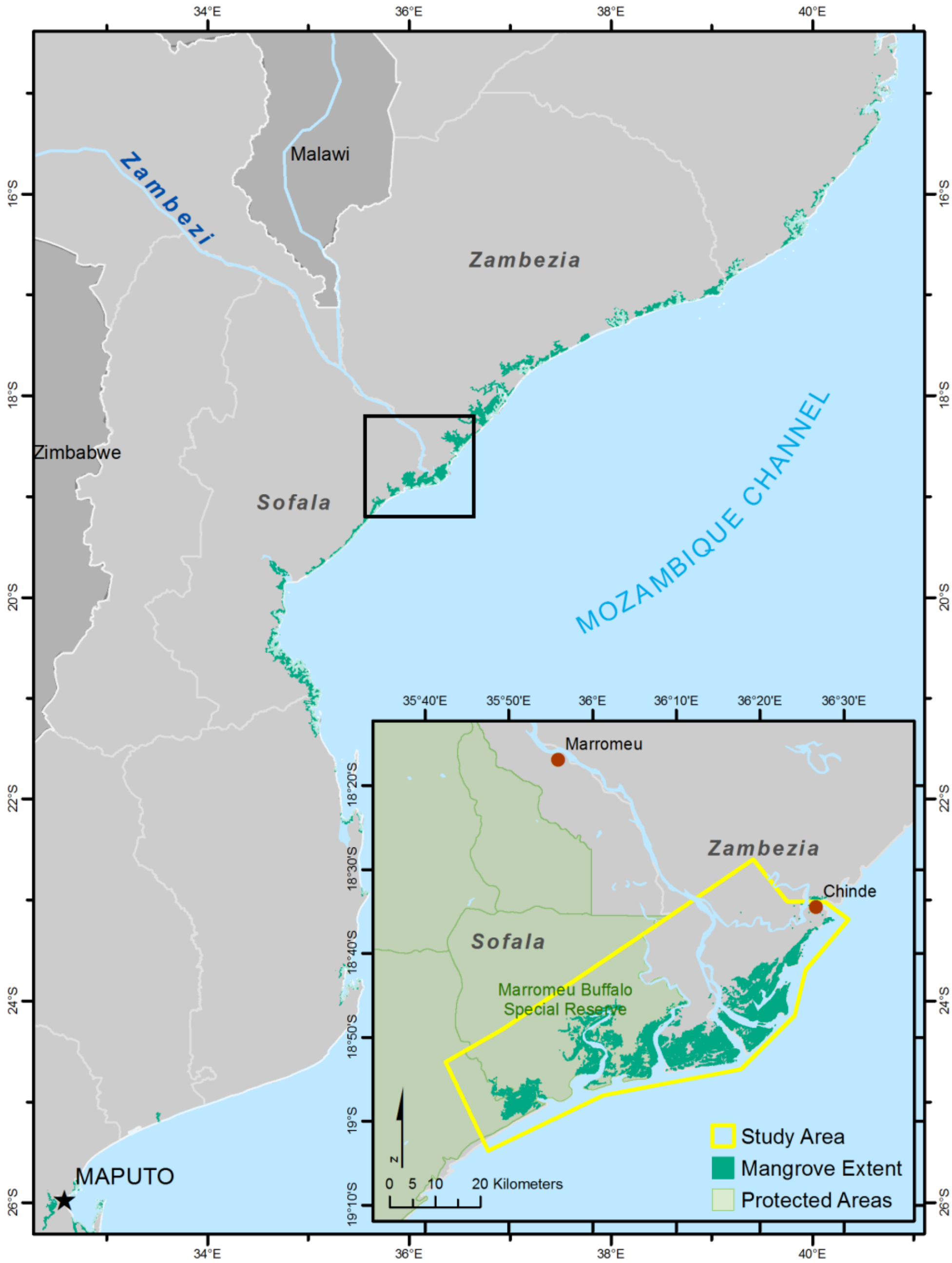

Figure 1. The distribution of mangroves along the southern and central coast of Mozambique [2]. The assessment boundary of mangroves within the Zambezi River Delta was defined from Chinde on the north to the edge of the Marromeu Reserve in the south.

3. Materials and Methods

3.1. Remote Sensing of Mangrove Cover

In order to develop maps of mangrove extent over time, all available Landsat images since 1990 with a spatial resolution of 30 m were reviewed for quality, and cloud-free scenes selected for analysis (Table 1). Images were selected from July to August to reduce effects of seasonality. Data were acquired from the US Geological Survey (USGS) Landsat satellites 5, 7 and 8 (path 166, row 73) and were converted to top-of-atmosphere spectral reflectance using ENVI 5.0 [17].

Table 1. Landsat images selected for the land cover change analysis.

Image Id	Image Date	Satellite
LT51660731994205JSA00	24 July 1994	Landsat 5 Thematic Mapper
LE71660732000198EDC01	17 July 2000	Landsat 7 Enhanced Thematic Mapper
LC81660732013225LGN00	13 August 2013	Landsat 8

We employed a semi-automated mapping technique (Figure 2) to maximize consistency of mangrove mapping for different images and allow for repeatable, user independent mapping of extent for the change analysis. This method begins with water masking using the near infrared (NIR) band, followed by a combination of standard methods for mangrove detection with Landsat including red and shortwave infrared (SWIR), and SWIR and NIR band ratios, followed by a Principle Components Analysis (PCA) to reduce data redundancy [10,18]. This analysis uses an unsupervised classification instead of supervised. Several classification methods were tested and the unsupervised provided the quickest processing time, with most accurate and consistent results for subsequent images for the Zambezi River delta independent of the user input, with minimal post-classification hand editing required. The thermal bands are not used for this analysis.

