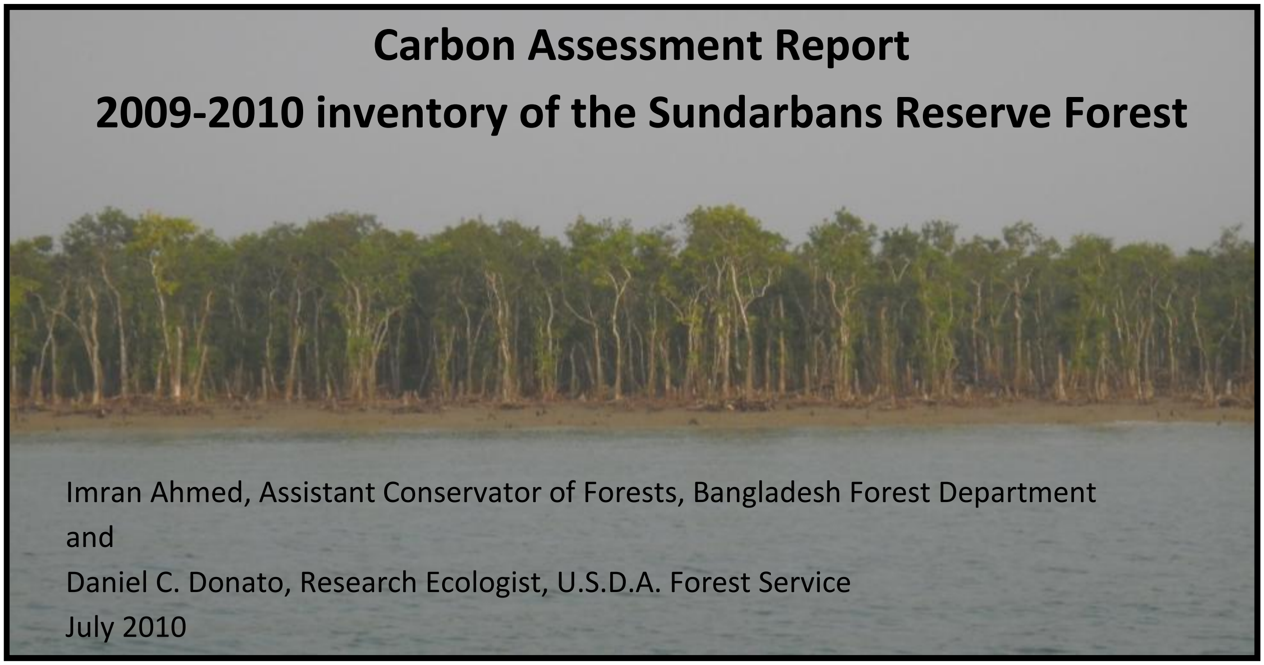

Carbon Assessment Report
2009-2010 inventory of the Sundarbans Reserve Forest

Imran Ahmed, Assistant Conservator of Forests, Bangladesh Forest Department
and
Daniel C. Donato, Research Ecologist, U.S.D.A. Forest Service
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1. INTRODUCTION

This document presents field-based carbon (C) stock estimates for the Sundarbans Reserve Forest of Bangladesh. First, it presents an estimate of current C stocks, obtained from the 2009-2010 field-based forest inventory. Second, it contains an estimate of change in C stocks since the previous inventory, which was conducted in 1996-1997. This latter analysis provides an estimate of certain "emission factors" over the recent past, which, when combined with remote sensing and other data on land-cover change ("activity data"), can be used to establish a baseline C trend against which future changes in C stocks can be evaluated.

Methods are briefly summarized here where relevant, but comprehensive methodological information can be found in the separate protocol and meta-data documents (hereafter 'the protocol'; see "Protocols for Measuring & Reporting Carbon Stocks in Mangrove Forests" by Daniel C. Donato, J. Boone Kauffman and Melanie Stidham, 2009).

This report provides some of the quantitative information necessary for carbon market/monitoring projects (e.g., REDD+ proposals)—specifically current C stocks, their distribution among aboveground and belowground pools, and recent trends in C stocks (relevant to baseline). Note that this is not a full project document for carbon market/monitoring projects, which requires many other components including management plans, remote sensing analyses, socio-political aspects, etc. This document is also not a forest resource inventory report (e.g., timber stock assessment), which requires a separate series of computations and summaries from the same dataset.

Background Information:

The current forest inventory began with an extensive training program led by the U.S. Forest Service (USFS) and USAID in November 2009, followed by a 5-month field campaign led by the Bangladesh Forest Department (FD) and the Integrated Protected Area Co-Management (IPAC) project, from December 2009 through April 2010.

For this carbon inventory, a Tier 3 approach (per IPCC sourcebooks) was considered most appropriate for the Sundarbans Reserve Forest. The reserve represents approximately half of all Bangladesh forests, and likely represents a key terrestrial carbon stock or sink/source for the country. In addition, the existing need for forest inventory data in support of an updated forest management plan already justified an intensive field campaign. The measurements required for a typical forest resource inventory and a Tier 3 carbon inventory are generally quite similar. Finally, an existing forest inventory plot grid in Sundarbans provided an opportunity to leverage past data to compare historic and future carbon stocks and emissions.

2. INVENTORY OF CURRENT C STOCKS

2.1 Methods – Current C stocks

2.1.1 Project Design Aspects

Project Area Boundary

The inventory area is defined as the Sundarbans Reserve Forest (SRF), the boundaries of which are well defined by relevant legislation and are well mapped. Note that aquatic portions of SRF—the rivers and sea channels—are not considered with respect to carbon storage under current regulations or markets. Carbon accounting and markets are currently focused on terrestrial carbon stores only, particularly forests. This means that, although the total area within SRF is ~600,000 hectares, only the ~412,000 hectares of actual land area are currently eligible for carbon accounting and carbon markets. This means that total carbon stocks in SRF were computed over the 412,000 hectares of land, not by the 600,000 hectares of total area.

Stratification of the Project Area

In some cases it may be desirable to stratify the project area into subpopulations, or 'strata,' that form relatively homogenous units. Because each stratum should have lower variation within it, fewer plots may be needed to achieve the same level of precision. Stratification could be based on, for example, land use or vegetation type, but should be carried out using criteria that are directly related to the variables to be measured—for example, the carbon pools in trees.

For Sundarbans, it was recommended not to *a priori* stratify the project area. This recommendation was for several reasons. First, an existing systematic sampling grid is already in place, with historic data available from those ground points. This will allow past, current, and future data to be evaluated in a consistent manner. Second, as long as a systematic sampling grid was started from a random point (which the SRF inventory grid was), that sample layout is considered the most rigorous and intuitive. Third, Sundarbans is a dynamic region, with short- and long-term changes in forest cover and biomass occurring due to changes in hydrology, sedimentation, disease, and human factors. Thus, a stratification employed today may not make sense in the future as vegetation communities and lands shift spatially. For information purposes, in addition to presenting reserve-wide estimates (non-stratified), we also present summaries by vegetation type and management unit.

Carbon Pools Measured

Most international standards divide forests into roughly five carbon pools: 1) aboveground and belowground biomass of live trees, 2) non-tree vegetation, 3) dead wood, 4) forest floor (litter), and 5) soil. Not all pools are required to be measured in every project; decisions can be made at the project level to streamline the effort involved in carbon assessment. A pool should be measured if it is large, if it is likely to be affected by land use, or if the land-use effects or size of the pool are uncertain. Small pools or those unlikely to be affected by land use may be excluded.

