Advancing forest functional process understanding through hyper-spatiotemporal LiDAR observation streams

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Abstract: Understanding forest functional processes like carbon sequestration, water regulation, and habitat provision is crucial for evaluating ecosystem services and sustainable management. While satellite-based earth observation offers global coverage, its limited spatial-temporal resolution and weather dependency hinder detailed analysis. The LiDAR Phenology Station (LiPhe), established in 2020 by the Finnish Geospatial Research Institute of the National Land Survey of Finland is the world's first permanent LiDAR system for forest observation, capturing dense 3D point clouds hourly even under adverse lighting conditions. Despite the challenges posed by processing its extensive dataset, with over three and a half years of continuous data, LiPhe offer transformative insights into the dynamics of boreal forest ecosystems by revealing the interconnection among local biotic and abiotic conditions, tree species, species- and tree- specific phenology, and species- and tree-specific growth strategy.

1. Introduction

Understanding the mechanisms of forest functional processes, such as carbon sequestration, water regulation, and habitat provision, is essential for evaluating forest ecosystem services, predicting forest responses to environmental changes, and managing forest sustainably. Forest functional processes are highly interconnected, influenced by wide-ranging factors such as climate, soil, forest structure, and species composition. Moreover, processes like forest regeneration, carbon flux, and water cycling operate over long timescales. Capturing and analysing these dynamics, particularly in the context of climate change, requires continuous and long-term monitoring.

Nowadays, long-term forest monitoring is primarily conducted through earth observation (EO) systems, especially for global-scale coverage. However, EO products, such as satellite images, often have limited spatial temporal resolution and are prone to meteorological conditions (e.g., sunlight and clouds), making them insufficient for capturing critical dynamic events in forests, such as phenological changes at a tree level. The spatial resolution of EO products is also limited to tens of meters per pixel typically, making them inadequate for accurately capturing tree-scale developments and responses over time. Until recently, there has been a lack of methods for providing long-term, tree-scale observations that serve as ground-truth references for proper interpretation and calibration of EO datasets. In this regard, close-range data acquisition initiatives such as PhenoCam (Richardson, 2023), StrucNet (Calders et al., 2023), and permanent laser scanning (PLS) systems (Eitel et al., 2013, Culvenor et al., 2014, Campos et al., 2021) have emerged and adapted for forest monitoring.

Here, we demonstrate the capacity of dense LiDAR time series for monitoring and analysing forest functional dynamics in a forest environment by discussing the latest discoveries using the LiDAR Phenology Station (LiPhe). LiPhe is a research infrastructure established in 2020 by the Finnish Geospatial Research Institute of National Land Survey of Finland (NLS-FGI), aiming to explore the potential of long-term in situ forest observation with high spatial and temporal resolution using a stationary LiDAR system. LiPhe is world's first permanent LiDAR (PLS) system designed for forest observations and the only operational system capable of capturing highly dense 3D point clouds of the observed forest on an hourly basis. Compared to permanent imagery systems like PhenoCam, close range sensing systems offer greater coverage at the local scale and 3D structures at a tree level, even under adverse lighting conditions (Liang et al., 2022). PLS are particularly effective for estimating volume of tree parts, plant and leaf area indexes, and biomass.

2. LiPhe setup and data

The LiPhe system was conceptualized to investigate the intrinsic diurnal movements of tree leaves and branches observed through LiDAR time series (Puttonen et al., 2016) and explore the driving factors behind these dynamic phenomena in a natural forest environment.

2.1 LiPhe setup

The LiPhe station is located at Hyytiälä Forestry Research Station (SMEAR II; 61°51′N, 24°17′E), southern Finland (Figure 1.a). The system comprises a laser scanner (RIEGL VZ-2000i), an accessories protective hood, a local computer server, and a network storage (NAS), which facilitated fully automated operational chain including data collection, data storage, and data transfer (Campos et al., 2021). The scanner is permanently mounted on a flux tower at 30 m above the ground, with 60 degrees tilted downwards to monitor the surrounding forest from an oblique perspective about 15 m above the forest canopy (Figure 1.c). The protective hood ensures the scanner to safely operate in all weather conditions throughout a year (-30 to 40 degrees). The system is configured to carry out one scan per hour during the local growth season (April to November) and one scan every six hours during the winter months, with non-stop except occasional technical interruptions. The data collection workflow is completely automated including hourly scan acquisition and local data storage, daily data transfer to cloud server, and weekly reboot of the scanner.

