CanoPyHydro: Leveraging LiDAR to Predict Precipitation Partitioning in Tree Canopies

31 August 2024

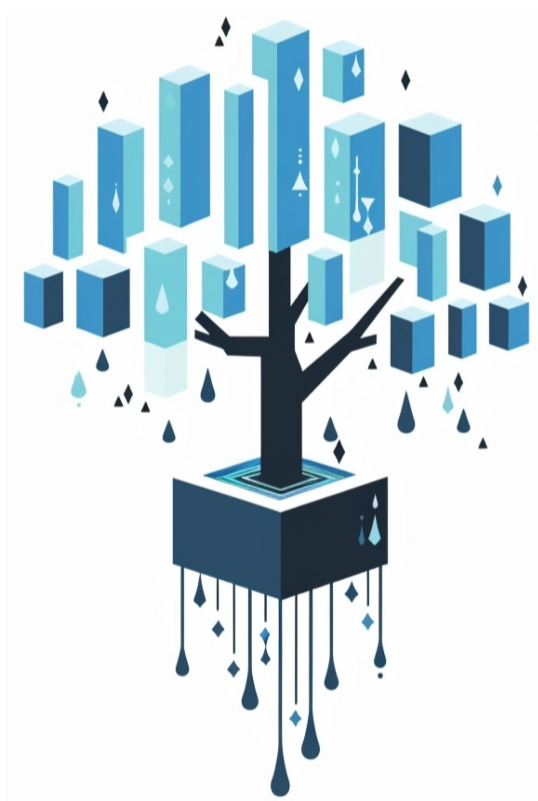


Figure 1: canoPyHydro logo

Summary Functionality Overview Publications and Acknowledgements Future Direction

Vegetation coverage has a marked effect on the spatiotemporal distribution of terrestrial rainfall, marking the initial step in terrestrial rainfall-to-runoff pathways. Growing interest from hydrologists and environmental scientists has led to numerous attempts to characterize these flows. However, these efforts have largely been correlative and regression-based, lacking clear frameworks to guide meaningful inferences (Van Stan et al., 2020). CanoPyHydro empowers researchers to derive mechanistic inferences into the drivers underlying variability in canopy rainfall drainage fluxes and has garnered interest for its versatility across related use-cases. By integrating precipitation partitioning data with increasingly available terrestrial lidar scans (TLS), canoPyHydro offers a tailored environment to explore canopy water distribution, enhancing the precision and depth of hydrological analyses.

Summary

Data is ingested by canoPyHydro in the form of quantitative structural models (QSMs), which distill TLS point clouds into topologically ordered cylinders representing a tree's canopy structure. Broadly speaking, CanoPyHydro's functionality is encompassed in two major categories:

QSM Ingestion and Exploration CanoPyHydro offers robust visualization capabilities for subsetting, highlighting and displaying features of interest. On the quantitative side, a variety of industry standard metrics (i.e. woody area index, trunk lean) are available at the subset level, as well as some more novel metrics. The latter including detailed_intra-canopy shading data as well as the use of Alpha Shapes to enable a novel, situationally-improved interpretations of canopy coverage area.

Characterizing Canopy Watersheds CanoPyHydro's novel approach to percipitation partitioning treats tree canopies as watersheds and reveals tributary-like flows within branch networks. It precisely distinguishes which flows reach the trunk (thus becoming stemflow) and delineates areas where water drips to the forest floor (as throughfall).

Statement of Need

Net rainfall (throughfall + stemflow) reaching the surface beneath plant canopies influences all subsequent terrestrial hydrological processes, contributing to runoff (Savenije, 2004), recharging subsurface water (Friesen, 2020), or returning to the atmosphere via evaporation (Coenders-Gerrits et al., 2020). However, there is substantial spatiotemporal variability in net rainfall amount, timing, and distribution, complicating reliable assessments of terrestrial water balances (Van Stan et al., 2020). The costly, labor-intensive techniques required to observe throughfall and stemflow (e.g., Voss et al., 2016; Zimmermann and Zimmermann, 2014) challenge current approaches to modelling and managing terrestrial water interactions (Gutmann, 2020).

