Study Materials: Airborne Laser Scanning - A Global Perspective

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1 Introduction

Airborne Laser Scanning (ALS), also known as LiDAR (Light Detection and Ranging), is a remote sensing technology that uses pulsed laser light to measure distances to the Earth's surface. It has become a critical tool for characterizing forest structure and mapping terrain at high resolution.

This document provides an overview of ALS technology, its applications in forest ecology, important considerations when working with ALS data, and resources for further learning.

2 Terminology and Technology

2.1 What is ALS?

Airborne Laser Scanning (also referred to as **lidar**, **LiDAR**, or **ALS**) is an active remote sensing technology that operates from aircraft or drones. The system emits rapid laser pulses toward the ground and measures the time it takes for the light to return to the sensor.

Key Terms

- **ALS / LiDAR**: Airborne Laser Scanning / Light Detection and Ranging
- **Point Cloud**: Three-dimensional collection of georeferenced points representing surfaces
- **Terrestrial LiDAR**: Ground-based variant for high-resolution local measurements (Jucker et al. 2023)
- **Full Waveform**: Complete energy distribution of returned laser pulse

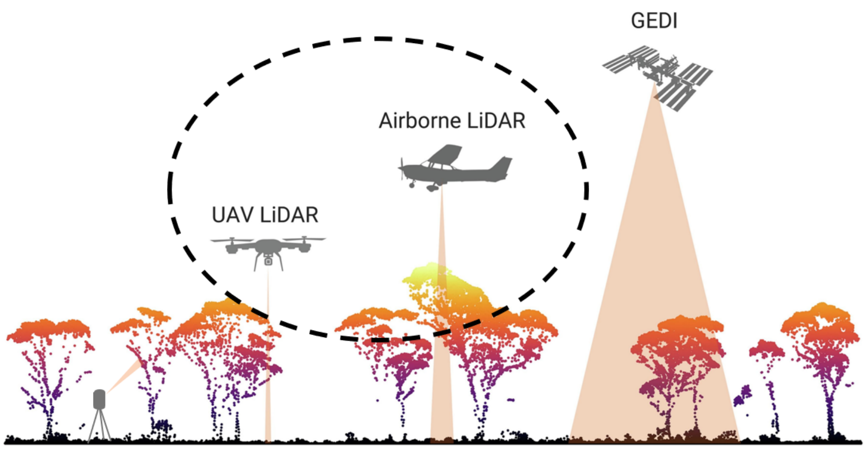

Figure 1: Figure 1: Terrestrial LiDAR system. Adapted from Jucker et al. (2023)

2.2 How It Works: Full Waveform vs. Point Clouds

ALS systems can operate in two main modes:

1. **Full Waveform LiDAR**: Records the complete energy distribution of the returned laser pulse, providing detailed information about vegetation structure at multiple heights

2. **Discrete Return (Point Clouds)**: Processes the waveform into individual return points, typically capturing:

   - **First return**: Top of canopy
   - **Intermediate returns**: Mid-canopy vegetation
   - **Last return**: Ground surface

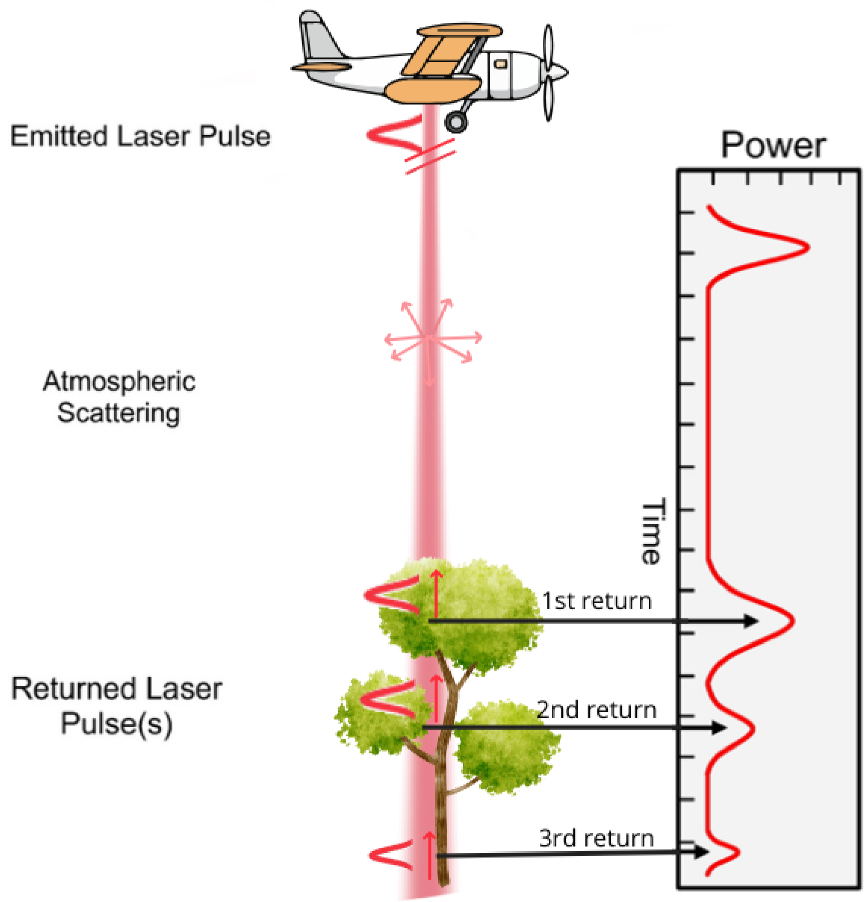

Figure 2: Figure 2: Comparison of full waveform data and discrete point cloud returns. Adapted from Yan, Shaker, and El-Ashmawy (2015)

Figure 3: Figure 3: NEON airborne laser scanning data example. Source: NEON (2024)

3 Why Airborne Laser Scanning?

ALS provides several key advantages over other remote sensing approaches for forest structure characterization.