RIEGL VZ-2000i is a long-range scanner with a theoretical mapping range of up to 2,500 meters. The nominal 3D position accuracy is 5 mm at 100 meters, and the 3D point spacing is smaller than 1 cm at 100 meters. Considering the degradation of data quality and the occlusions along the sight of view from the scanner, the valid LiPhe coverage is defined as an area that is less than 200 m distance from the scanner (Figure 1.b). Figure 1 provides an overview of the LiPhe scanner's location, setup, and coverage. Panel a) illustrates the approximate position of the SMEAR II station. Panel b) the valid study area (brown) within 200 m radius from the LiPhe scanner's position (black triangle).

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Panel c) highlights the LiPhe setup, showing the scanner installed on the flux tower, while Panel (d) shows the scanner looking at the canopy below. The observed forest is a typical boreal forest dominated by Scots pine (*Pinus sylvestris L.*), mixed with other two main species, i.e., silver birch (*Betula pendula Roth*) and Norway spruce (*Picea abies H. Karst.*).

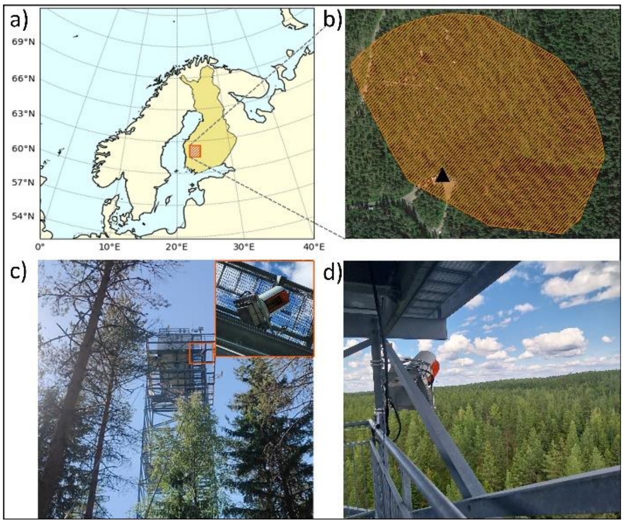

Figure 1. Overview of the LiPhe location, setup, and coverage: a) SMEAR II station location in Finland. b) Scan area within a 200-meter radius from the LiPhe scanner's position (marked by a black triangle). c) LiPhe scanner setup, and d) view directed toward the monitored forest canopy below.

2.2 LiPhe data

LiPhe started its operation since April 2020, which accumulated more than 25,000 scans that covered three full growth seasons until end of 2024. Data collection between September 2021 and June 2022 was interrupted due to equipment maintenance. A total of approximately 4000 trees, predominantly Scots pine, were mapped within the 6.4 ha test area, located within 200 m in the (x, y) direction from the scanner. According to conventional field measurements in 2018, the average diameter at breast height (DBH) of trees in the area was 20.3 cm, and the average tree height of was 18.6 m. The stem density in the test area was around 635 stems/ha.

Individual trees are detected and segmented from the entire point cloud. The individual tree stems were automatically detected from the LiPhe point cloud using a method from Liang et al.(2012) and a stem map of the whole area was generated with respect to a scan from day one. Because the locations of tree stems do not change over time, tree-wise point clouds of an individual tree can be coarsely segmented from the time series by applying an identical stem location and circular buffer zone around the stem throughout each LiDAR scan in the time series. Following the coarse segmentation, a fine segmentation (Hakula et al., 2023) was implemented to derive better delineation of the targeted tree from its neighbouring trees. The automatic stem detection map was matched with the field survey information (e.g., species) using the tree stem position.

Due to sensor-to-target viewing geometry (VG) limitations and forest occlusions, most of the trees in the test area were only partially recorded in the data, resulting in incomplete and sparse point clouds. For trees with good visibility from the scanner, individual trees with higher completeness and higher density of can contain 5 to 15 million points according to the size of the tree. Considering the completeness and the spatial resolution, the tree-wise point clouds were classified to four quality categories. Figure 2 shows the four quality categories of tree-wise point clouds, where in Panel a) examples of tree-wise LiDAR point cloud data with high spatial resolution but varying levels of completeness, particularly due to occlusion, while panel b) shows examples of fully digitized trees with different spatial resolutions.

