DeepTrees Symposium: Deep Learning and Remote Sensing in Tree Monitoring

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Book of Abstracts

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deadtrees.earth - A Database of Centimeter-Scale Aerial Imagery as Reference Data for Mapping Global Tree Mortality

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Today, excessive tree mortality is a global concern. Accurate monitoring for ecological insights and environmental predictions is urgently required. Earth observation data, combined with supervised machine learning, offer a promising approach to map tree mortality over time.
However, global-scale machine learning requires broad training data covering a wide range of conditions and forest types. Drones provide a cost-effective solution by capturing high-resolution orthoimagery for this purpose. Here, we introduce deadtrees.earth, an open-access platform hosting a database of over 1,500 centimeter-resolution orthophotos annotated with standing deadwood labels. deadtrees.earth is a community-sourced and rigorously curated dataset that shall serve as a foundation for a global initiative to gather comprehensive reference data. The platform aims to enhance our understanding of tree mortality patterns from local to global scales by attracting contributions from underrepresented regions. The dynamic nature of this database together with the collective effort of the community is meant to continuously increase our capacity to detect and understand tree mortality patterns.

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SELF-SUPERVISED BACKBONES FOR FOREST REMOTE SENSING

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Self-Supervised Learning (SSL) presents an opportunity to leverage large volumes of unlabeled data to improve outcomes for tasks for which training data is limited. This is the case in forest remote sensing where high quality annotated datasets are often too small to fully take advantage of data hungry deep learning models. Recognizing this, we have pre-trained two classes of neural network backbones that can be adapted to multiple use cases: different Vision Transformers (ViTs) (Dosovitskiy, 2020) and ResNet-50 (He et al, 2016). These backbones have been pre-trained on publicly available high resolution aerial image data from North Rhine-Westphalia (NRW), using two SSL frameworks: DINO (Caron et al, 2021) and MAE (He et al, 2016). We conducted four comparisons:
1. Pre-training on either remote sensing data or the ImageNet dataset, to assess whether pre-training with remote sensing data offers an advantage.
2. Pre-training the backbones on the NRW dataset to assess whether ViTs are superior to ResNet-50.
3. Training directly in a supervised manner to assess performance improvements due to pre-training.
4. Pre-training using DINO and MAE to assess the influence of the pre-training method.

The results can be summarized as follows:
- Pre-trained SSL models outperform supervised models on downstream tasks.
- Pre-training with NRW dataset offers improved downstream task performance over pre-training with ImageNet dataset.
- ViTs perform better than ResNet-50 at the pre-training task which translates to improved performance on downstream tasks.

- In terms of performance on downstream tasks, DINO emerges as a better pre-training method than MAE.

The outcomes of testing the models on three downstream tasks are summarized below:
- Classification: On a task involving orthophotos of 7334 trees across 10 species from Gartow (Germany), the Vision Transformer achieved the highest performance.
- Binary Semantic Segmentation: On a task involving 39 orthophotos with binary segmentation masks (tree and background) from Gartow, the Vision Transformer, coupled with a ClipSeg segmentation decoder (Lüddecke et al, 2022), achieved the highest performance.
- Multiclass Semantic Segmentation: On a task involving 47 orthophotos of forest across 15 tree species from the FORTRESS dataset (Schiefer et al, 2022), the Vision Transformer, coupled with ClipSeg segmentation decoder, achieves the highest performance.

Our experiments show that in the case of small scale datasets, pre-training with remote sensing data significantly improves outcomes in comparison to initializing models with ImageNet pre-trained weights. They further show that Vision Transformers outperform ResNet-50 and require fewer epochs to reach optimal accuracy. These results point to a possibility for building a full-scale foundational model, trained on even larger areas, that could help to improve diverse forest related remote sensing tasks.