3.1 Spatial Coverage and Resolution

ALS provides **continuous, high-resolution coverage** over large areas, which cannot be achieved with ground-based measurements and generally offers much higher spatial detail than spaceborne alternatives.

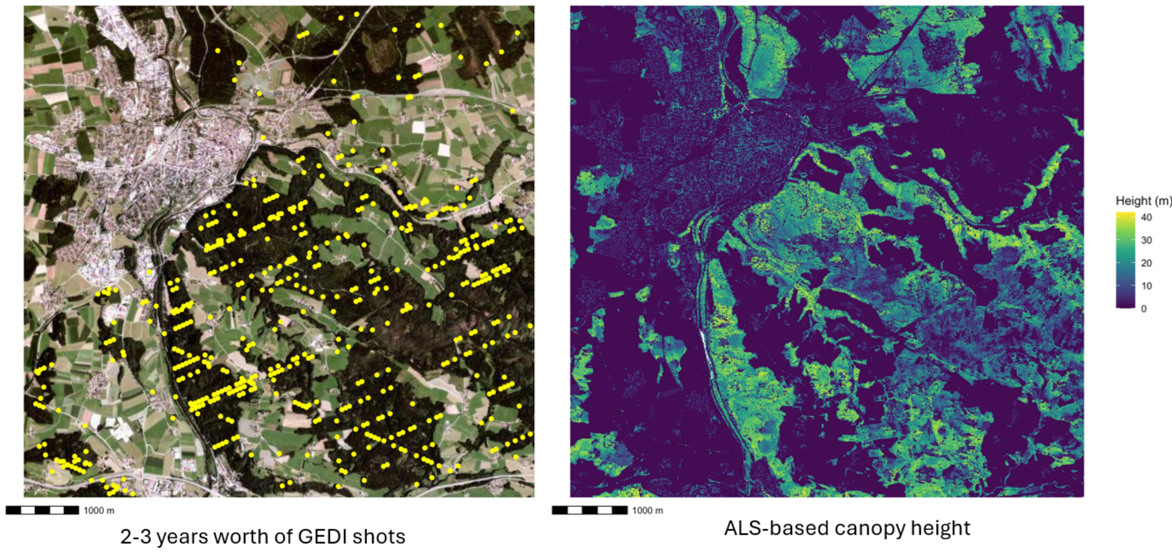

Figure 4: Figure 4: Comparison 2-3 years of GEDI satellite shots (discrete points) versus ALS-based canopy height (continuous coverage).

3.2 Key Applications

4 General Applications

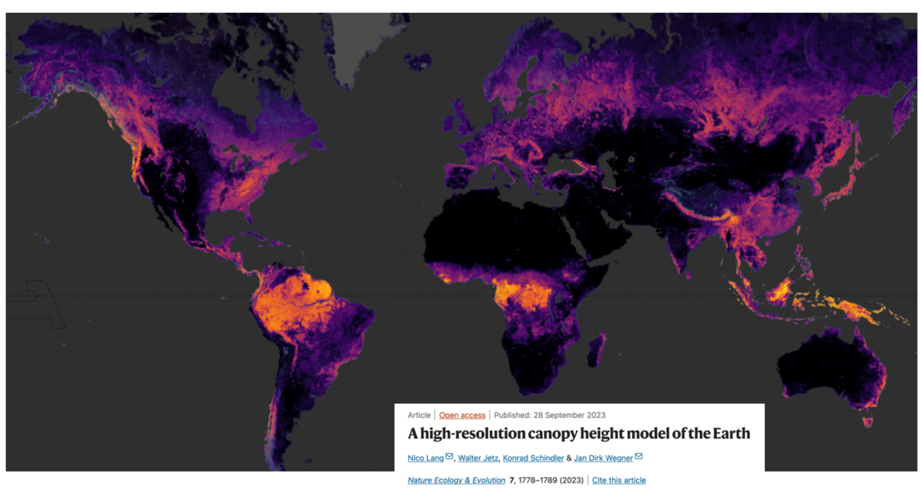

Figure 5: Figure 5: Key applications of airborne laser scanning in ecology and forestry. Adapted from Lang et al. (2023).

5 Global Models

ALS serves as **reference data** for training and validating global-scale models of forest structure, biomass, and carbon stocks

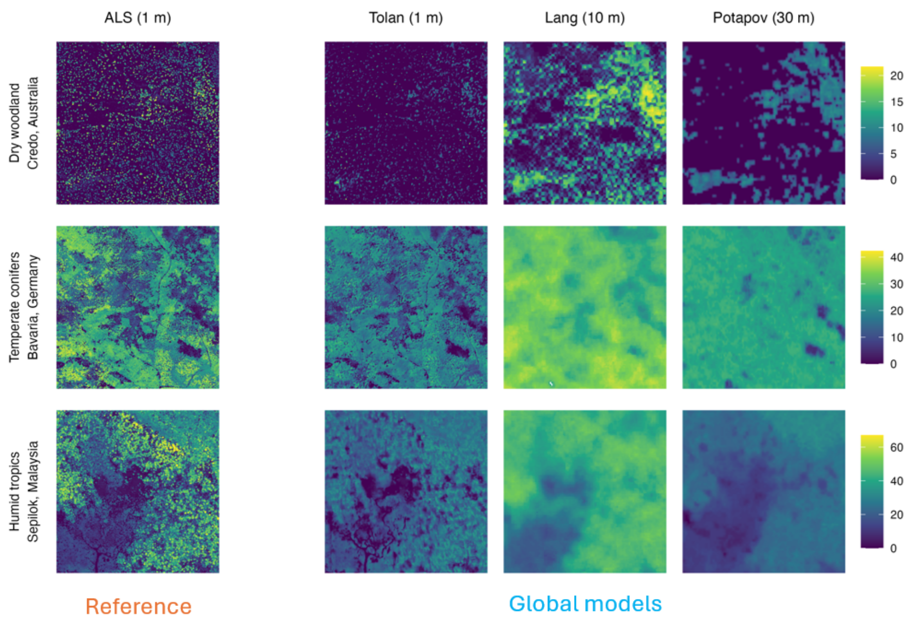

Figure 6: Figure 6: ALS as reference data for global models. Source: Fischer et al. (in preparation).

