MODELS FOR ABOVEGROUND FOREST CARBON STOCK ESTIMATION IN TROPICAL REGION USING AIRBORNE LIDAR

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ABSTRACT: Quantifying amount of carbon stored in tropical forests remains challenging and retains greatest uncertainties in understanding their role in the global carbon cycle. This uncertainty demands methods that can accurately and precisely measure forest carbon dynamics and provide carbon density map for a larger geographic extent. In this study, we examined LiDAR derived forest parameters with field measured data and developed aboveground forest carbon stocks (AFCS) models for a tropical forest that comprised of a variety of natural (peat swamp and dry moist forests, regrowth, and mangrove) and plantation (rubber and coconut) forests in Sumatra, Indonesia. To cover these variations of forest type, eight LiDAR transacts crossing 41 field plots were acquired for calibrating the models. The field plots consisted of AFCS ranging from 4 – 161 t/ha. Five alternatives with increasing complexity and reduced uncertainty were purposed. The high performing LiDAR to AFCS model enabled to predict the AFCS with R^2 = 0.87 and root mean square errors (RMSE) = 17.4 t/ha.

1. INTRODUCTION

Determining the role of forest carbon storage in the global carbon cycle and implementing mitigation efforts requires accurate estimates of terrestrial forest carbon storage and its processes. Growing interests in REDD+ (http://www.un-redd.org), accounting of aboveground forest carbon stock (AFCS), and sustainable forest management have increased the need for timely and accurate measurements of vegetation structure for larger forest areas in Asia (Thapa et al., 2013, 2014a). Spaceborne and airborne remote sensing have become key technologies to monitor terrestrial carbon storage and fluxes and have been identified as potential tools for AFCS monitoring. The light detection and ranging (LiDAR), a spaceborne systems, are based on laser ranging that measures geographically referenced horizontal and vertical information on forest allowing us for accurate measurements of vertical forest structure, including canopy height, volume, biomass, and AFCS. Relatively small amount of field measurements calibrates airborne LiDAR based AFCS model. Modeling results can be employed to extend the field data, providing a spatially extensive and detailed source of forest attribute information for modeling the wide variety of spaceborne data, including synthetic aperture radar (SAR) and optical imageries covering larger areas (Thapa et al., 2014b). This article examines LiDAR–derived forest parameters and presents potential models for estimating AFCS in Sumatran tropical forests.

2. MATERIALS AND METHODS

We collected field measurement data and airborne LiDAR data for a study site located in Central Sumatra of Indonesia. In recent years, the natural forest landscape in this area has seen a major shift in land use to economic plantations recording high in carbon emission in Indonesia (Thapa et al., 2013). The site is within the geographic coordinates of 0˚55´7´´S to 1˚0´31´´ N latitude and 101˚37´2´´ to 103˚39´48´´ E longitude. Topography reaches an elevation of up to 400 m and forms peat–swamp, basins, mountains, rivers and coastal areas. The study area consists of natural and plantation forests with high variability in forest structure and biomass volume. In the present study, a total 41 field plots within the LiDAR data acquisition areas were established, selecting plots to capture maximum variability in forest types (peat swamp, dry moist, mangrove, regrowth, rubber and coconut) across the region. Each plot consists of an area of 1 ha in size, which is widely accepted as minimum reporting spatial unit for aboveground biomass measurement. Details on field measurement method adopted can be found in Thapa et al. (2014b). The aboveground biomass was converted to AFCS using the standard conversion factor of 0.47 (IPCC, 2006) where reporting unit is t/ha (tons per hectare).

Airborne LiDAR surveys were conducted for eight sites with a swath of 200 meter using two different LiDAR systems. At first, we used LM–5600 laser system to acquire LiDAR data for 3600 ha in February 2012. This system produced low point density (1.2 per m^2 in average). We used more advanced system, i.e. Optec ALTM 3100EA with an average point density of 3.6 per m^2, and covered 4,472 ha in second time (November and December 2012).