Attempts to correlate whole canopy characteristics with stemflow measurements have produced inconclusive results (Sadeghi et al., 2020), despite advances in tree scanning and structural modelling tools (see references in Wischmeyer et al., 2024). A definitive method for accurately delineating these flux origins, crucial for understanding rainfall distribution, remains elusive.

CanoPyHydro addresses this gap with an innovative, bottom-up approach to estimating precipitation redistribution, supplementing QSMs generated using existing tools (Hackenberg et al., 2021) with complemntary, graph-based models. CanoPyHydro's algorithm traverses these graph models to percisely delineate stemflow and throughfall drippoint drainage areas. Leveraging detailed canopy structural data from terrestrial LiDAR scans (TLS) to map out precise water pathways, CanoPyHydro transforms how rainfall drainage pathways are predicted and analyzed, offering configuration options to compare rainfall distribution under varying environmental conditions.

CanoPyHydro supports the application of model outputs with a robust suite of analytical tools suitible for various use cases. Its user-friendly filtering capbabilities allow users to isolate branch subnetworks based on specified criteria (branches with a radius >10cm, branches with a branch order of 0 within 100cm of the ground, etc.). These filters may be used in tandem with integrated visualization functions to further enable the exploration and analysis of tree structures and hydrological processes.

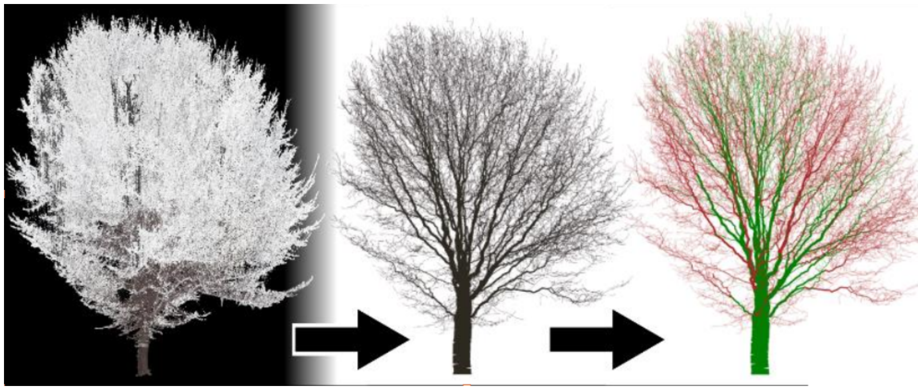
By bridging the gap between advanced canopy scanning technologies and the need for precise hydrological insights, CanoPyHydro empowers researchers and environmental managers, enhancing their understanding of water flows in forested ecosystems and supporting more informed conservation and sustainability practices.

Functionality

QSMs - 2D Projection - Flow Identification - Shade - Visualization

QSMs

Quantitative Structural Models are 3D representations of tree branching structures using cylinders of varying radii, orientations, and spatial locations. These models effectively reduce point cloud data while preserving high level structural information. The QSMs used in the creation of CanoPyHydro were generated by processing TLS point cloud data through the SimpleForest program (Hackenberg et al., 2021) , resulting in .csv files.



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(Left to right) A point cloud rendering of a tree, followed by a SimpleForest-generated Quantitative Structural Model (QSM) that approximates the tree's branch structure using cylinders, and finally, a canoPyHydro visualization of the same QSM, highlighting the model's features with color to distinguish different hydrological contributions such as stemflow and throughfall areas.