6 Open Data Access

Large collections of ALS data are increasingly available through open-access platforms (OpenTopography 2024).

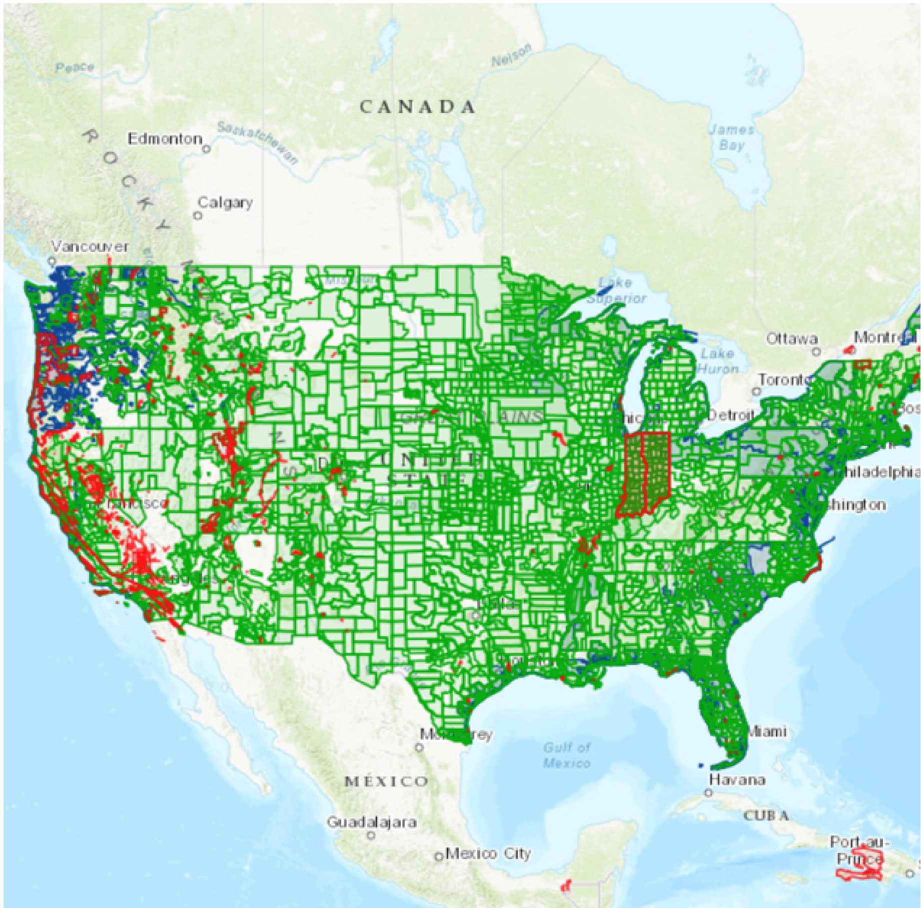

Figure 7: Figure 7: OpenTopography platform for accessing lidar data. Source: OpenTopography (2024).

7 Forest Monitoring

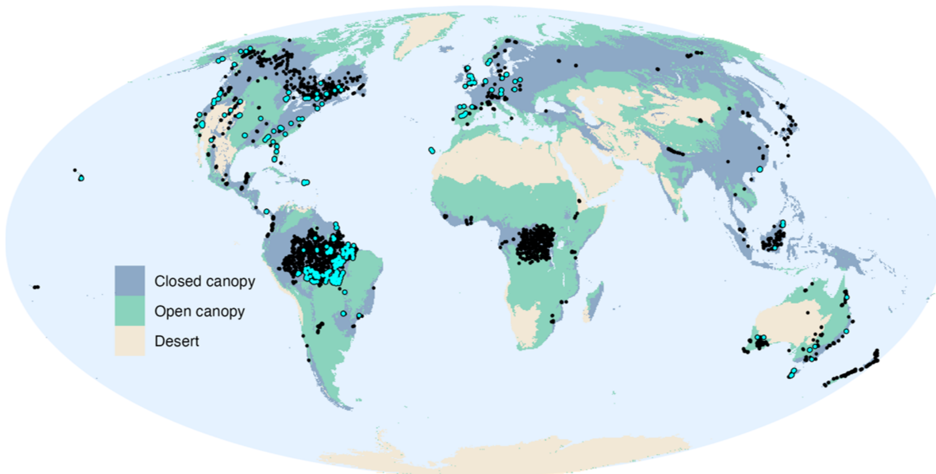

Figure 8: Figure 8: ALS applications in forest monitoring and research. Source: Fischer et al. (in preparation).

8 Ecosystem Studies

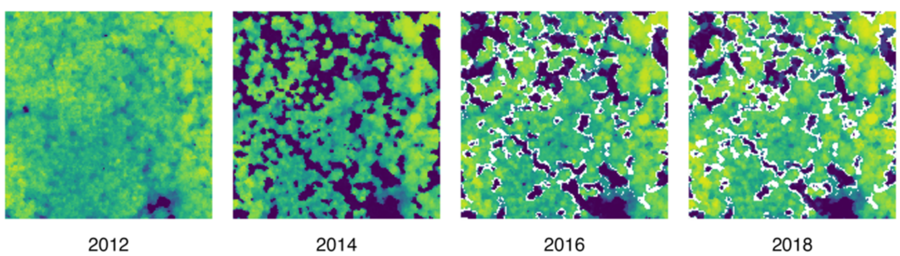

Figure 9: Figure 9: Ecosystem-level applications of ALS technology. Source: Fischer et al. (in preparation).

