BANGLADESH TREE COVER MONITORING (2000-2014) USING SATELLITE DATA

A Joint Study of Bangladesh Forest Department (BFD) and University of Maryland (UMD), USA.

Resource Information Management System (RIMS) Unit

Bangladesh Forest Department

Banbhaban, Agargaon, Dhaka.

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Acknowledgement

This study was jointly conducted by Bangladesh Forest Department (BFD) and University of Maryland (UMD), USA. Global Land Analysis and Discovery (GLAD) lab and Resource Information management System (RIMS) lab of BFD were used to process, interpret and analyze satellite data. Silvacarbon programme and UMD provided all necessary software and hardware for this study.

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Executive Summary

Bangladesh, a South Asian country with rich floral and faunal biodiversity, are under anthropogenic pressures since last few decades. It has a tropical semi- evergreen forest in hilly areas, moist deciduous forest in the central region and World's largest contiguous mangrove, the Sundarbans in the southwest. The country is also a pioneer in creating mangrove afforestation in newly accreted land along the coastal frontier. But it's highly dense population (approximately 1063 person per square kilometer, BBS July 2014) has been putting tremendous pressure on forest ecosystems and biodiversity. Usually, the growing population leads to deforestation for household, agriculture or industry. Global Forest Resources Assessment (GFRA) shows significant deforestation in the country, especially in the hilly region. The National Forest Assessment (NFA, 2005-07) shows tree cover loss in hill forest but substantial gain in village tree covers. This increments in village tree resource are the result of Government's massive social forestry program implemented in last three decades.

Nationwide satellite-based tree cover monitoring has never been done by the Bangladesh Forest Department (BFD). The University of Maryland (UMD), USA with the assistance of USAID SilvaCarbon program, came forward to accomplish the job for the first time. A four weeks training at UMD on October 2015 made four BFD officials capable complete the work properly. The Landsat TM satellite imageries during 2000 to 2014 have been used for this monitoring.

The team initially prepared "Tree canopy cover extent for the year 2000". Using Landsat images, pixels with greater than or equal to 50% tree crown cover within a 30m x 30m pixel were considered as "trees", and less than 50% as "no trees". Gross tree canopy cover loss and gain were mapped for the entire analysis interval (2001-2014, with the year 2000 as a reference year) using supervised classification.

Two sets of decision tree models were created and applied independently; gross tree cover loss and gross tree cover gain. Tree cover loss was defined as clearing of trees within Landsat pixel, with at least 50% tree canopy reduction. The loss was only mapped within tree cover extent mask. The gain was defined as the establishment of tree cover extents (ha) over the year 2000 areas without trees. Gross gain was mapped only outside the year 2000 tree cover extent mask. Gain must represent at least 50% tree cover increase, that is present in the year 2014 (i.e. areas where tree cover increased after 2000, but that have been cleared before 2014, were not mapped as "gain" class).

The sample-based total area covered by tree crowns in the year 2000 (with 95% confidence interval) is 3,165.5 ± 269.3 thousand ha. The total tree canopy covers equaled 21% of the country area. More than a half of total tree canopy cover (54%) within the country was from trees outside forest including rural settlements, orchards and smallholder tree plantations.

The gross tree cover loss estimated using sample-based assessment was 272.6 ± 88.4 thousand ha. Gross loss represents 8.6% of the year 2000 tree canopy cover. Of the gross tree cover loss area, 48.7 ± 26.4 thousand ha. (17.9% of gross loss) restored tree cover by 2014. The gross tree cover gain, measured outside areas covered with trees in the year 2000, was estimated to be 359.6 ± 132.5 thousand ha or 11.4% of the tree cover in the year 2000. The net tree cover change was estimated as +135.7 ± 161.4 thousand ha. and represents an overall increase of the tree canopy cover within the country by 4.3% during the 2001-2014-time interval.

Gross tree cover loss mostly was found within hill forests, contributing 56.5% to the total loss. Hill forests have low tree recovery rate and small tree gain area. As a result, hill forests experienced net tree cover loss of 80.8 thousand ha. Trees outside forest (village home gardens, orchards, smallholder plantations) characterized by strong net tree cover increased by 219.3 thousand ha. (12.9% increase compared to the year 2000 area). Mangroves did not experience net tree cover change. New households and road networks in rural areas resulted in huge increase in tree cover in rural Bangladesh. Huge tree cover enhancement in Trees outside Forests contributed Bangladesh to reach tree cover 22.3% in 2014.

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1. Introduction

Deforestation and degradation in the tropics are important global issues due to their role in carbon emissions, biological diversity loss, and reduction of other ecosystem services. Of global gross tree canopy cover loss from 2000 to 2012, 32% occurred within tropical rainforests (Hansen et al 2013). The international negotiations on Reducing Emissions from Deforestation and Forest Degradation (REDD+) sponsored by the United Nations Framework Convention on Climate Change (UNFCCC) provides methodological guidance for conservation of forest carbon stocks, sustainable management of forests, and enhancement of forest carbon stocks in developing countries. Many national and international initiatives aimed at reducing deforestation and forest degradation are underway in Bangladesh, several of them specifically in support of the REDD+ national program. Preparation activities (i.e. the readiness phase) for the implementation of REDD+ at the national level have been developed in Bangladesh since 2010. The Ministry of Environment and Forests (MoEF) is the focal government agency responsible for the national REDD+ implementation. One of the important tasks of MoEF is development and implementation of a robust and transparent national forest monitoring system (NFMS) for monitoring and reporting of the REDD+ activities. The national forest policy 1994 emphasizes on conserving and monitoring of forest resources. The proposed national forest policy 2016 emphasized the importance of regular periodic forest monitoring. The National Information and Communication Technology (ICT) Policy (2012) also emphasized for the use of GIS and ICT technologies that set the premises for regular forest monitoring using remote sensing.

According to the Intergovernmental Panel on Climate Change guidelines (IPCC, 2006), the primary data that is required for national reporting on greenhouse gas emissions include forest area change over time (activity data) and emission factors (coefficients quantifying emissions per unit of forest area loss). The data on forest area change provided by an NFMS should be clearly documented, complete at the national scale, consistent between time intervals, comparable with other countries, and include uncertainty estimates (IPCC, 2006). Satellite observations provide the most feasible and temporally consistent data source for annual monitoring of forest extent and changes at the national scale (Hansen and Loveland, 2012).

Bangladesh Forest Department (BFD) started its remote sensing-based mapping in 1995, however, limited to some specific forest areas, at sub-national scales. BFD conducted first ever National Forest Assessment (NFA) during 2005-07, whereby data was collected from 296 sampling tracks (15X10 min interval) across the country, the wall-to-wall land cover map was prepared using Landsat imageries of 2005. The NFA findings show clear deforestation in the hill forests and plain land deciduous forest region.

After completion of NFA, several satellite-based monitoring was done for some protected area (National parks and wildlife sanctuaries). Realizing the importance of Carbon and Biomass, BFD completed carbon assessment of Sundarbans mangrove in 2010 and some 13 protected areas thereafter. BFD recently initiated the National Forest Inventory (NFI) Programme and the national land cover map is under preparation with technical assistance from FAO of the UN. The inventory protocol contains not only measuring above ground carbon but also below ground carbon from 1,858 clusters of plots across the country. BFD has started field measurements of biophysical parameters and it is expected to complete NFI by end of 2018. This NFI will be a milestone for Bangladesh National Forest Monitoring System (NFMS) history.

