Biomass and Carbon in Mangrove: Measuring and Managing through Remote Sensing Technique

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Abstract

Mangroves are salt tolerant woody plants that form highly productive intertidal ecosystems in tropical and subtropical regions. Despite the established importance of mangroves to the coastal environment, including fisheries, deforestation continues to be a major threat due to pressures for wood and forest products, land conversion to aquaculture, and coastal urban development. The importance of immediate protection measures and conservation activities to prevent the further loss of mangroves are essential. However, carbon emissions resulting from mangrove loss especially biomass are uncertain. The information on mangrove's biomass toward carbon stock is needed because when the changes occurs much of carbon stock in the ecosystem released to the atmosphere. In this context, remote sensing is a tool of choice to provide spatio-temporal information on mangrove ecosystem biomass and carbon studies through digital image processing and modeling. Remote sensing techniques have demonstrated a high potential to detect, identify, map and monitor mangrove conditions and changes. This paper provides reviews and highlighting remotely sensed data applied for measuring biomass and carbon in mangrove forest from remote sensing perspective. The use of remotely sensed data and analysis in this context is growing steadily in geospatial technology for natural resource management.

Keywords: *mangrove ecosystems, biomass estimation, remote sensing, coastal zone management*

Introduction

Information on the spatial variation in carbon sequestration in different types of forest cover in the land could achieve further improvements of accuracy of global sinks. According to Fuchs et al. (2009), forest ecosystems are an important part of the global carbon cycle because they store a large part of the total terrestrial organic carbon and exchange CO_2 with atmosphere. Trees act as a sink for CO_2 by fixing carbon during photosynthesis and storing excess carbon as biomass. As the tree biomass experience growth, the carbon held by the plant also increases carbon stock (Bipal et al. 2009). Mangroves forests have long been known as a harsh environments and extremely productive ecosystems in cycling carbon.

The information on mangrove's carbon is essential because when the changes occurs much of carbon stock in the ecosystem released to the atmosphere. Mangrove forest accounts for about 2.4% of tropical forest and to improve accuracy of global carbon sink quantification of carbon dynamics is essential in the mangrove swamps (Chmura et al. 2003). Coastal mangrove forests store more carbon than almost any other forest on Earth (Daniel et al. 2011). The carbon content of 25 mangrove areas per hectare across the Indo-Pacific region found that it's can store up to four times more carbon than most other tropical forests around the world. The use of satellite remote sensing to measure and map mangroves biomass for carbon accounting has become widespread as it can provide accurate, efficient, and repeatable assessments.

Remote sensing data may provide a useful means for measuring carbon stocks in forests, and a range of remote data collection technologies are now available including satellite imagery to aerial photo-imagery from low flying airplanes (Brown 2002). For existing forests, inventory data are the most practical means for estimating aboveground biomass carbon as the data are generally collected at the required scales and from the population of interest in a statistically well-designed manner. The ability to accurately and precisely measure the carbon stored and sequestered in forests is increasingly gaining global attention in recognition of the role forests have in the global carbon cycle, particularly with respect to mitigating carbon dioxide emissions (Kauppi and Sedjo 2001). Therefore, This paper provide a comprehensive review and addressing remotely sensed data applied for measuring biomass in mangrove from remote sensing technique and data analyses, to further discussion on their potential and limitations.

The importance of biomass and carbon in terrestrial ecosystem

Quantification of terrestrial carbon and monitoring of these stocks over time are important for reasons of climate change mitigation. Improved management of the carbon stored in the world's terrestrial vegetation and soil in existing and new terrestrial carbon pools, above and below ground, are significant to environmental assets, necessary part of the global effort to avoid dangerous climate change. Terrestrial carbon stocks are also important indicators for other development and environmental goals where changes in stocks may have direct implications on the socio-economic health of local communities as well as on biodiversity.