8.1 Advantages Over Other Methods

Method	Coverage	Resolution	Canopy Penetration	Cost
ALS	Regional to landscape	Very high (cm-m)	Excellent	High
Satellite LiDAR (GEDI)	Global (discrete)	Footprints (~25m)	Good	Low (public)
Optical imagery	Global	Medium-high	None	Low-Medium
Field measurements	Local plots	Very high	Complete	High

9 Word of Warning: Important Considerations

While ALS is a powerful tool, several factors affect data quality and interpretation. Understanding these limitations is crucial for proper application.

9.1 Ecosystems Vary

⚠ Method Performance Varies by Forest Type

Many established ALS processing methods have been **developed and tested primarily in:**

- Open canopy systems
- Conifer-dominated forests
- Temperate deciduous forests

These methods include:

- Ground point detection
- Individual tree segmentation
- Understory characterization

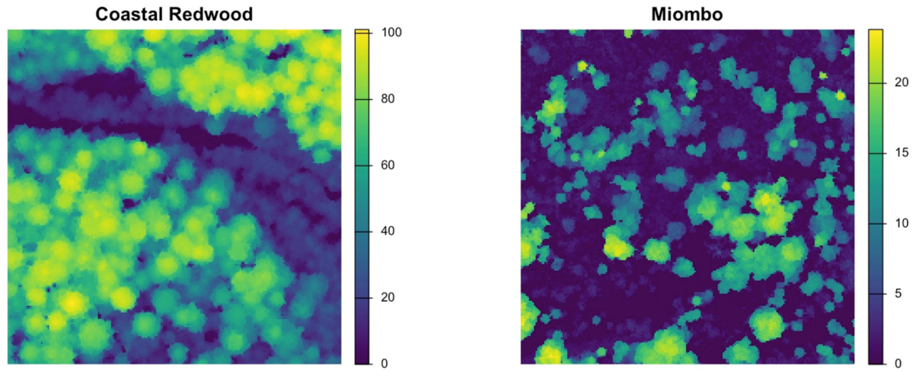

Figure 10: Figure 10: Example of coniferous forest: a lot of methods have been developed and work well in conifer forests or open systems (ground detection, tree segmentation, understory assessments).

❗ Challenges in Dense Forests

Many methods do not work as well in:

- Dense, closed-canopy deciduous forests
- Tropical and subtropical forests
- Multi-layered forest structures

In these environments:

- Ground detection becomes unreliable
- Tree segmentation is highly uncertain
- Individual tree metrics may be impossible to extract

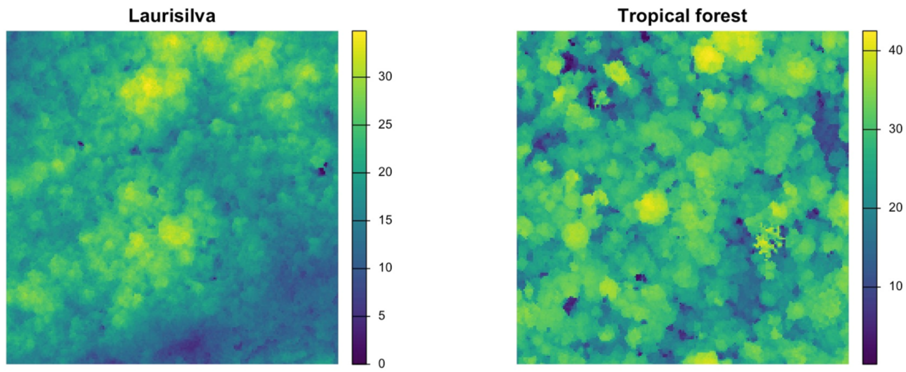

Figure 11: Figure 11: Dense tropical forest: a lot of methods do not work so well in dense, closed-canopy deciduous forests (especially in the tropics and subtropics).

9.2 Instruments Vary

ALS data quality and characteristics depend heavily on:

- **Acquisition season**
- **Sensor specifications**
- **Flight parameters**
- **Processing approaches**