The goal of the current FD UMD joint initiative was to develop and prototype an efficient methodology for initial tree canopy cover and change assessment in the context of the development of an NFMS in Bangladesh. The choice of data and methods was guided by several requirements: (i) wall-to-wall annual national coverage of satellite data; (ii) cost-effective and fast data processing algorithm; (iii) statistically validated results. Landsat data were selected for the national assessment as the only medium spatial resolution data available free-of-charge. The Landsat data processing and analysis algorithm was developed by the University of Maryland (UMD) for the global forest cover and change mapping (Hansen et al 2013) and was applied at the national scale using an improved version of the global data processing system. Given the high spatial heterogeneity of tree cover within the country and the importance of the total tree canopy cover estimate (including natural, planted forests and trees within agroforestry systems), BFD decided to estimate not only within forest area but also trees outside forests (TOF) within the country. Tree cover extent and change were mapped at the annual intervals, and the national area estimates were obtained using probability-based sampling. Using sample-based analysis, the total tree canopy cover extent and change was disaggregated by forest type. The work was carried out as a collaboration between the BFD, UMD and Silva Carbon program as part of technical capacity development for developing countries in support of REDD+ reporting. Source Landsat data were processed by UMD while national wall-to-wall mapping and sample-based assessment were performed by the BFD. The results depicted national tree canopy cover extent and change from 2000 to 2014 and are presented as a baseline of activity data for national REDD+ activities measuring and reporting.

2. Data

Two satellite datasets were used for our national analysis: (i) wall-to-wall medium spatial resolution multi-temporal data for tree canopy cover and change mapping; and (ii) time-series of medium and high spatial resolution data for sample-based analysis. The wall-to-wall dataset consisted of Landsat multispectral imagery and digital elevation data; the sample- based dataset consisted of Landsat annual time-series data and time-series of very high resolution (VHR) imagery available through Google Earth.

2.1. Landsat data

For this analysis, we used the entire archive of Landsat TM, ETM+, and OLI/TIRS imagery available at the United States Geological Survey National Center for Earth Resources Observation and Science (USGS EROS). The total number of Landsat scenes used for national mapping was 7,225. All images were acquired in the standard terrain-corrected L1 T format, which provides systematic radiometric, geodetic and topographic accuracy. We used four reflectance bands (red, near infrared, and two shortwave infrared bands) along with the emissive thermal infrared band. All Landsat images were automatically processed to flag cloud/shadow contaminated observations. Spectral reflectance was normalizing to reduce the effects of atmospheric scattering and surface anisotropy. Landsat images were aggregated into 16-day composites; observations with higher quality (lower atmospheric contamination) were prioritized during compositing.

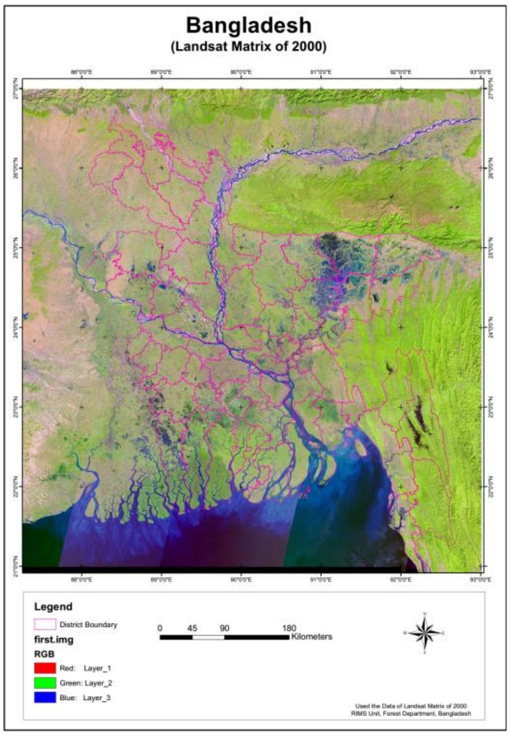

Figure 1: Landsat Matrix 2000

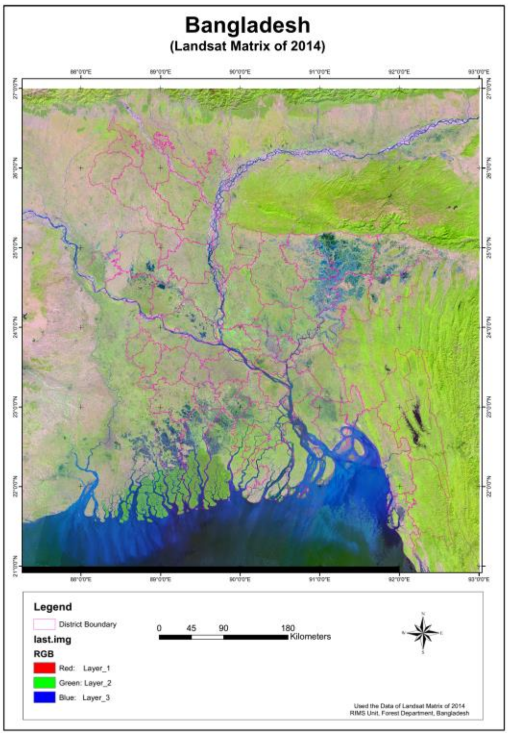

Figure 2: Landsat Matrix 2014

To map tree canopy cover for the year 2000, we employed the entire Landsat data collected from 1999 to 2001. Using three years of observations allowed us to create a consistent, gap-free, cloud-free national dataset which would be impossible to obtain using a single year of observations. Normalized reflectance 16-day time-series from the year 1999 to 2001 were composited into a set of metrics reflecting median, minimum, maximum, and certain percentiles of per-band ranked data, and averages between percentiles.

For tree canopy change the mapping between the year 2000 and 2014 we derived a set of multi-temporal metrics per Landsat pixel from 16-day observations without cloud/shadow contamination. First, we defined start and end date of observation timeframe: the first date was selected as close as possible to the end of the year 2000, and the last date to the end of 2014. Year 2000-2014 metric set was build using all observations between the first and the last date and includes: (i) reflectance values representing maximum, minimum and selected percentile values (10, 25, 50, 75 and 90% percentiles) using per band and band ratio rank orders and values associated with rank orders of NDVI and brightness temperature values; (ii) mean reflectance values for observations between selected percentiles (for the max-10%, 10-25%, 25-50%, 50-75%, 75-90%, 90%-max, min-max, 10-90%, and 25-75% intervals); and (iii) slope of linear regression of band reflectance value versus 16-day composite date. These metrics have been shown to perform well for long-interval tree cover dynamics mapping.

In addition, annual metric sets were derived for each year 2000-2014. All annual cloud/shadow free observations was used to generate annual metrics, and, in case the number of annual observations was less than five, additional observations were selected from the preceding/following years. Annual metric set includes median, minimum and maximum reflectance values, as well as reflectance values corresponding to the minimum and maximum values of NDVI, NDWI (normalized ratio of NIR and SWIR bands), and brightness temperature. The annual metrics were used to apply annual tree cover model and to allocate tree cover loss events by date.