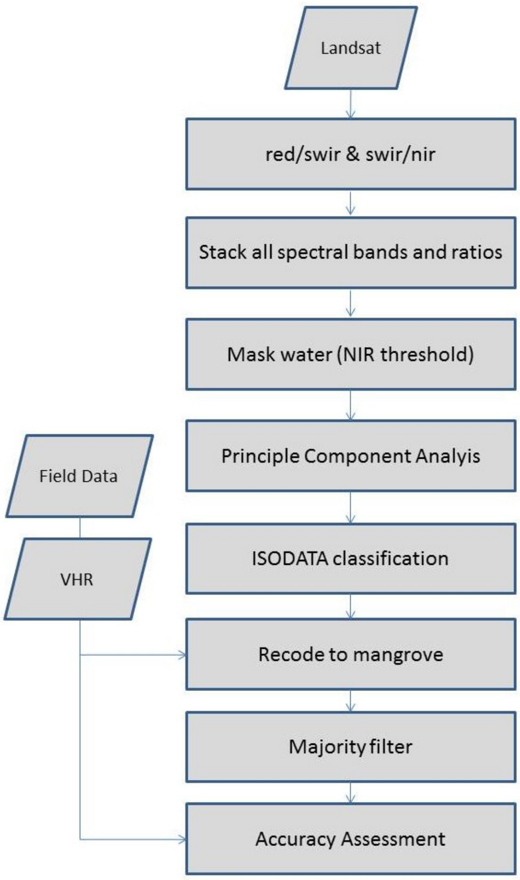

Figure 2. Mapping method for mangrove detection using Landsat, very high resolution (VHR) data and field data.

Mangrove extent was mapped from the three Landsat images and a post-classification change analysis was used to estimate gain and loss between each time period. A majority 3 × 3 window filter was used to clean results, remove single erroneous pixels and all areas below the defined minimum mapping unit (1 ha) were sieved. Any mangroves mapped in areas outside the coastal zone were removed by contextual editing.

While medium resolution data such as Landsat is useful for large scale mapping of mangroves over time, very high resolution data (<4 m resolution) is also beneficial for validation, identifying small patches of mangrove forest which may be missed with medium resolution, and potentially identifying species composition or causes of mangrove change [2]. To assess the Zambezi River Delta in higher resolution, WorldView-2 data collected between July and November 2013 was acquired for a 45,000 ha area of the Delta from Digital Globe Inc, USA. These data cover a smaller area than Landsat data due to limited budget for commercial data and availability of cloud-free imagery, but is an area sufficiently large to provide a basis for comparison among the two satellite sensors.

Object-Based Image Analysis (OBIA) was used to develop a high resolution map of mangrove extent in 2013 using ECognition Developer software version 9.0 from Trimble Systems. OBIA is a technique that has been derived as an alternative to pixel level analyses for high resolution imagery, grouping pixels into the objects and using spectral information as well as shape and texture to extract features [19]. Information and photos from the field inventories described below as well as visual interpretation of the high resolution imagery were used to develop the rulesets to complete the OBIA, producing a map with four major land cover classes: mangrove vegetation, non-mangrove vegetation, bare land and water bodies [19]. The final high resolution map was resampled to 2 m resolution as part of the OBIA mergin process.

3.2. Land Cover Field Data

In 2014, a field mission to the Zambezi Delta was conducted to collect training and validation data for the satellite mangrove mapping. GPS locations were collected for two independent datasets, which included 148 training points, and 300 validation locations in the central part of the Delta, which was accessed on foot or by motorboat. For training data, photos in all four cardinal directions and detailed site information on vegetation cover, canopy height and human impact were collected. For validation data, the major land cover was identified. We used two Trimble Juno 3 series GPS with ArcPad software from ESRI.

3.3. Accuracy Assessment

Area-weighted accuracy assessments, using the proportion of the estimated area of each class with independent field data and high resolution imagery were used to estimate user accuracy (or errors of commission) and producer accuracy (errors of omission) of both persistent forest and change mapped by Landsat [20]. This method also allows for reporting confidence intervals for area estimates of change. As older imagery and data were not available, areas of loss or gain were assessed by current coverage in the high resolution imagery, and by observations in the field (young or dead mangrove). For this assessment, gain and loss were grouped, regardless of year of detection. Accuracy assessment points were located where field data were present, and randomly within each strata of current mangrove, mangrove gain and mangrove loss covering VHR data. Accuracy assessment was also performed on the high resolution map using the independent field dataset for accuracy (separate from that used for training).

3.4. Carbon Inventory

The mapped mangrove extent was combined with information from a recent carbon inventory [4] to determine the change in total carbon stock of the mangroves between 2000 and 2013 using a gain-loss method that estimates carbon emissions by subtracting the biomass changes from area of loss from the biomass increase [21]. The carbon stock inventory within the Zambezi Delta employed an objective inventory design, utilizing available ICE Sat/GLAS and Shuttle Radar Topography Mission (SRTM) data as a basis for classifying the forest into height classes. Five canopy height classes were derived from the mangrove area delineated in the canopy height database for Africa [22], and used as the basis for a stratified sampling design to measure carbon stocks of mangrove by height class [4]. The mangrove area used in the carbon inventory however, was 4579 ha less than the area determined from Landsat, attributable to differences in data types (active *vs.* optical passive) and resolution (much higher for optical Landsat). All areas of mangrove identified outside SRTM data were assigned to height class 1 in order to produce a most conservative estimate of biomass, which assumes that all areas of mangrove outside the SRTM data are more recent, and therefore the smallest class, and because no auxiliary information was available to assign specific canopy height to areas identified as mangrove outside SRTM. From the year 2000 mangrove extent, standing stock was calculated by multiplying the area of each height class by the total biomass from Table 2. Additionally, the carbon density of all new mangroves (gain in 2013 from Figure 3) was estimated along with the carbon decrease associated with mangrove loss from 2000 to 2013. Net carbon change, and rates of carbon sequestration and loss were calculated on an annual basis.