Three–dimensional point clouds of LiDAR discrete returns were analyzed using FUSION software (McGaughey, 2013). Ground points were processed to derive digital terrain model (DTM) at 1 m spatial resolution. Heights above the created DTM surface were calculated by subtracting the respective DTM heights from the height values of all non–ground points. A total forty-one LiDAR plots of 1 ha in size, geographically coinciding with the field plots, were created for the development of AFCS models. More than 70 height metrics from the canopy returns for each LiDAR plot were computed for evaluating potential parameters contributing to AFCS model.

Model calibration was conducted carefully observing the regression parameters, including R^2, p–value and root mean square error (RMSE). Parameters with higher R^2, lowest RMSE and significance of p–value were selected, resulting in the five best alternative models for discussion. In addition, p–value of each variable was considered to filter out those variables that are not contributing to the model. The leave–one–out (LOO) cross validation method was used, following a similar approach used by Thapa et al. (2014b) to provide confidence in the modeling results for the selected parameters. The mean value and standard deviation (SD) of the LOO statistical parameters including R^2 and RMSE (Equation 1) were calculated for each model to determine confidence in the model performance and the uncertainty of AFCS estimates, as follows:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}} \qquad (1)$$

where P_i is the model–predicted value, O_i is the observed value, and N is the number of observations.

3. RESULTS AND DISCUSSION

Among the 41 field measurement plots, 24 are natural forests, including peat swamp and dry moist (11), regrowth (5), and mangrove represent (8). The remaining plots are from plantation forests, including rubber (10) and coconut (7). The AFCS for the forest types ranges from 4.6 to 163.3 t/ha. The lowest AFCS was recorded in coconut plantation areas, while the highest AFCS was recorded in dry moist plots. We observed diverse forest types and the high variability of AFCS among the selected field measurement plots that support minimizing biases in model calibration.

LiDAR to AFCS models were calibrated using the field measurement plots data. First, models using field measured AFCS as the dependent variable and individual LiDAR metric as the independent variable were examined. Among the models explored, the following three power models using a single predictor variable (LiDAR metric) provide the highest R^2 and the lowest RMSE. The variable in each model contributed significantly to the AFCS prediction ($p < 0.0001$).

$$\mathrm{AFCS} = 1.3593 \times \mathrm{MCH}^{1.5415} \qquad \text{(Model – 1)}$$

$$\mathrm{AFCS} = 1.2572 \times \mathrm{QMCH}^{1.4050} \qquad \text{(Model – 2)}$$

$$\mathrm{AFCS} = 0.9477 \times \mathrm{P75}^{1.5099} \qquad \text{(Model – 3)}$$

where, MCH is mean canopy height, QMCH is quadratic mean canopy height and P75 is the 75th percentile of the canopy height.

The predictive capability of each model is indicated by R^2 values of 0.732, 0.734, and 0.732 for the models 1, 2, and 3, respectively (Table 1). The modeling uncertainties (RMSE) for these models are 24.99 t/ha (Model – 1), 24.85 t/ha (Model – 2), and 24.96 t/ha (Model – 3). These levels of uncertainties are comparable to other forest regions, including the tropical forests in Amazon and Kalimantan. Although the LiDAR metrics in these models consist of different mathematical formulations, they produce very similar aggregated results. Nevertheless, slightly different patterns of prediction are observed at the plot level. Among the three models, Model – 2 produces slightly better estimates, indicating the QMCH metric as the best predictor of AFCS for the forests in central Sumatra. However, there are only minor differences in the regression coefficients and RMSE values between these models.

