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Título (máximo 30 palabras):
Multi-Source LiDAR Approaches for Direct Retrieval of Canopy Structure Parameters in Mediterranean Forests

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Resumen (máximo 400 palabras):
Wildfires represent an escalating hazard in Mediterranean ecosystems, particularly in the Iberian Peninsula, where rising frequency and severity threaten biodiversity, landscape resilience, and human well-being. The potential for crown fire development, which is markedly more destructive than surface fires, highlights the urgent need for spatially explicit information on forest canopy fuel properties. This study presents a framework for directly quantifying four critical canopy fuel parameters, canopy height (CH), canopy cover (CC), canopy base height (CBH), and canopy bulk density (CBD), in central Portugal through the integration of spaceborne LiDAR (GEDI), airborne laser scanning (ALS), and field measurements.

Simulated GEDI waveforms, generated from ALS point clouds, were decomposed using Gaussian functions to characterize vertical canopy structure. ALS measurements served as a reference for CH and CC, while field plots were used to calibrate CBH and CBD. Among Relative Height (RH) metrics, RH85 yielded the best match with ALS CH ($r = 0.95$; RMSE = 1.81 m), and GEDI-based CC estimates also agreed strongly with ALS reference values ($r = 0.87$; RMSE = 0.13). A novel stratification method, based on Gaussian peak separation and full width at half maximum (FWHM), enhanced CBH retrieval by representing vertical gaps between canopy layers, achieving a correlation of $r = 0.72$ with field observations. CBD was estimated from waveform-derived structural metrics, plant area index, and canopy length, showing moderate agreement with field data ($r = 0.65$; RMSE = 0.025 kg/m³). Validation with actual

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GEDI footprints confirmed the reliability of these estimates across diverse canopy conditions, with r ranging from 0.73 to 0.86 for all four parameters.

By combining simulated GEDI pseudo-waveforms with ALS and field data, the approach enabled parameter estimation even in areas without overlapping measurements. To extend the analysis wall-to-wall, random forest models were trained with GEDI footprints and multi-sensor satellite data (Sentinel-1, Sentinel-2, ALOS PALSAR-2), as well as biophysical and topographic variables, producing spatially continuous maps and associated uncertainty layers for all four canopy fuel parameters. The resulting products provide robust inputs for wildfire behavior modeling and risk assessment, advancing the capacity to monitor and manage fire-prone landscapes at regional scales.

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