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State of research on carbon sequestration in Bangladesh: a comprehensive review

Sahadeb Chandra Majumder ^a, Kamrul Islam ^b and Mohammad Mosharraf Hossain^a

^aInstitute of Forestry and Environmental Sciences, University of Chittagong, Chittagong, Bangladesh; ^bDepartment of Systems Innovation, Graduate School of Engineering, The University of Tokyo, Tokyo, Japan

ABSTRACT

A deep interest is evident in carbon sequestration modeling in Bangladesh from the development of several allometric equations to estimate carbon sequestration by plants. It is linked to the evolving carbon offsetting approaches, for example, Clean Development Mechanism (CDM) and the REDD+, which require certifiable estimate of carbon captured by trees and forests. This review compiled a snapshot of state of the art in carbon modeling in Bangladesh. More than half of the published research focused on the development of allometric equations and forest carbon estimation. The comparison among available studies was challenging due to the use of different terminologies and assumptions and arbitrary combinations of parameters including age, topography, season, slope, crown diameter, etc. The spatial distribution of reports indicated narrow geographical focus outside forests in Chittagong and Sundarbans. Surprisingly, no attempts were evident to explore carbon stocks at the Chittagong Hill Tracts (CHTs) where majority of pristine forest areas of the country occurs. Bangladesh is likely to reforest the vast deforested areas in CHTs under CDM and REDD+ projects which requires extensive carbon modeling. Majority of the reports used conversion factor to calculate soil carbon instead of analytical estimation which might cause inaccurate estimation of soil carbon. Blue carbon assessment and policy implication of carbon studies are two areas where insufficient attention is evident. Bangladesh apparently needs to conduct wide-scale carbon modeling through the integration of GIS, remote sensing, etc to increase precision and accuracy of carbon stock assessments. .

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Carbon stock estimation; allometric equations; CDM; REDD+; carbon sequestration

1. Introduction

Climate change – the outcome of anthropogenic global warming – is the single biggest environmental crisis facing Earth, which may lead to unfathomable humanitarian disasters (Mal, Singh, Huggel, & Grover, 2018; Milfont, Wilson, & Sibley, 2017; O’Beirne et al., 2017; Xue et al., 2017). In the fifth assessment (AR5) of 2014, the Intergovernmental Panel on Climate Change (IPCC) asserted increasing concentrations of greenhouse gases (GHG) mainly from anthropogenic activities as the cause of global warming (IPCC, 2014). AR5 climate model projected a rise of global surface temperature by 0.3–1.7°C and 2.6–4.8°C, respectively, under the lowest and the highest emission scenarios (Stocker et al., 2013). AR6 expected to limit global warming within 1.5°C (IPCC, 2018) by keeping GHG emission under check through internationally binding instruments (Mehling, Metcalf, & Stavins, 2018; Weitzman, 2017) including carbon quota, Clean Development Mechanism (CDM), and REDD+. Houghton and Nassikas (2018) emphasized on arresting deforestation and allowing the secondary forests to grow to

reduce global carbon emissions by about 120 PgC between 2016 and 2100. As forests, trees, or vegetation acts as the carbon sink, these can be used in devising mechanisms to cope with the adverse impact of global climate change (Rahman, Sarker, & Hossen, 2013; Shin, Miah, & Lee, 2007). Achievement of full carbon mitigation potential requires estimation of country-level carbon stocks through statistically validated methods (Mahmood, Siddique, & Akhter, 2016). As a signatory of the Kyoto protocol, Bangladesh needs accurate estimations of existing carbon stocks throughout the country to implement carbon trading CDM projects (Saatchi et al., 2011). Now, the Government of Bangladesh is taking initiatives to meet up nation-wide carbon stock data and prepared the REDD+ Readiness Roadmap (BFD, 2018). The reliable quantification of carbon sequestration by vegetation will help the policy makers, researchers, and entrepreneurs of developing countries like Bangladesh to sell Certified Emission Reduction to developed countries (Ahhammad, Hossain, & Husnain, 2014; Ahmed & Glaser, 2016) in global carbon markets under REDD+ and CDM (Al-Amin, 2016; Shin, Miah, & Lee, 2008) as they

CONTACT Kamrul Islam  ksujonifescu@gmail.com; kamrul-islam@g.ecc.u-tokyo.ac.jp  Department of Systems Innovation, Graduate School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

 Supplementary data for this article can be accessed [here](#).