The below code demonstrates two different ways that canoPyHydro can read in QSMs:

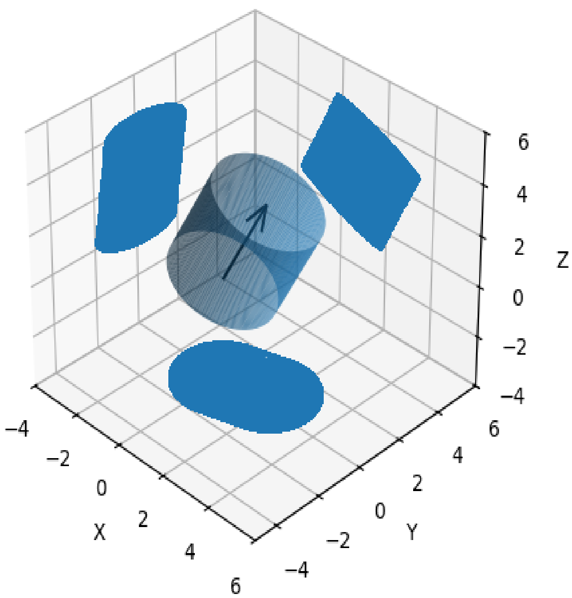
```python
# A CylinderCollection object can be initialized directly
myCollection = CylinderCollection()

# Using the details of a QSM model stored in example_tree.csv
# to create a CylinderCollection object

myCollection.from_csv('example_tree.csv')


# Alternatively, the 'Forester' class can be used
myForester = Forester("data/test/")
print(f"Files available: {list(map(str,myForester.file_names))}")

# ... Read in single QSMs
myForester.qsm_to_collection("example_tree.csv")
print(len(myForester.cylinder_collections))
```

Additional information can be found in the canoPyHydro documentation under QSMs and in the documentation for SimpleForest.

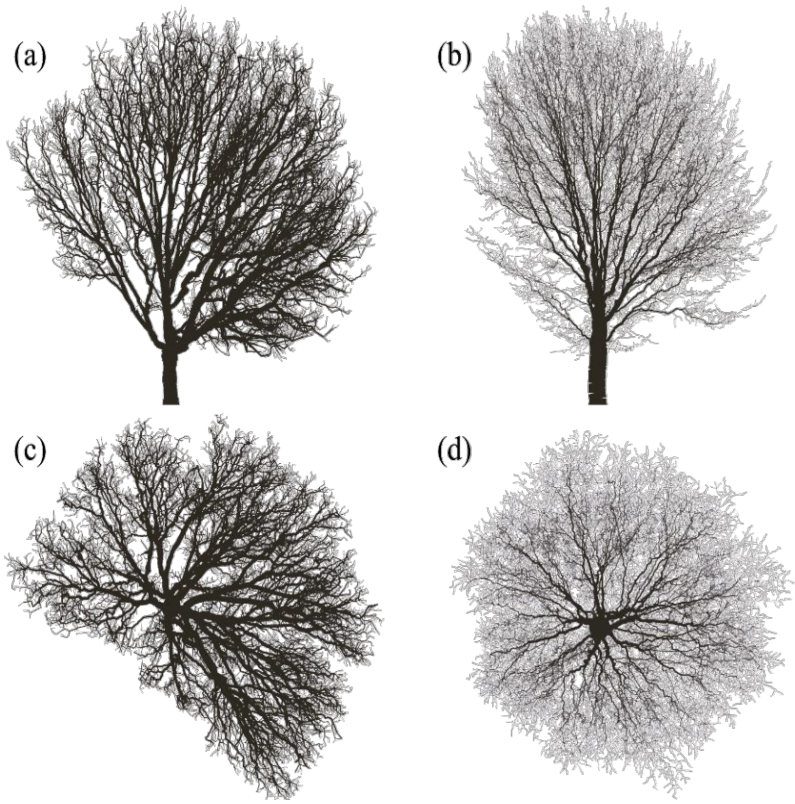
Projection

Many of the metrics calculated by CanoPyHydro are derived from projections of QSMs onto the XY, XZ, and YZ coordinate planes. For a tree oriented upright, these projections represent the tree from different perspectives: the XY plane provides a top-down view, while the XZ and YZ planes offer perpendicular side views, depending on the orientation of the point cloud data. These 2D projections are essential for several key functions:

- The projected 2D cylinder area is used to calculate the yield of water [L m-2] generated by a given canopy drainage area.
- Projections are also used to calculate canopy coverage and woody area index, both key metrics in the study of canopy precipitation partitioning.
- By comparing the 2D projected areas of different branch subsets, CanoPy-Hydro provides detailed data on in-canopy shading and light penetration.