For the SRF carbon assessment, consultation with FD personnel suggested a recommendation to measure trees, non-tree vegetation, dead wood, and soil. Trees are the most susceptible to land use activities, and soil may be the largest and most uncertain carbon pool in mangroves. Dead wood and non-tree vegetation may be a significant biomass component in SRF and may change significantly with logging activities. Forest floor is usually a minor or even negligible biomass component in Asian-Pacific mangroves; as SRF is similar, this pool was excluded.

Methods for measuring trees, non-tree vegetation, and dead wood were adapted from relevant IPCC-associated sourcebooks (see the protocol for full descriptions of measurements for each C pool). In brief, trees were quantified by stem surveys for large and small trees, non-tree vegetation was quantified by counts combined with allometric destructive harvests, and dead wood was quantified by line-intercept transects. Because mangrove soils are often C-rich and vulnerable to land-use change to deeper layers, soils were measured to 1-meter depth rather than only 30 cm as commonly recommended. To reduce the amount of material to be processed, subsampling was employed, taking advantage of the fact that mangrove soils are typically non-differentiated over the top meter of soil. Thus, rather than taking a core of the entire top meter, manageable subsamples of 5 cm were taken representing 0-30 cm depth and 30-100 cm depth, respectively. Field supplies for measuring all C pools are listed in Appendix I.

Determining Type, Number, and Location of Measurement Plots

Type— Permanent or Temporary:
Sourcebooks describe options for 'permanent' sample plots, in which all trees within plots are tagged and tracked through time, or 'temporary' sample plots, in which trees are not tagged. [Note that the latter plots are called 'temporary' even if they are permanently marked and revisited over time.] In the latter method, trees are treated like other C pools and are tracked at the plot level over time, rather than as individuals. For the time and logistical constraints imposed by mangrove field work, it was recommended here that trees are not tagged.

Plot shape and clustering:
The shape and size of sample plots is a trade-off between accuracy, precision, time, and cost for measurement. Plots can either be one fixed size or 'nested,' meaning that they contain smaller sub-units for various C pools. Nested plots are generally more practical and efficient in forests with a range of stem diameters and densities, and were used in this inventory.

Clustered plot designs (using multiple 'subplots') tend to capture more microsite variation in vegetation, soils, etc., thereby reducing among-plot variation (increasing overall precision). For the SRF carbon assessment, a clustered plot composed of five circular subplots was employed, thus taking advantage of the increased precision of clustered sampling, and the fact that this plot design was employed during the previous forest inventory for SRF.

Number and location of plots:
Plot locations can be selected randomly or systematically (plot grid with random origin). However if some parts of the project area have higher carbon content than others, systematic selection usually results in greater precision than random selection. Systematic sampling is also easily recognized as credible.

The last SRF inventory, conducted in the 1990s, sampled approximately 1200 plots situated on a systematic grid at 1-minute intervals of latitude/longitude. Based on logistical constraints communicated by the Forest Department, approximately 150-300 plots is the maximum number that can be sampled in a given census effort now (300 would take two field seasons). Although 300 is the desired and recommended number, 150 may be adequate to achieve reasonable precision. The lower number is still likely adequate for the C assessment given local circumstances, and is similar to plot densities in difficult-access roadless areas that has been used by the United States' Forest Inventory and Analysis program.

To facilitate these options, the original plot grid was subsampled by selecting every second plot in both the x and y directions. This yielded 295 plots (the full option). To attain a lower plot density, every second row of this new grid was sampled; this yielded 155 plots. See relevant map in protocol document.

To determine that plots are representative of the entire project area, periodic checks should be made to ensure that the overall activity is performing in the same way as the plots. Field indicators of carbon stock changes or high-resolution satellite imagery can be used to accomplish this task.

<u>Determining Measurement Frequency</u>

Frequency of plot monitoring is yet to be determined. An initial recommendation is to conduct a re-inventory every 5 years if possible.

2.1.2 Field Inventory

The field inventory started with four days of *in-situ* field training, during which the first plots were surveyed. Officials from the USFS, Bangladesh Forest Department, and IPAC accompanied the participants. Participants learned the field protocols, practiced the use of instruments, and discussed probable questions regarding the inventory process. The actual inventory started in December, 2009, led by two Assistant Conservator of Forests (ACFs). The local NGO Codec organized the logistics including the hiring of vessels, labor for the team, medical support, and purchasing miscellaneous supplies.

Of the 155 inventory plots (originally established in 1996-97) targeted for re-sampling, 5 were now under water due to erosion, subsidence, or canal migration (and possibly sea-level rise). At least two of these five losses were apparently due to recent cyclone damage. Thus, a total of 150 plots were sampled in the 2009-10 inventory. Plots which were partially under large canals were recorded as such, with an estimate of the percent of the plot area under water and measurements taken as normal in above-water portions.

Two field inventory groups, each led by an ACF, were formed for the SRF inventory team. Each group consisted of one ACF, one Forest Ranger/Deputy Ranger, two foresters, two students, two laborers, and two armed guards. Each group was assigned a small engine boat with boatman. The team leaders and some of the crew had participated in the USFS training. The students were from the Forestry program at Khulna University, which is located near the SRF. The team leaders and the Forest Ranger/Deputy Ranger worked mostly as recorders and reviewers of data. The foresters and students worked as enumerators. Each trip was seven to ten days long depending on stored food and availability of fresh water.

Before starting each journey, both groups sat together with detailed maps and GPS units to plan for the next plots. Local knowledge of laborers, guards, FD district staff, and even fisherman aided the crews' efforts to find suitable routes to plots and minimize hiking time. Generally each group completed one plot per day, but often this pre-planning activity helped the groups to complete more than one plot a day. Working in more than one plot a day was subject to the developed skill of the crew members and easy access to the plot. Sometimes both groups worked together to complete a third plot in a given day.

2.1.3 Data and Sample Management

Field data were entered into computerized spreadsheets periodically and backed up electronically in multiple physical locations. See Appendix II for examples of field data forms. Strict precautionary measures were taken in the process of data collection and data entry to minimize error (see QA/QC section below). Completed data forms were checked and reviewed in the field and data entry was also reviewed. At the end of the inventory, completed data forms were photo-copied and stored in two physically separate secure locations (Forest Department and IPAC offices). The final electronic data files, including one version with only field-collected numbers and one version with C computations, are stored with FD personnel, IPAC offices, and USFS personnel. Soil samples were air-dried in the field, oven-dried to constant mass at 60 °C at the Khulna IPAC cluster office, then sent to Chittagong for carbon analysis. Soil carbon analyses were conducted in the laboratory of the soil sciences division of the Bangladesh Forest Research Institute (BFRI).

2.1.4 Data Analysis

Aboveground and root C pools were computed using both locally derived allometries (via destructive harvests of various shrub species outside the plots) and international standard common mangrove tree allometries (see protocol and references therein) combined with local tables of wood density by tree species. Soil C storage was calculated as the product of soil C concentration (% of dry mass determined by wet oxidation techniques by BFRI), soil bulk density, and soil depth range. All plot-level computations were corrected for the portion of the plot falling on a canal >30 m width, so as not to bias the land-based C density estimates with areas that are officially considered water. (Insofar as we can tell, the GIS vegetation layer and official documents use 30 m as the cut-off between small streams that are part of the forest matrix and large streams that are part of the official water coverage.)

At the time of writing of this report, the soil C concentration analyses had not been completed by BFRI; thus this report focuses on aboveground and root C pools, but not soils. Soil data will be added to another version of this report at a later time.