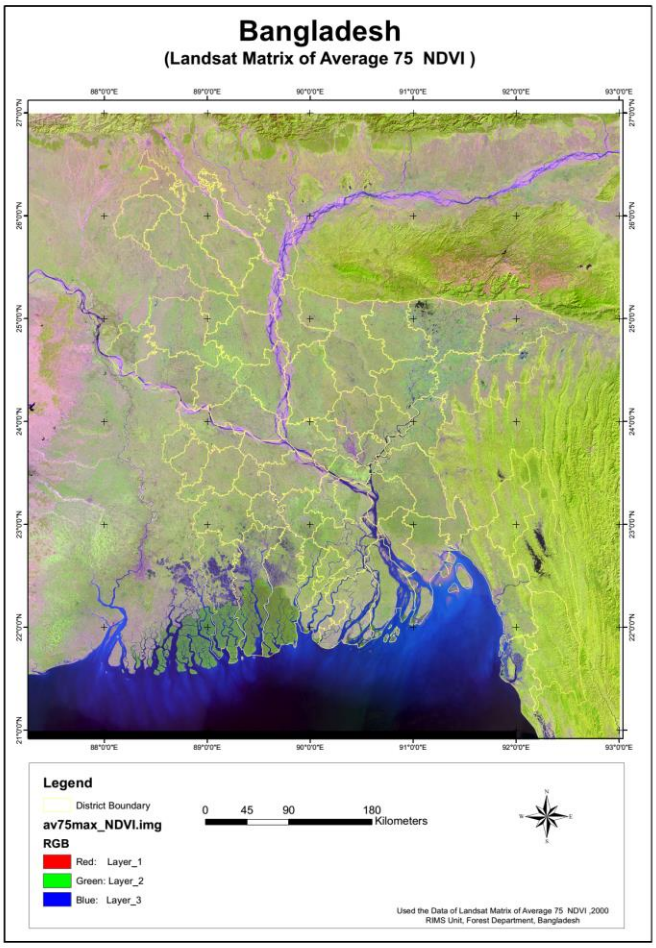

Figure 3: Landsat NDVI 2000

Landsat data processing was performed by UMD team using high-performance computing resources available only at the university.

2.2. Topography data

Elevation above sea level, slope, and aspect were added as additional data layers for the classification. We used void-fill seamless Shuttle Radar Topography Mission (SRTM) digital elevation model available at http://srtm.csi.cgiar.org, and calculated slope. Topography metrics were re-projected and resampled to match the 30 m Landsat pixel size.

2.3. Sample time-series data

Sample-based assessment involved interpretation of tree canopy cover and change using time-series of satellite data. For each sample area (which represent a 30x30m Landsat data pixel), an annual Landsat time-series data were collected. In addition, we employed all VHR imagery presented on Google Earth platform. Both medium and high-resolution datasets for each sample were used simultaneously to facilitate correct land cover and change interpretation

Tree cover 2000

Figure 4: Landsat 2000, base image

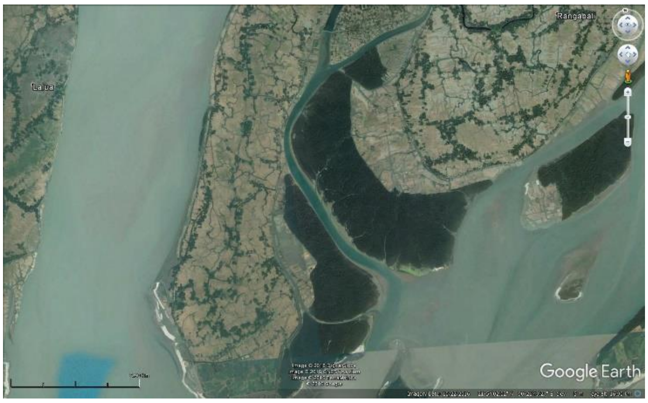

Figure 5: Corresponding Google earth image,2002

Tree cover Gain

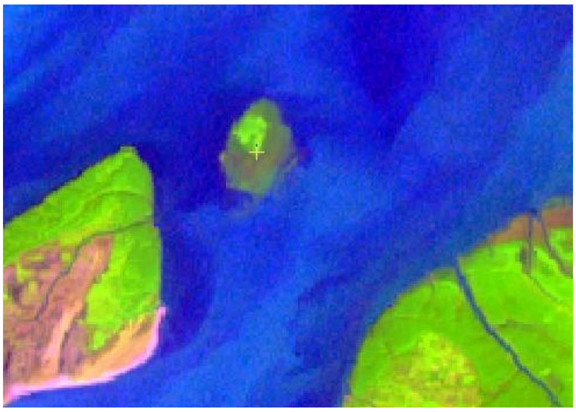

Figure 6: Landsat 2000*, base image*

Figure 7: *Corresponding* Google Earth Image 2002

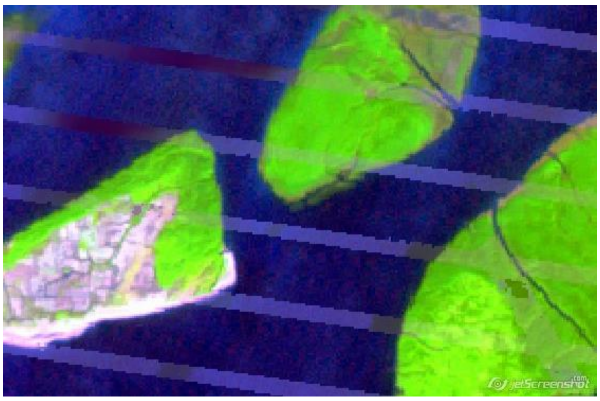

Figure 8: Landsat 2014, Land accretion and forest gain is visible

Figure 9: Corresponding Google Earth Image 2013

Forest loss

Figure10: Landsat 2000, *base image*

Figure 11: Corresponding Google Earth Image,2001

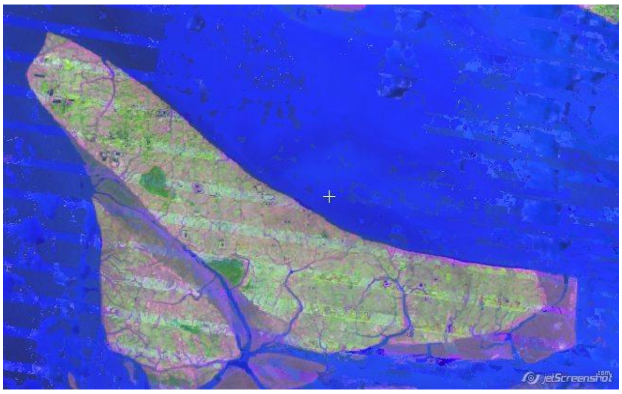

Figure12: Landsat 2014, land erosion and forest *loss is visible*

Figure 13: Corresponding Google Earth Image 2013

Figure14: Landsat 2000, *base image*

Figure 15: Corresponding Google Earth Image 2002

Figure16: Landsat 2014, *loss is visible*

Figure 17: Corresponding Google Earth Image 2014

3. Methods

3.1. Mapping tree cover extent for the year 2000

While the goal of our assessment was to estimate the tree canopy cover area, we employed a binary (trees/no trees) classification at Landsat pixel scale to map national tree cover extent. Tree canopy cover was defined as crown cover from vegetation above 5 m tall. At Landsat scale, pixels with greater than or equal to 50% tree crown cover within a 30x30m pixel were considered as “trees”, and less than 50% as “no trees”.