: Here you can see how these projections function on the cylinder level



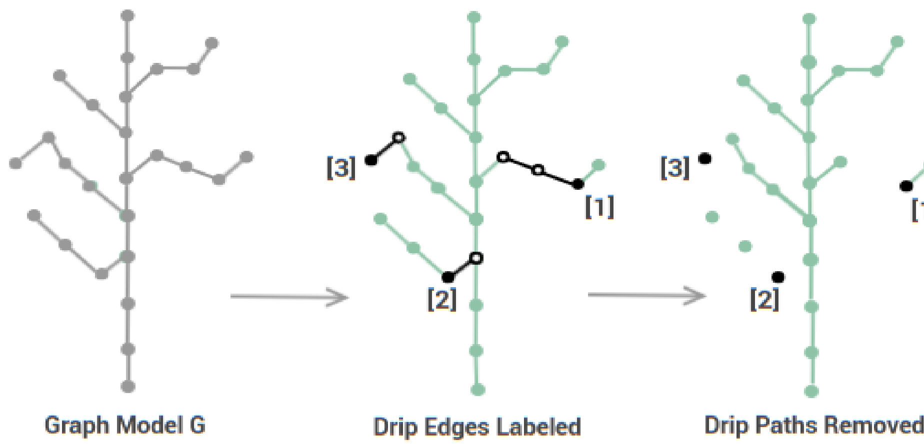
: Here you can see an example of the XY and XZ projections of two trees.

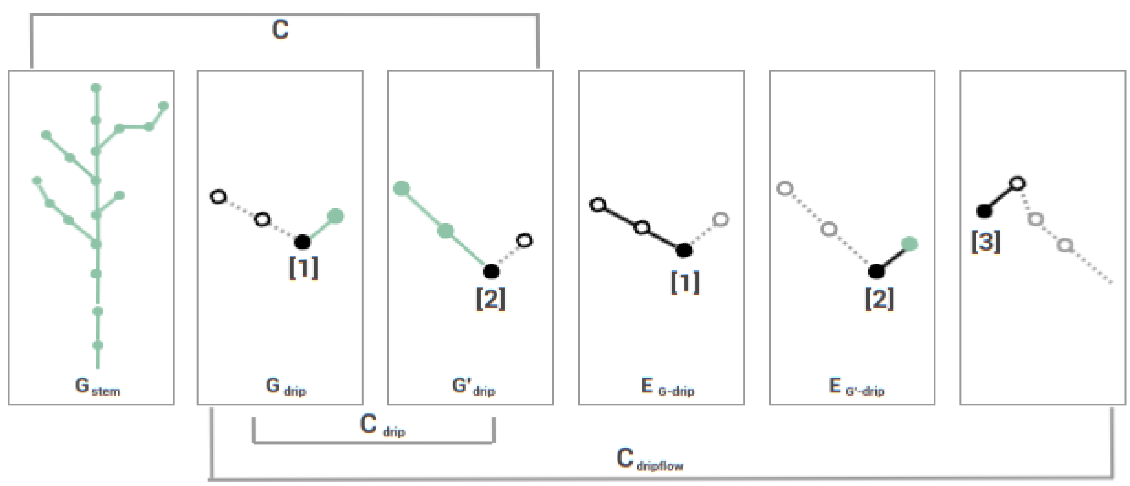
```
# Initializing a CylinderCollection object
myCollection = CylinderCollection()
myCollection.from_csv('example_tree.csv')

# Projecting the cylinders onto the XY plane
myCollection.project_cylinders('XY')

# Projecting the cylinders onto the XZ plane
myCollection.project_cylinders('XZ')
```

Flow Identification

CanoPyHydro's hydrological estimates classify QSM cylinders as contributing either to stemflow or throughfall. Each cylinder is assigned to a 'flow' object, which represents the precipitation intercepted by that cylinder. Water is assumed to flow toward the tree's stem unless it encounters a cylinder too steep to traverse. These steep areas, where water drips off rather than continuing to the stem, are termed 'drip-points.'

