Abstract

Forests regulate regional climate and the global carbon cycle through biomass stocks and seasonally varying carbon and water exchanges. The assessment of aboveground biomass (AGB), as a proxy of carbon stock, is hindered by dense canopies in tropical ecosystems. In addition, the phenology and ecosystem productivity responses to hydroclimate variability are poorly resolved at sub-seasonal scales. This study uses a multi-sensor and machine-learning framework across three ecosystems in India, representing (i) mangrove forest: (Bhitarkanika Wildlife Sanctuary, BWS), (ii) tropical moist deciduous forest (Similipal Biosphere Reserve, SBR), and (iii) sub-tropical evergreen forest (Sikkim Himalaya) for investigation. Three objectives are framed to (1) estimate AGB, (2) examine the linkages between phenology and local-scale hydrometeorology, and (3) analyse seasonal carbon–water (gross primary productivity: GPP; Evapotranspiration: ET) exchanges and their climate sensitivity. Objective 1 introduces fusion between C-band Sentinel-1 and L-band ALOS-2/PALSAR-2 backscatter for multi-sensor AGB estimation using four machine learning (ML) algorithms, such as Support Vector Regression (SVM), Gradient Boosting (GB), Random Forest (RF), and a semi-parametric Generalised Additive Model (GAM). Across 314 mangrove plots, fusing C+L-bands achieves the best skill ($R^2 = 0.93$, RMSE = 28.35 Mg ha^{-1}), with strong partial effects from HH×HV and $\sqrt{(HH \times HV)}$. RF best predicts AGB in SBR ($R^2 = 0.82$ and RMSE = 32.12 Mg ha^{-1}), aided by GEDI canopy-height metrics and L-band features, and Sikkim ($R^2 = 0.71$ and RMSE = 72.98 Mg ha^{-1}), using L-band and GEDI variables as the best predictors. Objective 2 analyses observational data from a "Pheno-Met" station (Phenocam + Automated Weather Station) in SBR to resolve daily phenology via the Green Chromatic Coordinate (GCC) index. Interannual data show a lower early-season greenness in 2024, an earlier start of season, but a ~12-day delay to peak, implying a shortened growing season due to pre-monsoon water and thermal stress. Phase-wise ML modelling identifies dominant drivers: LF1 – subsurface and surface soil moisture (20 cm and 5 cm; $R^2 = 0.67$); LF2 – soil temperature and moisture ($R^2 = 0.88$); and LF3 – relative humidity ($R^2 = 0.43$). Granger-causality networks reveal short-lag responses (≤6 days) to moisture, humidity, air temperature, and radiation, and a long soil temperature (~25–26 days). Sentinel-2 derived EVI best reproduces Phenocam GCC ($R^2 = 0.88$), followed closely by Sentinel-2 GCC, rather than NDVI. This could denote NDVI saturation and phase lag. Objective 3 employed MODIS GPP and ET with ERA5 climate data to quantify seasonal carbon–water dynamics and water-use efficiency (WUE). The study reveals the strongest seasonal plasticity in deciduous forests (moisture/VPD-limited pre-monsoon), relative stability in evergreen forests (canopy persistence), and intermediate variability in mangrove forests (temperature-sensitive under tidal control). Overall, the study highlights (i) robust AGB estimation through C+L band data fusion, (ii) climate regulation using high temporal-resolution phenology, and EVI as the best vegetation proxy, and (iii) climate change impact on carbon–water dynamics. The study contributes to advancement in AGB monitoring and strengthens MRV (monitoring, reporting, and verification) for carbon accounting and climate change impact awareness in $REDD^+$ planning and restoration targeting.

Keywords: Aboveground biomass; SAR fusion; Phenology; Phenocam; Tropical Forests; Carbon fixation

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