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DeepTrees: Tree Crown Segmentation and Analysis in Remote Sensing Imagery with PyTorch

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Summary

DeepTrees is a Python package for tree crown segmentation and analysis in remote sensing imagery. It uses PyTorch for training and predicting on large-scale datasets. Designed for direct integration with geospatial workflows, DeepTrees provides data loaders, transforms, and utility functions, enabling efficient experimentation in tree crown segmentation and tree traits analysis.

Statement of Need

Accurate tree crown segmentation is essential for ecological modeling, biomass estimation, and forest management (Food & United Nations, 2022). Traditional methods often depend on labor-intensive manual delineation or specialized scripts. With the rise of high-resolution imagery from satellites, aircraft, and UAVs, a scalable, open-source tool is needed to:

- Automate the segmentation of tree crowns across diverse landscapes and across sensor types.
- Seamlessly integrate with geospatial workflows for data loading, tiling, and inference.
- Provide methods for crown morphological and traits analysis.
- Support reproducible research with transparent and customizable training pipelines.
- Go beyond tree crown segmentation and into analysis.

Deep learning has been widely applied to crown detection, especially with CNNs and U-Net-based models on RGB, multispectral, and lidar data (Freudenberg et al., 2022; Zhao et al., 2023). Semi-supervised and cross-site learning approaches improve generalization across environments (Weinstein et al., 2019, 2020). Despite the advancements in detection, segmentation tools remain limited. Some methods target specific domains, such as orchard segmentation with RGB-D imagery (Cong et al., 2022) or canopy height maps from laser scanning (Sun et al., 2022). Yet, in heterogeneous landscapes, challenges persist—overlapping crowns, diverse canopy structures, and seasonal variation hinder generalization (Moussaid et al., 2021; Zheng et al., 2024).

Few tools go beyond detection to include structural or ecological analysis. Most focus on crown detection/segmentation alone, without integrating downstream applications like canopy height modeling, carbon estimation, or forest structure analysis (Fayad et al., 2024; Pan et al., 2024; Tolan et al., 2024). This leaves a gap for tools that combine segmentation with ecological insights, especially for urban forests (Sharma et al., 2024) and large ecosystems.

Library overview

The DeepTrees package offers a comprehensive framework for tree crown segmentation and analysis, supporting both single-image and batch inference. It generates multiple outputs—tree crown masks, outlines, distance transforms, uncertainty (entropy) maps, individual tree rasters, and crown polygons. These facilitate detailed morphological analysis and integrate seamlessly with geospatial workflows, aiding ecological monitoring and forest management (Figure 1).

A key feature is model fine-tuning and training. Users can train models from scratch or fine-tune pre-trained ones on new datasets. We include the original U-Nets from the TreeCrownDelineation project (Freudenberg et al., 2022). Transfer learning helps adapt models to varied environments and imaging conditions, improving segmentation performance across ecological and geographic contexts. Custom backbones are supported, allowing integration of new architectures like Geospatial Foundation Models (GFMs).

Beyond segmentation, DeepTrees computes key tree traits critical for ecological studies and forest management. Users can derive indices like the Green Chlorophyll Index (GCI), Hue Index, and Normalized Difference Vegetation Index (NDVI), which assess vegetation health and chlorophyll content from spectral bands. The module also calculates structural traits such as the longest spread and cross-spread of tree crowns, providing insights into crown morphology. These outputs support downstream tasks like biomass estimation and vegetation health monitoring.

A significant challenge in training deep learning models for remote sensing applications is the limited availability of annotated data, as tree crown delineation requires domain expertise. To address this issue, DeepTrees addresses this via an active learning loop that reduces labeling effort. By quantifying uncertainty at pixel and tile levels during inference, it identifies the most informative samples for manual annotation—accelerating model performance gains (Wu et al., 2022).

Built with PyTorch Lightning (Falcon & The PyTorch Lightning team, 2024), DeepTrees ensures scalability and reproducibility. Its modular architecture supports extensibility and ease of use, comprising:

- `TreeCrownDelineationDataModule`: Standardizes data handling for training and inference.
- `TreeCrownDelineationBaseDataset`: Handles loading and preprocessing, extended by:
  - `TreeCrownDelineationDataset`: Generates random raster crops for training.
  - `TreeCrownDelineationInferenceDataset`: Provides full raster tiles for inference.
- `DeepTreesModel`: A LightningModule supporting multiple backbones with training, validation, and evaluation metrics.
- `Trainer`: Manages training and inference on CPU or GPU (GPU recommended for efficiency).