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need to offset their higher per capita carbon emission. Carbon estimation is also necessary for Bangladesh to implement climate change mitigation policies (Miah & Shin, 2009; Saatchi et al., 2011). Carbon stock estimation includes quantification of soil organic carbon, carbon in living trees, understory vegetation, woody debris, and litters of forest floor in form of above-ground carbon and below-ground carbon (Gibbs, Brown, Niles, & Foley, 2007; Patra et al., 2013). In Bangladesh, researchers have estimated carbon stocks in different forms at different parts of the country and have developed allometric models. However, most of the available estimation is limited to application of few variables that miss the vast pools of ecosystem carbon (Donato et al., 2011; Miah & Shin, 2009). Again, most of the works reflect allometric equation of some common tree species, palm, and shrub species (Mahmood et al., 2016). This study was undertaken in the pretext that it is now necessary to review the geographic distribution of these studies to check the coverage of different forest types, carbon pools, and robustness of models in terms of inclusion of pertinent variables. Considering the above backdrop, this review intends to specify the state of art in carbon sequestration-related studies in Bangladesh.

2. Analytical methodology

Current study is based mainly on the published literature related to carbon estimation in Bangladesh with investigation into some associated secondary data. The documents were collected exhaustively through online literature databases including Google Scholar, Nature, Springer Link, Science Direct, Plos, Wiley online library, Tandfonline, and Cabdirect. Resource person consultation along with literature review from different books, blogs, newspapers, thesis papers, term papers, essays, and statistical yearbook has also been taken into consideration. A total of 49 studies were found relevant and considered for current study. ISI indexing of research papers for choosing them for current study was not considered, as only limited number of carbon studies exist for Bangladesh in ISI indexed journals.

3. Findings and discussion

3.1. Source of carbon study researchers in Bangladesh

It is evident from current study (Figure 1) that lead authors of published carbon studies focusing on Bangladesh are mainly from academic institutions (55.10%). Surprisingly, second largest chunk in the pie (28.57%) is occupied by lead authors from foreign institutions, followed by other government organizations, NGOs, and Bangladesh Forest Department

(BFD) with 10.20%, 4.08%, and 2.04%, respectively. Lead authors in published studies from BFD are unexpectedly low, though BFD is the government-accredited organization to deal with such matters. Detailed information regarding the lead and co-authors' institution has been added in the Supplementary material 1.

3.2. Focus of carbon sequestration-related research in Bangladesh

Analysis of existing carbon sequestration-related studies in Bangladesh (Figure 2) showed that majority, around 51.02%, focused on biomass carbon estimation. Mahmood et al. (2016) also reported similar findings in their study that covered the period between 2011 and 2016. These studies included estimation of mainly above-ground biomass, while only a handful of studies included the below-ground biomass estimation with specific equations. Majority of the researchers just estimated below-ground carbon as 15% of the above-ground carbon. Species diversity and forest fragmentation were considered for better estimation of carbon stocks (Islam, Deb, & Rahman, 2017). About 25% of the studies were on soil carbon estimation which included gross estimation of soil carbon by using wet oxidation method and highlights of approaches to improve soil carbon stock. The other areas of studies were policy analysis and review (10.20%), blue carbon (10.20%), and GIS and remote-sensing application (4.08%). More detailed information on major highlights of existing carbon studies in Bangladesh is included in Supplementary material 2.

3.3. Estimate of carbon by forest types

Carbon estimation at national scale for Bangladesh requires allometric models for all major forest types of the country and for the major species. The models also need to cover all possible carbon pools by taking ecosystem complexity into consideration. Researchers have been estimating carbon sequestration or stock for different parts of the country by using different allometric equations as summarized in Table 1. It

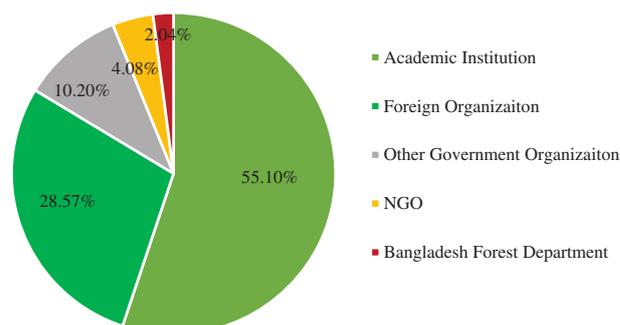


Figure 1. Institutional attachments of lead researchers of carbon studies of Bangladesh.