All data computations can be followed in the complete 2009-2010 inventory excel data file ("SRF Forest Inventory_Carbon_Assessment_080610"), while referring to the protocol as well as relevant notes documented in the meta-data file ("Metadata for SRF C Inventory").

2.2 Summary of Findings – Current C Stocks

2.2.1 Carbon Density

Estimated current carbon pools are shown in Table 1. Mean total C density (excluding soil) was 136 Mg/ha (95%CI: ±16 Mg/ha), or moderate to high compared to other mangroves around the world. Total C density of non-soil pools ranged from a low of 20 Mg/ha in one Gewa-dominated stand to a high of 446 Mg/ha in one Sundri-dominated stand. Trees constituted the bulk of the C density across the forest reserve, with a mean of 82 Mg/ha aboveground and 36 Mg/ha belowground, which combines to account for 87% of all non-soil C.

Table 1. Mean carbon pools in the Sundarbans Reserve Forest, 2009-10 inventory.

C pool	C density (Mg/ha)	95% CI
Trees aboveground (stems + foliage)	82	*± 11*
Trees belowground (roots)	36	*± 4.2*
Saplings + seedlings aboveground	1.4	*± 0.1*
Saplings + seedlings belowground	1.0	*± 0.1*
Non-tree vegetation	2.8	*± 1.1*
Goran	7.9	*± 2.0*
Down wood	4.3	*± 0.9*
Soil 0-30 cm	TBD	*± TBD*
Soil 30-100 cm	TBD	*± TBD*
TOTAL (not incl. soil)	136	*± 16*

Uncertainty estimates (95% confidence intervals, or 95% CIs) were computed using standard techniques outlined in the protocol. The 95% CI for the total C density was derived through basic error propagation (square root of the summed squares of component pools), as outlined in the protocol. Note that, because certain pools were highly correlated, we aggregated those pools in an ecologically sensible way for error propagation (e.g., tree aboveground and belowground pools were obviously correlated and were combined into a single 'tree' pool for the uncertainty propagation step).

Although the plot sampling was not strictly stratified *a priori*, the grid-based sample covered all major land types and allowed *post hoc* analysis of different strata (e.g., vegetation types, management units). With respect to vegetation type, plots classified as Sundri-dominated forest contained by far the highest C density at 169 Mg/ha, followed by Gewa-dominated classifications which contained 102 Mg/ha (Table 2). Low-stature Goran-dominated vegetation contained the lowest C density at 64 Mg/ha, with Goran shrubs comprising 41% of C pools in that vegetation type (Table 2).

Table 2. Mean carbon pools (Mg/ha) in SRF from the 2009-10 inventory, by major forest type.

C pool	SUNDRI dominated		GEWA dominated		GORAN dominated	
	C density	95% CI	C density	95% CI	C density	95% CI
Trees aboveground (stems + foliage)	109	*± 15*	56	*± 15*	20	*± 4.1*
Trees belowground (roots)	47	*± 5.5*	25	*± 5.9*	11	*± 2.3*
Saplings + seedlings aboveground	1.5	*± 0.2*	1.4	*± 0.2*	1.0	*± 0.3*
Saplings + seedlings belowground	1.1	*± 0.1*	1.0	*± 0.1*	0.7	*± 0.2*
Non-tree vegetation	2.1	*± 0.8*	4.0	*± 3.1*	2.8	*± 3.8*
Goran	2.6	*± 0.9*	11	*± 3.6*	26	*± 7.8*
Down wood	5.4	*± 1.4*	3.5	*± 0.9*	1.7	*± 0.8*
Soil 0-30 cm	TBD	*TBD*	TBD	*TBD*	TBD	*TBD*
Soil 30-100 cm	TBD	*TBD*	TBD	*TBD*	TBD	*TBD*
TOTAL (not incl. soil)	169	*± 21*	102	*± 21*	64	*± 11*

Note: Forest type was determined by cross-referencing the inventory plot grid with the vegetation map layer created by FD RIMS office in 1990s, supplemented with cross-checking a subset of plots to verify that stand composition corresponded with mapped classification. Future in-depth analyses of stand composition in 2009-10 may shift the designation of some plots in the new inventory.

Separated by management unit (range; see Table 3), the Chandpai Range contained the most C-rich forests at 193 Mg/ha; the Satkhira Range contained the lowest C density at 57 Mg/ha.

Table 3. Mean carbon pools (Mg/ha) in SRF from the 2009-10 inventory, by management range.

C pool	CHANDPAI C density	CHANDPAI 95% CI	KHULNA C density	KHULNA 95% CI	SATKHIRA C density	SATKHIRA 95% CI	SHARANKHOLA C density	SHARANKHOLA 95% CI
Trees aboveground (stems + foliage)	127	*± 36*	93	*± 14*	20	*± 3.1*	101	*± 19*
Trees belowground (roots)	52	*± 13*	43	*± 5.5*	11	*± 1.7*	41	*± 6.7*
Saplings + seedlings aboveground	1.5	*± 0.3*	1.4	*± 0.2*	1.0	*± 0.2*	1.7	*± 0.2*
Saplings + seedlings belowground	1.1	*± 0.2*	1.0	*± 0.1*	0.8	*± 0.1*	1.2	*± 0.2*
Non-tree vegetation	2.7	*± 2.0*	3.2	*± 1.8*	2.5	*± 2.3*	2.6	*± 3.0*
Goran	1.2	*± 1.2*	4.6	*± 2.4*	19	*± 4.7*	4.7	*± 3.1*
Down wood	7.2	*± 3.0*	3.0	*± 0.7*	1.9	*± 0.5*	6.4	*± 2.0*
Soil 0-30 cm	TBD	*TBD*	TBD	*TBD*	TBD	*TBD*	TBD	*TBD*
Soil 30-100 cm	TBD	*TBD*	TBD	*TBD*	TBD	*TBD*	TBD	*TBD*
TOTAL (not incl. soil)	193	*± 48*	150	*± 20*	57	*± 7.1*	158	*± 26*

Several measures of stand structure were also assessed for their relationship to C density (Figures 1 and 2). The two attributes most strongly related to C density were height of co-dominant trees and stand basal area (Figure 1). Mean tree diameter (at breast height; dbh) was also correlated to C density, although not as strongly as height and basal area (Figure 1). This latter relationship included all trees including small saplings; future analyses may improve the correlation by including only medium to large trees. The strong relationship between tree height and C density suggests good potential for using LiDAR, which can measure forest height remotely, to track changes in C stocks in the future.

Stand density (trees per hectare) and canopy cover were not strongly related to total C density (Figure 2). These attributes can be high even when overall forest stature is low, for example when dominated by low shrubs.