Relying on a single metric and ignoring other potential metrics which limit opportunities to improve predictions. Although including more LiDAR metrics as predictors increases the complexity of the model, they may provide better estimates by lowering prediction uncertainty. Therefore, the effects of multiple LiDAR metrics in predicting AFCS were examined. Several models were evaluated with different combinations of metrics. The following two models (4 and 5) reduce the uncertainties in carbon stock estimates. Model – 4 and Model – 5 are significant at the $p<0.05$ and $p<0.005$ levels, respectively.

$$AFCS = -24.270 + (0.0645 \times MCH\_cover) + (2.984 \times P90) \quad \text{(Model – 4)}$$

$$AFCS = 259.488 - (146.373 \times MCH) + (4.738 \times MCH2) - (4.881 \times Cover) + (3.513 \times MCH\_cover) - (0.0954 \times MCH2\_cover) - (1.583 \times QMCH\_cover) + (22.568 \times P50) + (26.118 \times P90) \quad \text{(Model – 5)}$$

where, Cover: percent of all LiDAR returns above the MCH; MCH_cover: MCH × Cover; P90: 90th percentiles of the canopy height; MCH2: MCH squared; MCH2_cover: MCH2 × Cover; QMCH_cover: QMCH × Cover; P50: 50th percentiles of the canopy height.

Table 1. Calibration and validation indicators for the selected LiDAR to AFCS models.

Models	Calibration		Validation - leave one out		
	R^2	RMSE t/ha	No. of models	R^2 (SD)	RMSE (SD) t/ha
Model – 1	0.732	24.99	41	0.732 (0.01)	25.00 (0.05)
Model – 2	0.734	24.85	41	0.734 (0.01)	24.86 (0.04)
Model – 3	0.732	24.96	41	0.732 (0.01)	24.97 (0.04)
Model – 4	0.753	23.99	41	0.753 (0.01)	24.02 (0.08)
Model – 5	0.871	17.35	41	0.872 (0.01)	17.51 (0.39)

Model – 4 is slightly more complex and includes two metric variables (MCH_cover and P90). It improves the R^2 value to 0.753 and reduces the modeling uncertainty (RMSE) to 23.99 t/ha. These two variables are different than those used in the previous models but produced the best combination in terms of AFCS estimates. Model – 5 is very complex compared to the previous other models and more demanding in terms of data and computational resources. It requires eight variables including MCH, MCH2, Cover, MCH_cover, MCH2_cover, QMCH_cover, P50, and P90. This model increases R^2 to 0.871 and decreases RMSE to 17.35 t/ha. The R^2 value is better than that of Model – 4 by 0.12 and of Model – 1 by 0.14, reducing AFCS uncertainty by 6.64 t/ha compared to Model – 4 and 7.64 t/ha compared to Model – 1.

Outcomes of the 41 models for each model were evaluated within the LOO framework for measuring the performance and uncertainty of all proposed models (Figure 1). Although some ups and downs are observed in each model, the LOO validation results demonstrated that the proposed general models are relatively stable and can be used to predict AFCS reasonably well using LiDAR data. The validation R^2 and the modeled R^2 for the proposed models are very similar except for Model – 5 (Table 1). The validation R^2 of the general Model – 5 is slightly higher than the modeled R^2. The model stability is high, as indicated by the low values for SDs (i.e., 0.01) of the validation R^2 for all models. Furthermore, the validated RMSE values show that any one of the three models using only a single LiDAR metric, i.e., Model – 1 (MCH), Model – 2 (QMCH), and Model – 3 (P75), can provide AFCS estimates with a RMSE value not greater than 25 t/ha in the study region. This level of modeling accuracy is quite reasonable considering the field–measured AFCS and the sample size used for the development of the general model in such diverse tropical forest conditions. Model – 4 is more complex than the single metric models and shows a decrease of 1 t/ha in RMSE estimation. Although Model 5 is much more complex, it provides most accurate AFCS estimates with a validation RMSE of 17.51 t/ha.

4. CONCLUSION

This study has demonstrated the development of LiDAR to AFCS models for tropical forests combining the data from natural and plantation forests in Sumatra. Employing field and airborne LiDAR measurements, potential models were developed, capturing a wide variety of forest species. A range of modeling outcomes using various LiDAR metrics has provided more options for forest carbon assessment in the region. The LiDAR metrics related to canopy cover, forest structure, and height percentiles, which have been successfully used in other forest regions, were the most important predictors in estimating forest carbon stocks in the study area. The performance of each model is promising and the accuracy is comparable to other studies in tropical regions. Depending on the accuracy requirements and acceptable model complexity acceptance, any of the proposed models can be used for accurate forest carbon mapping in the region.