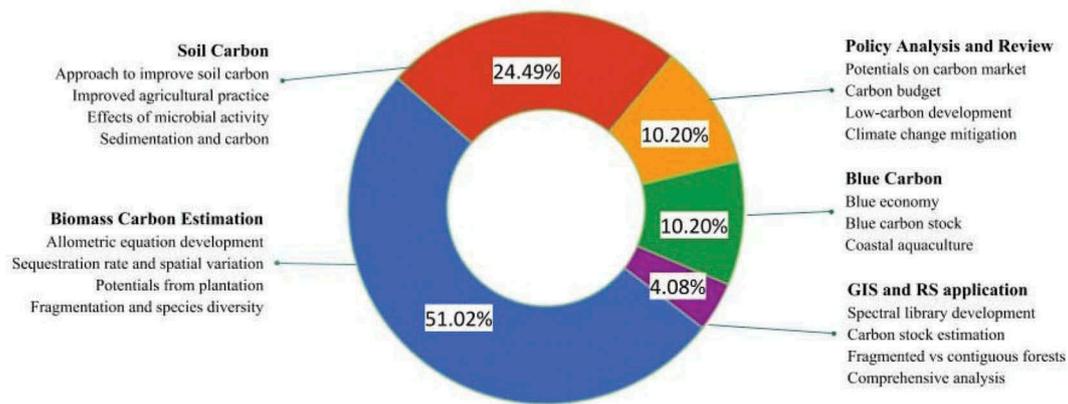


Figure 2. Major focal areas of carbon sequestration related-studies in Bangladesh.

shows the rates of carbon sequestration for different forest types of the country according to the available literature. Contrary to the intuition, roadside plantations showed the highest above-ground carbon sequestration rate ($165.81 \text{ Mg C ha}^{-1}$) among plantation forests in Bangladesh followed by institutional plantations ($150.00 \text{ Mg C ha}^{-1}$). Among the natural forests, protected areas ($195.8 \text{ Mg C ha}^{-1}$) accumulated the highest amount of above-ground carbon followed by mangroves ($76.80 \text{ Mg C ha}^{-1}$). Again, the estimated below-ground carbon for fast-growing species ($100.84 \text{ Mg C ha}^{-1}$) was compared to the above-ground carbon ($110.25 \text{ Mg C ha}^{-1}$). These anomalies dictate the necessity of developing more rational estimates and revisiting the counterintuitive results.

Zomer et al. (2016) found around 20% of the international studies suggested increasing rate in total carbon stocks in Bangladesh. Interestingly, local studies showed the opposite trend with

rapid fluctuations. The estimated total carbon stocks in Bangladesh forest ecosystems were 251.8 million Mg in 2014 (Mukul et al., 2014), of which they estimated that a whopping 49.4% was stored solely at the Sundarbans mangrove forest. Comparing to other mangrove-holding countries, Bangladesh lacks equivalent mangrove carbon stocks. Hamilton and Friess (2018) found that Bangladesh ranks three places lower globally if ranked upon mangrove carbon stocks in mangrove area holding.

3.4. Forest areas covered: spatial distribution of existing studies

Bangladesh has 2.56 million hectares of forestland including the hill forests in south-eastern and north-eastern hill forests, west and central Sal forests, south-western and coastal mangrove forests with diverse plant species (BFD, 2018). We have found five articles for the whole country emphasizing on carbon policy implications. Region-wise distributions of the studies are shown in Figure 3. The highest number of studies (15 studies) was conducted on forests in Chittagong followed by 13 studies on Sundarbans mangrove forest. However, one of the main forest stock of the country in Chittagong Hill Tracts remained unexplored in terms of carbon estimation. The rapid loss of vegetation cover in all forest types may result in an estimated annual GDP loss of 0.5–1.5% annually (Rahman et al., 2013). An intensified research on carbon stock estimation in these forests is needed to ensure funding from carbon offsetting mechanisms to maintain the existing vegetation with elevated reforestation efforts (Shin et al., 2007). The analysis in this review indicates the need for more elaborate geographic coverage of carbon estimation studies in the future. Detailed data on district-wise spatial distribution of existing carbon studies have been provided in Supplementary material 3.

Table 1. Reported rates of above- and below-ground carbon sequestration at different forest types in Bangladesh.