Methods to measure and monitor changes in terrestrial carbon stocks from emissions and removals are also increasingly used to inform national land-use policy and in attracting new investment in sustainable land use projects and payments for environmental goods and services, including carbon credits (Havemann 2009). Information on the spatial variation in carbon sequestration in different types of forest cover in the land could achieve further improvements of accuracy of global sinks. About 62% to 78% of the global terrestrial carbon is sequestered in the forests, and about 70% of this carbon is stored in the soil (Dixon et al. 1994, Schimel 1995). Changes in carbon dynamics in tropical forest with 50% contribution to global terrestrial gross primary production (GPP) (Grace et al. 2001) could alter the pace of climate change (Adams and Piovesan 2005). Regional studies of carbon exchange vary in showing disequilibrium state of Tropical forest and in increasing stocks of tree carbon (Phillips et al. 1998, Lewis et al. 2009). Apart from resource availability and pollution stress, succession and global change could have varying importance at different region to produce different spatial and temporal pattern of carbon uptake by trees (Muller-Landau 2009). Mangrove forest accounts for about 2.4% of tropical forest and to improve accuracy of global carbon sink quantification of carbon dynamics is essential in the mangrove swamps (Chmura et al. 2003).

Mangrove, biomass and carbon studies in South-east Asia

Around 1980, the total mangrove area in Southeast Asia totalled 6.8 million ha which is about 34-42 % of the world's total. However by 1990 this had dropped to under 5.7 million ha, representing a decrease of about 15 percent or more than 110 000 ha per year. Between 1990-2000 the annual loss had decreased to 79 000 ha, but as the total area had also decreased there was still a 13.8 % decline in mangrove area during this decade. The largest areas of mangrove in Southeast Asia are found in Indonesia (almost 60% of Southeast Asia's total), Malaysia (11.7%), Myanmar (8.8%), Papua New Guinea (8.7%) and Thailand (5.0%) (Giesen et al. 2007). Since 1980's the trend of biomass studies in mangrove forest are increasing due to deforestation issue and the importance to mitigate tsunami and climate change. The summation of the studies that has been carried out is listed in Table 1 as reported by Komiyama et al. (2008) and other researchers. The highest above-ground biomass, 460 t ha^{-1}, was found in a forest dominated by *R. apiculata* in Malaysia (Putz and Chan 1986). Above-ground biomass of more than 300 t ha^{-1} was also reported in mangrove forests in Indonesia (Komiyama et al. 1988). The above-ground biomass was less than 100 t ha^{-1} in most secondary forests or concession areas. The lowest aboveground biomass reported was 40.7 t ha^{-1} for a *Rhizophora apiculata* forest in Indonesia (East Sumatera).

Table 1 List of mangrove above ground (ABG) and below ground (BGB) biomass in South-East Asia.

Region/area	Location	Forest status/ age	Species	ABG (t/ha)	BGB (t/ha)	Height (m)	Reference
Malaysia (Matang)	4°15'N, 100°2'E	VJR	*R. mucronata stand*	146.61	65.93	32.0	Juliana and Nizam (2004)
Thailand (Trat Eastern)	12°12'N, 102°33'E	Secondary forest	Mixed forest	142.2	50.3	10.8	Poungparn (2003)
Thailand (Southern Pang-nga)	8°15'N, 79°50'E	Secondary forest	Mixed forest	62.2	28.0	6.5	Poungparn (2003)
Thailand (Satun Southern)	7°22'N, 100°03'E	Secondary forest	*C. tagal* forest	92.2	87.5	5.2	Komiyama et al. (2000)
Indonesia (East Sumatra)	0°21'N, 103°48'E	Concession area	*B. sexangula* stand	279.0	–	21.7	Kusmana et al. (1992)
Indonesia (East Sumatra)	0°21'N, 103°48'E	Concession area	*B. parviflora* stand	89.7	–	18.8	Kusmana et al. (1992)
Indonesia (East Sumatra)	0°21'N, 103°48'E	Concession area	*B. sexangula* stand	178.8	–	20.1	Kusmana et al. (1992)
Indonesia (East Sumatra)	0°21'N, 103°48'E	Concession area	*B. sexangula* stand	76.0	–	17.1	Kusmana et al. (1992)
Indonesia (East Sumatra)	0°21'N, 103°48'E	Concession area	*B. parviflora* stand	42.9	–	19.5	Kusmana et al. (1992)
Indonesia	0°21'N,	Concession	*R. apiculata*	40.7	–	29.5	Kusmana et