Table 2. Carbon densities within canopy height classes of the above- and belowground biomass and soil pools [4].

Class	Canopy Height Class (m)	Total Above Ground Carbon (Mg C/ha)		Total Below Ground Carbon (Mg C/ha)		Soil Carbon (Mg C/ha)		Total Mean Carbon (Mg C/ha)
		Mean	SD	Mean	SD	Mean	SD	
1	2–6.9	75.4	12.6	23.8	3.1	274.6	25.0	***373.8***
2	7–9.9	115.9	16.8	36.0	5.0	282.2	11.2	***434.1***
3	10–12.9	152.5	17.7	46.9	5.1	314.1	14.8	***513.5***
4	13–17.9	206.0	20.5	59.7	5.2	279.8	13.6	***545.5***
5	18–29	268.5	36.6	72.8	9.4	279.6	17.6	***620.9***

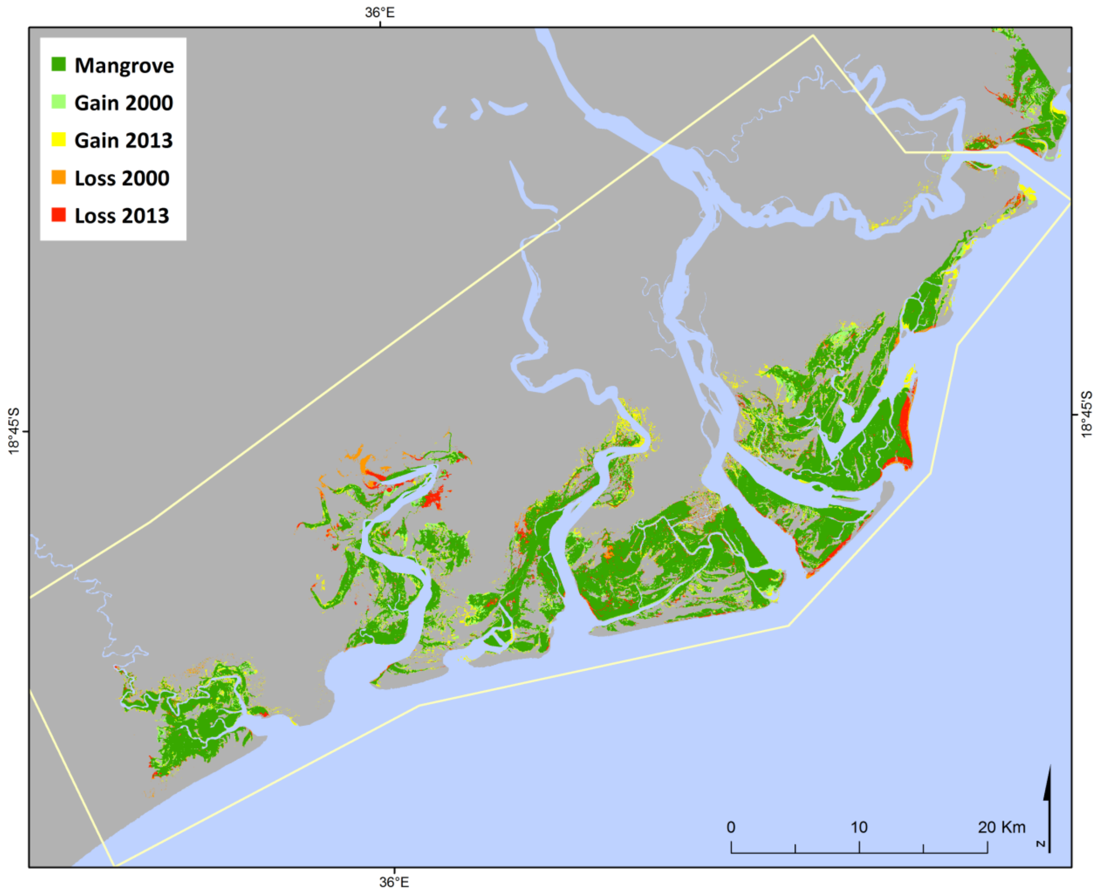

Figure 3. Change in mangrove extent within the Zambezi River Delta from 1994 to 2013 detected with Landsat data.

4. Results

4.1. Change in Mangrove Extent over Time

A total of 37,034 ha of mangrove was measured in 2013, a net increase of 3723 ha compared to 1994 (Table 3). The mangrove cover is dynamic with large and small gains and losses over time (Figures 3 and 4). The largest areas of loss were observed in coastal zones, while mangrove expansion was discerned primarily along the inland margin and on newly formed islands and flats along the river. Mangrove loss was also observed in a few distinct areas inside the Marromeu Reserve. Areas of loss along the coast were verified during the field mission, where large dead mangrove trunks were observed, with roots covered in sand. In some inland areas, mangrove mortality was also seen, with grassy lichens covering dead mangrove tree canopies. Gains in mangrove areas are evident throughout the Delta, particularly on new land formations (Figure 4) as well as in the most upstream edges, where mangrove patches become denser over time and increase along channel edges, which show that mangroves are expanding their range upstream. In mud flats, numerous areas of young colonizing mangrove species were observed.

