Integrating Sentinel-1 Radar and Sentinel-2 Optical Data for Mangrove Biomass and Carbon Stock Estimation Using Machine Learning

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Mangrove ecosystems are important coastal habitats that contribute significantly to biomass carbon accumulation and climate change mitigation through the organic storage in vegetation and soils. Accurate estimation of these carbon stocks is essential for ecosystem monitoring, blue carbon assessment, and sustainable management. However, conventional in-situ measurements are financially demanding, logistically challenging, and scale poorly across vast ecosystems. Integrating remote sensing with machine learning offers a viable, scalable alternative. This study investigates the integration of Sentinel-1 radar and Sentinel-2 optical data for predicting mangrove biomass and carbon stocks in Côte d'Ivoire. Despite their potential, a research gap exists in combining these data sources. A dataset comprising 300 observations from the Fresco and Sassandra regions was utilized, including field-measured above-ground biomass, below-ground biomass, total biomass, soil carbon stock, and total carbon stock, together with Sentinel-2 optical bands (B2, B3, B4, and B8) and Sentinel-1 radar backscatter variables (VV and VH). Data preprocessing involved normality assessment, logarithmic transformation, and multicollinearity analysis using Variance Inflation Factor (VIF). Normalized Difference Vegetation Index (NDVI) was derived and retained as a key predictor. Two modeling approaches, chosen for their ability to handle non-linear relationships and uncertainty, were evaluated: a Random Forest model with 10-fold cross-validation and a Bayesian Generalized Linear Model (GLM) with Leave-One-Out Cross-Validation (LOO-CV). The Random Forest model achieved superior predictive performance, with an RMSE of 0.885, MAE of 0.686, and R^2 of 0.283, reflecting signal saturation in dense canopies and tidal background noise across landscapes. The Bayesian GLM yielded an RMSE=0.924, MAE=0.695, and Bayesian R^2=0.227. Variable importance analysis identified NDVI as the strongest predictor, followed by radar backscatter variables VH and VV. Similar trends were observed for carbon stock estimation, highlighting the value of integrating optical and radar information. The findings demonstrate that combining Sentinel-1 and Sentinel-2 data provides a scalable framework for operational monitoring, restoration planning, and blue carbon management.

Keywords: *Mangrove biomass, Carbon stock estimation, Sentinel-1 Radar, Sentinel-2 Optical data, Machine learning, Blue carbon*