Airborne Laser Scanning - A Global Perspective

Fabian Jörg Fischer

2025-12-18

Table of contents

1 Introduction **2**

2 Terminology and Technology **3**
- 2.1 What is ALS? . . . 3
- 2.2 How It Works: Full Waveform vs. Point Clouds . . . 3

3 Why Airborne Laser Scanning? **6**
- 3.1 Spatial Coverage and Resolution . . . 6
- 3.2 Key Applications . . . 7

4 General Applications **7**

5 Global Models **8**

6 Open Data Access **8**

7 Forest Monitoring **10**

8 Ecosystem Studies **10**
- 8.1 Advantages Over Other Methods . . . 11

9 Word of Warning: Important Considerations **11**
- 9.1 Ecosystems Vary . . . 12
- 9.2 Instruments Vary . . . 13
  - 9.2.1 Seasonal Effects . . . 14
  - 9.2.2 Sensor Characteristics . . . 15

10 Robust Interpretation Approaches **16**
- 10.1 Surface Models (Pixels) . . . 16
- 10.2 Volume Models (Voxels) . . . 19

10.3 Choosing an Approach 20

11 Resources for Learning and Analysis **21**
11.1 Tutorials and Documentation 21
11.2 Data Access 22

12 Practical Applications and Exercises **23**
12.1 Getting Started with ALS Analysis 23
12.2 Pre-Analysis Questions to Consider 24
12.3 Hands-On Practice 24

13 Summary and Key Takeaways **25**

14 Technology **25**

15 Applications **25**

16 Considerations **25**

17 Best Practices **25**

18 Conclusion **26**

19 References **26**

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. **The perspective presented here draws from analysis of a global collection of airborne laser scanning data** spanning diverse forest types and ecosystems, from tropical rainforests to boreal forests, providing insights into both the capabilities and limitations of ALS across different environments.

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 airborne platforms. **When we refer to "airborne laser scanning" or "airborne LiDAR," this includes both traditional aircraft/helicopter-based systems and UAV-based LiDAR systems.** 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 and Terminology

Interchangeable terms (all mean the same thing): - Airborne Laser Scanning (ALS) - Airborne LiDAR - lidar - LiDAR
Don't be confused by the different spellings and capitalizations!
Additional important terms: - **Point Cloud**: Three-dimensional collection of georeferenced points representing surfaces - **Terrestrial LiDAR (TLS)**: Ground-based variant for high-resolution local measurements (Jucker et al. 2023) - **Full Waveform**: Complete energy distribution of returned laser pulse - **Returns**: Individual reflections detected from a laser pulse (first return, last return, etc.)

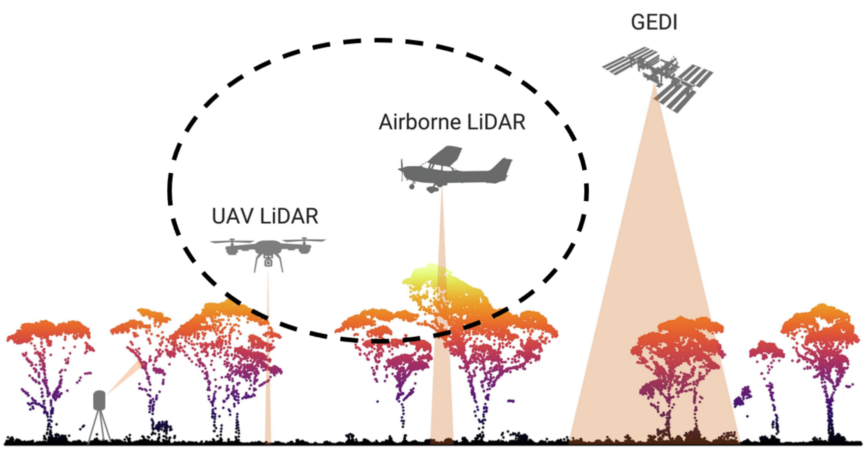

Figure 1: Figure 1: Terrestrial LiDAR system. Adapted from Jucker et al. (2023)

2.2 How It Works: Full Waveform vs. Point Clouds

ALS systems technically record complete waveforms, but most applications use discretized data:

1. **Full Waveform LiDAR**: Records the complete energy distribution of the returned laser pulse, providing detailed information about vegetation structure at multiple heights. However, this is very information-rich and computationally demanding.

2. **Discrete Return (Point Clouds)**: Processes the waveform into individual return points using algorithms (usually provided by manufacturers). **Approximately 99% of ALS applications** use this discretized version, which is more compressed, easier to analyze, and simpler to share. Discrete returns typically capture:

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

> **Waveform to Point Cloud Conversion**
>
> The conversion from full waveform to discrete returns involves identifying peaks in the returned energy signal. This discretization makes the data more manageable while retaining most of the useful structural information for forest analysis.