To create a wall-to-wall national tree cover extent map, Landsat spectral metrics from the 1999-2001 interval were characterized using supervised decision tree classification. Classification training was created manually, using circa the year 2000 Landsat image composite and VHR imagery from Google Earth as a reference. The classification process was performed iteratively until the desired classification result was obtained.

3.2. Sample-based estimation of national tree canopy covers for the year 2000

The objective of the sample-based assessment was to obtain the unbiased area of tree crown cover for the year 2000, the uncertainty of the area estimate, and to separate the total area of tree cover by forest type. We employed a stratified sampling design (Olofsson et al., 2013; 2014). Samples were allocated within areas mapped as “trees” and “no trees” by the wall-to-wall map. To better account for mixed pixels, special strata were selected: “tree cover periphery” and “buffer around tree cover areas”, which included boundary pixels of the respective classes. Together with “core tree cover” and “core no trees”, four strata were created, and samples were allocated to each stratum in amounts between equal and proportional representation (Table 1).

Table 1. Stratified sampling design for tree cover estimate for the year 2000

Stratum	area, ha*1000	count, pixels	% total	N samples
Core tree cover	1337.2	18820603	8.9	200
Tree cover periphery	1324.3	18726681	8.8	200
Core no trees	10639.5	150956982	71.2	400
Buffer around tree cover areas	1666.7	23605677	11.1	200

Each sample represented a pixel 30mx30m in extent. Samples were interpreted using Landsat data for the year 2000 and available high-resolution data from Google Earth. Analysts recorded percent tree canopy cover per sample in 5% increments, as well as forest type (for pixels with trees present). To collect data for map validation, we also recorded binary interpretation of tree cover extent (yes/no), using 50% tree canopy cover threshold. From all samples (N=1,000), 14 were marked as "low certainty" due to a disagreement between the analysts. Out of 1,000 samples, only 293 lacked VHR data circa 2000. For these samples tree canopy, cover interpretation may be incorrect due to changes that may happen between the year 2000 and the date of the first available VHR image.

3.3. Gross tree canopy cover loss and gain mapping

Gross tree canopy cover loss and gain were mapped for the entire analysis interval (2001-2014, with the year 2000 as a reference year) using supervised classification. Two sets of decision tree models were created and applied independently: gross tree cover loss and gross tree cover gain. Tree cover loss was defined as clearing of trees within Landsat pixel, with at least 50% tree canopy reduction. Loss event was detected only once (i.e. in the case of fast rotating tree plantation, only first clearing was recorded). Areas that gained tree cover after the loss were still marked as a loss. The loss was only mapped within tree cover extent mask (see section 3.1). The gain was defined as the establishment of tree cover over the year 2000 areas without trees. Gross gain was mapped only outside the year 2000 tree cover extent mask. Gain must represent at least 50% tree cover increase, that is present in the year 2014 (i.e. areas where tree cover increased after 2000, but that have been cleared before 2014, were not mapped as "gain" class).

Tree canopy cover change training was manually created using a set of selected multi-temporal metrics (composites for circa years 2000 and 2014, annual tree canopy cover temporal trends, maximum reflectance composite) and VHR image time-series from Google Earth. The classification process was performed iteratively. Due to ambiguity of small-scale tree canopy cover change interpretation at Landsat scale, only relatively large, (at least 9 Landsat data pixels) unambiguous area of tree cover change were used as training data. Thus, we expect that the classification model has low sensitivity to small-scale and sub-Landsat-pixel change events.

3.4. Sample-based estimation of national tree canopy cover changes 2001-2014

The sample-based analysis was performed independently for tree cover loss and gain. Similar to the tree cover 2000 validation, we selected 1000 samples for each product using stratified design, with four strata: "core" change and no change, peripheral change (1-pixel periphery of all change patches), and 1-pixel buffer around all change patches. The sampling design presented in table 2.

After initial sample-based results assessment we decided to add additional samples to (i) decrease the overall change estimation uncertainty; and (ii) to allow a separate sample-based change estimation for the Sundarbans Forest Reserve (SFR) area. The final sampling design (including additional samples) presented in Table 2

Table 2. Stratified sampling design for tree cover change estimate, 2001-2014

Gross tree cover loss

code	Loss	area, ha*1000	count, pixels	% total area	N samples
1	core	34.2	480602	0.2	128
2	periphery	161.3	2272793	1.1	275
3	no loss	14476.8	205192754	96.7	824
4	buffer	295.4	4163794	2.0	279
Total samples					1506

Gross tree cover gain

code	Gain	area, ha*1000	count, pixels	% total area	N samples
1	core	17.5	245952	0.1	122
2	periphery	98.1	1383985	0.7	273
3	no gain	14627.6	207311191	97.7	821
4	buffer	224.5	3168815	1.5	270
Total samples					1486

The following reference data were used for sample-based interpretation:

- Annual Landsat image composites (cloud-free, gap-filled annual data).
- Temporal profiles of annual minimal NDVI, maximal annual shortwave reflectance, and annual tree canopy cover.
- Google Earth high-resolution imagery time-series.

All data were available from a purposely build web interface. Figure 1 shows an example of Landsat time-series data representation using the UMD-GLAD sample validation interface.