DeepTrees uses Hydra for configuration, accepting YAML config files and arguments that define module parameters for training and inference scripts.

By unifying segmentation, active learning, and tree crown analysis, DeepTrees offers a robust, scalable solution for crown delineation and analysis. Its modular, open-source design makes it ideal for researchers and practitioners using aerial, UAV, or satellite imagery at scale.

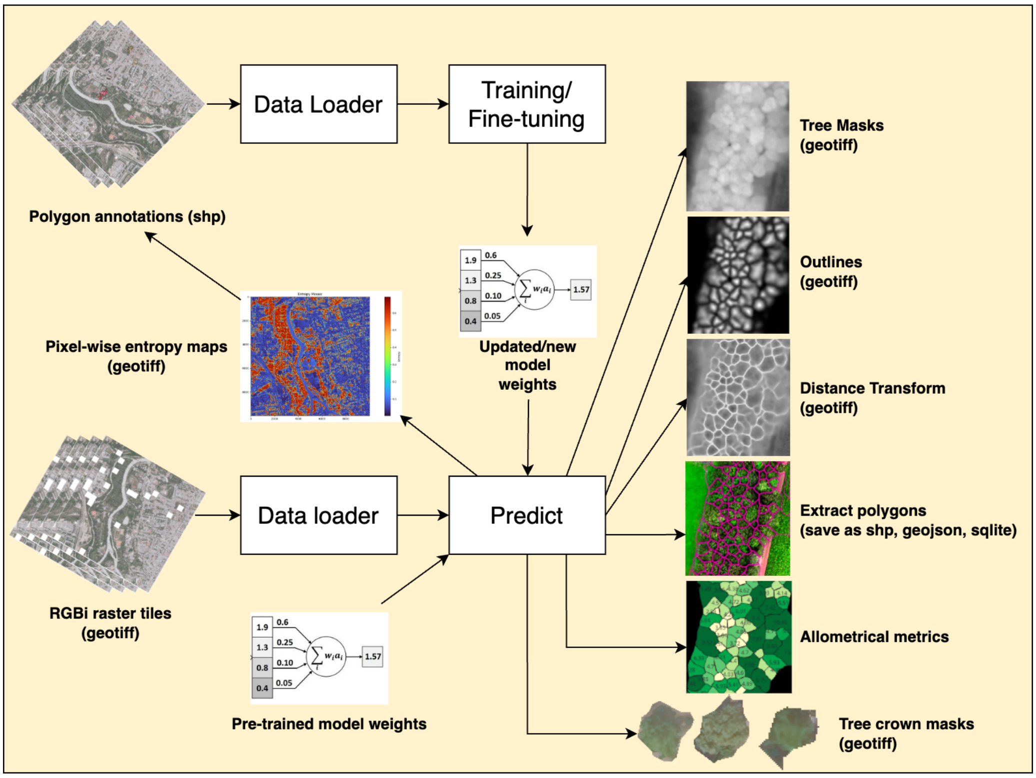

Figure 1: Overview of the DeepTrees workflow for tree crown segmentation and analysis. The system processes high-resolution RGBi raster tiles (GeoTIFF format) using a data loader, which prepares input data for training, fine-tuning, or prediction. The model can be trained using polygon annotations (SHP format) and fine-tuned based on pixel-wise entropy maps (GeoTIFF format) to improve segmentation quality through active learning. During inference, DeepTrees generates multiple outputs, including tree masks, crown outlines, distance transform maps, tree crown polygons (exportable as SHP, GeoJSON, or SQLite), and allometric metrics. The system supports both pre-trained and updated model weights, enabling flexible and adaptive tree crown delineation.

Pre-trained Models and Datasets

DeepTrees includes pre-trained models from Freudenberg et al. (2022) and our own training data.

Additionally, the package provides a labelled dataset of tree crowns in the Halle region as ESRI shapefiles, which can be used for training and evaluation (Taimur Khan, 2025). The tree crowns are labelled with the following classes:

- 0 = tree
- 1 = cluster of trees
- 2 = unsure
- 3 = dead trees

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