9.2.1 Seasonal Effects

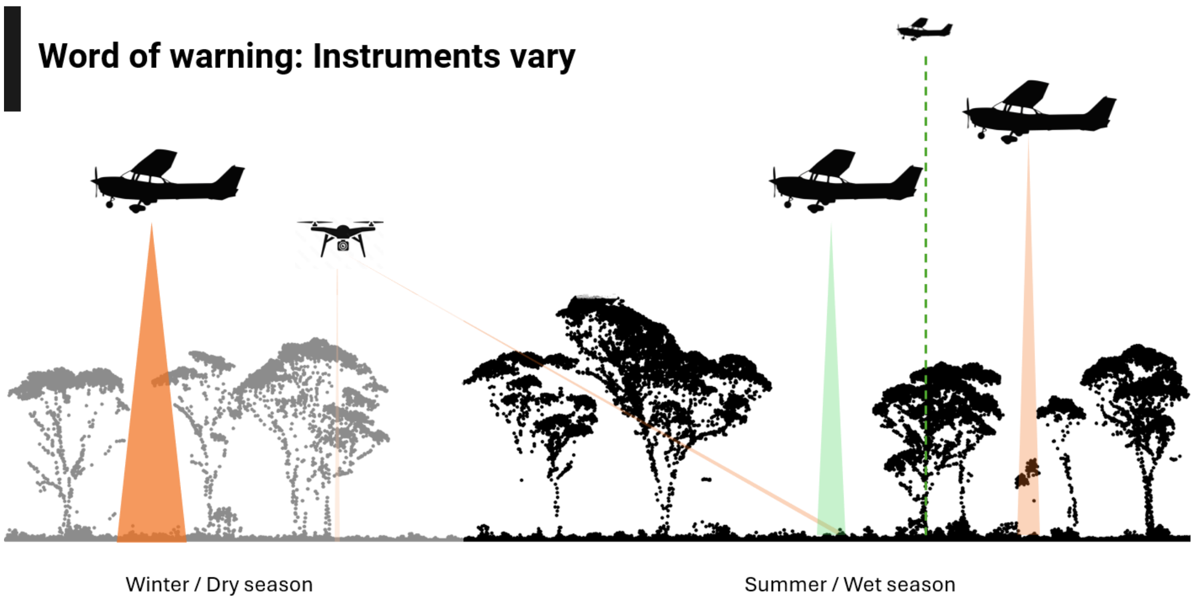

Figure 12: Figure 12: Comparison of winter/dry season (leaf-off) versus summer/wet season (leaf-on) acquisitions. Leaf-off conditions provide better ground penetration, while leaf-on better represents canopy structure

> **ℹ Seasonal Trade-offs**
>
> **Winter / Dry Season (Leaf-off):**
>
> - Better ground detection
> - Improved terrain modeling
> - Underestimates canopy metrics
> - Missing deciduous foliage
>
> **Summer / Wet Season (Leaf-on):**
>
> - Complete canopy structure
> - Accurate height measurements
> - Reduced ground penetration
> - More challenging DTM generation

9.2.2 Sensor Characteristics

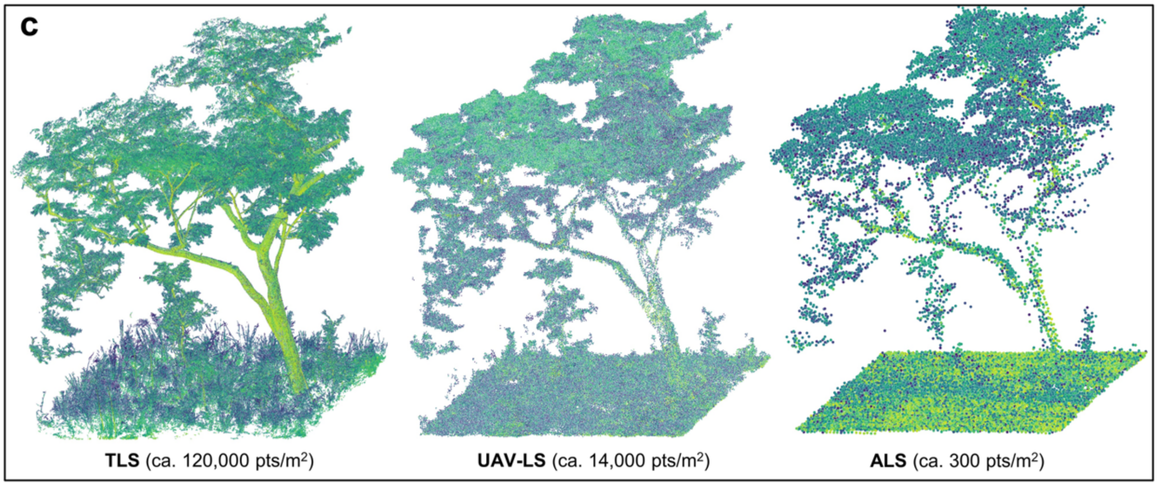

Figure 13: Figure 13: Impact of different sensor characteristics on forest structure retrieval. Adapted from Demol et al. (2024)

Key sensor parameters affecting data quality:

- **Pulse density**: Higher is generally better (5-15+ pulses/m^2 recommended)
- **Wavelength**: Near-infrared (1064 nm) vs. green (532 nm)
- **Beam divergence**: Affects footprint size and penetration
- **Scan angle**: Central scan (nadir) vs. oblique angles
- **Flight altitude**: Trade-off between coverage and resolution

10 Robust Interpretation Approaches

To maximize reliability and minimize artifacts, different modeling approaches can be applied depending on research objectives and forest characteristics.

10.1 Surface Models (Pixels)

Raster-based approach creating 2D gridded products. This is the most common and well-established method.