Table 3. Mangrove extent within the Zambezi River Delta mapped in 1994, 2000 and 2013 using Landsat data.

Year	Total Mangrove Area (ha)
1994	33,311
2000	34,846
2013	37,034

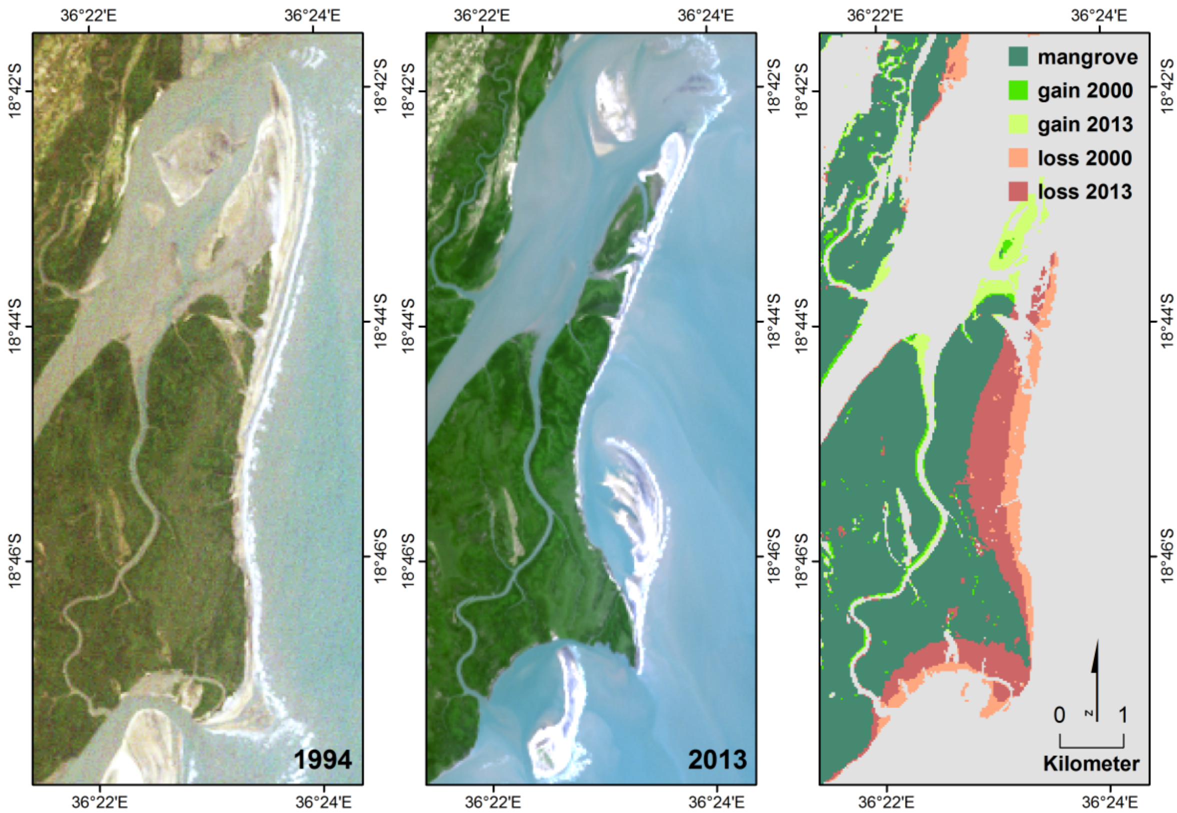

Figure 4. An area within the Zambezi River Delta which experienced extensive erosion in the coastal margin and development of new islands between 1994 (**left**) and 2013 (**middle**), areas of loss are shown in red and gain in green (**right**).

There were net gains in mangrove area in both of the assessment periods (Table 4), but the annual rate of gain and loss were both larger in the 1994–2000 period. During that first six-year period, the net gain averaged 251 $ha\cdot yr^{-1}$, over the latter 13-year period the average gain was 170 $ha\cdot yr^{-1}$.

Table 4. Gain and loss of mangrove area (ha) measured for 1994–2000 and 2000–2013 using Landsat data, the proportional change (%) is shown in parentheses.

Time Period	Gain (ha)	Annual Gain (ha/year)	Loss (ha)	Annual Loss (ha/year)
1994–2000	2911 (8.7)	485 (1.5)	1404 (4.2)	234 (0.7)
2000–2013	4291 (12.3)	330 (0.9)	2074 (6.0)	160 (0.5)

Areas of change were also assessed by number and average size of contiguous area. Overall there were nearly twice as many polygons of mangrove gain, which measured on average the same size as areas of loss. The largest area of loss covered an area of 190 ha and is shown in Figure 4. The largest areas of loss are centered in the northern half of the Delta along the shore, and in a few areas upstream along the Luáua river in the Marromeu Reserve. These areas were verified during the 2014 field mission, where mangroves were observed standing in sand, or falling over into the sea or channel. When verified with current high resolution imagery, the areas of loss inland and upstream mostly occur in extensive mud flats with very little vegetation.

For the most part, human impacts appeared to be limited throughout the study area, with little evidence of burned forest, clearings or expanding agriculture observed on the ground. Additional field work directed at these large areas of loss in the Marromeu Reserve is necessary to determine the actual cause of mangrove decrease in that area.

The area weighted accuracy assessment for the Landsat change analysis showed an overall accuracy of 85%, and user accuracy of 90% and producer accuracy of about 70% for current mangrove cover. For non-mangrove areas however, producer accuracy was greater than 90%. User accuracies were above 90% for mangrove gain and loss, though both had low producer accuracies (less than 50%).