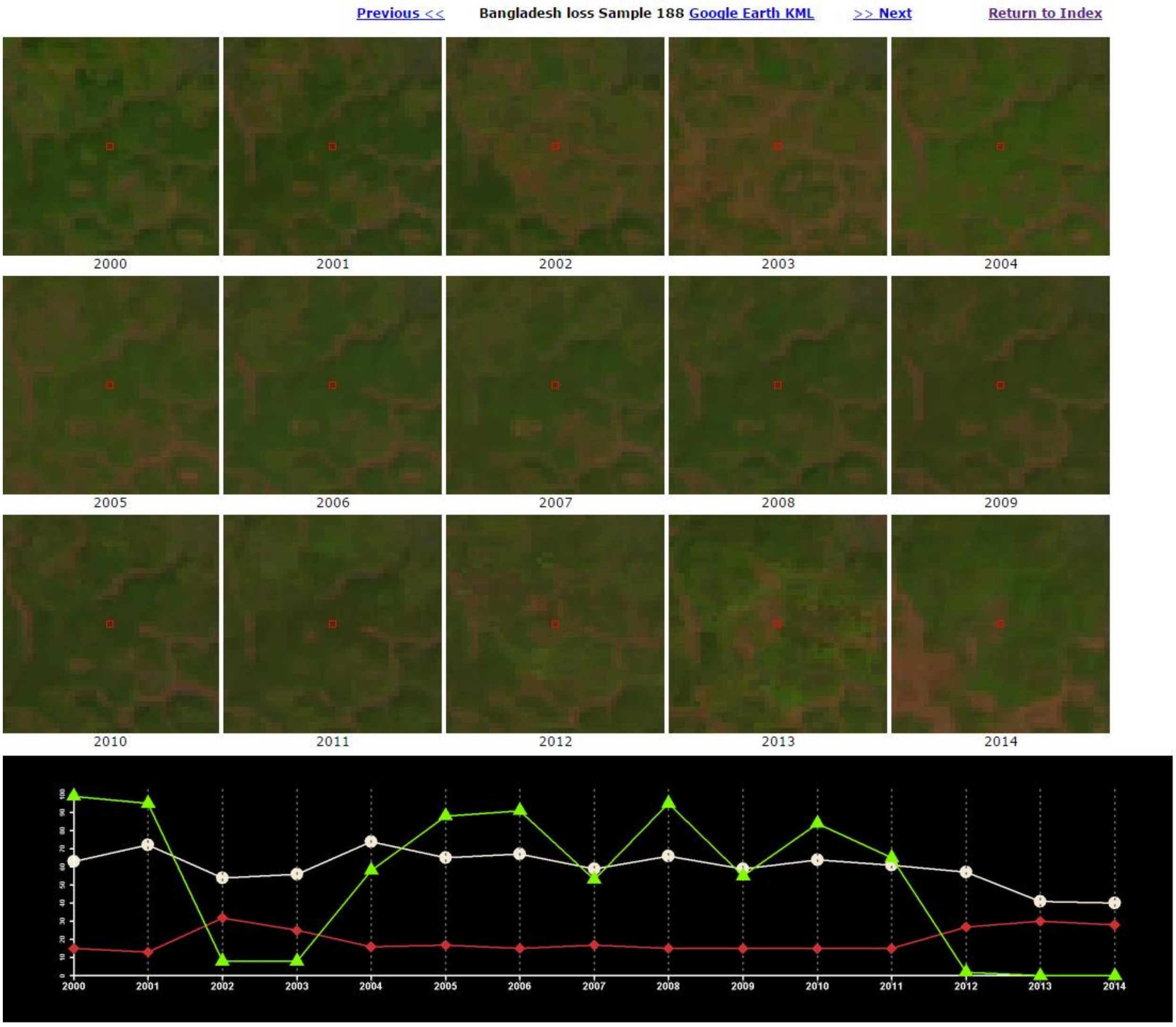

Figure 18. Reference Landsat data example. Image subsets represent cloud-free annual Landsat data campsites centered at the sample pixel. The graph shows annual tree canopy cover (green), annual minimal NDVI value (white) and annual maximal shortwave infrared band reflectance (red). In this example (forest plantation), tree cover loss was detected twice, in the year 2002 and 2012. The tree cover has not recovered by the year 2014.

Sample interpretation was performed by the RIMS team and re-examined by the UMD team. We collected the following information for each sample:

Loss sample assessment:

- Percent tree cover loss;
- Tree cover loss binary interpretation (yes/no), using 50% target class threshold;
- Loss event date (only for the first disturbance event),
- Forest type for the year 2000 (before loss)
- Land-use for the year 2014 (after loss)
- Percent tree cover gain after loss (by the year 2014)
- Interpretation certainty.

Gain sample assessment:

- Percent tree cover gain;
- Tree cover gain binary interpretation (yes/no), using 50% target class threshold;
- Forest type for the year 2014 (after gain event)
- Interpretation certainty.

4. Results

4.1. Tree canopy cover for the year 2000

The sample-based total area covered by tree crowns in the year 2000 (with 95% confidence interval) is 3165.5 +/- 269.3 thousand ha. The total tree canopy covers equaled 21% of the country area (22% if the only country land area is considered).

The total tree canopy cover area was disaggregated by forest type using reference information collected for each sample (Table 3). Forest area (which include hill, sal, swamp, and mangroves forests and forest plantations) was estimated as 1464 thousand ha and made up 9.8% of the country area. The area of natural sal and swamp forests were very small, and that is why it was estimated with low precision. More than a half of total tree canopy cover (54%) within the country was from trees outside forest including rural settlements, agroforestry, and smallholder tree plantations.

Table 3. Tree canopy cover area within Bangladesh in the year 2000 by forest type

Forest type	Area, thousands ha	95% confidence interval of area estimation, +/- thousands ha	Proportion of the total tree cover area, %
Hill forests	937.9	169.4	29.6
Mangroves and mangrove plantations	503.0	98.9	15.9
Sal forests	16.6	21.3	0.5
Swam forests	6.6	13.0	0.2
Trees outside forests	1701.4	248.3	53.8
Total tree canopy cover	3165.5	269.3	

We compared the total tree cover area disaggregated by forest types with National Forest Inventory (NFI) 2005-2007 data (FAO 2014) (Table 4, Fig. 2). The sample-based estimate of tree canopy covers within forests (including hill, sal, swamp, and mangroves forests) if 1.5% higher compared to the NFI estimate (1,464 thousand ha and 1,442 thousand ha, respectively). A possible explanation of this difference is inclusion of some shifting cultivation areas as “forests” by our analysis and the inclusion of tree canopy cover that existed in the year 2000 but was cleared from 2000 to 2005. The total tree canopy cover (including forests and trees outside forests) estimated by our method is 16% lower compared to the total forested area estimated by NFI (3166 and 3780 thousand ha, respectively). The most probable cause of this difference is an overestimation of rural tree cover by the NFI data. While rural settlement area consists of a mosaic of houses, infrastructure, crops, and trees, the entire settlement area was considered as tree cover by the NFI.

Table 4. Sample-based estimated national tree cover area 2000 and NFI data 2005-2007. The area is shown in thousand ha. Sample-based results include 95% confidence interval (shown in brackets)

<table>
<tr><th colspan="2">Sample-based estimate for the year 2000</th><th colspan="2">NFI 2005-2007</th></tr>
<tr><td>Forest and forest plantations</td><td>961.1 (+/- 203.7)</td><td rowspan="2">Forest</td><td rowspan="2">1442</td></tr>
<tr><td>Mangroves forests and plantations</td><td>503.0 (+/- 98.9)</td></tr>
<tr><td rowspan="3">Trees outside forests</td><td rowspan="3">1701.4 (+/- 248.3)</td><td>Other wooded lands</td><td>289</td></tr>
<tr><td>Wooded land with shifting cultivation</td><td>372</td></tr>
<tr><td>Rural settlement with trees > 0.5 ha</td><td>1677</td></tr>
<tr><td>Total</td><td>3165.5 (+/- 269.3)</td><td>Total</td><td>3780</td></tr>
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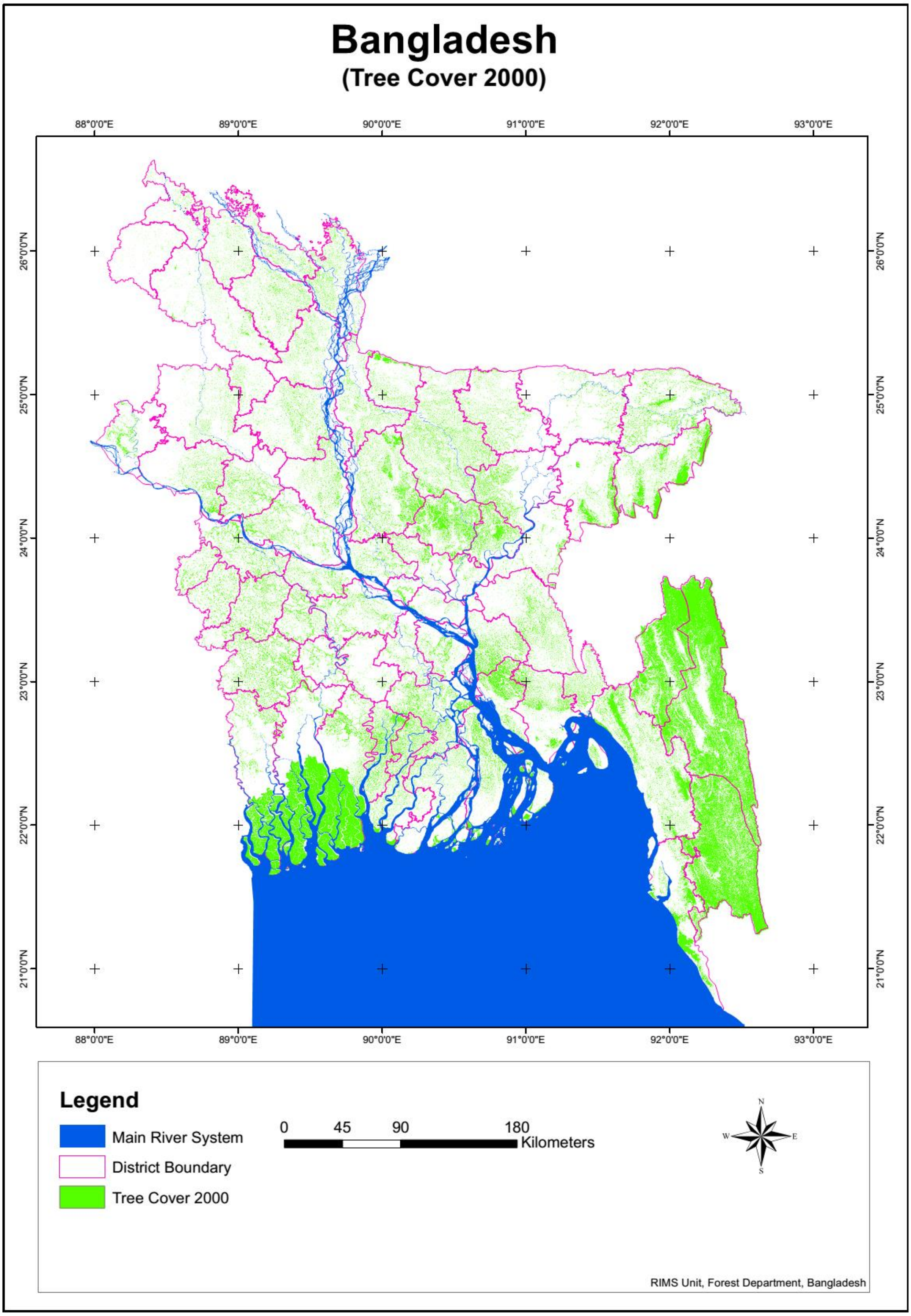

