EGU26-21041, updated on 21 May 2026
https://doi.org/10.5194/egusphere-egu26-21041
EGU General Assembly 2026
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Mapping recruitment patterns at alpine treeline ecotones using UAV-based LiDAR and multispectral data

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Monitoring vegetation dynamics is crucial for assessing the effects of global change on mountain ecosystems, particularly at treeline ecotones where tree recruitment success is highly variable and largely influenced by fine-scale site conditions. This study integrates ground-based surveys with UAV-based LiDAR and multispectral (MS) data to investigate recruitment patterns across two Alpine treelines in Italy (Mt. Genevris, Piedmont; Mt. Becco di Mezzodì, Veneto). During the 2024 and 2025 summer seasons, we conducted ground-based measurements along altitudinal transects spanning the treeline ecotone, from the upper ecotone limit down to the closed-canopy forest. We mapped trees and saplings using a GNSS rover, and we measured basal diameter and tree height. On the same slopes, we acquired and processed UAV LiDAR and MS imagery to derive high-resolution 3D point cloud. With the collected data, we derived canopy height model, microtopography, land-cover classification and MS metrics describing vegetation spectral variability. We used field-mapped individuals to train and validate machine-learning models for detecting individual trees and producing georeferenced point datasets across entire slopes. These individual-level spatial data enabled spatial point-pattern analyses to assess recruitment structure along the treeline, testing for facilitation versus competition among individuals in relation to key biotic elements (i.e. shrubs and patches). In addition, we examined establishment patterns in relation to microclimatic proxies derived from UAV-based topographic features, including indices of potential solar radiation, heat load and moisture availability. This integrated LiDAR–MS UAV framework, anchored to ground-truth data, enables individual mapping of treeline recruitment across entire slopes at spatial resolutions not achievable through ground surveys alone. By linking 3D structure, spectral information and spatial point-pattern analysis, this research approach improves the interpretation of micro-environmental controls on establishment niches and provides a transferable framework for scalable treeline monitoring under ongoing climate change.