Category	Carbon stock status (Mg C ha^{-1})		Reference
	Above ground	Below ground	
Mangrove	76.80	41.10	(Kamruzzaman, Ahmed, Paul, Rahman, & Osawa, 2018)
Bamboo	50.44	2.52	(Sohel, Alamgir, Akhter, & Rahman, 2015)
Palm	22.35		(Dey, Islam, & Masum, 2014)
Institutional plantation	150.00	24.23	(Islam, 2013)
Roadside plantation	165.81	26.99	(Rahman, Kabir, Akon, & Ando, 2015)
Fragmented forest	16.30	17.26	(Islam et al., 2017)
Contiguous forest	31.21	21.62	(Islam et al., 2017)
Home garden	44.29	8.00	(Jaman, Hossain, Islam, Helal, & Jamil, 2016)
Fast growing species	110.25	100.84	(Ullah, Banik, & Banik, 2014)
Protected areas	195.8	37	(BFD, 2018)

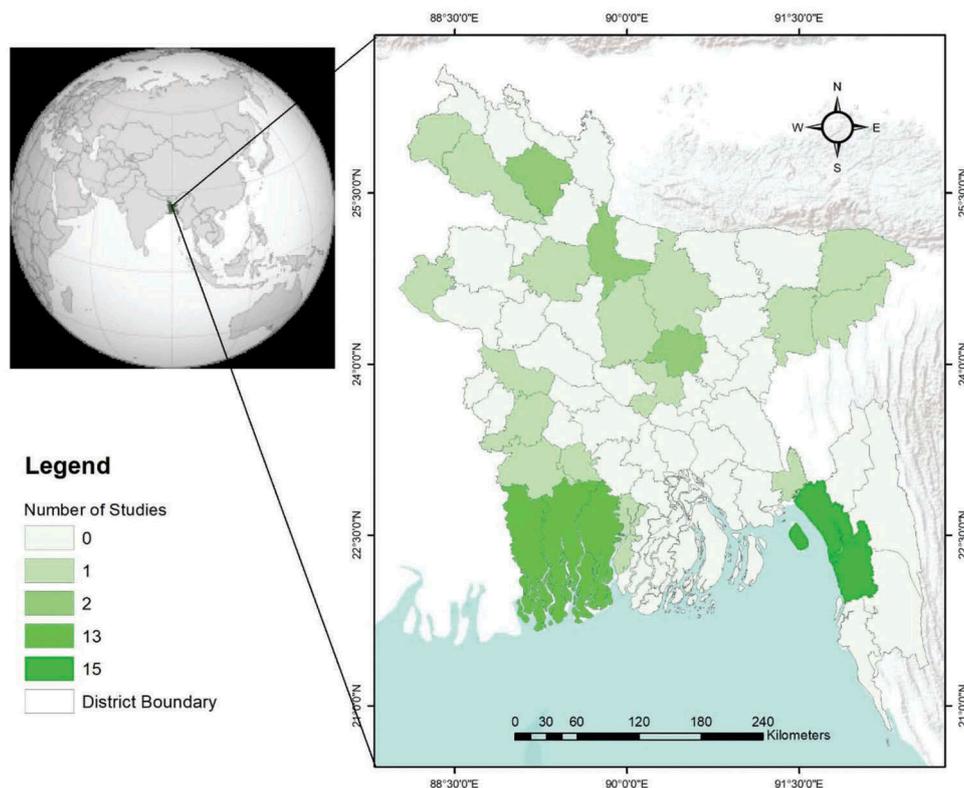


Figure 3. Spatial distribution of published studies on carbon estimation in Bangladesh.

3.5. Carbon estimation methods used

Selection of rational allometric equations is the key to objective estimation of carbon stock. Table 2 summarizes the commonly used equations in Bangladesh. Though the number of allometric equations specific to Bangladesh has increased, half of the models lack statistical validity. Mahmood et al. (2016) concluded that only 5% tree species and shrubs in Bangladesh have allometric equation to estimate the biomass. National Forest Assessment in Bangladesh in 2005–2007 used allometric equations developed for other countries as were in the Sundarbans carbon inventory 2009–2010 (Chanda et al., 2016). Even though species richness limits the use of species-specific allometric equations (Mizanur, Khan, Hoque, & Ahmed, 2015), the use of common equations of other countries will yield unreasonable estimates which posed doubt on the accuracy of national estimation (Ahiduzzaman and Islam, 2016; Mizanur et al., 2015). Carbon sequestration rate under the same environment solely depends on the species (Nahiyen, Baidya, Dip, Sultan, & Ahmed, 2017) which dictates the need to develop species-specific localized allometric equations (Aysha et al., 2015; Mukul et al., 2014). In majority of the studies, below-ground carbon stock was calculated as 15% of above-ground carbon stock (Miah, Uddin, Bhuiyan, Koike, & Shin, 2009; Ullah & Al-Amin, 2012), but in another study, it was found 14% in real field (Rahman et al., 2015) which added further errors into the estimates. In addition, confusion