(East Sumatra)	103°48’E	area	stand				al. (1992)
Indonesia (Halmahera)	1°10’N, 127°57’E	Primary forest	*B. gymnorrhiza* forest	436.4	180.7	22.4	Komiyama et al. (1988)
Indonesia (Halmahera)	1°10’N, 127°57’E	Primary forest	*B. gymnorrhiza* forest	406.6	110.8	26.4	Komiyama et al. (1988)
Indonesia (Halmahera)	1°10’N, 127°57’E	Primary forest	*R. apiculata* forest	356.8	196.1	21.2	Komiyama et al. (1988)
Indonesia (Halmahera)	1°10’N, 127°57’E	Primary forest	*R. apiculata* forest	299.1	177.2	15.5	Komiyama et al. (1988)
Indonesia (Halmahera)	1°10’N, 127°57’E	Primary forest	*R. apiculata* forest	216.8	98.8	–	Komiyama et al. (1988)
Indonesia (Halmahera)	1°10’N, 127°57’E	Primary forest	*Sonneratia* forest	169.1	38.5	15.9	Komiyama et al. (1988)
Indonesia (Halmahera)	1°10’N, 127°57’E	Primary forest	*R. stylosa* forest	178.2	94.0	22.3	Komiyama et al. (1988)
Thailand (Ranong Southern)	9°N, 98°E	Primary forest	*B. gymnorrhiza* forest	281.2	106.3	–	Komiyama et al. (1987)
Thailand (Ranong Southern)	9°58’N, 98°38’E	Primary forest	*Rhizophora* spp. forest	298.5	272.9	–	Komiyama et al. (1987)
Thailand (Ranong Southern)	9°N, 98°E	Primary forest	*Sonneratia* forest	281.2	68.1	–	Komiyama et al. (1987)
Malaysia (Matang)	4°48’N, 100°35’E	>80	*R. apiculata* dominated forest	270.0	270.0	–	Putz and Chan (1986)
Thailand (Ranong Southern)	9°N, 98°E	Primary forest	*Rhizophora* spp. forest	281.2	11.76	10.6	Tamai et al. (1986)
Malaysia (Matang)	4°N	28-year-old	*R. apiculata* stand	211.8	–	15.0	Ong et al. (1982)
Malaysia (Matang)	4°N	28-year-old	*R. apiculata* stand	211.8	–	15.0	Ong et al. (1982)
Thailand (Phuket Southern)	8°N, 98’E	15-year-old	*R. apiculata* forest	159.0	–	8.0	Christensen (1978)

Remote sensing biomass-carbon inventories

Remote sensing captures spectral and spatial characteristics of mangroves area and therefore be an efficient method to estimate vegetation cover, as well as density and structure (Mohd Hasmadi et al. 2008, Mohd Hasmadi et al. 2011). The benefits of these methods are that they can produce spatially-explicit information at various scales, ranging from < 1m (aerial photography) to 180 km and that they can collect information in inaccessible areas and may allow for repeated coverage. There are a number of different sensor types, each with its own benefit and limitation, as well as a suite of different data classification and interpretation methods. One point to note is that this section deals with the most typical and well-tested methods. The pace of technology development in this field is fast therefore this summary may not fully capture some of the newer operational methods for automated mapping of biomass cover (Havemann 2009). According to Hamdan et al. (2011), the study showed that L-band ALOS PALSAR data had successfully predicted aboveground biomass for tropical forest.