4.2. High Resolution Mangrove Mapping

The distribution of mangroves observed with WorldView-2 was very similar to what was estimated with Landsat. Within the portion of the Delta covered by the WorldView-2 data, a total of 35,840 ha of mangrove were identified by the OBIA. In comparison, 32,838 ha were mapped by 2013 Landsat data for this same area. Most differences between the maps are seen in patchy mangrove areas and along forest edges bordering bare areas (Figure 5). The high resolution mangrove map was also assessed with available field data, and accuracy was lower than with the Landsat analysis (Table 5); however, the field data were limited to a central accessible portion of the Delta. The high resolution mapping had 56% overall accuracy, and user and producer accuracies for mangrove of 70% and fewer errors of omission and commission.

Table 5. Area-weighted error comparison for Landsat and Worldview-2 overall error, and producer (omission) and user (commission) accuracies for the mangrove class.

Sensor (Resolution)	Overall Map Accuracy (%)	Producer Accuracy (%)	User Accuracy (%)
Landsat (30 m)	84.6	69.3	89.8
Worldview-02 (2 m)	55.7	82.9	72.4

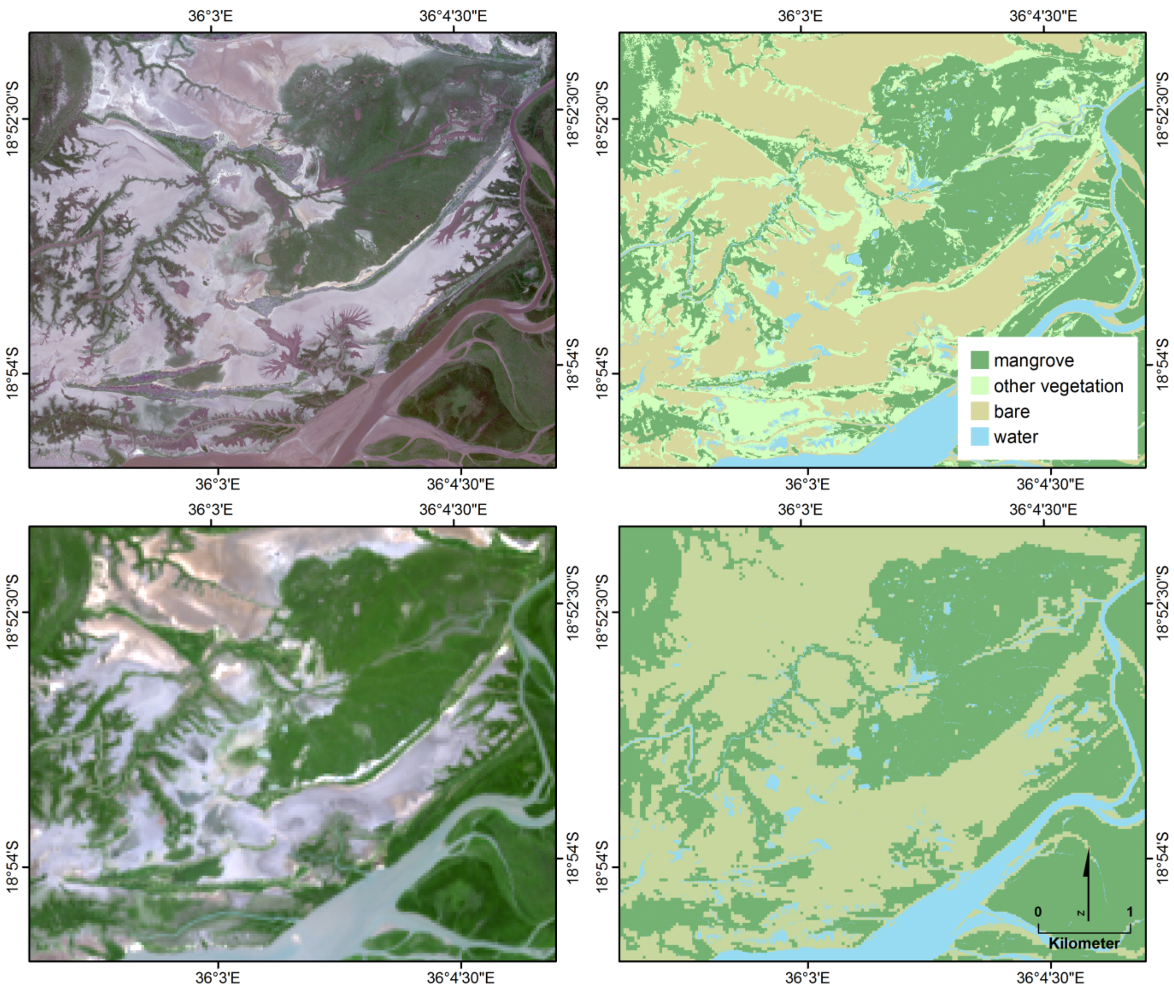

Figure 5. Comparison of mangrove mapping in 2013 with high resolution WorldView-2 (**top row**) and Landsat (**bottom row**) data within the Zambezi River Delta; the satellite image is shown on the left and the classified data on the right.