compounded when someone used 0.50 (Dey et al., 2014; Islam, 2013; Shin et al., 2007) as the carbon conversion factor from biomass and some other used 0.58 (Akter, Rahman, & Al-Amin, 2013; Sohel et al., 2015). Similarly, Rahman et al. (2013) subtracted 1.87 from loss on ignition during carbon percentage calculation, while Sohel et al. (2015) subtracted 1.47.

3.6. Variables considered

The allometric models depict relationship between different variables related to trees including diameter at breast height (DBH), height of the tree trunk, total height of the tree, crown diameter, height–diameter ratio (H/D), tree species richness, etc. (Hossain et al., 2016a; Islam et al., 2017). The choice of these variables varied among different studies. Also, some reports considered hill slopes which definitely affect the biomass yield (Haque & Karmakar, 2009; Shin et al., 2007). Few papers considered the age to estimate carbon stock for trunk, litter, and soil of plantation species to get more accurate results (Shin et al., 2007). There are reports where herb, shrub, trees, and grass species were included in total carbon estimation (Ullah & Al-Amin, 2012). Some researchers estimated the carbon stock solely based on DBH (Dey et al., 2014; Hossain et al., 2016a), while few one considered 10–12 parameters (Rahman, 2004). Mizanur et al. (2015) found that dominant mangrove species are the key indicator of ecosystem carbon stock. Soil

Table 2. Commonly used equations in carbon studies in Bangladesh.

Name	Expression	Specification	Reference
Above-ground biomass	$\log Y = \log \beta_0 + \beta_1 \log X$	X = physical parameter of trees (e.g., height, DBH)	(Hossain et al., 2016b)
	$Y = \exp(-\beta_0 + \beta_1 \ln(D^2HS))$	H = height D = diameter S = oven dry density	(Akter et al., 2013; Alamgir & Al-Amin, 2007; Islam et al., 2017; Shin et al., 2007; Ullah & Al-Amin, 2012; Ullah et al., 2014)
	$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2$	Y = total carbon stock X = physical parameter of trees (e.g., height, DBH)	(Dey et al., 2014; Hossain, Saha, Abdullah, Saha, & Siddique, 2016a; Hossain & Banik, 2005; Ullah et al., 2014)
	$Y = \rho \cdot \exp(-\beta_0 + \beta_1 \ln X + \beta_2 \ln X^2 - \beta_3 \ln X^3)$	ρ = wood density X = physical parameter of trees (e.g., height, DBH)	(Islam, 2013; Jaman et al., 2016; Kamruzzaman et al., 2018; Mizanur et al., 2015)
Below-ground biomass	$BGB = \beta_0 \rho^{B1} D^{B2}$	BGB = below-ground biomass ρ = wood density D = DBH	(Kamruzzaman et al., 2018; Mizanur et al., 2015)
	$BGB = \exp(-\beta_0 + \beta_1 \ln AGB)$ BGB = 15% of the total above-ground biomass	AGB = above-ground biomass	(Islam, 2013; Jaman et al., 2016) (Islam et al., 2017; Miah et al., 2009; Ullah & Al-Amin, 2012; Ullah et al., 2014)
	BGB = 20% of the total above-ground biomass		(Hanif, Bari, & Rahman, 2015)
Moisture content	Moisture content (%) = $(W2 - W3 / W3 - W1) \times 100$	W1 = weight of Petri dish W2 = weight of Petri dish with moist soil W3 = weight of Petri dish with dry soil	(Akter et al., 2013; Alamgir & Al-Amin, 2007; Rahman et al., 2013; Sohel et al., 2015; Ullah & Al-Amin, 2012)
Loss on ignition (LOI)	LOI (%) = $(W1 / W2) \times 100$	W1 = loss in weight W2 = weight of oven dry soil	(Rahman et al., 2013; Sohel et al., 2015)
Carbon (%) from LOI	Carbon (%) = $0.476 \times (\%LOI - 1.87)$ Carbon (%) = $0.476 \times (\%LOI - 1.47)$		(Rahman et al., 2013) (Sohel et al., 2015)
Carbon in the stand by using GIS and remote sensing	Carbon, C = $f(D, A, L, R, H, O, S, F, P, Cr, B, W)$	D = average tree diameter at breast height A = stand age L = leaf area index H = canopy height O = canopy cover R = total area of the stand S = stems per unit area F = forest type P = species Cr = crown height B = bole height W = crown width Cl = leaf cluster index	(Al-Amin, 2016; Rahman, 2004)