To identify such areas, a user-defined ‘drip cut-off angle’ is applied, which assumes water can only flow down branches with angles above the specified threshold. The below diagram illustrates how graph-based models use these assumptions to idifferentiate between flows that contain a drip point (throughfall) and those that do not (stemflow).





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The above diagram shows a minimal example of a QSM to demonstrate the core concepts of canoPyHydro’s flow finding algorithm.

The algorithm assigns an ID to each of the identified flows, with ‘stemflow’ always receiving an ID of 0. These flow IDs are stored in the cylinder collection within the ‘cyl_to_drip’ variable, a dictionary keyed by cylinder IDs. These IDs can be used later to calculate the flow ‘size’ (see the Metrics section below) and to generate visualizations of the canopy watershed.

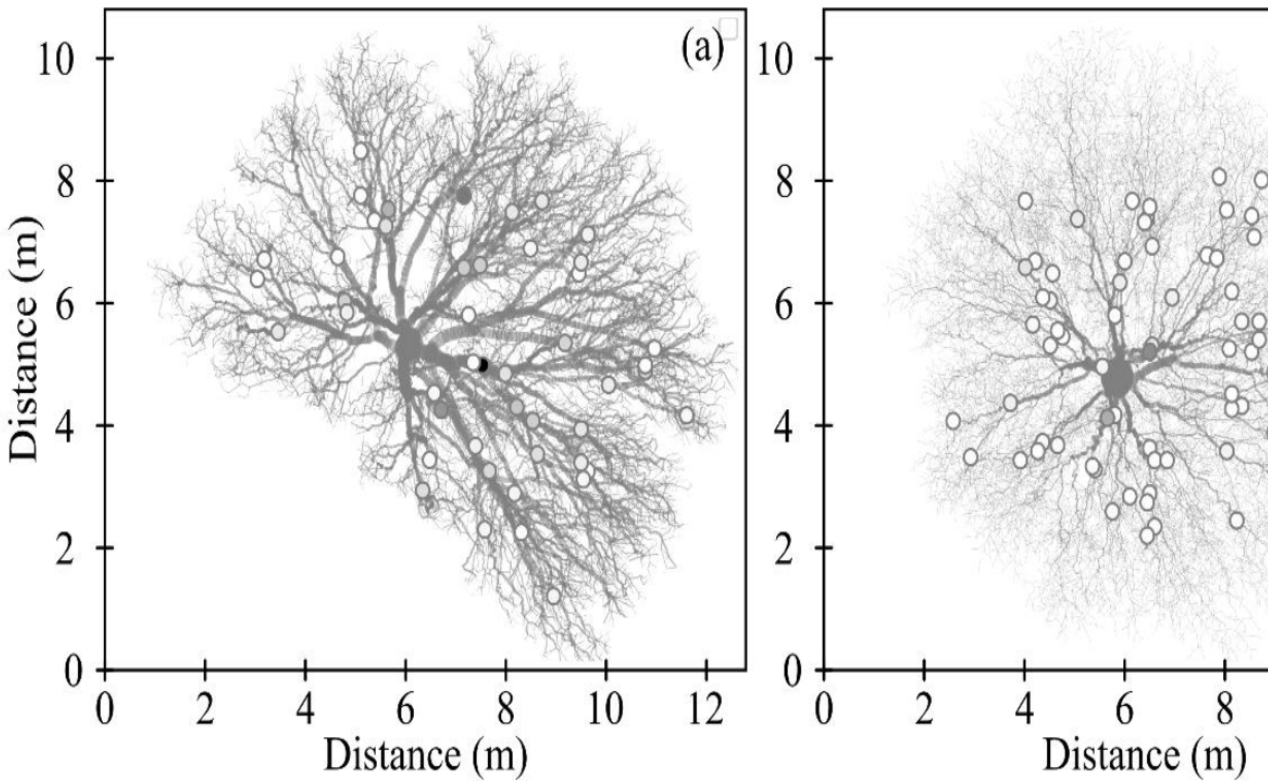
The below code demonstrates how the above is done in practice. Details regarding the various objects and functions used can be found in the canoPyHydro documentation, with .ipynb and .py example files in the docs section of canoPyHydro git repository.

```
# Initializing a CylinderCollection object
myCollection = CylinderColle ction()
myCollection.from_csv('example_tree.csv')

# Setting a cut-off angle (in radians)
cut_off_angle = -0.166

# Initializing the graph based model
myCollection.initialize_digraph_from(in_flow_grade_lim=cut_off_angle)

# Running the above described algorithm
myCollection.find_flow_components()

# Printing the results of the algorithm

## Keys are equal to the cylinder ids of the cylinders in our collection
cyls = myCollection.cylinders
print(cyl_to_drip)
```