4.3. Changes in Mangrove Carbon Stocks

Standing carbon stock, based on estimates within canopy height classes show that forests with greatest biomass are found along the main channel, and upstream in the western mangrove block (Figure 6). Changes in ecosystem (e.g., above and belowground) carbon stock were estimated using the gain-loss method recommended for REDD+ Measuring, Reporting and Verification (MRV) [21]. There was a net increase of 691,032 Mg of carbon in the mangroves within the Delta during the 2000–2013 period (Table 6). The annual rate of change included gains of 123,383 Mg C·yr^{-1} for new mangroves, and losses of 70,226 Mg C·yr^{-1}, indicating that the net gain in C within mangroves on the Zambezi Delta could be more than double the annual loss. This accounting, however, does not include the increase in carbon stock that would be associated with the annual gains in biomass from persistent mangrove stands, as this rate was not measured. The loss of mangrove area over the 13 year period was 5.9%, varying from 9.9% to 1.9% among the five canopy height classes that were used in the carbon inventory. The gain in mangrove area represented a 12.3% increase over the area in 2000.

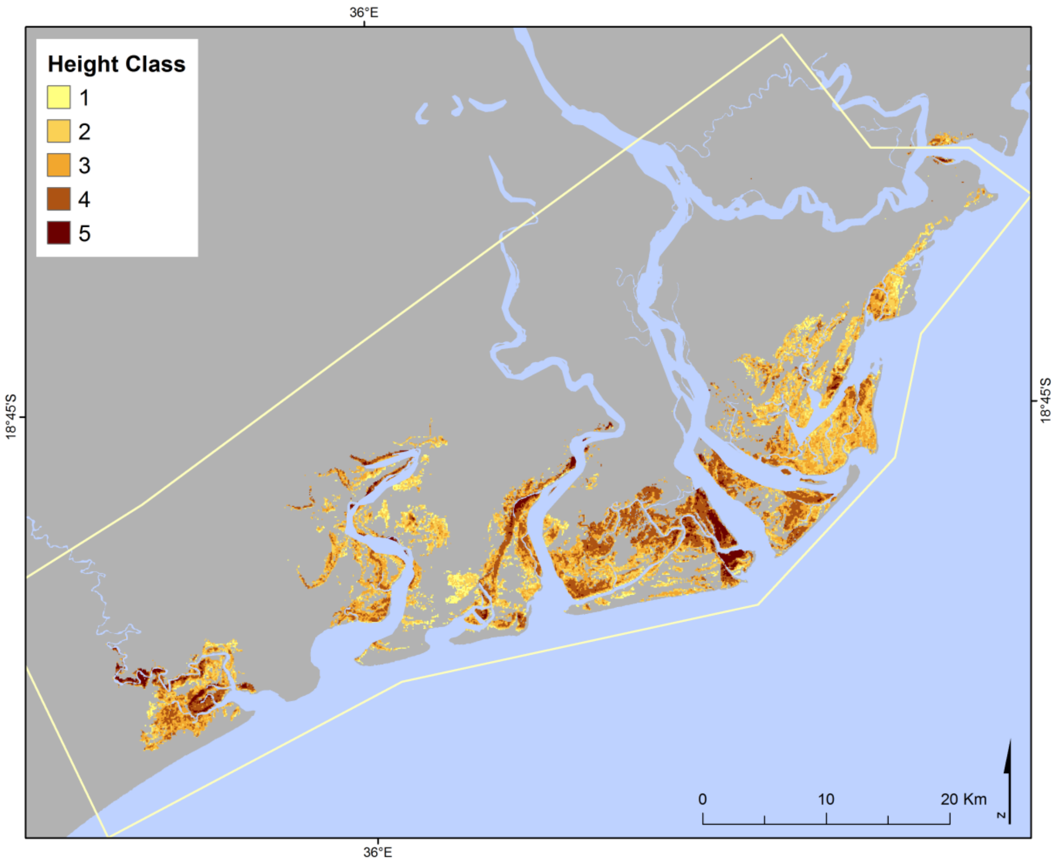

Figure 6. Mangrove extent in 2014, mapped by canopy height class. Higher height classes have greater total biomass; refer to Table 2 for above and below ground biomass estimates from the carbon inventory.

Table 6. Ecosystem stock of mangroves in 2000, and gains and losses attributed to changes in mangrove extent through 2013. Carbon density assumed to be constant over the assessment period. Canopy height class used as the basis for carbon inventory [4].

Canopy Height Class	Mangrove Area 2000 (ha)	Ecosystem Carbon Stock (Mg C)	Mangrove Area Gain 2000–2013 (ha)	New Ecosystem Carbon Stock (Mg C)	Mangrove Loss 2000–2013 (ha)	Ecosystem Carbon Stock Loss (Mg C)
1	9173	3,429,028	4291	1,603,975	907	339,037
2	7862	3,413,029	-	-	456	197,950
3	9153	4,700,112	-	-	450	231,075
4	7321	3,993,927	-	-	236	128,738
5	1334	829,553	-	-	26	16,143
total	**34,843**	**16,365,649**	**4291**	**1,603,975**	**2074**	**912,943**

5. Discussion

5.1. Comparison of Mangrove Extent and Change with Other Research

There has been a wide range in estimates of mangrove extent in the Zambezi River Delta (Table 7), with greater than three-fold difference between highest and lowest estimates [1,2,6,8,9,14].

The large discrepancy among estimates of mangrove area can be attributed to differences in data and analytical methods, and inadequate or lack of field validation. A comparison among recent assessments illustrates the importance of consistent analyses and the challenges of comparing area estimates among different methods despite the use of a common sensor (Table 7). Giri *et al.* [2] used similar methods of clustering and recoding, with the principal difference being our use of band ratios and PCA. However, the authors were unable to produce statistically robust validation for their large global dataset so the results are difficult to precisely compare. The differences in area reported by [22] are likely attributable to the scene selection, classification approach and data filtering. In contrast the data from [9] appears to be a combination of classification and hand-editing yielding coarse generalized vectors, which have much less complexity at mangrove edges, include water in the margins, or lump patches; this approach may result in an over estimation of mangrove cover. This study likely underestimates mangrove cover due to lower producer accuracy, meaning larger errors of omission, so that in this case mangrove area may actually be underestimated by this analysis, and the actual area is more likely to be in between this study and the RCMD published values. Further highlighting difficulties in large scale assessments for specific locales, Coleman *et al.* [23] reported that the land conversion of wetlands in the Zambezi Delta average 2400 ha yr^{-1}. While that study was not specific to mangroves, it identified little anthropogenic change in the lower delta, where most mangroves are located. Consversion of wetlands to agricultural use is primarily in the upper delta area, and likely targets non-mangrove ecosystems.