The strong correlation between aboveground biomass and radar backscattering coefficient in HV polarisation from ALOS PALSAR image had produced an alternative for assessing aboveground biomass, which was one of the most important forest stand parameters. Overall, the aboveground biomass values ranged from 25.9±10.9 to 569.3±10.9 t ha^{-1} which covered all types of standing forests. From this information, a spatially distributed map that showed spatial pattern of aboveground biomass for the whole study area was produced. Aboveground carbon stocks were between 12.95±5.45 and 284.65±5.45 t C $ha^{-1.}$ Natural and mature standing planted forest showed higher concentration of living biomass compared with some regions with less or sparsely distributed mature, big and tall trees. Results also indicated that despite its limitations, the use of L-band SAR could provide an alternative for rapid assessment of biomass as well as carbon stocks in a large area. There are several important criteria for selecting remote sensing data and products for terrestrial carbon inventory (IPCC 2006); (i) *Adequate land-use system stratification scheme*. Stratification of the project area has to be robust and clear to be able to distinguish between them. The stratification should be of adequate spatial resolution to enable use of remote sensing. (ii) *Appropriate spatial resolution*. If broad categories or distinct land-use differences are sought, such as forested and non-forested land, low-resolution remote sensing might be adequate, compared to a detailed categorization of different agricultural land that requires high resolution.(iii) *Appropriate temporal resolution*. Estimating land use changes in boreal forest systems might require data that span over decades, whereas for estimating changes in grassland, data for even a single year may be sufficient. Seasonality of the vegetation is an important factor since peak vegetation period is usually the best time for inventory of terrestrial carbon. (iv) *Availability of historical assessment*. Often the limitation of conducting a remote sensing survey is the availability of historical data. In that sense the future is promising, since more, readily available, sensors and products are being developed. (v) *Transparent and consistent methods applied in data acquisition and processing*. Since carbon inventories are performed frequently and require monitoring over time, the methods that are used have to be repeatable. (vi) *Consistency in data and availability over time*. The products used should be consistent over time for the same reason as stated in point five above. According to Myeong et al. (2006), the paper presents a method based on the satellite image time series, which can save time and money and greatly speed the process of urban forest carbon storage mapping, and possibly of regional forest mapping.

Satellite imageries collected in different years were used to develop a regression equation to predict the urban forest carbon storage from Normalized Difference Vegetation Index (NDVI) computed from a time sequence (1985–1999) of Landsat image data (Myeong et al. 2006). Changes in total carbon storage by trees in Syracuse, New York, USA were estimated using the image data from 1985, 1992, and 1999 respectively. Radiometric correction was accomplished by normalizing the imagery to the 1999 image data. After the radiometric image correction, the carbon storage by urban trees in Syracuse was estimated to be 146,800 tons, 149,430 tons, and 148,660 tons of carbon for 1985, 1992, and 1999, respectively. The results demonstrate the rapid and cost-effective capability of remote sensing-based quantitative change detection in monitoring the carbon storage change and the impact of urban forest management over decades. The studies implies that image analyses can produce estimates of carbon storage from urban trees reasonably well and image normalization procedures offer a promising method for detecting changes over time. Although this study simplified some complex analysis through image processing, it showed the potential payoff can be substantial. Figure 2 shows the estimated biomass maps calculated by the NDVI and Radarsat fine mode by Li et al.,(2007). The study is carried out in the Guangdong Province in South China. The comparison between Landsat TM and Radarsat images and regression and analytical model were used to establish the relationship between remote sensing and mangrove biomass. Results showed that Radarsat finemode images have significant accuracy improvement in terms of Root Mean Square Error (RMSE) whereas the use of the single NDVI may produce much error in biomass estimation. The Radarsat images can obtain more accurate trunk information about mangrove forests because of higher resolution and side-looking geometry. The study can be repeated and extended geographically to gain more economical and timely estimation of the biomass resource and improved environmental management continuously.

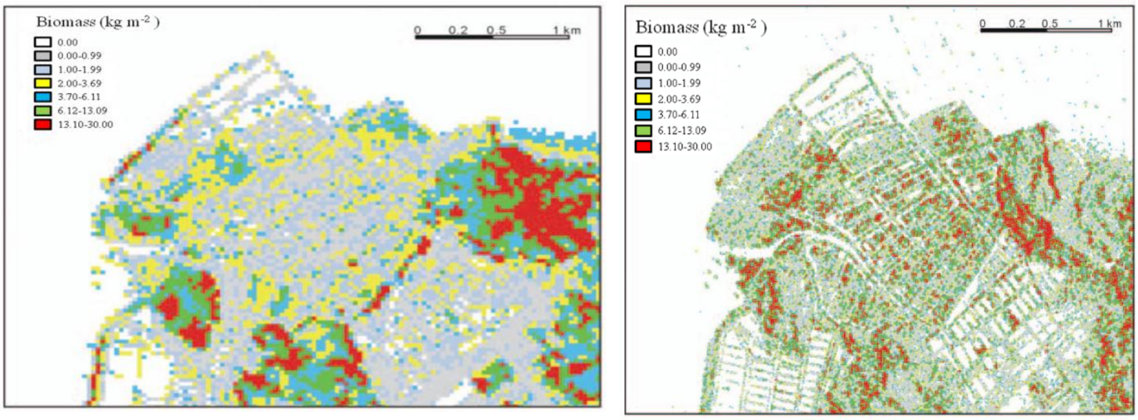

Figure 2 Biomass estimated from the NDVI (left) and backscatter models (right)