Deeptrees updates / 3

Fine-tuning and evaluating deep learning models for tree crown segmentation

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The DeepTree project uses deep learning models to segment tree crowns in orthoimages. Building on pretrained models [1], we fine tune them with labeled orthoimages from the city of Halle (Saale), Germany. We present a deep learning model that is optimized for segmenting tree crowns in orthoimages from this region.
The deep learning model is evaluated based on the city's registry of trees [2] and hand-drawn polygons provided by UFZ. We discuss the model's ability to identify tree crowns correctly. Furthermore, we show that fine-tuning on the specific dataset can improve performance over the out-of-the-box pretrained model.
Gathering labeled data requires substantial human effort. These ground truth labels are essential to train and evaluate the deep learning models.
In order to direct the labeling efforts most efficiently, we implement active learning. The deep learning model estimates how certain it is in segmenting a given tile. We then select the tiles with the highest uncertainty, create ground truth labels, and fine-tune the model. This iterative approach can substantially speed up model fine tuning.
[1] M. Freudenberg et al, TreeCrownDelineation, https://github.com/AWF-GAUG/TreeCrownDelineation/releases/tag
[2] Baumkataster. Open Data Halle. https://webapp.halle.de/komgis30.hal.opendata/fa3930b7-b3ed-b3fc-20d9-2fc8fd054b0e.html

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Using AI to detect and identify tree species from satellite images in Hawaii

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The application of artificial intelligence (AI) in ecology presents significant opportunities for enhancing biodiversity monitoring and informing conservation efforts, particularly in tropical regions. This project aims to apply the DeepTrees pipelines to a tropical setting at two spatial scales.

First, at a large scale, we aim to identify key species of interest for restoration and conservation on the island of Kauai, Hawaii. Specifically, we will focus on canopy trees that are noxious weeds, foundational native species, and important for food security. We will use both aerial photos or satellite images and ground truth data from forest inventories and from the National Tropical Botanical Garden. Deep learning models will be applied to quantify the number, size, and identity of these strategically significant trees across the entire island. A comprehensive database on tree locations and biomass will be developed and maintained, providing a valuable resource for ongoing research and management.

Second, at a smaller scale, we aim to identify all canopy tree species in a 0.25 km2 coastal forest in Hana, Maui. A restoration project is planned for this site that will begin in January 2025, with the goal of removing the invasive African tulip tree, and providing more space for vulnerable native species, such as Pandanas and Metrosideros. Drone sampling in November 2024 will capture high-resolution images for the area, and local scientists will annotate a subset of these images to locate and identify individual canopy trees. The DeepTrees pipelines will be applied to locate and identify all canopy trees in the target area. This information can immediately be used to efficiently plan the restoration work. In future years, new drone images and these same pipelines can capture canopy change in response to habitat restoration.

It is our goal that these collaborative projects will support ecological research and practical conservation measures in Hawaii, and also provide a useful out-of-domain test of the DeepTrees pipelines. We will provide feedback and work to improve the pipelines for ecological applications worldwide.

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Integrating UAV Imagery and LiDAR Data for Tree Structural Properties

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Forests cover approximately 31% of the global land area and are essential for biodiversity, supporting 80% of terrestrial species. However, these ecosystems are vulnerable to human-driven climate change, necessitating automated systems to monitor structural changes at the individual tree level and assess forest responses to climate anomalies. UAV-based tree canopy detection is valuable for estimating essential ecosystem variables (EEVs) and biodiversity variables (EBVs). However, applying UAVs to specific projects can be complex due to the range of data and processing requirements. To address this, we developed Drone4Tree, a user-friendly platform built on Streamlit and Flask that provides an end-to-end solution for processing UAV imagery. The platform processes UAV-acquired data to generate orthomosaics, delineate tree crowns, and derive tree attributes, with user-friendly options for standard and advanced processing modes. It uses structure-from-motion (SfM) through

OpenDroneMap to generate orthomosaics and digital surface models (DSM), from which individual tree heights are calculated. Drone4Tree employs U-Net-based segmentation for tree canopy delineation. This workflow facilitates an analysis-ready time series of individual tree canopies, enabling detailed phenological and ecological assessments. Canopy boundaries generated by the platform will help build spectral libraries for species detection and mapping, contributing to studies of forest structure, ecosystem function, and species diversity.

In addition to UAV data, we used LiDAR data to analyze tree height and diameter at breast height (DBH) and validate UAV-derived measurements. Comparative analysis shows strong agreement between field DBH and LiDAR-derived DBH, indicating reliable DBH estimation from LiDAR data. For tree height, the LiDAR-based measurements correlated well with heights derived from the UAV-based canopy height models (CHM), though comparisons with field-measured heights revealed a lower correlation. These results indicate that LiDAR and UAV data complement each other, with UAVs offering efficient monitoring capabilities while LiDAR provides additional precision. This platform enables accurate, scalable individual tree monitoring, supporting ecological research and forest management.