Flow Quantification

After the flows in a canopy's watershed have been identified, common statistics regarding these flows can be calculated though the use of the 'calculate_flows' function. In this process flows are characterized based off of the aggregate characteristics of the cylinders that contribute intercepted water to them. In this way, flows are discussed as having:

- A number of cylinders
- A projected area, volume and surface area
- each being the sum of the same for their contained cyliners
- A surface area to volume ratio
- A sum of the angles of their cylinders ** This is available to facilitate the calculation of average flow angle for one or many flows Most importantly, each non-stem flow also has a unique drip point and drip point location, representing a point in the canopy at which one would expect water to drip to the ground. Utilizing the above metrics, users can glean important information regarding a tree's rainfall-drainage watersheds. For example, the below graphic uses the projected area data for a tree's flows, along with canoPyHydro's visualization capabilities, to make the location and relative abundance of moisture beneath two tree canopies.



Two trees with differing hydrologic characteristics, with drip points indicated and shaded based on their respective flow's volume.

Visualization

```
myCollection = CylinderCollection()
myCollection.from_csv('example_tree.csv')
myCollection.project_cylinders('XY')
myCollection.initialize_digraph_from()
myCollection.find_flow_components()
myCollection.calculate_flows()
myCollection.draw('XY', highlight_lambda=lambda:is_stem,
save = True, file_name_ext="docs_ex")
myCollection.draw('XZ', highlight_lambda=lambda:is_stem,
save = True, file_name_ext="docs_ex")
```

Here we see an example of the visualization capabilities of canoPyHydro. The above images show the same tree from two different angles, with the stemflow contributing cylinders highlighted in blue

Metrics

Though a variety of metrics are available through this package, the majority are straight forward, summations of cylinder characteristics. Details regarding these metrics and more are available in the glossary section of the canoPyHydro documentation. However, there are also custom functions are available for the calculation of more novel metrics. These functions will be highlighted in this section.

Shading Fraction

The internal shading of the canopy, as well as the ground beneath it, impacts the energy balance, surface temperature, and wind exposure. In turn, these environmental conditions influence moisture availability via related processes like evaporation. To support data exploration, CanoPyHydro includes robust tools for calculating these shade patterns.

In the calculation of canopy coverage area, we compute alpha shapes surrounding canopy boundary points [1], rather than the traditional circular regions. This approach provides a more precise, often lower, estimate of canopy coverage compared to a circular approximation; an important consideration when assessing throughfall distribution in sparse branch networks.

Future Direction

- We hope to widen the use cases for our tool by integrating additional real world data (i.e wind speed and direction, rain intensity and average angle, etc.).
- By integrating python libraries for spacial analysis (scipy-spacial, open3d) into canoPyHydro, we hope to allow for the projection of cylinders at an arbitrary angle. This will lead directly into supporting the afformentioned integration of weather data.
- Improve the efficiency of the flow finding algorithm and the flow caluclation algorithm. This will allow for the processing of larger QSMs and the use of more complex models (i.e. tessellated meshes). Future Direction As we continue to develop CanoPyHydro, several key advancements are planned to broaden its functionality and enhance its utility across a range of research applications. These improvements will focus on integrating real-world environmental data, advancing spatial analysis, optimizing computational efficiency, and expanding the scope of canopy hydrology modeling. Below are the primary directions for future development:

[1] A note on terminology: For a given set of points, the alpha shape with the lowest curvature coefficient thus, tightest fit, is refered to as a concave hull.