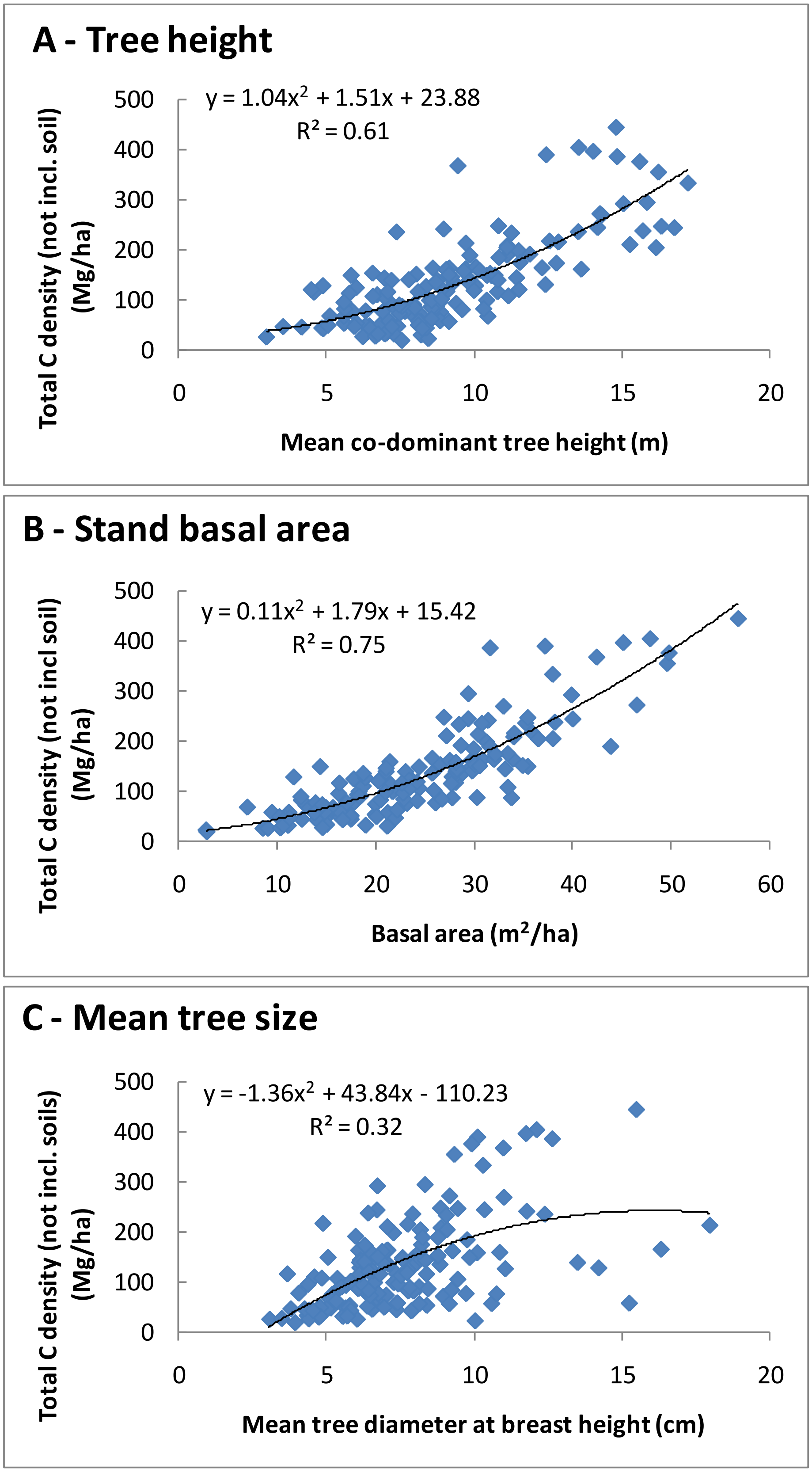

Figure 1. Relationship between total carbon density (sum of all non-soil pools) and plot-level estimates of **(A)** co-dominant tree height, **(B)** stand basal area, and **(C)** mean tree size. Total carbon density is fairly well correlated with these measures of stand structure. The relationship between tree height and C density suggests good potential for using LiDAR imagery to predict C density.

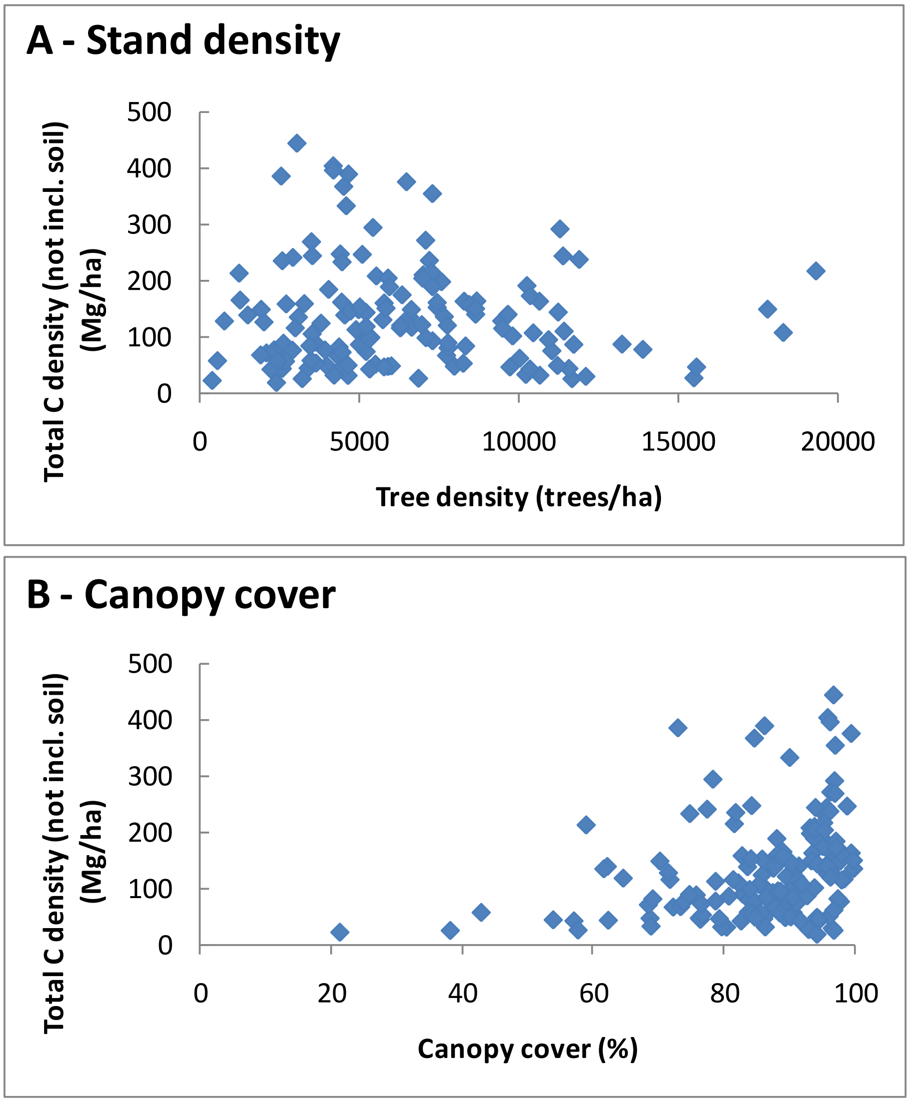

Figure 2. Relationship between total C density (sum of all non-soil pools) and plot-level estimates of **(A)** tree stem density and **(B)** canopy cover. These measures of stand structure are poor predictors of C density ($R^2 < 0.15$).

2.2.2 Carbon Stock

The total C stock of the SRF, which is obtained by multiplying the mean per-hectare C density by the land area, is estimated to be 55.8 Megatonnes (Mt, or 55.8 x 10^6 Megagrams). The 95% CI for the total C stock is 49.4 to 62.5 Mt. These values do not include C storage in soils, and may approximately double when soils are considered.

The amount of carbon dioxide (CO_2) equivalents contained in the SRF, obtained by multiplying by a molecular conversion ratio of 3.67, is estimated at 205 Mt (± 24.5 Mt), or over 4 times the annual CO_2 emission rate of Bangladesh from fossil fuel consumption.

Table 3. Total C stock and CO_2 equivalents across the Sundarbans Reserve Forest, 2009-10.