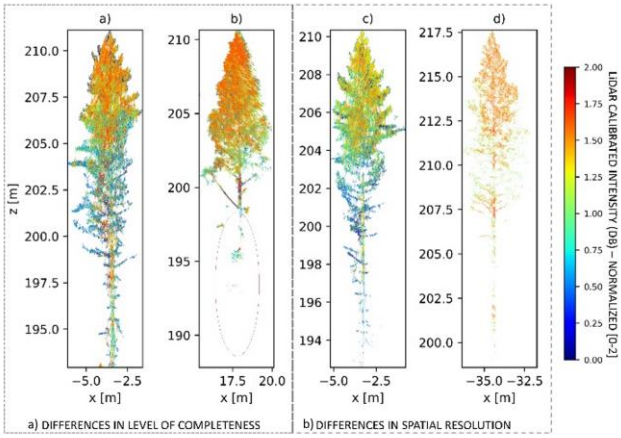

Figure 2. Examples of LiPhe tree-wise point clouds of different quality categories in a) and b).

3. Demonstrative applications

The LiPhe station established a living lab environment to study the functional processes of trees in a forest, offering unprecedented laboratory-like observations in a real-world forest setting. Several studies have demonstrated the new frontiers in forest research facilitated by LiPhe observations, which are introduced in this section.

3.1 Species-specific phenology

Shcherbacheva et al. (2024) demonstrated, for the first time, that dense tree-level LiDAR annual time series of calibrated intensity, extracted from individual tree point clouds acquired by the LiPhe scanner, can capture the phenological dynamics of individual trees. This could only be observed due to the high temporal resolution of LiPhe data acquisition. These dynamics form species-specific patterns can be used to identify tree species. The study utilized a subset of LiPhe data comprising 156 trees (30 silver birches, 79 Scots pines, and 47 Norway spruces), with 76 time points recorded for each tree between April 2020 and April 2021, including two time points per week during the local growth season.

As shown in Figure 3, the overall variations in tree-wise LiDAR backscattering intensity over time presented distinct patterns, with different shapes observed for different tree species. These patterns reflect annual phenological events and their timing, demonstrating strong intra-species consistency and clear inter-species differences.

Understanding on such species-specific phenological patterns support proper timing of data collection for species classification. In the context of boreal forest, November was the most optimal time window for one timepoint data collection. With two timepoints allocated in late spring and late autumn, high classification accuracy (above 85%) can be achieved even with 15 pts/m^2 point density. Shifting the exact date of data acquisition in a two-week time window will not significantly influence the overall accuracy. The study also revealed the importance of stem-level information for accurate species classification. If stem-level information is absent in data, the overall accuracy for tree-wise species classification using LiDAR backscattering intensity can be expected to between 70 - 80% and hardly higher.

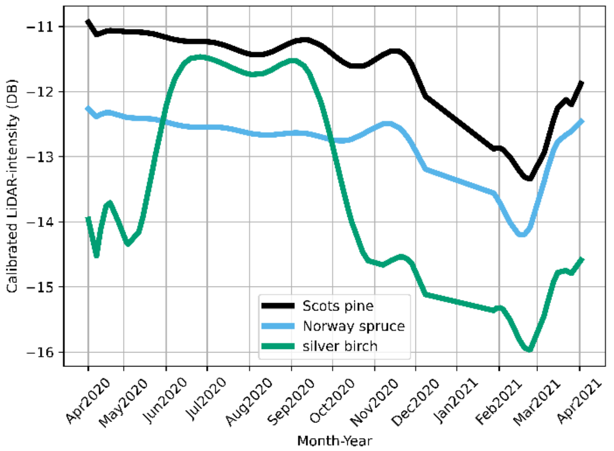

Figure 3. Annual tree-wise LiDAR backscattering intensity pattern of Scots pine (black), Norway spruce (cyan), and silver birch (green) (adapted from Shcherbacheva et al., 2024).

3.2 Tree-specific phenology and growth

Leaf status significantly affects LiDAR backscatter intensity due to the varied physical and chemical characteristics (Korpela et al., 2023). Therefore, phenological events and their durations can be identified from annual variations in the mean reflectance of individual tree point clouds, specifically as LiDAR is resilient to changing light conditions.

Campos et al. (2024) highlights the value of LiPhe observations in detecting fine-scale structural and phenological changes at the tree level, enabling detailed study of complex interactions, such as variations in deciduous tree phenology and growth. Utilizing LiPhe dataset, the timing and duration of phenological events can be accurately estimated for individual trees (Figure 4.).

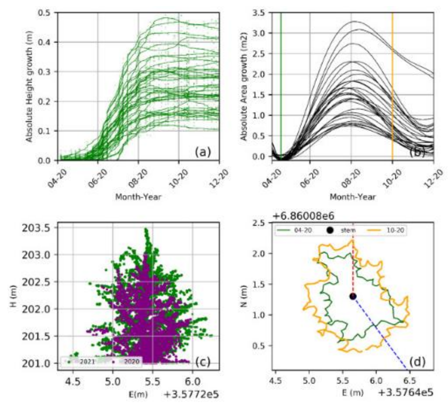

Figure 4. (a) Height and (b) crown area growth of 50 birch trees from April 2020 to December 2020; (c) example of tree height growth; (d) example of crown area outline growth (source: Campos et al., 2024).