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DeepTrees: Deep-Learning based spatiotemporal tree inventorying from public orthoimages

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Field-based methods for tree inventorying are time-consuming, labour-intensive, and often expensive. With the advent of remote sensing technologies and deep learning, it is now possible to leverage digital public orthoimages and artificial intelligence to automate and enhance the tree inventorying process [1].

The DeepTrees project aims to develop and implement deep learning models for tree crown segmentation, tree trait detection and tree species classification for the publicly available imagery from the Digital Orthoimages Program (DOP) at 20 cm scale in Germany. The resulting tree inventories and monitoring data can be used for various applications, including forest management, biodiversity monitoring, and ecological research.

Segmented tree crowns can give a wealth of information about the individual trees. The significance of a tree's fitness is closely tied to both the structure and size of its crown [2]. These factors influence the tree's access to resources, its utilisation and occupation of space, the magnitude of its growth, as well as seed production and dispersal. In densely populated environments, the growth of crown size results in competition for space, leading to social differentiation, reduced growth of suppressed trees, mortality, and self-thinning [3]. Furthermore, the practical and economic relevance of crown structure and size should not be overlooked. Wider crowns contribute to heightened mechanical stability due to lower slenderness (h/d ratios), but this comes at the expense of wood quality, influenced by the number and thickness of branches [4]. This finer level of detail holds importance in the analysis, modelling, or management of diverse environments, spanning natural forests, planted forests, urban forests, and orchards.

DeepTrees has three components:
1. A Python Package that allows users:
i. to aggregate training and prediction of deep learning models for standardised tree inventorying.
ii. to analyse the delineated trees (tree allometry + tree classes).
2. A public spatiotemporal database of trees in Sachsen and Sachsen-Anhalt, ready for scientific applications.
3. Training datasets for further downstream learning tasks.

The DeepTrees project website can be found here: https://deeptrees.de

References:
1. Zhao, H., Morgenroth, J., Pearse, G., & Schindler, J. (2023). A Systematic Review of Individual Tree Crown Detection and Delineation with Convolutional Neural Networks (CNN). Current Forestry Reports, 1-22.
2. White, E. P., Ernest, S. M., Kerkhoff, A. J., & Enquist, B. J. (2007). Relationships between body size and abundance in ecology. Trends in ecology & evolution, 22(6), 323-330.
3. Knoke, T., Ammer, C., Stimm, B., & Mosandl, R. (2008). Admixing broadleaved to coniferous tree species: a review on yield, ecological stability and economics. European journal of forest research, 127, 89-101.
4. Pretzsch, H., & Rais, A. (2016). Wood quality in complex forests versus even-aged monocultures: review and perspectives. Wood science and technology, 50, 845-880.

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Challenges in Crown Spread and DBH Estimation from Segmented Tree Crown Polygons

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Tree traits such as crown area (CA), crown radius (CR), and diameter at breast height (DBH) provide insight into a tree's growth dynamics, biomass, and the overall biophysical and biochemical processes of ecosystems. Accurately measuring these traits is essential for carbon estimation, urban tree management, and biodiversity assessments. The allometric relationships between CA, CR, and DBH are often nonlinear and can vary significantly across regions due to differences in climate, species composition, and management practices. Multi-species allometry is especially challenging due to the variability in species-specific growth forms, particularly when comparing needleleaf and broadleaf species. Traditional field measurements for these parameters are often labor-intensive and time-consuming, especially in large-scale studies or densely forested areas.

We used the segmented tree crown polygons from the DeepTrees tree crown delineation model to calculate crown area and crown spread of individual trees. We evaluated the accuracy of 4 different crown spread calculation methods by comparing them to verified ground-truth data from a local tree inventory ("Baumkataster"Halle/Saale). The best calculation method gave a 31 % match with the Baumkataster data and 87 % of the modelled crown spread fell within an acceptable margin of the ground-truth data. Trees with particularly small (< 5 m crown spread) or very large (> 15 m crown spread) crowns tend to be more challenging to estimate accurately, indicating that better estimations are only possible with more accurate tree crown segmentations since the segmentation model has large error rates for small and large trees.