Table 7. Mangrove area within the Zambezi River Delta as reported from recent assessments at varying scales using Landsat data. The comparison is for the area within the Delta boundary as shown in Figure 3.

Area (ha)	Year	Project Scale	Source	Overall Accuracy (%)
37,034	2013	Strict Delta Area	This study	85
36,461	2000	Global	[2]	Not assessed
30,267	1999–2002	Continental Africa	[22]	93
38,505	Not reported	Mozambique	[9]	84

The comparison amongst these aforementioned estimations is also difficult for the Zambezi Delta as the projects themselves differ in scale—these are often national products, with likely limited detailed information and field data specifically for the Delta area. Accordingly, the analyses presented here were focused on the Delta area and present the most robust to-date, resulting from standard methods [10] applied specifically for Zambezi mangroves, tailored and verified by VHR and field data. The relative consistency between estimates mangrove area derived from Landsat time series affirm that the total area is much less than the largest estimates (e.g., >50,000 ha) previously reported [6,8]. The repeatability of our method with minimal visual interpretation and post-classification hand editing is also vital for reliable change detection and new estimates over time.

An accurate assessment of change in forest cover is fundamental for developing a strategy for REDD+ and monitoring progress towards emissions reduction targets. It is difficult to provide accurate estimates of change derived from various data sources, such as tabular statistics, or aerial photo interpretation combined with newer satellite image derived estimates, many of which lack specifically targeted field data or accuracy estimates [8]. Correspondingly, large scale or global datasets may provide reliable general estimates, but inevitably lack the specificity for a particular area or forest type, and consistent accuracy assessment of these datasets may simply not be possible. Accordingly, there have not been any reliable estimates of change in mangrove cover for Mozambique. Hand-edited data which may be very accurate are unsuited for large scale or automated monitoring due to extensive user dependent interpretations. While large-scale automated tools appear to hold promise, the Google Forest Cover Change analysis, assessing forest cover change based on analysis of Landsat imagery from 2000 to 2013 did not show any gain or loss in mangrove forest cover within the Delta [24].

Studying the distribution of mangroves throughout Mozambique, Fatoyinbo *et al.* [8] found large decreases in mangrove area in the Zambezi Delta based on Landsat data from 1990 to 2002. While that work contained a validation assessment, these data were collected from a different mangrove ecosystem in southern Mozambique, where the mangrove forest composition and structure are quite different than in the central and northern portions of the country. In contrast, in a study focusing on the Zambezi Delta, Beilfuss *et al.* [16] reported loss of mangrove forest that was balanced by the development of new mud flats supporting aggrading mangroves between 1960 and 2000, resulting in no overall change in mangrove area over the 40 year period. Large river deltas are dynamic systems subject to persistent tidal forces and seasonal flooding, resulting in changes to flow-paths, shoreline position and development of new lands, which can result in changes in mangrove cover, notably directional changes or shifts along geomorphological patterns [6,25]. On the ocean coast, regression has been observed, evidenced by dead trees and stumps in exposed mud and sand, a natural consequence of shifting shorelines from wave erosion and tropical storms. Other causes of mangrove cover loss include burning and cutting by local communities, though most areas suspected of being burned are located in the Marromeu Reserve, which was not visited during the field expeditions. Local observations of cut mangroves were in stands that were already dead or eroded on the shore. Mangroves are expanding upstream, which may be attributed in part by salinity regimes as a result of sea level rise and altered freshwater discharge from upstream dams. Many new young stands of *Avicennia marina* were observed along inner channels and mud flats in the delta which was also documented by Tinley [26] and Beilfuss *et al.* [16]. It should be noted that the increase in mangrove extent observed here is likely specific to the Zambezi and other relatively undisturbed deltas and estuaries.

There are relatively few inhabitants with the Zambezi Delta [6]; accordingly, the pressures from anthropogenic disturbance (e.g., burning and cutting) are bound to be low, which is consistent with a recent report on the anthropogenic effects of coastal erosion [27]. As a result, the total area of mangroves appears not to diminish due to human impacts as seen elsewhere, and the mangroves of the Zambezi are relatively intact despite the dynamic nature of its distribution. The widely varying reports of deforestation for the Zambezi Delta attest to the need for specific assessments, which include field validation for the area under consideration. It is quite possible that mangroves are decreasing for various reasons elsewhere in Mozambique, which unfortunately, are trends also observed worldwide [8,26,28,29]. Understanding the varying baseline condition and natural rate of gains and losses in mangrove forests is fundamental to REDD+ or other conservation mechansisms, and has important ramifications for restoration.

