EGU24-1844, updated on 20 May 2024
https://doi.org/10.5194/egusphere-egu24-1844
EGU General Assembly 2024

Tracking shifts of mountain forest ecotones in aerial imagery with deep learning

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Forest ecosystems are sensitive to global change; especially at the ecotones we expect high sensitivity to changes in climate, disturbance regimes or land use. For instance, the treeline ecotone is expected to move upward in elevation with global warming. The advent of machine learning, specifically computer vision, provides powerful tools for monitoring ecotones across large spatial scales using remote sensing data. In this study, we focused on the spatiotemporal development of ecotones bracketing the subalpine forest belt (i.e., the upper boundary, formed by the treeline, and the ecotone to montane forests as the lower boundary) in a protected forest landscape in the European Alps. Our objectives were threefold: First, we aimed to identify trees and shrubs on historic and recent orthophotos using deep learning, with special attention to integrating multiple sensor types into one computer vision framework. Second, based on the computer vision inference, we sought to map the a) treeline and b) montane-subalpine ecotone. Third, we aimed to describe the spatiotemporal changes occurring in both ecotones.

We based our analysis on historic and recent aerial images of Berchtesgaden National Park in the Northern Alps, covering roughly 210 km² in nine time steps from 1953 to 2020. The images were captured through both analog (panchromatic and color infrared) and digital (color infrared, RGB) sensors. To generate training data for deep learning, we manually interpreted randomly distributed 0.5 ha segments across all time steps, resulting in over 110,000 annotations of coniferous and broadleaved trees, shrubs, and standing dead trees. We tested different instance segmentation frameworks and selected the best performing model architecture to create wall-to-wall tree maps for each time step. Using structure and composition of the tree maps, we spatially delineated the ecotones and tracked their changes over time.

We did not find a spatially consistent pattern of ecotones shifting upwards, however we were able to identify areas of change and stability linked to climate, topography, disturbances and land use. We observed remarkable local upward shifts in ecotones, particularly of the montane-subalpine ecotone, which shifted up to five times faster than the treeline. In general, we found that subalpine forests, situated between the two ecotones, decreased in area because of an upward shift of its lower boundary, and exhibited an increase in crown cover over time.

Changes in these ecotones and related vegetation zones pose challenges to conservation, restoration and management. Our approach can help to address these challenges, e.g., in the combination with habitat modelling.