Mean total C density (Mg/ha)	Land area (ha)	Total C stock over whole SRF (Mt)	95% CI for total C stock (Mt)	CO_2 equivalents (Mt)	95% CI for CO_2 equivalents (Mt)
136 (± 16)	411,693	55.8	49.4 - 62.5	205	181 - 230

Notes:

- 1 Mt = 10^6 Mg.
- Land area is from RIMS office GIS data.
- 95% confidence limits for total C stock and CO_2 equivalents are simple propagation of lower and upper confidence limits of C density multiplied by the land area. No uncertainty estimate was available for land area, precluding full error propagation incorporating uncertainties in both parameters.

2.2.3 Comments on Stand Condition

Sundri top-dying:
This syndrome has been afflicting Sundarbans forests for many years, and has been cited by several authors as a significant ecological and management problem. The 2009-10 inventory indicates that top-dying was not a major factor at that time. While 58% of plots with Sundri trees had some sign of top-dying, an average of just 3% of individuals were affected within plots. The maximum proportion of individuals affected within a plot was 28%. Moreover, it was not always clear in the field whether a given tree with a partially dead top was actually affected by top-dying versus some other factor; as such, these percentages may be overestimates. These low levels of affliction apparently affected overall carbon storage very little, as there was no relationship between infection rate and C density (R^2 <0.10).

Cyclone damage:
On average, two or three cyclones strike Bangladesh per year. Several cyclones recently impacted the Sundarbans area, most notably Cyclone Sidr in 2007 and Cyclone Aila in 2009. Aerial reconnaissance in late 2009 and the inventory plot data both indicated a range of apparent cyclone damage, but only a small portion of the forest area was affected overall. Additionally, there was apparently high resilience to all but the most severe storm effects. According to the crew's assessment at each inventory plot, a total of 22 plots, or 14% of the total sample, showed some evidence of cyclone damage. However, nearly half of these 22 plots showed only light damage. A total of 8 plots, or only 5% of the total sample, showed severe damage. Surprisingly, there was no strong negative association between cyclone damage rating and C density, with associations as follows: No damage, 119 Mg/ha; Light

damage, 229 Mg/ha; Moderate damage, 179 Mg/ha; Severe damage, 227 Mg/ha (including at least two plots that were completely removed by the storms and had 0 C density).

Forest degradation (overcutting of trees):
Ten plots, or 4.3% of the sample, were classified by the crews as 'degraded' or 'deforested', as indicated by recent evidence of significant illegal tree cutting, abundant stumps, skid trails, and loss of canopy cover. On the basis of those data, it would appear that illegal timber cutting or overharvest has not recently been a major factor affecting forest C storage.

3. ASSESSMENT OF CHANGE IN C STOCKS, 1997-2010

The current inventory re-sampled a subset of a previous field inventory, which was conducted in 1996-97. This allows a direct comparison between C stocks at the different time points, and an assessment of associated C emissions or uptake during the interim.

The two main approaches to estimating land-use emissions are the stock-change approach and the gain-loss approach. The stock-change approach estimates the difference in carbon stocks at two points in time, while the gain-loss approach estimates the net balance of additions to and removals from a carbon stock. The stock-change approach is used when carbon stocks in relevant pools have been measured and estimated over time (such as in forest inventories), and is the approach used here.

Tracking of plot-level data is currently the primary way to assess forest *degradation,* the reduction in forest carbon density in lands remaining technically as forest cover. *Deforestation*, the loss of forest cover, is best assessed using remote sensing data ("activity data"). The latter analysis will be underway later this year, led by the FD RIMS office. Upon completion of that analysis, the activity data can be combined with the plot-level ground data to complete a comprehensive baseline assessment.

3.1 Methods – Change Assessment

All effort was made to conduct the change assessment using consistent methodologies. Computations of C density and C stocks in the 1996-97 inventory followed the exact same procedures as that for the 2009-10 inventory. For consistency, only the 155 plots in common between both surveys were included in the change assessment (rather than using all 1200 from the 1996-97 inventory). For details, see excel file "1997_Inventory_C_Computations_combined".

It should be noted that the re-sampled plots were in the same locations in both inventories, but some spatial error likely existed. In some cases the crews noticed markings of old plots; however, these were inconsistent and not reliable overall (durable plot markings are especially challenging in mangroves). This error is difficult to avoid but, over the course of >150 plots, any associated sampling error should balance out (i.e., not result in directional bias).

Certain differences existed in the 1997 dataset, requiring some adjustment of method and limiting what could actually be compared between time points. Mainly, the 1997 inventory was largely a timber resource inventory rather than a carbon inventory, so effectively only trees were measured. Non-tree pools were largely ignored in the previous survey. (Golpatta was measured in some plots in 1996-97, but the sample size was insufficient to include in the change assessment.) Therefore, only tree pools (aboveground and belowground) could be tracked over time. Trees are the most ready indicator of forest change and degradation, so this change assessment should still yield quite valuable insight.

Because of a local desire to track non-tree C pools, this assessment also evaluates whether there are strong enough correlations between tree and other pools to estimate changes in non-tree C pools between inventories. I.e., by knowing tree pools, it may be possible to predict/estimate other pools, allowing a comparison of total C density between surveys.

For the five inventory plots that were surveyed in 1996-97 but were under water in 2009-10 due to land subsidence, erosion, channel migration, sea-level rise, or cyclone damage, we included these in the change assessment. The loss of standing C stock in these sites (reduction to zero tree biomass) was factored into the estimate of change. Note that, because these five plots were included, this necessarily used an adjusted estimate of mean C density for the 2009-10 dataset compared to the estimate presented above, which excluded areas now under large canals. This difference was relatively minor. Also note that land accretion and gains of forest could have occurred, but there is no way to assess this by tracking plot data; rather this should be detected and accounted for by the remote sensing analysis if significant.

3.2 Summary of Findings – Change Assessment

3.2.1 Carbon Density and Carbon Stocks

Estimated 1997 carbon pools and comparisons with 2010 pools are shown in Table 4. Mean C density in 1997 (trees and sapling/seedlings only) was 76 Mg/ha (95%CI: ±6.6 Mg/ha). Carbon density ranged from a low of 15 Mg/ha to a high of 188 Mg/ha.

Multiplying by land area to obtain total C stock, the 1997 inventory indicates a C stock of 31.4 Mt at that time (95% CI: 28.6 - 34.0 Mt). Molecular conversion to CO_2 yields an estimate of 115 Mt CO_2 equivalents (95% CI: 105 – 124.8 Mt) stored in SRF in 1997.

Table 4. Comparison of mean C pools in SRF between the 1996-97 and 2009-10 inventories.

C pool	1997 inventory		2010 inventory		Change (2010 minus 1997)	
	C density (Mg/ha)	95% CI	C density (Mg/ha)	95% CI	Δ C density (Mg/ha)	95% CI
Trees aboveground (stems + foliage)	46	*± 4.3*	80	*± 11*	**(+)** 34	*± 12*
Trees belowground (roots)	27	*± 2.3*	35	*± 4.2*	**(+)** 7.2	*± 4.8*
Saplings + seedlings aboveground	1.6	*± 0.2*	1.3	*± 0.1*	**(-)** 0.3	*± 0.2*
Saplings + seedlings belowground	1.0	*± 0.1*	1.0	*± 0.1*	0.0	*± 0.1*
TOTAL (tree + sapl/seed only)	76	*± 6.6*	117	*± 15*	**(+)** 41	*± 17*

Note: Only tree and sapling/seedling pools could be compared because these were the only pools measured in the 1996-97 inventory.