Figure 19: Tree cover mask 2000

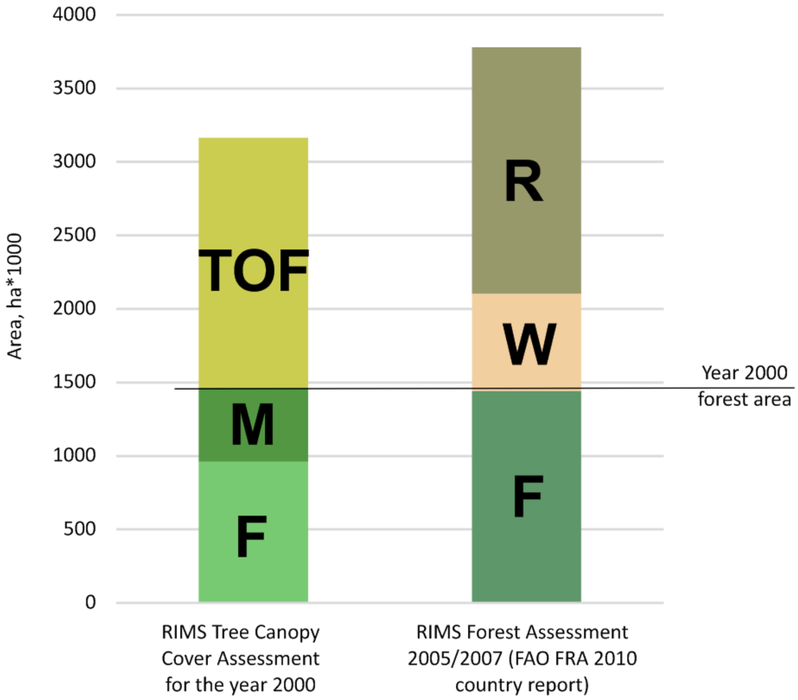

*Figure 20. Comparison of the national tree canopy covers estimate by forest types for the year 2000 with the FAO FRA 2010 national report based on the NFI 2005/2007 data. For the current product ("RIMS Tree Canopy Cover Assessment"), **F** stands for forests (including hill, sal, and swamp forests and forest plantations); **M** stands for mangroves and mangrove plantations, and **TOF** stands for trees outside forests. For the Forest Assessment 2005/2007, **F** stands for forests, **W** for other wooded areas (including areas of shifting cultivation), and **R** stands for rural settlements with trees. The horizontal line shows sample-based forest area estimates for the year 2000.*

The sample reference data were also used to assess the quality of our Landsat-based tree cover extent mask. The reference data were converted into two binary categories of "tree cover" and "no trees" using a 50% crown cover threshold within sample area and compared with the forest cover extent map for the year 2000. The resulting confusion matrix (in percent country area) is presented in Table 5.

Table 5. Confusion matrix for the national tree cover extent 2000 map (percent country area). "Tree cover" defined as an area having tree canopy cover above 50%.

	Reference	
Map	*Tree cover*	*No trees*
Tree cover	15.71	1.99
No trees	7.71	74.59

The Overall accuracy of the classification was 90.3%, with a User's accuracy of 88.8%, and a Producer's accuracy of 67.1%. Validation results revealed that that the binary Landsat-scale map tends to omit tree cover area. Sample-based assessment allowed the unbiased national tree cover area estimate. The uncertainty within 95% confidence interval is only 8.5% of the total estimated tree cover area.

4.2. Gross tree canopy cover loss, gain, and net tree cover extent change from 2001 to 2014

The total gross tree cover loss estimated using sample-based assessment was 272.6 (+/- 88.4) thousand ha. Gross loss represents 8.6% of the year 2000 tree canopy cover. Of the total gross tree cover loss area, 17.9% (48.7 +/- 26.4 thousand ha) restored tree cover by 2014. These areas represent tree rotation within tree plantations, shifting cultivation and agroforestry systems. The gross tree cover gain, measured outside areas covered with trees in the year 2000, was estimated to be 359.6 (+/- 132.5) thousand ha, or 11.4% of the tree cover in the year 2000. To estimate net tree canopy cover change, we subtracted gross tree cover loss from the area of gross tree cover gain and tree cover restoration within gross loss areas (Eq. 1). The standard error was estimated using the error propagation method (Eq. 2). The net tree cover change was estimated as +135.7 (+/- 161.4) thousand ha and represents an overall increase of the tree canopy cover within the country by 4.3% during the 2001-2014-time interval. The 95% confidence interval for the national net tree canopy cover change estimate is quite large, and spans from the small negative change (-26 thousand ha) to substantial gain (+297 thousand ha). Such high relative uncertainty was expected in the highly heterogeneous landscape of Bangladesh, where change (both loss and gain) is pervasive, but individual change patches are very small, and net change area is negligibly comparing to the total tree cover area.

$$C_n = G_g + G_l - L_g$$

Equation 1. C_n – net tree cover change; G_g – gross tree cover gain; G_l – gain of tree cover within areas of tree cover loss; L_g – gross tree cover loss

$$SE_{C_n} = \sqrt{SE_{G_g}^2 + SE_{G_l}^2 + SE_{L_g}^2}$$

Equation 2. SE – standard error. Other variables denoted as in Equation 1.