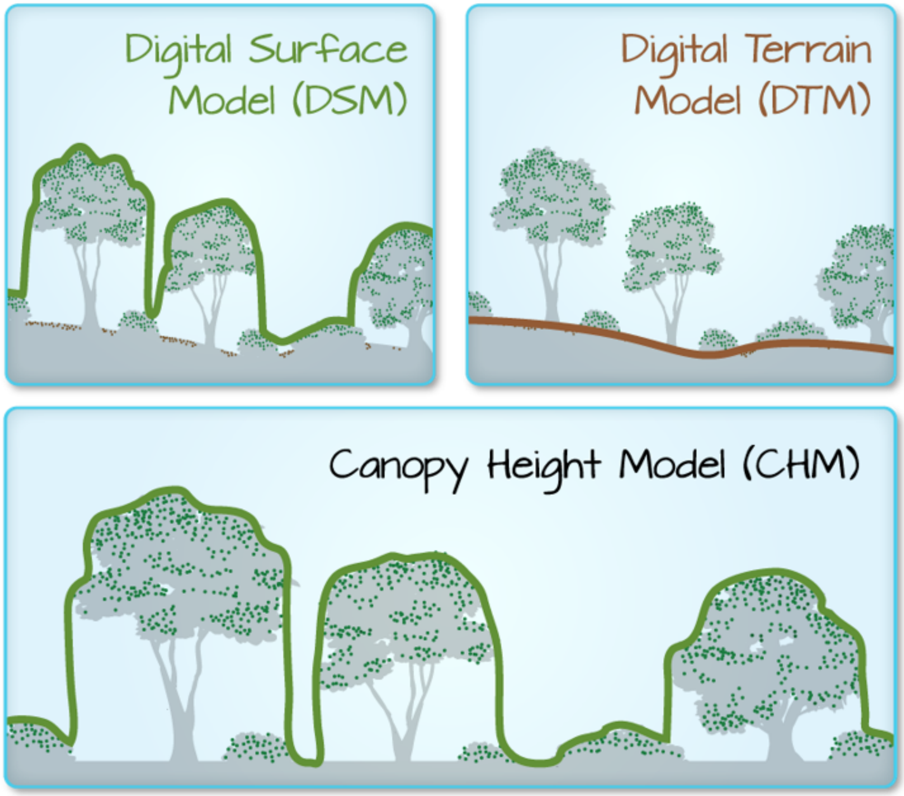

Figure 14: Figure 14: Example of pixel-based surface model approach. Source: NEON (2024).

Common raster products:

- **Digital Terrain Model (DTM)**: Ground elevation
- **Digital Surface Model (DSM)**: Top-of-canopy elevation
- **Canopy Height Model (CHM)**: Vegetation height (DSM - DTM)
- **Intensity**: Laser return strength

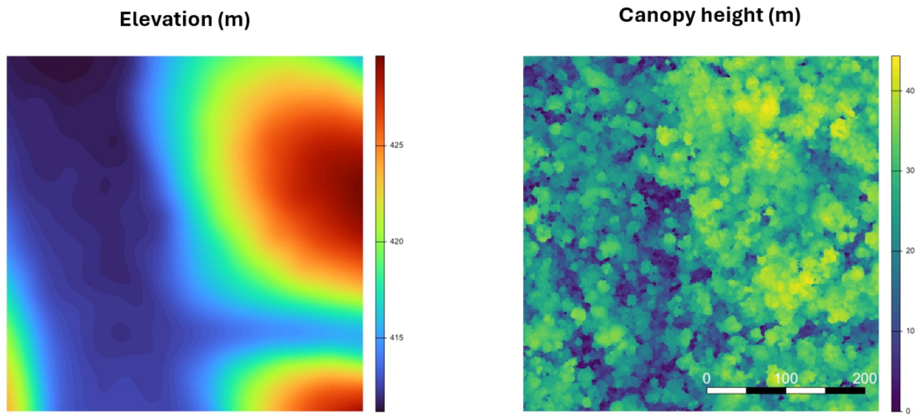

Figure 15: Figure 15: Example of elevation (left) and canopy height (right).

When to Use Surface Models

Advantages:

- Well-established processing workflows
- Computationally efficient
- Easy to integrate with other spatial data
- Suitable for large-area analysis

Best for:

- Regional forest inventories
- Biomass estimation
- Terrain mapping
- Change detection over time

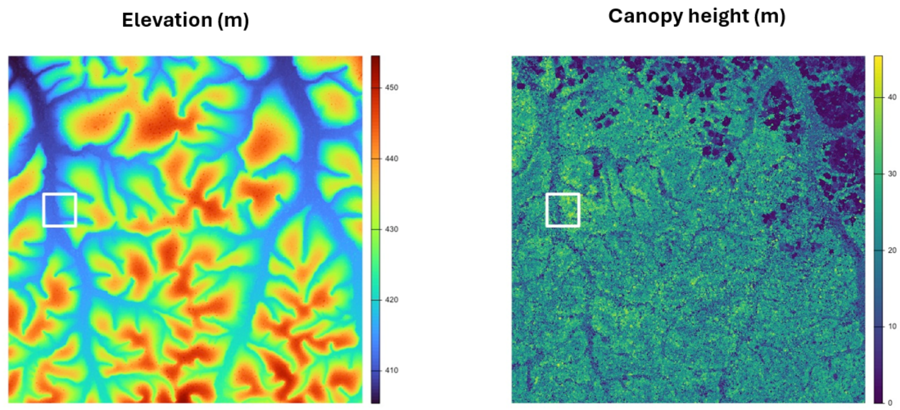

Figure 16: Figure 16: Detailed view of canopy height and elevation.

10.2 Volume Models (Voxels)

Three-dimensional volumetric approach that preserves vertical structure information. More computationally intensive but provides richer ecological information.

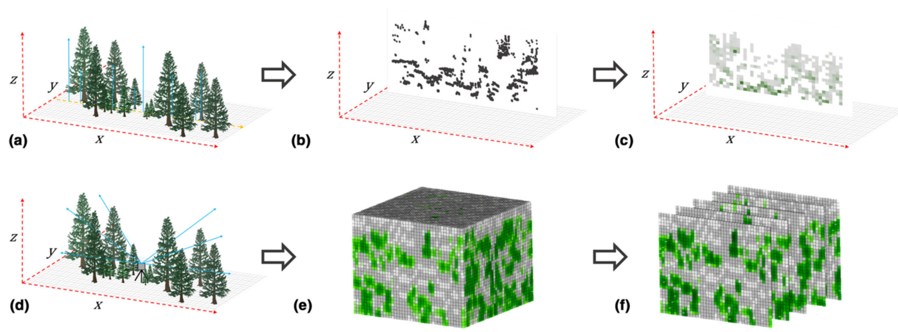

Figure 17: Figure 17: Voxel model example: example of voxel-based volume model approach. Source: Atkins et al. (2018)

Voxel-based products:

