CanoPyHydro: Leveraging LiDAR to Predict Precipitation Partitioning in Tree Canopies

31 August 2024

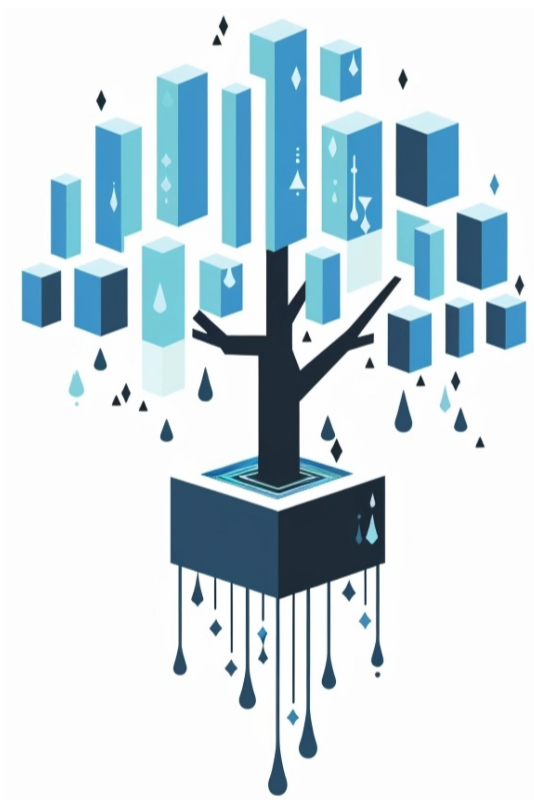


Figure 1: canoPyHydro logo

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, Hildebrandt, 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, Schilperoort, and Jiménez-Rodríguez 2020). This redistribution of rainfall has marked effect on a host of environmental processes: plant nutrient uptake and leaching (Aubrey 2020), litter decomposition (Qualls 2020), surface runoff (Gotsch, Draguljić, and Williams 2018); (Ji et al. 2022), soil erosion (Dunkerley 2020)and plant microbiome composition and function (Van Stan, Morris, 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, Hildebrandt, et al. 2020). The costly, labor-intensive techniques required to observe throughfall and stemflow (Voss, Zimmermann, and Zimmermann 2016; ‘ Zimmermann and Zimmermann 2014) challenge current approaches to modelling and managing terrestrial water interactions (Van Stan and Friesen 2004).

Attempts to correlate whole canopy characteristics with stemflow measurements have produced inconclusive results (Sadeghi, Gordon, and Van Stan 2020a), 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 (Sadeghi, Gordon, and Van Stan 2020b) 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 capabilities 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 Mapping - Shade - Canopy Coverage Area

QSMs

Quantitative Structural Models are 3D representations of tree canopies consisting of topologically ordered cylinders. Each cylinder has a radius, an orientation, start/end coordinates and a variety of meta data fields corresponding to a given section of the tree. These models effectively function to isolate canopy structural information from the detailed topological data available in point clound data. The QSMs used in the creation of CanoPyHydro were generated by processing TLS point cloud data using the SimpleForest plug-in (Sadeghi, Gordon, and Van Stan 2020b) for the Computree platform(Team 2020)

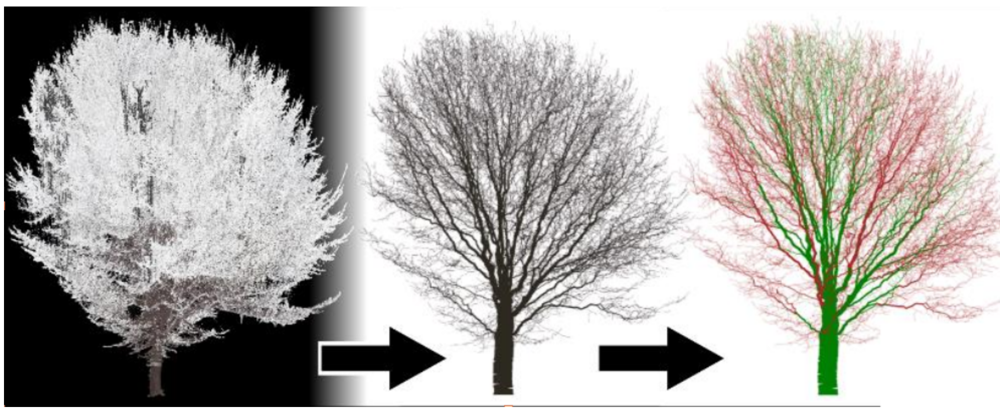


Figure 2: A point cloud, a raw QSM and a QSM with hydrologic characteristics highlighted via canoPyHydro

Figure 2 above llustrates the steps in a workflow leveraging caopPyHydro. A TLS scan is used to generate a point cloud rendering of a tree, then the same point cloud is processed using the Computree plugin *SimpleForest* to generate a Quantitative Structural Model (QSM). This QSM is a lower-resolution representation approximating the tree's branch structure using cylinders canoPyHydro visualization of the same QSM, highlighting the model's features with color to distinguish different hydrological contributions such as stemflow and throughfall areas.