(+) and **(-)** in change column indicate increases or decreases, respectively, during the 1997 to 2010 time period. Estimates for 2010 pools are slightly adjusted from previous section because this analysis included plots that were land in 1997 but now submerged in 2010 (land subsidence, etc.). These were excluded from the land-based C density estimate for the current C stock analysis, but were included as negatively changing plots in the change assessment. The difference is minor.

Comparing the two time points, the 2010 tree C pools were significantly higher than those from the same plots in 1997, suggesting an increase in C storage over this time period (Table 4). The estimated total increase, accounting for trees only, was 41 Mg/ha (95%CI: ±17 Mg/ha). The majority of plots, 68%, showed an increase in C density between the time points, while 32% showed a decrease (Figure 3). The distribution of changes was positively skewed, with the median change being +17 Mg/ha, but the mean change being +41 Mg/ha due to several plots that apparently showed very large increases (Figure 3).

Converting this difference to changes in C stocks (multiplying the mean per-hectare change by the entire land area of SRF) indicates an increase of 16.9 Mt of C storage over this time period (95% CI: 10.0 – 23.7 Mt). The confidence interval is strongly different from zero and suggests that the change is significant. Over the 13-year time interval, this change in C stocks suggests an average annual sequestration rate of 1.3 Mt C per year (95% CI: 0.8 – 1.8 Mt C per year).

In CO_2 equivalents, the estimated change in stocks was 62.0 Mt CO_2 (95% CI: 36.7 – 87.0 Mt C). The estimated annual sequestration rate over the 13-year period was 4.8 Mt CO_2 per year (95% CI: 2.9 – 6.6 Mt CO_2 per year), or ~10% of Bangladesh's annual fossil fuel CO_2 emissions.

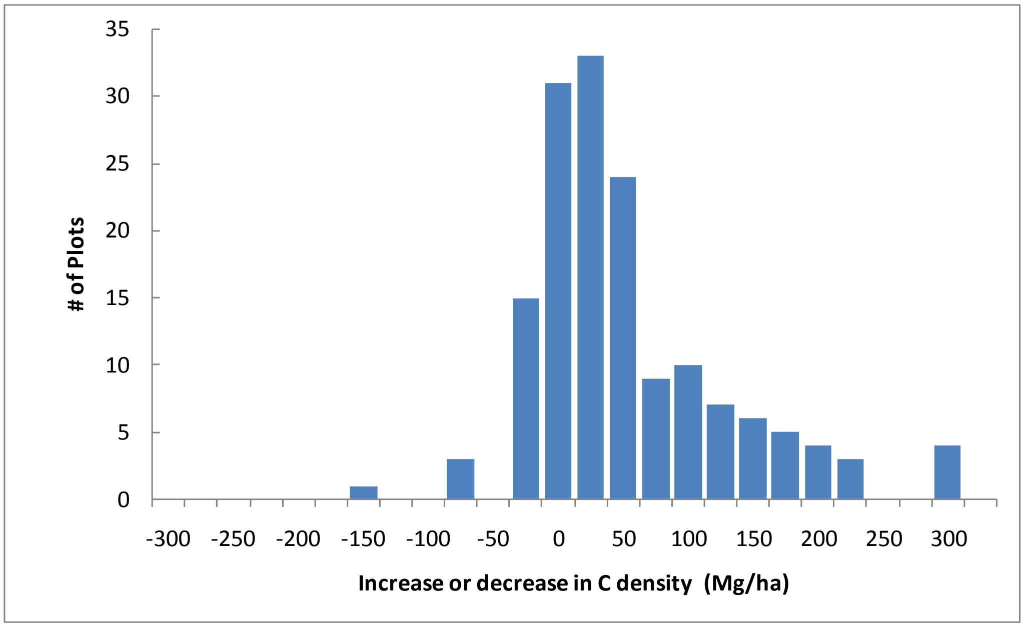

Figure 3. Histogram showing the number of plots that increased or decreased in C density between 1997 and 2010. Overall, 105 plots (68%) showed an increase in C density over this time period, while 50 plots (32%) showed a decrease. The shape of the histogram is skewed, with the median change across the whole sample being +17 Mg/ha, but the mean change being +41 Mg/ha due to several plots apparently showing quite large increases (see also Table 4).

Table 5. Estimated changes in total C stock and CO_2 equivalents across the SRF, 1997 to 2010.

Δ C stock		Δ CO_2 equivalents		Annual sequestration rate	
Change in C stock over whole SRF (Mt)	95% CI for change in C stock (Mt)	Change in CO_2 equivalents (Mt)	95% CI for change in CO_2 equivalents (Mt)	Sequestration rate in CO_2 equivalents (Mt/yr)	95% CI for sequestration rate (Mt/yr)
16.9	10.0 – 23.7	62.0	36.7 – 87.0	4.8	2.9 – 6.6

Note: Only includes trees pools, as these were the only pools measured in 1996-97 inventory.

The observation that C stocks apparently increased over the past 13 years was unexpected. Although most or all of the SRF is officially protected from most resource extraction, it is commonly stated/assumed that forests of the Sundarbans are being degraded due to illegal timber extraction, overharvest of fuel wood, etc. Thus, the expectation for this assessment was that the change in forest C storage would be negative (i.e., a loss of C stocks resulting in emissions rather than sequestration). However, the change quantified here was strongly positive, with confidence intervals significantly different from zero. A significant portion of this difference could be an artifact of sampling error. For example, some of the changes in C density within particular plots were extremely high (e.g., >200 Mg/ha change in 13 years) and likely unrealistic in biological terms. Errors in re-locating exact plot locations could also play a role. In addition, metadata and protocol descriptions for the 1996-97 inventory were lacking, meaning that the data had to be interpreted through the inventory report results only. (For example, it is not clear whether dead trees were measured in that survey; if not, adding those would have increased the 1997 C stocks and reduced the amount of positive change between surveys.) We feel this latter challenge was largely overcome, but there is likely still some non-trivial uncertainty in that regard. Finally, the quality of the 2010 field data collection and data management was documented for the current inventory, but documentation of QA/QC for the 1997 inventory was not available. The degree to which any or all of these errors may have affected the change estimate is almost impossible to know with certainty.

It is worth noting that the *general* pattern of observed change is ecologically sensible. In the absence of major disturbance, a typical stand development pattern is that tree densities thin out over time (through competitive exclusion and other mortality), with the remaining trees increasing in size. Indeed, compared to the 1997 data, the 2010 inventory showed lower stem densities, especially of small trees, but larger mean stem size and total basal area (Figure 4). The magnitude of this difference was large for a 13-year period, but the general pattern is fairly reasonable. Whether due to actual successional dynamics, sampling error, or some combination of the two, this difference is largely what explains the higher C stocks in 2010.

Changes in the density and basal area of the major tree species of the Sundarbans show a similar trend (Figure 5). This analysis was limited to overstory trees (>15 cm dbh), and this larger size class showed increases in density and basal area for most of the major species, especially Sundri and Gewa.