This study revealed that spring and autumn phenology are triggered and influenced by distinct environmental variables. Among the local factors studied, species diversity and competition between trees, i.e., both affecting light availability, emerged as the most significant drivers of leaf flush and growth. In contrast, senescence and leaf drop were more strongly influenced by local topography, which impacts water and nutrient availability as well as wind exposure.

Additionally, the high temporal resolution enabled measurements of tree height and crown area growth, which are challenging to capture with traditional techniques. This enabled separate study on growths of tree height and crown area. For instance, the research of Campos et al. (2024) also revealed that growth in canopy area was positively affected by an earlier leaf burst, and delayed beginning of senescence, while no clear relationship between height growth and phenology was found.

Using LiPhe time-series data to estimate tree height changes throughout the 2021 season, Yrttimaa et al. (2024) examined the relationship between height and DBH growth (based on dendrometer measurements). Their findings revealed that tree height growth in the LiPhe study area occurred earlier and over a shorter period than stem diameter increment. Additionally, the authors emphasized the advancement of using laser scanning time-series data to measure intra-seasonal changes in tree height, which enhances the understanding of interactions between different tree growth processes, such as height growth, diameter increase, and phenology. In the same direction, Campos et al. (2023) showed that silver birch trees under LiPhe study area can present different height, crown and phenology growth timing, suggesting that tree size, competition, neighboring species, and water availability affect the rate of vertical (height) growth of the studied silver birch trees.

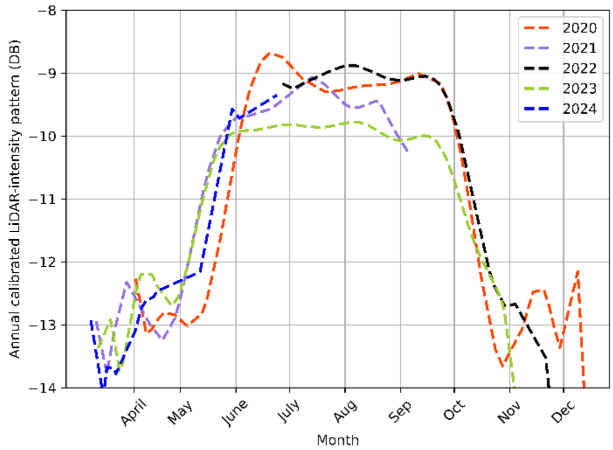

Figure 5. Shifting of phonological timing of an identical birch tree over five different years.

Future research could examine multi-year variability to explore how the interactions between spring and autumn phenology influence crown growth and biomass accumulation under changing environmental conditions. For example, Figure 5 shows an example of phenology monitoring for one silver birch tree over five years, demonstrating the shifting of phenological timing of the same tree under specific climate condition of each year. Such studies could provide valuable insights into the mechanisms by which species respond to environmental changes and improve predictions of plant responses to global change scenarios.

3.3 Branch dynamics

Trees appear to be relatively static from a human perspective, but they are in fact quite active and constantly adjusting the posture of their branches due to various driven forces and purposes. With hourly observations from LiPhe over a long period of time, subtle branch movements are captured to be presenting both circadian and annual rhythms, as shown in Figure 5.

Junttila *et al.* (2022) revealed that the circadian rhythm of branch movements significantly correlates to variations in leaf water content. That is, an increase in the water content, and consequently the mass of the branches and leaves/needles during the nighttime, cause the branch to bend downwards. Meanwhile, the stiffness of branches increases with increasing water content, which could inflict a counterforce to the gravitational pull due to the increased water mass. Therefore, the magnitude of branch movements is affected by mechanical factors such as the wood property, the branch age, the branch thickness, and the initial branch angle. A more comprehensive model that incorporates various wood properties and more detailed branch dimensions is needed to fully understand and simulate the branch movements.