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.

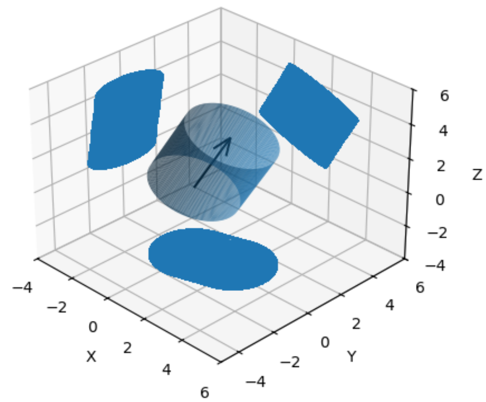
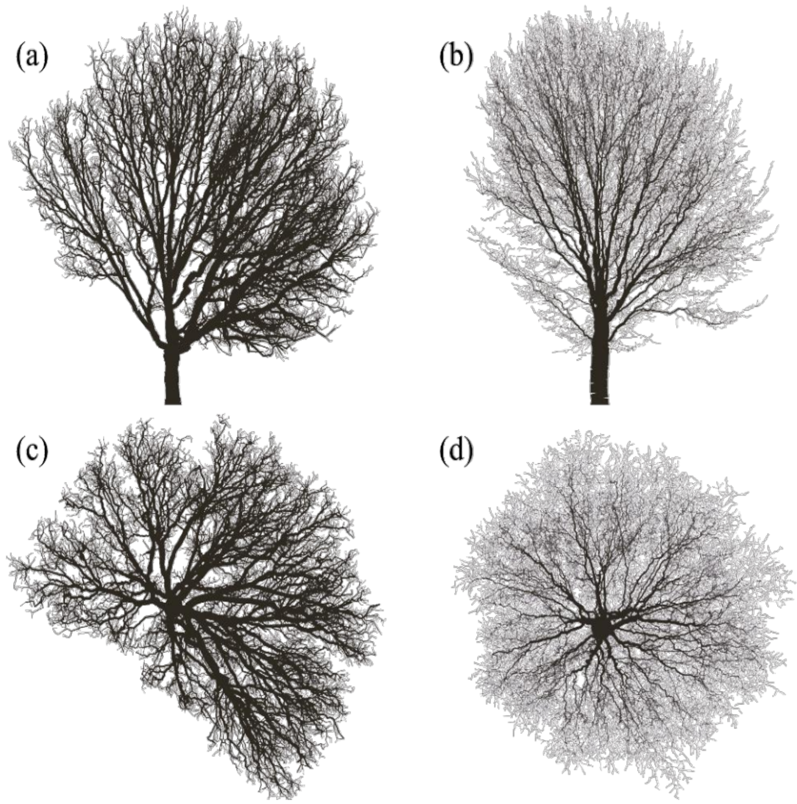


Figure 3: A 3D cylinder and its XY, XZ and YZ projections

Below, you can see how this concept is extended to whole tree canopies to create visualizations and compare canopy structure.



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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).

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.

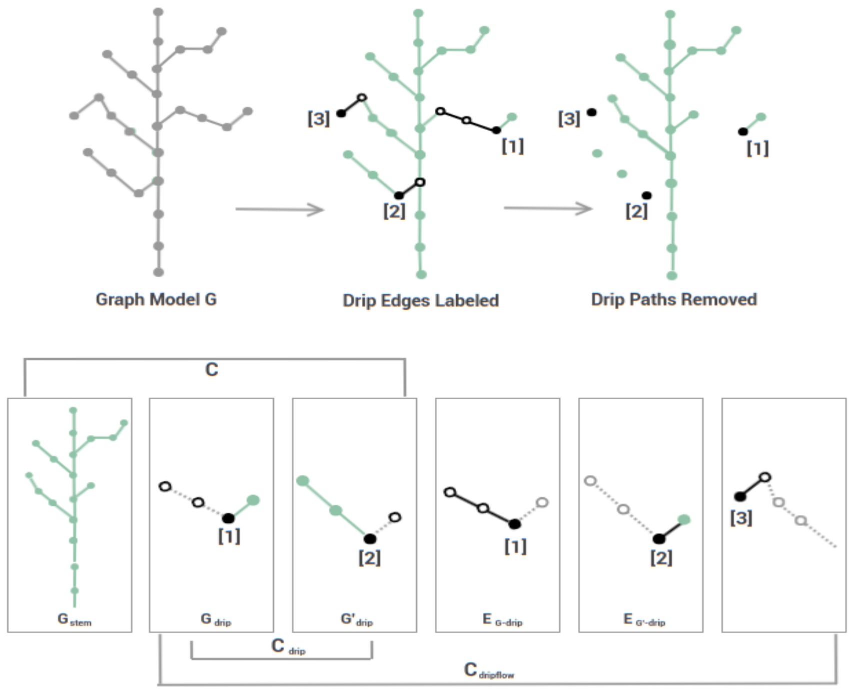


Figure 4: A minimal example to demonstrate the core concepts of canoPyHydro's flow finding algorithm.