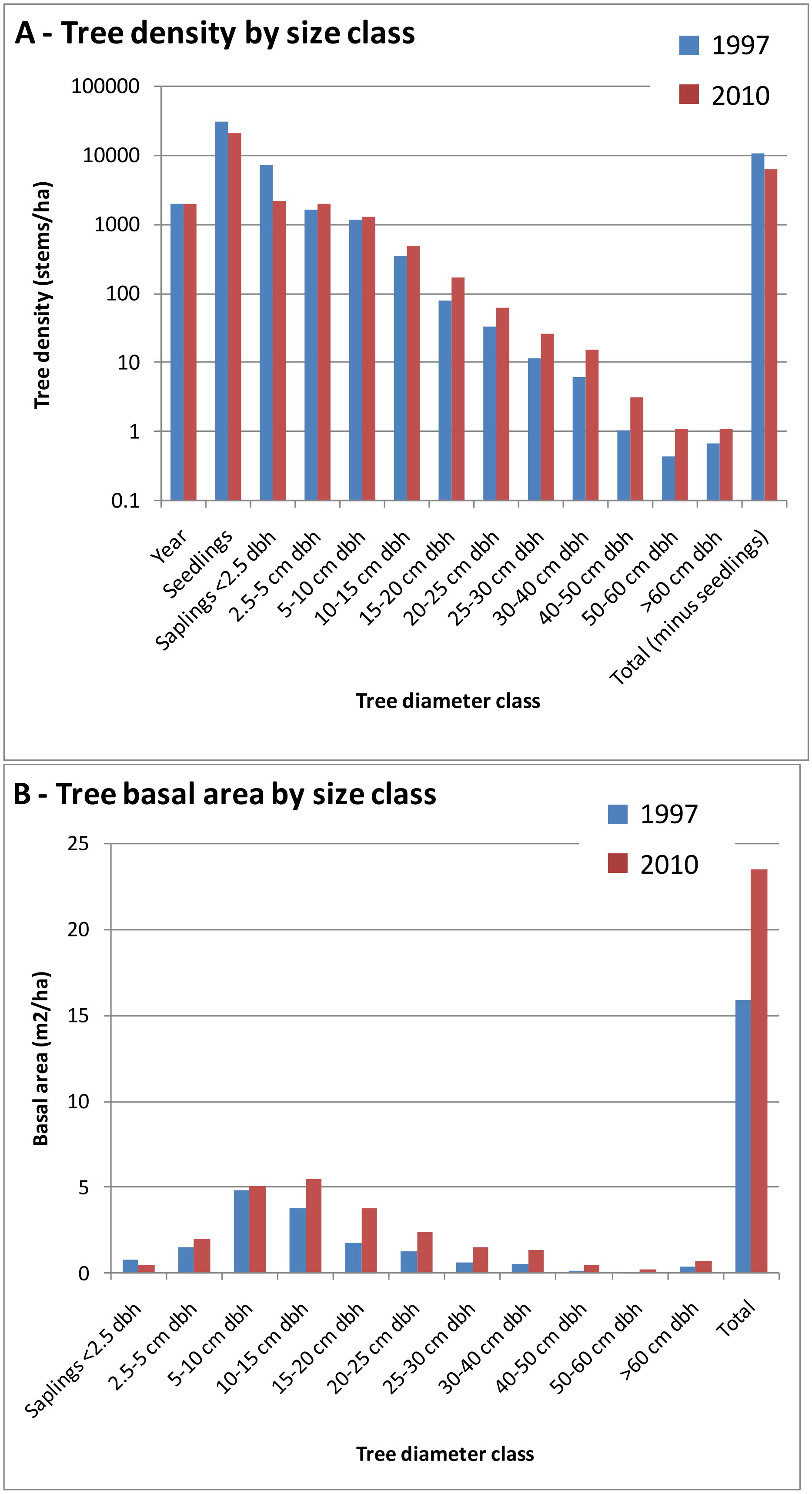

Figure 4. Tree density **(A)** and basal area **(B)** *by tree diameter class* in the 1997 and 2010 inventories. Note log-transformed y-axis in panel A. The 2010 inventory showed fewer small stems, and fewer total stems (apparent reduction in stem density), but more large stems. The basal area trend was similar.

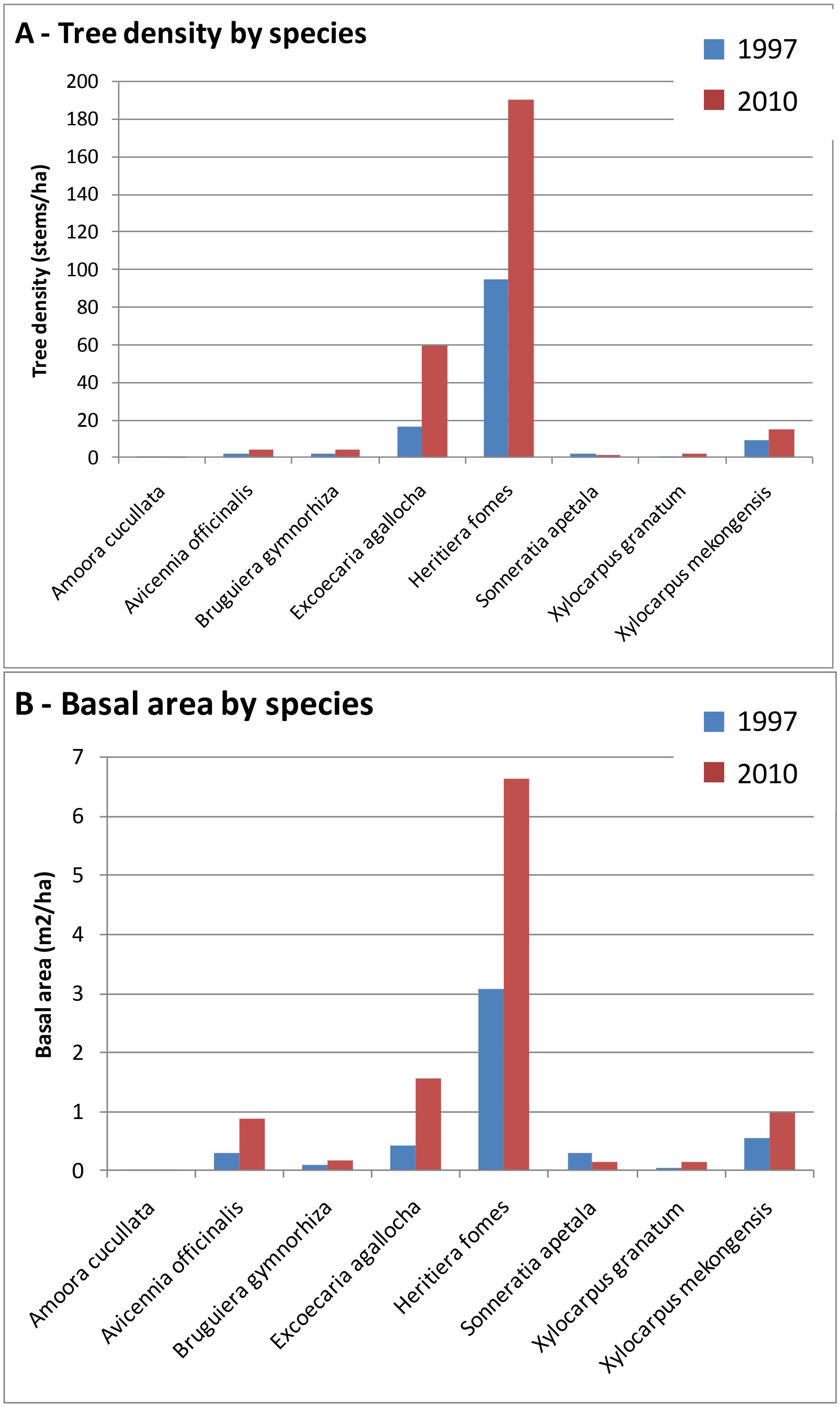

Figure 5. Tree density **(A)** and basal area **(B)** *by species* in 1997 and 2010 inventories. Only overstory trees (>15 cm dbh) of the 8 most common species are included here. Trends in stem density and basal area were generally similar. Sundri (*Heritiera fomes*) and Gewa (*Excoecaria agallocha*) dominated compositionally, and both were substantially higher in density and basal area in 2010 compared to 1997.