Proisy et al. (2007) used Fourier-based textual ordination (i.e. principal components analysis of Fourier spectra) with IKONOS near-infrared and panchromatic imagery to estimate biomass based on detection of canopy structure as shown in Figure 3. Result showed that a significant non-linear relationship between the tree stage (e.g. pioneer, mature, dead) and the principal components of the Fourier spectra. The best model used the panchromatic imagery with a 30 m window and explained over 90% of the total and trunk biomass with a relative error of 16.9%. The P-band PolSAR best estimates tree height and above-ground biomass, although the HV polarization of L-band SAR also performs well, explaining 93%, 96%, and 94% of basal area, tree height, and above-ground biomass, respectively (Mougin et al., 1999). The relationships between PolSAR coefficients and biomass are, however, non-linear and change sign multiple times over the biomass range. In a follow-up study by Proisy et al. (2000), PolSAR signal modelling illustrated difficulties predicting the interaction of PolSAR with three-dimentional heterogeneous components, specifically interactions between soil surface, trunk, and canopy volume components. These findings were confirmed by Proisy et al. (2002). In pioneer and declining mangrove stands, a substantial fraction of scattering was due to the interaction of surface and canopy volume components. Proisy et al. (2002) conclude based on model results that statistical relationships of PolSAR to biomass are limited to homogeneous closed canopies where interaction effects are less pronounced. In a separate study using AIRSAR to assess the potential of space-borne L-band PolSAR, Lucas et al. (2007) note that L-band HV data can delineate different mangrove zones based on species and biomass/stage, but that the separation of surface, volume, and signal remains a significant challenge due to inconsistent empirical results. The implications of these results suggest that an interaction components from the PolSAR given SAR signal results from different combinations of forest structure.

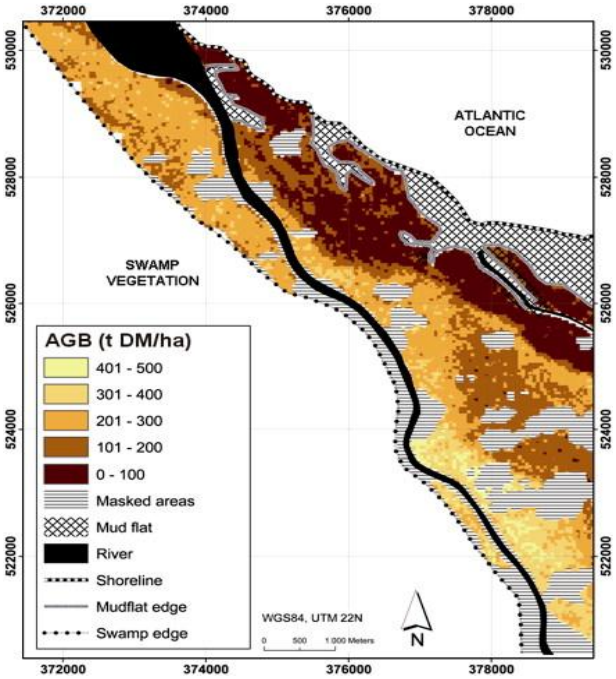

Figure 3 Derived above-ground biomass estimated of the Kaw site in French Guiana, South America.