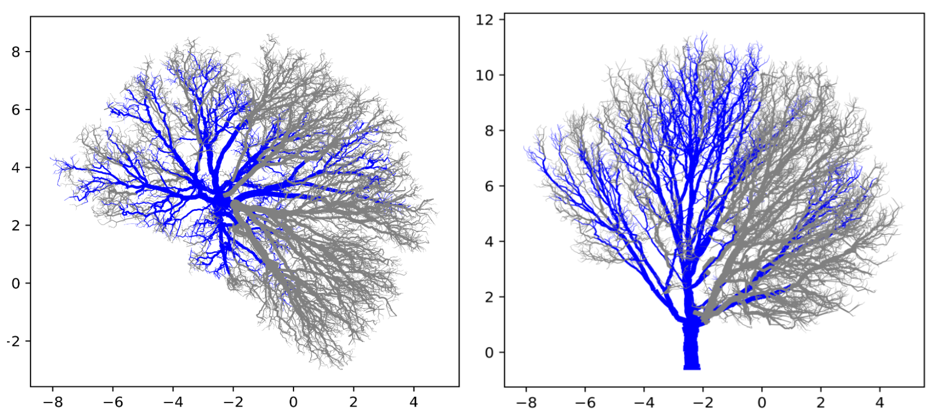
Detai;s regarding the various objects and functions used can be found in the canoPyHydro documentation, with .ipynb and .py example files in the docs section of canoPyHydro git repository.

Flow Quantification

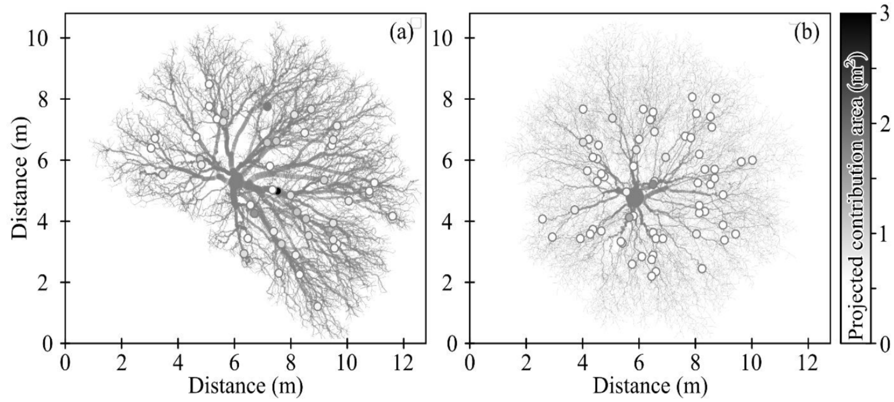
After the flows in a canopy's watershed have been identified, common statistics regarding these flows can be calculated though the use of the 'calculate_flows' function. In this process, flows are characterized based off of the aggregate characteristics their constituent cylinders. In this way, flows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

- A number of cylinders
- A projected area, volume and surface area * the sum of the same for its constituent cylinders
- An average angle of decline
- A unique drip point with corresponding (x,y,z)-coordinates

The last of these, the so-called drip points, represents the location in the canopy at which the water intercepted by the flow's cylinders either drips to the ground (becoming throughfall) or reaches the ground by traversing the stem (becoming stemflow). The below code demonstrates how these flows are identified in practice, and how the data generated can be used to enrich QSM visualizations. The resulting are two images showing views of the same tree from two different angles, with the stemflow contributing cylinders highlighted.



The above demonstrate how this approach can be used to evaluate canopy water availablity, but utilizes only a single flow's data - the flow that ends at the tree's base. The below graphic demonstrates how the remaining, throughfall, generating flows can be coupled with rainfall data to map and compare the relative abundance of moisture beneath ree canopies.



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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.

Canopy Coverage Area

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

As we continue to develop CanoPyHydro, several key advancements are planned to broaden its functionality and enhance its utility across a range of research

[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.

applications. These improvements will focus on integrating real-world environmental data, advancing spatial analysis capabilities to include the creation of QSMs, and optimizing computational efficiency. Below are the primary directions for future development:

- Leverage existing python libraries for spacial analysis (scipy-spacial, open3d) into canoPyHydro to allow for: the projection of objects at an arbitraty viewing angle, the use of 3D meshes to represent tree structures, and the calculation of canopy coverage area using voxel-based models.
- Integrate environmental data such as wind speed, wind direction, rain intensity and average rain angle into calcluations for canopy saturation. e. 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
- Optimizing the computational efficiency of this tool wll plan a critical role in enabling CanoPyHydro to process a large number of trees. In turn, this will enable the application of CanoPyHydro to larger-scale studies, such as watershed management and forest hydrology research.

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'.

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