- Integrating Real-World Environmental Data We aim to broaden CanoPyHydro's application by incorporating additional real-world environmental data, such as wind speed and direction, rain intensity, and rainfall angle. These integrations will enhance the precision of canopy water distribution modeling by factoring in dynamic environmental conditions, allowing researchers to simulate and predict hydrological processes under various weather scenarios. This will be particularly useful for studying the effects of storm events, seasonal changes, and long-term climate impacts on canopy water redistribution.
- Advancing Spatial Analysis with Python Libraries By incorporating advanced Python libraries for spatial analysis, such as scipy-spatial and open3d, we aim to enable the projection of cylinders at arbitrary angles. This advancement will allow CanoPyHydro to support the aforementioned integration of weather data, improving the accuracy of stemflow and throughfall predictions. Additionally, this enhancement will facilitate more complex spatial queries, such as identifying microclimates within a canopy or evaluating wind-driven rain impacts on specific tree branches.
- Optimizing Computational Efficiency A critical goal is to improve the efficiency of the flow-finding and flow-calculation algorithms, enabling CanoPyHydro to process larger QSMs and handle more complex tree models, such as tessellated meshes. These improvements will expand the tool's scalability, making it more suitable for large-scale studies involving dense forest ecosystems or intricate tree structures. Under the branch improve-find-flows-efficiency, you can find current work toward this goal, which has shown promising results, with up to a 200x increase in algorithm speed. This improvement is attributed to migrating to Rust-based graph models using the rustworkx library and refactoring the flow-finding algorithm as a graph traversal process, enabling parallel processing. These developments will significantly reduce computational time and resource requirements, allowing users to run complex models on standard computing setups.
- Expanding Canopy Coverage Analysis In the future, we aim to integrate additional methods for calculating canopy coverage beyond Alpha Shapes. By offering options for alternative geometric representations, such as 3D meshes or voxel-based models, CanoPyHydro will enable more flexible and accurate analyses of canopy structure and its influence on rainfall distribution. This expansion will help researchers tailor their analyses to specific forest types, vegetation structures, or ecological research questions.
- Supporting Multi-Scale Hydrological Modeling We plan to extend CanoPyHydro's capabilities to support multi-scale hydrological modeling, allowing for the simultaneous analysis of both individual trees and larger forest stands. This will facilitate more comprehensive ecosystem studies, enabling users to model how water flows through entire landscapes, from canopy to forest floor, while considering the collective behavior of multiple trees. This functionality will be particularly beneficial for watershed management,

forest hydrology, and conservation planning at broader spatial scales.

- Customizable User Interfaces for Specialized Applications To make CanoPyHydro accessible to a wider range of users, we envision developing customizable user interfaces tailored to specific research applications. These could include simplified interfaces for educators and students, as well as advanced options for scientists requiring detailed control over modeling parameters and data inputs. Customization will also include the integration of automated workflows, enabling users to conduct common analyses with minimal manual intervention.

Through these future developments, CanoPyHydro will continue to evolve as a powerful and versatile tool for exploring tree hydrology, driving new insights into how tree canopies interact with environmental conditions and contribute to water redistribution in forest ecosystems.

Publications and Acknowledgements:

CanoPyHydro was developed in the process of authoring A LiDAR-driven pruning algorithm to delineate canopy drainage areas of stemflow and throughfall drip points., which has been accepted for publication by the *British Ecological Society's* 'Methods in Ecology and Evolution'. Said paper, and the code within this repository, represents a collaboration between non-academic data professional Collin Wischmeyer, ecohydroloy scholar Professor John Van Stan with notable contributions from industry geo-scientist Travis Swanson. Likewise, this tool could not exist without the data collected and the ideas put forward by several graduate students working in Cleveland State University's 'Wet Plant Lab'.

This paper's titular project and related efforts were made possible, in part, by the financial support of US-NSF DEB-2213623.

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