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Advancing Coffee Management Mapping through Multisensor Data and Multistep Ensemble Learning

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Located in the state of São Paulo, Caconde is one of Brazil's most important regions for the production of specialty coffees. The municipality is characterized by smallholder-based agriculture, mild climate, complex topography, and a highly fragmented landscape. In recent years, local producers have intensified plant density and adopted crop renewal strategies to mitigate productivity losses associated with climate variability. Among these practices, pruning techniques, particularly skeletonization, play a crucial role in regulating canopy growth and shadow management. However, such interventions increase spatial and spectral heterogeneity, complicating the remote sensing–based mapping and monitoring. In our recent study (https://doi.org/10.3390/rs17183168), we explored the potential of dense Harmonized Landsat and Sentinel-2 (HLS) time series of spectral indices for coffee mapping in Caconde. The results showed that multi-temporal fusion data improved class separability across diverse management systems, with unprecedent accuracy up to 95% with ensemble learning of Random Forest and Extreme Gradient Boosting models. Despite the advances, accurately identifying recently renovated and skeletonized coffee areas remains a challenge, as their altered canopy structure and reduced vigor produce spectral signatures similar to those of fallow or non-coffee areas. To address these limitations, upcoming research will focus on leveraging a space-time hybrid approach with deep learning and surface phenology modeling. Specifically, we plan to implement a workflow combining the spatial detail of Sentinel-2 with the temporal continuity of HLS. The first stage will apply U-Net-based convolutional networks for parcel delineation at 10 m resolution, followed by the extraction of phenological metrics from HLS time series to describe canopy recovery and seasonal dynamics. This workflow is expected to enhance both spatial precision and interpretability in distinguishing coffee management stages using machine learning supervised classification. This research is being conducted within the Semear Digital Project, a national initiative led by Embrapa that promotes digital agriculture through a network of ten Agrotechnological Districts (DATs) across Brazil.

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