3.2.2 Assessment of Other (non-tree) C Pools

To see whether tree C density was strongly related to that of other C pools, thereby allowing predictive ability for other pools based on tree pools, a regression was made between tree C density and all other pools combined from the 2010 dataset (Figure 6). Data were log-transformed to better meet the assumptions of linear regression. The observed relationship was quite weak, with tree C density explaining less than 20% of the variation in other C pools (Figure 6). For this reason, assessment of changes in non-tree C pools in the recent past is not reasonably possible based on the inventory data alone. This report therefore focuses on changes in tree C pools only.

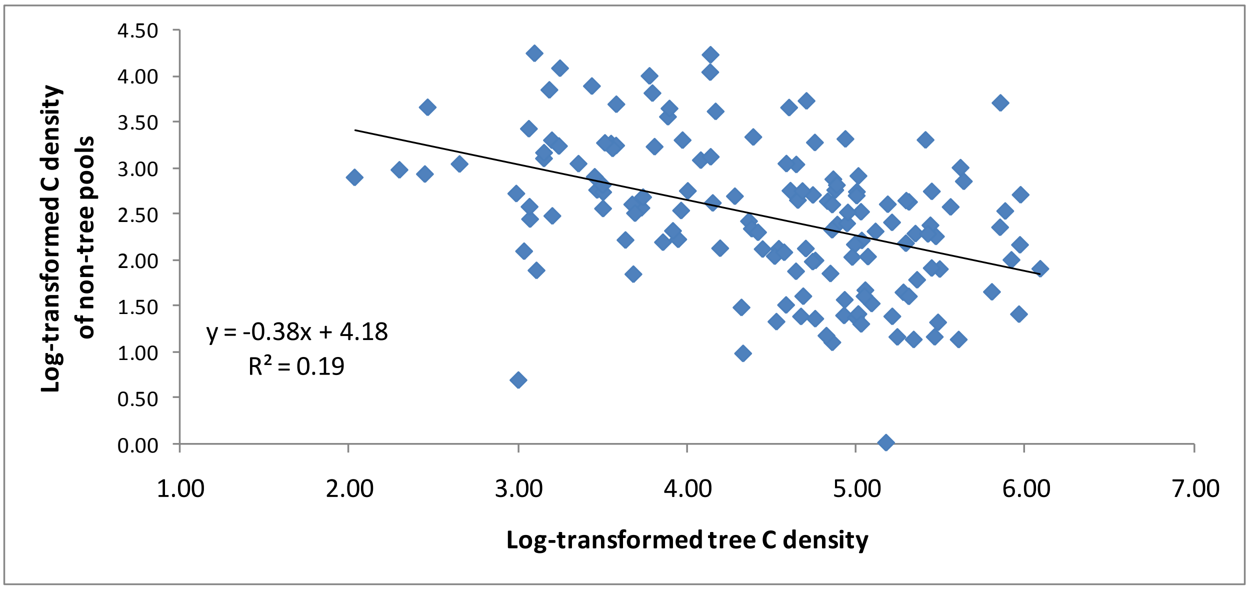

Figure 6. Relationship between tree C pools and non-tree C pools for the 2010 dataset. The relationship is weak and does not support prediction of other C pools (e.g., down wood, shrubs, soils) based on knowledge of tree pools. As such, the change assessment was limited to tree pools only.

4. QUALITY ASSURANCE / QUALITY CONTROL (QA/QC)

Quality assurance / quality control activities were emphasized from the outset of the 2009-10 inventory. Field procedures were subject to strict oversight and review by the project leaders. The crew carried the protocol at all times in the field, and any confusion could be solved by referring to the protocols as well as the local knowledge of team members. Before starting the journey, the plot location and access route were thoroughly studied using GPS units and detailed maps. The latitude/longitude points in the GPS and duly checked by the team leaders.

An important quality control activity was re-arrangement of team composition. Every week the team leader was changed; thus each team had the experience of working with both leaders. In this way, any gaps or methodological differences were minimized. The team composition itself was also changed occasionally during the field season. This shuffling helped in reducing observer/team biases and also improved efficiency.

Each completed data sheet was reviewed in the field. The bottom of every data sheet provides room to document quality control activities. At the end of every field outing, all data sheets were reviewed by a crew member for completeness, legibility and accuracy. Once satisfied by the quality of data recorded, the data reviewer recorded their name and the date of the review, along with any notes on issues that were noticed during the check so that they can be prevented in the future. The soil samples were re-packed from the plastic sample containers to whirl packs/zip bags after air drying. This re-packing was done by the crew on the main vessel. The team leaders monitored these processes to minimize mistakes.

Completed data sheets were filed separately by plot and stored in a safe location in the vessel. Upon return from a 7-10 day sampling trip, a copy of each data sheet was made and kept in the Khulna IPAC office. At the end of the inventory, completed data sheets were photo-copied and stored in two physically separate secure locations (Forest Department and IPAC offices).

Field data collection procedures were also observed and checked by higher officials of the Forest Department and IPAC. The officials accompanied the inventory team to a subset of plots to observe the data collection procedure. They also visited a subset of plots from where data had already been collected two months earlier, to check for actual visitation and accuracy of measurements (the plots were re-sampled by the crew with the officials present). It was found correct with the previous data, and the marking tape was found precisely at the center of the plot. The officials were satisfied with the quality of inventory work.

The data entry process was also conducted very carefully, with close oversight by the team leaders. Entered data were also checked and reviewed. After completion of data entry, a randomly selected 10% of plots were cross-checked for data entry errors, plus spot-checking of others. The observed error rate was less than 1%, which was deemed acceptable and highly unlikely to affect overall estimates significantly. The database was also checked for extreme outlier values (e.g., trees larger than 200 cm) to eliminate potentially influential errors. The final electronic data files, including one version with only field-collected numbers and one version with C computations, are stored with FD personnel, IPAC offices, and USFS personnel.

For data analysis, all data steps were recorded in understandable fashion in spreadsheet files, with separate meta-data documenting how various decisions and approaches were arrived upon during the computations. See electronic file "Metadata for SRF C Inventory.docx".

APPENDICES

Appendix I – Field supplies

Most of the field supplies were provided by the USFS; other items were locally obtained. The inventory team had the following supplies to complete the field survey:

- 100-m tapes
- 10-m dbh tapes
- 1-m extension for augers
- 30-m tapes
- 5-m dbh tapes
- AA batteries
- Auger handles
- Burlap sack
- Clinometer
- Clip boards
- Compasses w/declination
- Compasses, back up type
- Crescent wrenches
- Data box with files
- Densiometer
- Digital scale (500g)
- Drying oven with shelves and oven thermometers
- Duct tape
- Dutch auger tips
- Felco clippers
- Flagging
- Folding rulers
- Gauge for down wood size classes
- Gear box
- GPS w/ manual
- Hanging scales, large
- Hanging scales, small
- Havor sacks
- Jungle boots
- Laser rangefinder
- Maps
- Open face auger
- Packing tape
- Pens & pencils
- Permanent marker
- Plastic container for soil sample collection
- Rite-in-rain paper
- Rulers
- Serrated knives for soil sample collection
- Torches
- Water proof digital camera w/card, case, battery charger
- WD 40 protectant
- Whirlpaks
- Ziploc bags

Appendix II – Data sheets

Example data sheets attached separately.