EGU24-10296, updated on 20 May 2024
https://doi.org/10.5194/egusphere-egu24-10296
EGU General Assembly 2024

Characterizing Spatial Patterns of the Alpine Treeline Ecotone Across the European Alps

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Ecotones – transition zones between ecosystems – are sentinels of global change, as they are sensitive to changes in environmental conditions and land use. The alpine treeline ecotone - where the continuous, subalpine forest transitions into the treeless alpine zone – is a characteristic feature of many mountain ecosystems. The transition at the ecotone can be characterized by distinct treeline patterns. Treeline patterns can be simple, such as sharp transitions from forest to alpine vegetation, or complex, e.g., islands of trees and krummholz in a matrix of alpine vegetation. This variation can mediate the impact of global change at the alpine treeline ecotone. However, large-scale attribution, e.g., for an entire mountain range, and spatiotemporal quantification of treeline patterns remain challenging. Automated methods, such as deep learning-based computer vision systems, can help to overcome these challenges. Building on existing definitions of treeline patterns, we aim to characterize the alpine treeline ecotone for the entire mountain range of the European Alps. Our particular objectives are:

- To characterize the patterns of a representative sample of the alpine treeline ecotone of the European Alps based on remote sensing information as training data for deep learning.
- To quantify treeline patterns across the Alps and identify spatial differences in the prevalence of patterns.

In an alpine treeline ecotone, we considered the transition between three vegetation classes: trees (i.e., upright woody plants with a minimum height of 3m), krummholz (i.e., stunted trees and woody shrubs), and treeless alpine vegetation. Three spatial patterns were considered for trees and krummholz describing their state: closed, islands, or isolated individuals. The transitions between these states across elevation, a total of 24 combinations, were used to quantitatively characterize treeline patterns. We selected 1,000 randomly distributed elevational transects between 1,100 and 2,800 m.a.s.l. that include the alpine treeline ecotone across the European Alps. For each transect, we classified treeline patterns for areas of 90m×90m using satellite and orthophoto images. Based on this dataset, we quantified differences in treeline patterns and their distribution in elevation across the European Alps: While in the Prealps, the alpine treeline ecotone

is located in lower elevations and treeline patterns tend to be more complex, the ecotone is higher in elevation and less complex in the Central Alps.

The quantification of treeline patterns and their distribution can serve as a basis for further investigations of the alpine treeline ecotone and its spatiotemporal development. We provide an outlook for a deep learning approach that uses the presented dataset combined with a time series of spectrally unmixed satellite data, i.e., fractional abundances of land cover per pixel, as training data. Utilizing satellite data of the past 35 years in annual resolution, we will be able to automatically classify and analyze treeline patterns and their changes across the entire European Alps.