The observed tree covers dynamic (Table 6, Fig. 3 and 4) resulted in different net change area between different forest types. Gross tree cover loss mostly was found within hill forests (which include natural forest stands, timber plantations, and shifting cultivation areas), contributing 56.5% to the total loss. Hill forests have low tree recovery rate and small tree gain area. As a result, hill forests experienced net tree cover loss (-80,800 ha, or 8.6% of their year 2000 area). Trees outside forest (village forests, orchards, smallholder plantations) characterized by strong net tree cover increase. Their area increased by 219,300 ha (12.9% increase compared to their year 2000 area). Mangroves did not experience net tree cover change. Tree loss and gain within mangrove forests were spatially separated: while some patches of mangroves were flooded or cleared for agriculture, new plantations were established on newly formed islands in the river estuary. Sal forests did not experience significant tree cover area changes. We did not detect changes in swamp forest, mostly due to their small size which precludes correct estimation using national sampling design.

Table 6. Sample-based estimates of tree canopy cover change within the country from 2001 to 2014

	The year 2000 tree canopy cover, ha*1000	Gross tree canopy cover loss, ha*1000	Tree canopy cover gain within areas of loss, ha*1000	Gross tree canopy cover gain, ha*1000	Net tree canopy cover change, 2001-2014, ha*1000
Hill forests	937.9	153.9	35.8	37.3	-80.8
Mangroves	503.0	33.4	0.6	30.5	-2.3
Sal forests	16.6	0.5	0.0	0.0	-0.5
Swam forests	6.6	0.0	0.0	0.0	0.0
Trees outside forest	1701.4	84.8	12.2	291.9	219.3
Total (uncertainty within 95% confidence interval)	3165.5 (269.3)	272.6 (88.4)	48.7 (26.4)	359.6 (132.5)	135.7 (161.4)

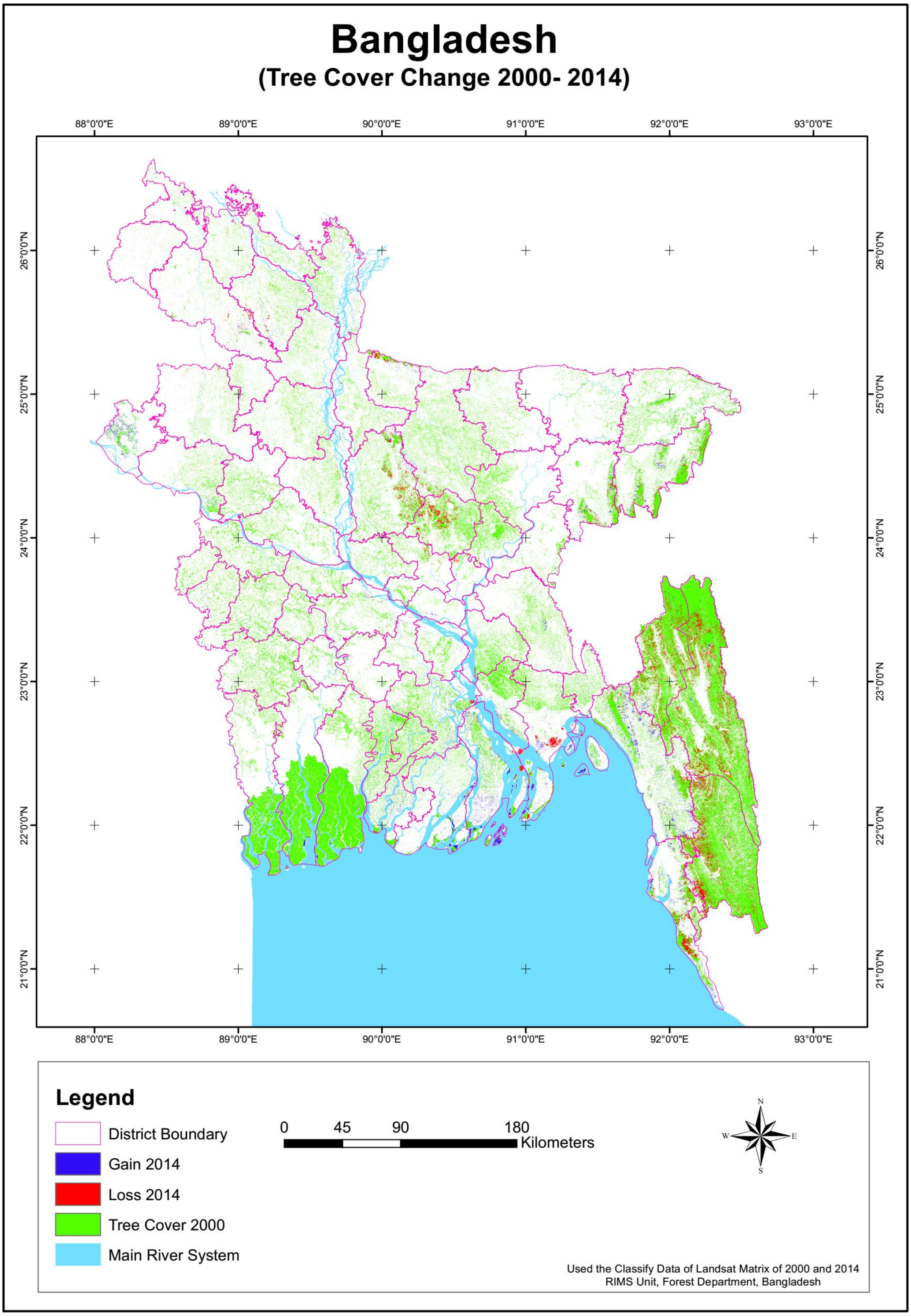

Figure 21: Tree cover change map 2000=2014

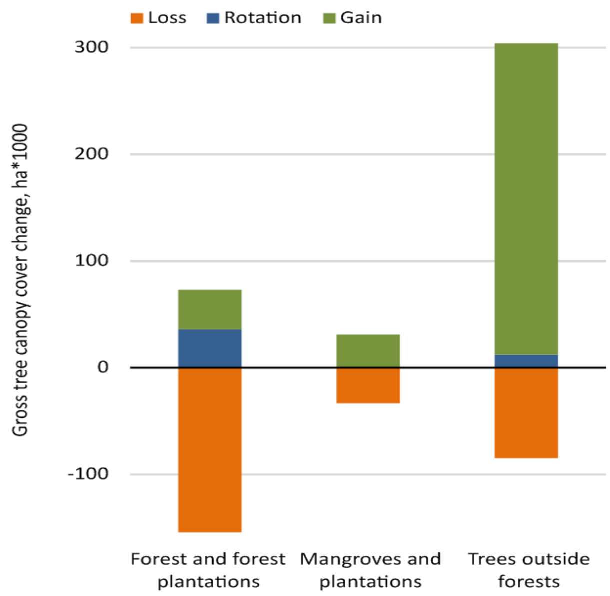

Figure 22. Gross tree canopy cover loss and gain 2001-2014 for different categories of forests. "Rotation" stands for tree cover gain after the loss event.