5.2. Application of High Resolution Data

It is a common misconception that higher resolution and detail results in better maps [30]. On the contrary, it is more difficult to achieve the same overall accuracy with higher resolution due to the complexity of the imagery, small features which may be difficult to classify or have spectral signatures influenced by neighboring pixels. In addition, logistical limitations of very high resolution imagery include purchasing cost and processing time, and the need to bring together data imaged on different dates because of smaller swath size. Some of these factors can be overcome with a well-defined minimum mapping unit (MMU) [30,31] or OBIA, still, most high resolution satellites have lower spectral resolution compared to Landsat (lack of short-wave infrared bands which are very useful for mangrove mapping), large data volumes and limited archives for long time series. In this case, funding was a limiting factor for purchasing the full spectral resolution of VHR. For the purposes of REDD+ MRV, one aims for consistent, simple and cost-efficient mapping which can be repeated over time, for which very high resolution data in this case may not be optimal.

In this analysis, the Landsat derived map produced higher overall accuracy than the Worldview-2 data. This can be attributed to the more adequate spectral resolution of Landsat for mapping mangroves, while the detail of higher resolution (15 times greater; Figure 5) and greater number of mapped classes generally reduce accuracy. While overall error may be higher with higher resolution, the higher producer accuracy indicates fewer areas of omissions, as this detailed imagery can identify sparse or small patches of mangrove. The high resolution data are also able to identify young mangrove stands with sparse tree cover and bare areas in between, which might not be visible in a Landsat pixel. VHR is nevertheless very useful for mapping mangrove cover in detail, often even species types, but requires more extensive field data, time intensive analysis and post-processing, in this case more than double the time than Landsat due to multiple vertical tiles treated separately. The classification based on high resolution data could be improved by including additional factors, such as mangrove structure, or revising methods [32] however, the effort required to produce the maps with OBIA or complex techniques requires specialized knowledge, data, software, storage and is highly software dependent. The fundamental consideration is whether meter or sub-meter detail is required or provides essential added value to MRV, which is likely not true in such dynamic ecosystems which grow and change so quickly requiring time series—one only needs to map the forest and not individual trees. Here we produced more accurate maps over a longer time frame at a fraction of the cost of mapping with VHR. This by no means discounts the value of high resolution for use in the field for orientation and localization, reconnaissance for inaccessible areas as well as ground truthing and validation of lower resolution data, or to help determine causes of mangrove loss. The recommendation for MRV is to use imagery for its strengths: Landsat, and the new Sentinel-2 satellite will provide consistent time series and just as important, the appropriate spectral bands for mapping change, while high resolution imagery provides detail needed in localized areas for verification of loss or gain, or to provide additional insight for inaccessible areas.

5.3. Change in Carbon Stocks

Mangroves are recognized for their large amount of carbon in above- and belowground biomass and soil pools [4], hence the widespread concern for their deforestation which can cause substantial carbon emissions [22,33]. With an understanding of baseline carbon stock, the land cover change analysis was used to assess the changes in biomass over time. In contrast to utilizing the SRTM data to estimate biomass [22], [4] measured carbon stocks directly, and used the canopy height classification based on remotely sensed data to extrapolate across the inventory area. Similarly, [34] used Landsat to classify land cover in Madagascar and inventory carbon stock in three different mangrove types. The use of an objective inventory design in combination with a land classification can provide the basis for assessing changes in carbon stocks based on land changes in land cover.

The dynamic redistribution of forest carbon stocks in mangroves has important implications for the design and implementation of sustainable management and conservation strategies to ensure the delivery of ecosystem goods and services. There was net increase in carbon stocks observed with in the Zambezi Delta over the 13 year period, which is driven by the increase in mangrove area over time. Loss in forest carbon stock occurred across all canopy height classes, though more change occurred in the smaller height classes. While we assumed the loss of mangrove cover resulted in a loss of all carbon, a preferred means would be to obtain carbon density measurements for new land cover conditions as well as changes such as sequestration provided by persistent mangrove. In the case of erosion, however, where the land has been replaced by water, the assumption of complete loss is tenable. From a carbon perspective, the ability to sustain an increase in forest carbon despite the lower carbon density on the lower stature height class 1 stands, is attributed to the gain in forest area with soils inherently high in C, which is not uncommon for mud flats and estuarine sediments [35]. The loss of carbon per unit area by deforestation occurs very quickly howrver, whereas it takes several years to build up carbon stocks in soil and trees.

6. Conclusions

The long-term data series from Landsat can be used to effectively assess land cover change of mangroves and should be supported by local validation within the assessment area. Large scale assessments of mangrove that extrapolate beyond the area used for validation have not proven to provide accurate assessments outside these zones. Another issue with previous work assessing change in mangrove cover in the Zambezi Delta is that comparisons were made among different published methodologies, often with different data sources. The mangrove area estimated from Landsat by this study within the Zambezi Delta was measured as 37,034 ha in 2013, which is smaller than many previous reports. This study shows, however, that there has been a net increase in mangroves since 1994, mostly due to expansion in the inland areas, which is overall larger than the areas of loss along coasts and channels. The algorithm to process Landsat data is consistent and reproducible, and has provided overall accuracy above 85%, which is suitable for monitoring for emissions reduction projects and to meeting monitoring needs. In order to showcase transparency of the effort, and make results useful and accessible to stakeholders, imagery and results are available for viewing in an interactive web map hosted by the WWF Global Observation and Biodiversity Information Portal (GLOBIL): http://arcg.is/1HQ8PFo and complete datasets are also available for download upon request.

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Author Contributions: Aurélie C. Shapiro oversaw the image puchases, analysis and processing, field mission, validation and accuracy assessment. Carl C. Trettin led the Zambezi mangrove project and biomass data collection and estimation. Sadroddin Alavinapanah executed the Landsat and high resolution image analysis. Helga Küchly developed initial draft maps and managed field data collection, validation, data preparation and compilation. Salomão Bandeira provided in-country support, planning and oversight of field expeditions, workshops and extensive expert knowledge of the Zambezi ecosystem.

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