- **3D occupancy grids**: Presence/absence of vegetation in 3D space
- **Plant Area Density (PAD)**: Vertical distribution of vegetation
- **Structural complexity metrics**: Diversity of vertical arrangements
- **Light penetration models**: Understory light availability

When to Use Volume Models

Advantages:

- Preserves full 3D structure
- Better for complex, multi-layered forests
- Captures understory information
- More ecologically meaningful metrics

Best for:

- Habitat quality assessment
- Biodiversity studies
- Structural complexity analysis
- Light environment modeling

Limitations:

- Computationally demanding
- Requires higher point densities
- More complex processing pipelines
- Larger data storage requirements

10.3 Choosing an Approach

Criterion	Surface Models (Pixels)	Volume Models (Voxels)
Processing complexity	Low	High
Computational demand	Low	High
Data requirements	Moderate point density	High point density
Forest type suitability	All types	Complex, multi-layered
Ecological detail	Canopy-focused	Full 3D structure
Analysis scale	Regional to global	Local to landscape

11 Resources for Learning and Analysis

11.1 Tutorials and Documentation

Essential Learning Resources

Interactive Introductions:

- NOAA Digital Coast Training (NOAA 2024): https://coast.noaa.gov/digitalcoast/training/intro-lidar.html
- NEON LiDAR Basics (NEON 2024): https://www.neonscience.org/resources/learning-hub/tutorials/lidar-basics

Open Source Processing:

- lidR Package for R (Roussel and Auty 2024): https://r-lidar.github.io/lidRbook/
- Terra Package for R (rasters) (Hijmans 2024): https://rspatial.org/spatial/index.html

Commercial Software:

- LAStools (Isenburg 2024): https://rapidlasso.de/product-overview/
- LAStools User Forum: https://groups.google.com/g/lastools

Methodological Papers:

- Surface models (pixel-based) (Fischer, Maréchaux, and Chave 2024): https://doi.org/10.1111/2041-210X.14416
- Volume models (voxel-based) (AMAP Laboratory 2024): https://amapvox.org/

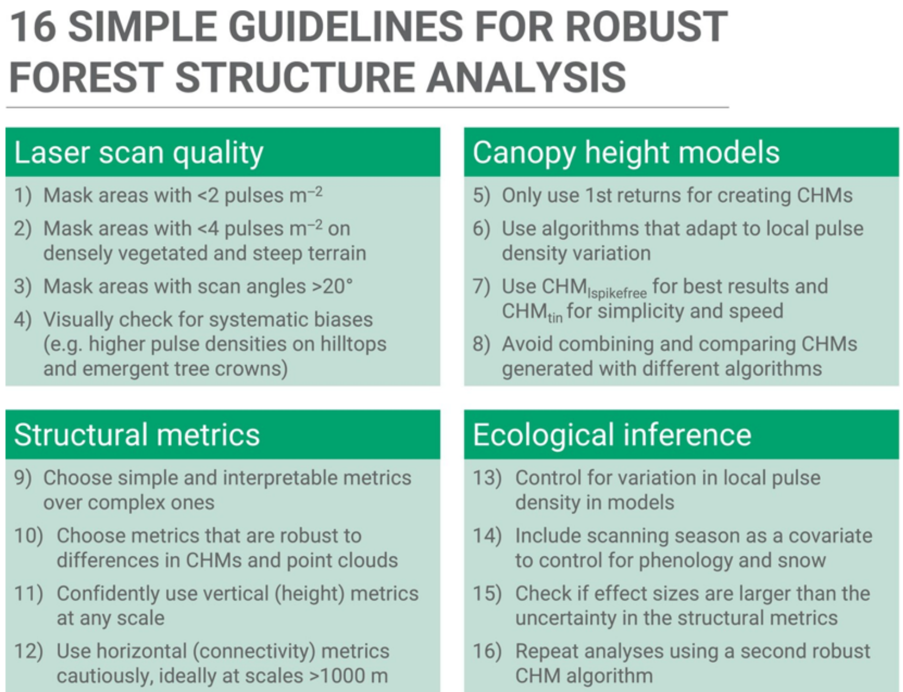

Figure 18: Figure 18: Key methodological paper on surface model approaches. Source: Fischer, Maréchaux, and Chave (2024).

11.2 Data Access

Where to Find ALS Data

Open Access Repositories:

- **OpenTopography** (OpenTopography 2024): https://opentopography.org/ (USA and international)
- **NEON** (NEON 2024): https://www.neonscience.org/ (USA ecological sites)
- **USGS 3DEP**: https://www.usgs.gov/3d-elevation-program (USA nationwide)
- **National Programs**: Many countries have open lidar programs

Tips for Data Access:

- Check if your study area has existing coverage
- Consider acquisition date and season
- Review metadata for pulse density and accuracy
- Download sample data before committing to large datasets

12 Practical Applications and Exercises

12.1 Getting Started with ALS Analysis

Recommended Workflow

Preparation:

1. **Form groups** of 2-3 people (at least one familiar with R/RStudio)
2. **Review tutorials** from lidR handbook and NEON
3. **Download sample data** for your region of interest
4. **Familiarize yourself** with basic concepts before analysis

Analysis Steps:

1. Start with simple metrics: DTM, CHM, mean height
2. Experiment with parameters: resolution, filtering, algorithms
3. Compare different methods (TIN vs highest point, different resolutions)
4. Validate results: Compare with field data or expectations

Key Considerations:

- What is the ecological context? (forest type, structure)
- What is the data quality? (pulse density, season, coverage)
- What are the research questions? (canopy height, biomass, diversity)
- What validation data are available? (field plots, imagery)

12.2 Pre-Analysis Questions to Consider

Before processing ALS data, think about:

1. **Forest Structure Expectations:**
   - What is the typical tree height in your study area?
   - Is the canopy open or closed?
   - Are there distinct canopy layers?
2. **Data Quality Assessment:**
   - What is the pulse density?
   - What season was it acquired?
   - Are there coverage gaps?
3. **Method Selection:**
   - Do you need individual trees or area statistics?
   - Is terrain modeling critical?
   - What spatial resolution is appropriate?
4. **Validation Strategy:**

- Are field measurements available?
- Can you compare with other data sources?
- How will you assess uncertainty?