organic carbon content is influenced by microbial activity (Rasid, Chowdhury, & Osman, 2016), pH (Bangladesh Rice Research Institute, 2014; Hossain, 2016), soil depth (Saha, Rahman, Khatun, Hossain, & Saleque, 2014), and applied fertilizer type (Rahman, 2015; Rahman et al., 2016). Again, type of forest whether it is fragmented or continuous influences the carbon content significantly (Islam et al., 2017). Holistic models are therefore necessary which take into account all pertinent variables in carbon estimation.

3.7. Anomalies in units

Researchers used different units to show carbon stocks including “Metric ton ha⁻¹” (Dey et al., 2014), “Mg C h⁻¹” (Barua & Haque, 2013; Islam, 2013; Rahman et al., 2015), and “Ton h⁻¹” (Islam et al., 2017; Sohel et al., 2015; Ullah et al., 2014), while “ton-year” was a more suitable unit in consideration of CDM (Shin et al., 2007).

3.8. Prospects ahead: carbon market

Global carbon markets are either “financing to maintain compliance” or “voluntary forest carbon markets.” CDM projects exemplify the former, while Bio-Carbon Fund managed by the World Bank exemplifies the latter. On the other hand, REDD+ has a broader domain of applicability (Ahmed & Glaser, 2016) as it mainly focuses to conserve the tropical forests through carbon payment. Some studies suggested the possibility of reforestation of Bangladesh’s large area of degraded land under CDM and REDD+ (Miah & Shin, 2009; Saatchi et al., 2011; Shin et al., 2007). There are other approaches as Dey et al. (2014) showed the significance of palm trees, and Sohel et al. (2015) showed the applicability of bamboo in carbon sequestration, while Ahiduzzaman and Islam (2016) showed the possibility of using rice husk energy to substitute 4.66 million ton wood fuel annually to save 24.14 thousand hectares of forest equivalent that may sequester 7.45 million ton of CO₂ per annum. Similarly, Islam (2013) showed the significance of institutional plantation in carbon sequestration. Few researchers

proposed using REDD+ to check blue carbon emission due to the shrinkage of mangroves and extension of coastal aquaculture (Ahmed, Cheung, Thompson, & Glaser, 2017; Ahmed & Glaser, 2016; Ahmed, Thompson, & Glaser, 2018; Hussain, Failler, Karim, & Alam, 2018; Islam, 2016). Roads and community-based home gardens were promoted in few reports to ensure reforestation by Payment for Environmental Services (PES) under UNFCCC's carbon mitigation strategies (IPCC, 2018; Mehling et al., 2018; Stocker et al., 2013).

4. Conclusion and policy recommendations

There are anomalies in the estimates of carbon among published reports due to the variations in the models and assumptions used for the estimation of carbon stock. Accordingly, global studies showed increasing carbon stock trend in Bangladesh, while local studies showed the opposite. On the other hand, the concentration of studies did not represent all important forest areas, and there is a general lack of species- and ecosystem-specific carbon estimation models, while available models lack in stringent statistical validation. Bangladesh needs more studies to develop pragmatic and rational models of carbon estimation to ensure the acceptability of estimates for getting certified carbon credits to participate in carbon offsetting mechanisms to save her forests.

5. Limitations

This study might be more meaningful and complete if it was possible to compare carbon study scenarios with some other South Asian countries. This would give us a clear picture where studies of Bangladesh lack. Another limitation is the inclusion of non-ISI indexed journal articles due to the availability of a limited number of studies on Bangladesh.

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No potential conflict of interest was reported by the authors.

ORCID

Sahadeb Chandra Majumder  <http://orcid.org/0000-0003-0024-8412>

Kamrul Islam  <http://orcid.org/0000-0003-3443-9030>

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