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Significant increase observed in tree mortality in boreal forests in Southern Finland

Samuli Junttila[1], Minna Blomqvist[2], Ville Laukkanen[3], Hannah O'Sullivan[2], Antti Polvivaara[1], Markus Holopainen[2], and Heli Peltola[1]

[1]School of Forest Sciences, University of Eastern Finland, Joensuu, Finland (samuli.junttila@uef.fi)
[2]Department of Forest Sciences, University of Helsinki, Helsinki, Finland
[3]Photoboiler Oy, Espoo, Finland

Simultaneous increases of severe drought and heat extremes with bark beetle outbreaks have recently increased tree mortality globally. The lack of accurate tree mortality data over large areas has limited the development and applications of tree mortality models. Available tree mortality data has mainly been collected using field observations with limited spatial extent. However, the use of high-resolution remote sensing data, such as aerial imagery with automated imagery analysis, may change this situation.

In this study, we analysed the development of tree mortality (standing dead wood) and factors contributing to it during 2017-2023 over an area of 117 366 ha of boreal forested landscape in Southern Finland. For this purpose, we developed a convolutional neural network (CNN) based on U-Net architecture, allowing segmenting of standing dead wood automatically from aerial imagery in 2017, 2020 and 2023 with a spatial resolution of 0.5 m. We trained the model using 22300 segments of manually delineated dead trees from various geographic regions in Finland. The model showed high accuracy in detecting the dead trees with an F1 score of 0.93 based on an independent validation dataset. We also combined the information on detected dead trees with open forest resource information based on extensive field campaigns and airborne laser scanning, to estimate standing dead wood volume during 2017-2023.

The total standing dead wood volume increased substantially in our boreal study area, by 543 % from 8660 m3 to 52659 m3 between 2017 and 2023. Similarly, the total forest area of standing dead wood increased by 456 % between 2017 and 2023. Both variables followed an exponential growth curve with a nearly perfect fit for the 2017, 2020 and 2023 time series, indicating that tree mortality increased rapidly. Tree mortality occurred mainly in Norway spruce (*Picea abies*) dominated forests on relatively fertile soils. The mean age of forest stands suffering from tree mortality decreased from 69.7 to 62.6 years between 2017 and 2023, indicating that tree mortality has transitioned towards younger forests. Our findings highlight the increasing risk of tree mortality in boreal forests and the need for large-scale monitoring to keep up to date on the fast-paced changes in boreal forest mortality. This is also required for timely risk management

measures in forestry under changing climate, associated with simultaneous increases of severe drought and heat extremes with bark beetle outbreaks.