The way forward of remote sensing in measuring carbon in forests

The image interpretation process can be complex, or relatively simple, depending on the chosen procedure. Higher accuracy might be achieved by using finer-resolution imagery, imagery repeated over time or imagery requiring higher level of expertise to analyze (Havemann 2009). Data collection using remote sensing includes optical, radar or LiDAR (laser) sensors mounted on aircraft or space-based platforms used individually or in combination. Remote sensing data offers a useful means for measuring carbon stocks in forests, and a range of remote data collection technologies are now available including satellite imagery to aerial photo-imagery from low flying airplanes. To improve the ability of remotely sensed biomass, sensors that can measure the height of the canopy or vertical structure will be needed along with the more traditional sensors on Landsat or SPOT.

A promising advance in remote measurements of forest biomass carbon is a scanning LiDAR (a pulsed laser), a relatively new type of sensor that explicitly measures canopy height. Mohd Hasmadi and Mohamad Sam (2011) stated that there are huge potential of using LiDAR technology for precision forestry. In general, the most important where the LiDAR can play a signifcant role is in some of the research area such as canopy and tree height estimation, LiDAR for forest structure and biomass and volume. LiDAR technology will become integrated with digital cameras and also by effective fusion techniques with photogrammetry and multispectral information. Finally, by integrating LiDAR systems with imaging sensors, more advance techniques will emerge.

NASA planned to include this sensor in one of its Earth System Science Pathfinder program missions (the Vegetation Canopy LiDAR Mission—VCL). The VCL Mission would collect data from 25-m wide footprints continuously over land between 67°N and S and would provide three measures: canopy top height, vertical distribution of canopy elements, and surface topography below the vegetation canopy. This sensor would be able to monitor 98% of the earth's closed canopy forests. To date, variations of the airborne LiDAR have been tested over several forest types and the tests have shown its ability to successfully measure canopy height for conifer forests of the Pacific Northwest USA (Means et al. 1999), deciduous forests in Maryland, USA (Lefsky et al. 1999), and various aged secondary and mature tropical forests in Costa Rica.

In the conifer forests of the Pacific Northwest, very high correlations were obtained with the sensor data and height, basal area, and total biomass (Means et al. 1999). The plane flies aerial transects across the area at a fixed low altitude, capturing 200-m wide georeferenced strips and a resolution of 50 cm with the wide-angle camera, and a 20-m wide georeferenced strips and a 3-cm resolution with the zoom camera. The plane also flies at higher altitudes to collect stereo images; these images are used to create 3D models of the terrain. From analysis of two sets of data, this system is able to produce tree crown area, tree height (from the pulse laser), crown density, number of stems per unit area; a combination of which has been shown to correlate highly with aboveground biomass of both complex tropical forests and eastern US hardwood forests. This technique is useful for measuring carbon in forests being harvested and for monitoring for small-scale human disturbance in protected forests as the presence and extent of forest gaps can readily be observed (Brown 2002).

Future opportunities include the application of existing sensors such as the hyperspectral HYPERION, the application of existing methods from terrestrial forest remote sensing, investigation of new sensors such as ALOS PRISM and PALSAR, and overcoming challenges to the global monitoring of mangrove forests such as wide-scale data availability, robust and consistent methods, and capacity-building with scientists and organizations in developing countries (Heumann 2011).

Conclusion

Measurement of biomass in forest ecosystems, including mangroves, is important for carbon storage and cycling studies, mitigation of climate change and management of natural resources. In this paper, we highlighted how remote sensing data can be used to estimate mangrove forest biomass and event estimate for carbon. In particular, concentration on remote sensing techniques by existing allometric equations has benefited the potential of using these technologies. However, remote sensing approach for carbon estimation also depends on field measurements since there are no remote sensing instruments that can measure forest carbon directly. While estimates of mangrove biomass have been achieved, even on a large scale, using different field and remote sensing techniques, challenges still remain. The capture and analysis of millions of square kilometres of imagery collected over decades – past, present and future – will require a globally accepted spatial accounting system that is timely, accurate and accessible. It must include a common baseline, ongoing monitoring, validation and verification. The technology platform to run the algorithms needed to process the required satellite remote sensing data does not yet exist. The cloud-computing resources to run the computationally-intensive image-processing algorithms over this data have yet to be identified. A shared global forest monitoring system has the potential to offer a fully open, transparent and verifiable system, where inputs and outputs can be traced from the original satellite imagery all the way through to carbon emissions calculation. This transparency is critical to the success of the forest carbon marketplace.

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