12.3 Hands-On Practice

Tutorial Workflow

Follow the companion tutorials (tutorial1.qmd and tutorial2.qmd) to:

- Process raw point cloud data
- Generate DTMs and CHMs
- Calculate forest structure metrics
- Analyze temporal changes
- Evaluate uncertainties and artifacts

Work through these systematically, paying attention to parameter choices and their effects on results.

13 Summary and Key Takeaways

14 Technology

Airborne Laser Scanning (ALS):

- Active remote sensing using laser pulses
- Creates 3D point clouds of terrain and vegetation
- Penetrates forest canopy to measure ground and structure
- Available as full waveform or discrete returns

15 Applications

Primary Uses:

- High-resolution canopy height mapping
- Terrain modeling (DTM/DEM)
- Forest biomass estimation
- Reference data for global models
- Habitat and biodiversity assessment

- Change detection and monitoring

16 Considerations

Important Limitations:

- Methods vary in effectiveness by ecosystem type
- Sensor characteristics strongly affect data quality
- Seasonal effects (leaf-on vs. leaf-off)
- Processing approach affects reliability
- Requires careful interpretation and validation

17 Best Practices

For Reliable Analysis:

- Understand your forest system characteristics
- Check data quality metrics (pulse density, coverage)
- Consider seasonal effects on your research question
- Choose appropriate modeling approach (pixels vs. voxels)
- Validate results when possible
- Document all processing steps and parameters

18 Conclusion

Airborne Laser Scanning has revolutionized our ability to measure forest structure at scales from individual trees to entire regions. However, successful application requires understanding both the technology's capabilities and its limitations.

Key recommendations for working with ALS data:

1. **Know your ecosystem**: Different forest types require different approaches
2. **Understand your data**: Sensor specs and acquisition conditions matter
3. **Choose appropriate methods**: Match analysis approach to research questions
4. **Validate results**: Ground-truth when possible, sanity-check always
5. **Stay current**: Methods and best practices continue to evolve

The resources provided in this document offer pathways for deeper learning, from introductory tutorials to advanced methodological papers. The combination of openly available data and open-source processing tools makes ALS analysis increasingly accessible to the research community.

These study materials were prepared from the presentation "Airborne Laser Scanning - A Global Perspective" by Fabian Jörg Fischer.

AMAP Laboratory. 2024. "AMAPVox: Voxel-Based LiDAR Analysis Software." https://amapvox.org/.

Atkins, Jeff W, Gil Bohrer, Robert T Fahey, Brady S Hardiman, Timothy H Morin, Atticus EL Stovall, Naupaka Zimmerman, and Christopher M Gough. 2018. "Quantifying Vegetation and Canopy Structural Complexity from Terrestrial Li DAR Data Using the Forestr r Package." *Methods in Ecology and Evolution* 9 (10): 2057–66.

Demol, Miro, Naikoa Aguilar-Amuchastegui, Gabija Bernotaite, Mathias Disney, Laura Duncanson, Elise Elmendorp, Andres Espejo, et al. 2024. "Multi-Scale Lidar Measurements Suggest Miombo Woodlands Contain Substantially More Carbon Than Thought." *Communications Earth & Environment* 5 (1): 366.

Fischer, Fabian Jörg et al. in preparation. "Global-Scale Canopy Height Modeling Using Airborne Laser Scanning and GEDI Data."

Fischer, Fabian Jörg, Isabelle Maréchaux, and Jérôme Chave. 2024. "Improving Aboveground Biomass Maps of Tropical Forests Using Airborne Laser Scanning and Sentinel Data: A Case Study from Central Africa." *Methods in Ecology and Evolution*. https://doi.org/10.1111/2041-210X.14416.

Hijmans, Robert J. 2024. "Spatial Data Analysis with Terra." https://rspatial.org/spatial/index.html.

Isenburg, Martin. 2024. "LAStools: Efficient Tools for LiDAR Processing." https://rapidlasso.de/product-overview/.

Jucker, Tommaso, Carl R Gosper, Georg Wiehl, Paul B Yeoh, Nat Raisbeck-Brown, Fabian Jörg Fischer, Jason Graham, et al. 2023. "Using Multi-Platform LiDAR to Guide the Conservation of the World's Largest Temperate Woodland." *Remote Sensing of Environment* 296: 113745.

Lang, Nico, Walter Jetz, Konrad Schindler, and Jan Dirk Wegner. 2023. "A High-Resolution Canopy Height Model of the Earth." *Nature Ecology & Evolution* 7: 1778–89. https://doi.org/10.1038/s41559-023-02206-6.

NEON. 2024. "NEON (National Ecological Observatory Network)." https://www.neonscience.org/.

NOAA. 2024. "NOAA Digital Coast: Introduction to Lidar." https://coast.noaa.gov/digitalcoast/training/intro-lidar.html.

OpenTopography. 2024. "OpenTopography: High-Resolution Topography Data and Tools." https://opentopography.org/.

Roussel, Jean-Romain, and David Auty. 2024. "lidR Package Documentation: Airborne LiDAR Data Manipulation and Visualization for Forestry Applications." https://r-lidar.github.io/lidRbook/.

Yan, Wai Yeung, Ahmed Shaker, and Nagwa El-Ashmawy. 2015. "Urban Land Cover Classification Using Airborne LiDAR Data: A Review." *Remote Sensing of Environment* 158: 295–310.