The DBH-calculation was based on different functions evaluated by Song et al. [1] and used the calculated crown spread as input. This calculation proved to be more challenging, not resulting in good matches with the ground-truth data.

These findings highlight the potential and some of the challenges in accurately assessing tree traits from 2D tree crown segmentations.

Reference:
1. Song, X., Li, J., & Zeng, X. (2024). Parameterization of height–diameter and crown radius–diameter relationships across the globe. Journal of Plant Ecology, 17(2), rtae005.

Opening Remarks + Keynote / 8

Seeing the trees in the forest (and other places)

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Why do we want to map trees and what are the obstacles on the road? And what is a tree by the way? This introductory talk will discuss some of the challenges, opportunities and applications of tree detection and delineation in very high resolution image data.

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Characterizing the high latitudinal treeline ecotone using multi-source remote sensing data

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The term treeline refers to the climatic limit of tree growth, occurring where seasonalmean temperatures decline to around 6 ℃ with a growing season of at least 3months (Körner 2020). Thereby, the treeline defines the boundary of the tree as a lifeform. However, treelines are shaped by various environmental factors and appear indifferent forms, typically classified as diffuse, abrupt, islands and krummholz.Characterizing changes in Arctic tundra vegetation is directly linked to understandingthe long-term dynamics in the high-latitudinal treeline. With longer vegetation periods and decline of permafrost stability, trees potentially migrate towards higher latitudes which can cause local shifts of the treeline and, consequently, a squeezing of the land area available for Arctic tundra.

The imagination of the treeline in the sense of hard boundary can be misleading as the turnover from forest to tundra is rather gradually following local conditions. These landscape gradients, also known as forest-tundra ecotones, are dynamic ecological transition zones where vegetation changes from tall trees to prostrate shrubs.

The inconsistent use of terminology and varying definitions of trees and treelineshave hindered standardized assessments of treeline dynamics as climate changeindicators so far. There is no single best method for monitoring forest-tundra ecotones and a multiscale approach integrating multiple methods is needed to provide a comprehensive understanding of changes and the factors influencing themRemote sensing data serve as one valuable source for understanding and monitoring changes in tree cover at large spatial extent without need for field access, which can be a particularly challenging limitation in the pan-Arctic region.

However, currently available remote sensing-based forest cover products lack the level of detail to characterize the high-latitudinal treeline ecotone.
In the session, we will discuss their major limitations and present ideas for improvement that include the application of single-tree detection from high-resolution multisource remote sensing data.

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The UFZ forest monitor

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The UFZ Forest Condition Monitor is a project funded by the Helmholtz Association within the Land Cover & Dynamics Working Group of the Remote Sensing Department at the Helmholtz Centre for Environmental Research - UFZ in Leipzig. The UFZ Forest Condition Monitor provides (remote sensing-based) comprehensive annual/seasonal derivations of forest condition continuously since 2017. This is valuable complementary information compared to common sample-based surveys, such as the Forest Condition Report. This report is based on precise and comprehensive forestry data acquisitions, but is therefore very time- and personnel-intensive and limited in the number of survey points. By utilising both components - Monitor + Report - a more robust regional perspective can be depicted for the first time, and a spatial translation of the statistically collected forestry data can be achieved. This makes the drastic climate change-induced dynamic changes in forests easily accessible even for non-experts.

In this project, current satellite data are compared with long-term observations to analyse changes in the forest and to identify anomalies. Subsequently, these anomalies are validated through forestry surveys and damage mappings at selected observation sites. The UFZ Forest Condition Monitor thus provides information for all forested areas in Germany. The maps from 2017 to 2022, especially for areas in central Germany such as the Harz, Sauerland, and Saxon Switzerland regions, show a significant increase in damaged forest areas, particularly from 2019 onwards. There are diverse causes for this phenomenon: heat, drought, pest infestations, and their interactions damage the forests, leading to subsequent effects such as windthrow and increased risk of forest fires. The scientific analysis using satellite data depicts the dynamics of forest condition induced by climate change in a spatial manner. In addition to forest condition, the project also derives other products such as dominant tree species, vegetation length (phenology), and the future distribution of tree species under the influence of climate change.