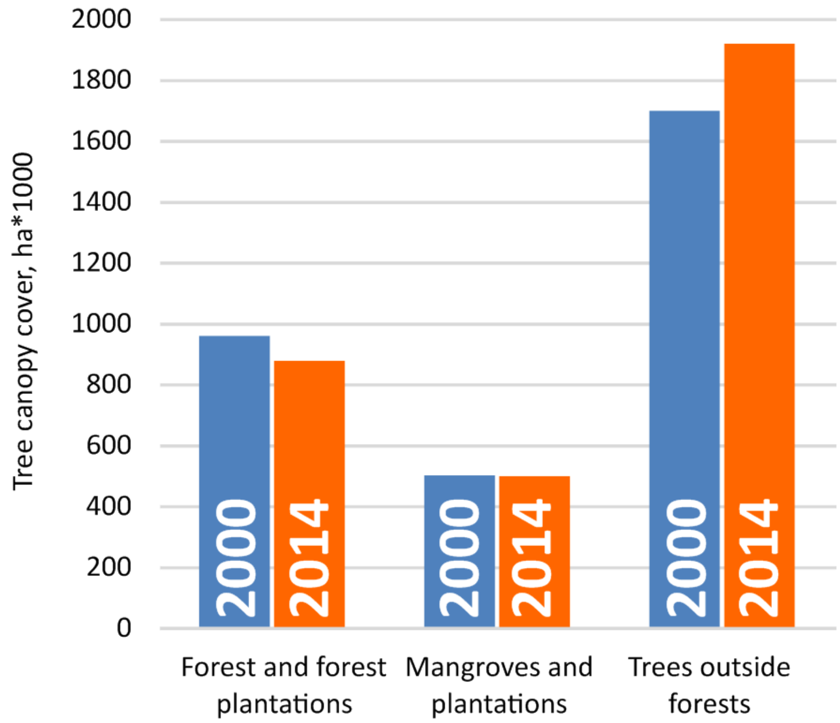

Figure 23. Tree canopy cover area for the years 2000 and 2014 per forests category.

Map accuracy metrics showed that both gross tree canopy cover loss and gain maps have high omission rates (Table 7). Overall accuracy is high, however, given the fact that commission error is relatively small, and the change classes area is less than 2% of the country land area. Comparing to an area-adjusted estimate of "loss class" and "gain class" (pixels with >=50% loss/gain), the map omitted 34.1% loss area and 67.5% gain area. The main reason for this omission was the small scale of change events that in most cases did not affect an entire Landsat pixel. The Sample-based analysis that relied on the high-resolution satellite image interpretation provides the only way to accurately estimate the tree canopy cover loss and gain within the highly heterogenic forest landscapes characterized by small-scale change dynamics as those within Bangladesh.

Table 7. Map accuracy metrics for the gross tree canopy cover loss and gain maps 2001-2014

	User's accuracy (SE)	Producer's accuracy (SE)	Overall accuracy (SE)
Gross tree cover loss	67.5 (2.4)	41.7 (5.8)	98.4 (0.3)
Gross tree cover gain	63.8 (2.6)	20.2 (3.6)	97.8 (0.4)

Annual gross tree canopy cover loss area was measured using sample reference data. However, not for all samples, we were able to detect the date of change event with high certainty. For samples that have only a few very high-resolution images available on Google Earth and where change date could not be detected from Landsat image time-series, change area was allocated equally to all years 2001-2014. Overall, from 441 samples with tree cover loss detected we confidently interpreted the date of the loss event for 346 samples. The sample-based annual gross tree cover loss varied from 6.6 thousand ha (in the year 2002) to 43.2 thousand ha (in 2011).

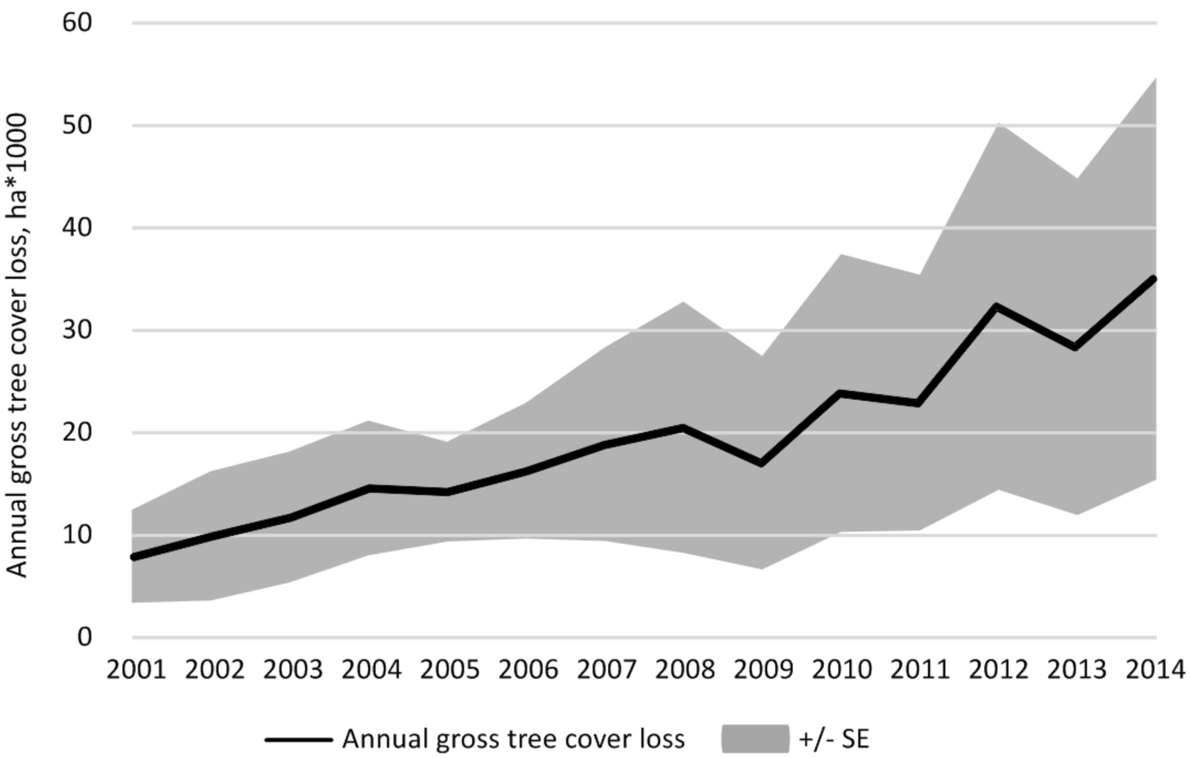

Figure 24. Annual gross tree canopy cover loss area. Black line represents annual gross tree cover loss in thousand ha; gray area represents standard error of this estimation. The annual area estimations were smoothed using 3-years rolling average filter.

We detected an increase in the annual gross tree canopy cover loss area during the analyzed time interval (Fig. 5). The average gross tree canopy cover loss for 2001-2005 interval (11.9 ha*1000*year^{-1}) was more than doubled by 2010-2014 interval (27.8 ha*1000*year^{-1}). The intensification of the gross tree cover loss, however, did not cause the net loss of tree cover. This may indicate that the gross tree cover gains also increased over this time interval, although we did not measure this in our analysis. It should be noted that the error of analyst-based date allocation is unknown. Given that most of the high-resolution images available through Google Earth were from later years, we assume that some of the earlier change events may be missed by an analyst. The extent of this uncertainty, however, could not be measured due to gaps in high-resolution data coverage in the early 2000s.

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