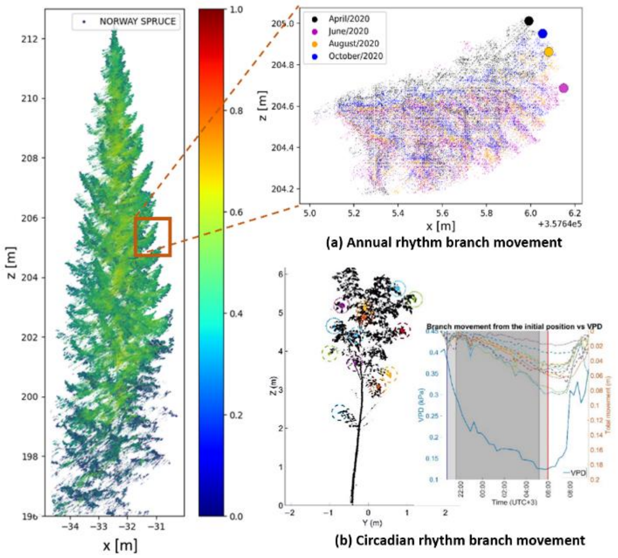

Figure 5. Examples of branch movements. (a) Varied branch end positions in different months; (b) Quangtified branch end translations within 24 hours in correlation with vapor pressure deficit (VPD).

Nevertheless, the capability of measuring branch movements opens new avenues in understanding whole plant water relations and provide implications also for forest health and resilience monitoring.

3.4 Open dataset

A subset of LiPhe data is published as “LiPheStream[1]” (Wittke *et al*., 2024) open access scientific data. The LiPheStream consists of 103 timepoints during 18 months between Apr.2020 and Sep.2021 (Figure 6). The subset was collected with favorable weather, i.e., no precipitation, no snow, a less than 3m/s wind speed, and a less than 90% relative humidity.

For each timepoint, the LiPheStream provides point clouds of 458 individual trees including 298 Scots pine, 77 Norway spruces, 79 trees silver birch, and 4 dead trees of unidentified species. Additional reference information provided for the individual trees includes the respective location, the species, the height at the beginning of the time series and the quality of the point cloud, regarding the data processing.

The tree-wise point cloud are classified into four qulity levels. Level 4 is the best quality for tree-wise LiPhe point cloud, in which both the stem and the canopy are digitized with minimal fragmentation (due to occlusions), and distortion and noise (due to degraded geometric accuracy). Level 3 has visible stem and canopy that can be slightly disturbed by fragmentation and neighboring noises. Level 2 has partially complete (more than 50%) stem and crown, and slight distortion (reduced accuracy but no deformation). Level 1 provides limited structural contour that could assist basic metric estimation such as the tree height.

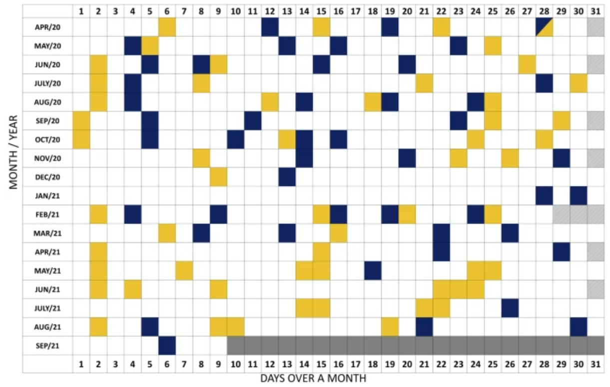

Figure 6. Dates of opened LiPheStream scans. Yellow represent daytime scans; blue nighttime scans; White represents dates with normal LiPhe operation but data not included in LiPheStream. Grey represents dates when LiPhe data collection was interrupted for maintenance requirements (source:Wittke et al., 2024).

A relevant processing tool kit “LiPheKit[2]” is also provided jointly with the LiPheStream to facilitated convenient usage of the dataset. The LiPheKit includes the code to generate individual tree data from any full-scan point cloud data. The complete processing chain is publicly available in the GitLab repository, covering the entire processing workflow for deriving segmented single-tree point clouds and the extraction of tree metadata from full-scan LAZ file.

4. Summary

The LiPhe station is operating with no predetermined end date. So far, it has accumulated a three-and-a-half-year-long time series, which continues to grow daily. Such long-term dense time series of high quality LiDAR forest observation offers numerous research opportunities. Meanwhile, such a large and accumulating volume dataset also presents significant processing and analysis challenges, requiring substantial effort to address and explore. Nevertheless, multi-year observations and analyses have a great potential to deepen our understanding of the dynamics and interactions among trees and their local environments in a typical boreal forest scenario. The FGI LiPhe team actively seeks new collaborations to explore innovative research ideas and advance the development of the LiPhe concept.

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[1] LiPheStream dataset: https://doi.org/10.23729/cf81f7f3-faaa-4729-aa1c-aa4dd38951aa (v1.0)

[2] LiPheKit code: https://gitlab.com/fgi_nls/public/liphekit

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