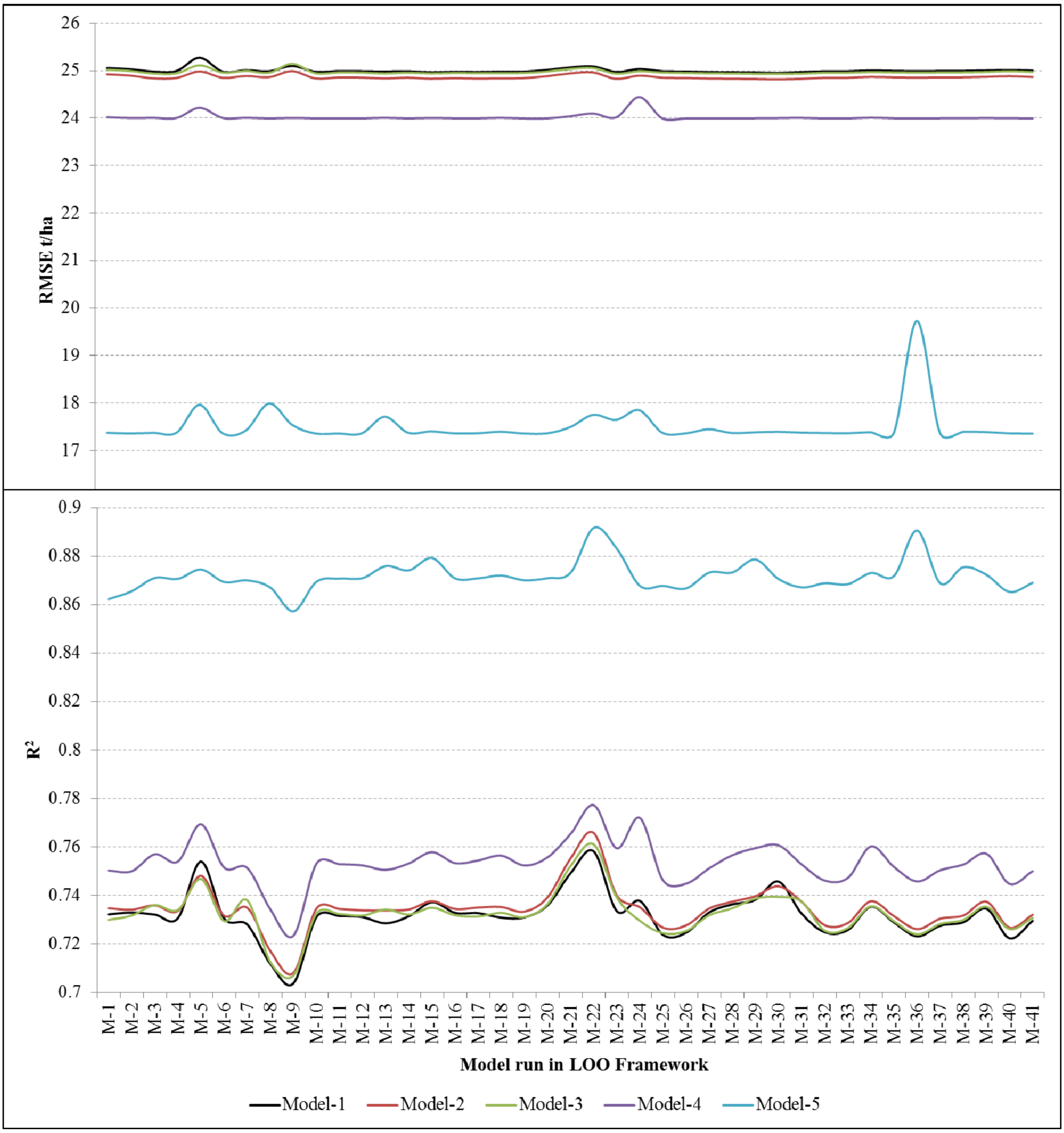

Figure 1. Performance of five models in LOO framework.

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