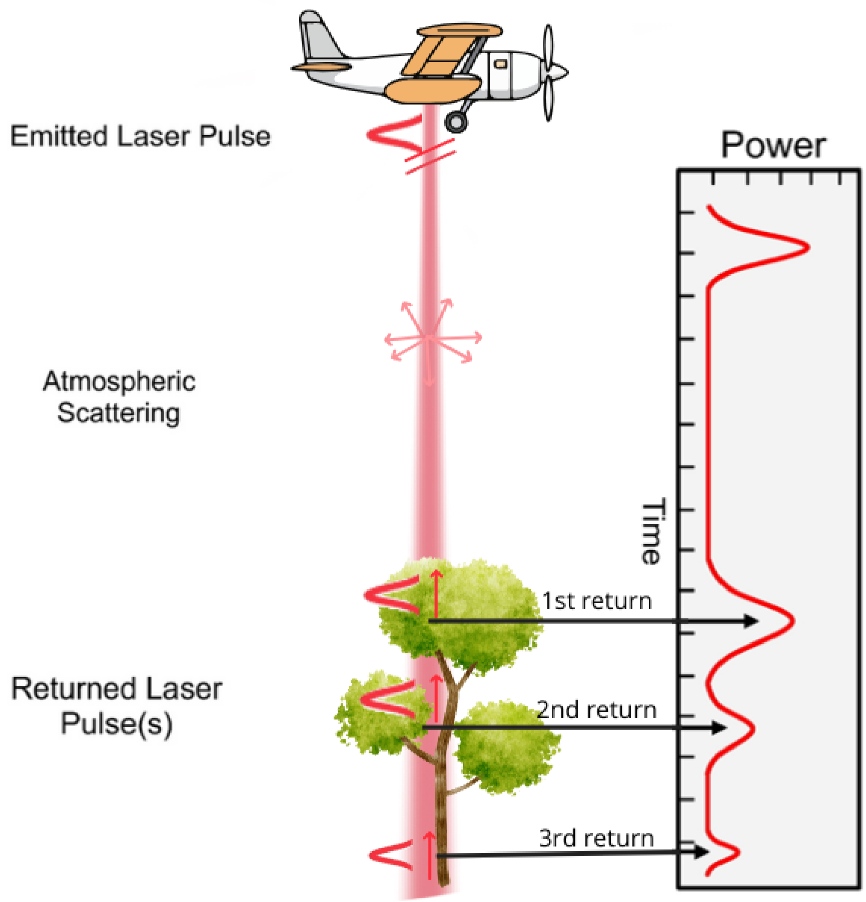

Figure 2: Figure 2: Comparison of full waveform data and discrete point cloud returns. Adapted from Yan, Shaker, and El-Ashmawy (2015)

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.

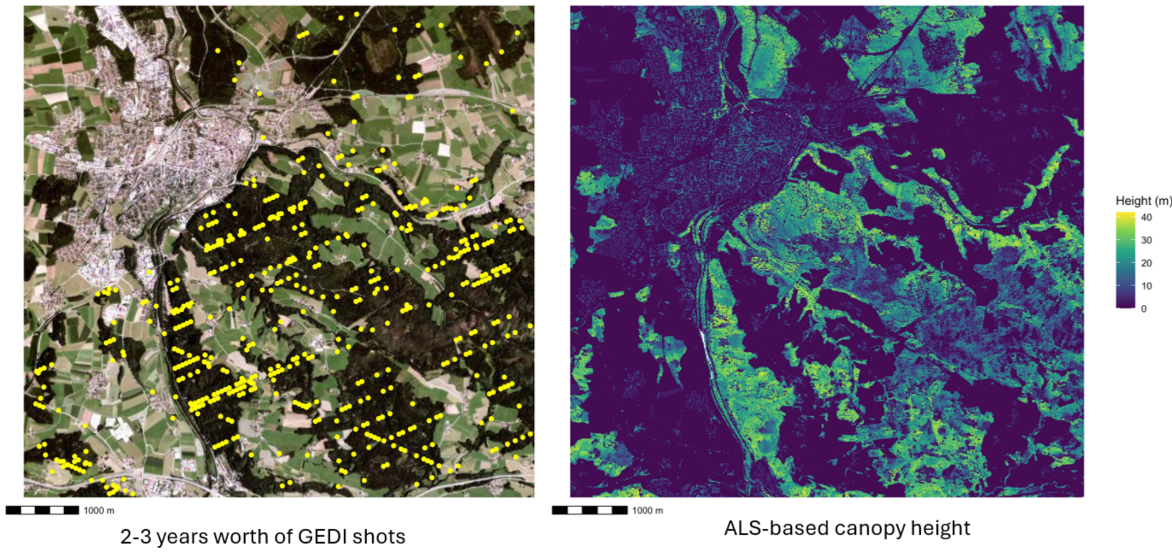

Figure 4: Figure 4: Comparison 2-3 years of GEDI satellite shots (discrete points) versus ALS-based canopy height (continuous coverage).

3.2 Key Applications

4 General Applications

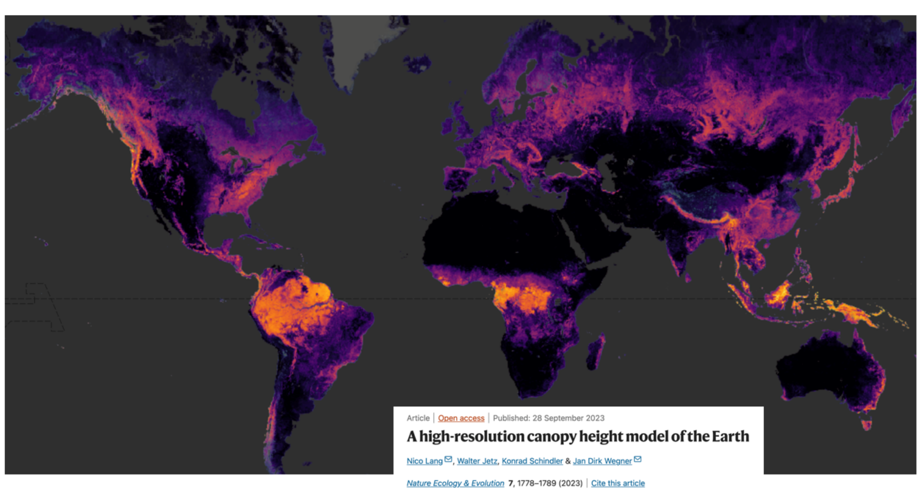

Figure 5: Figure 5: Key applications of airborne laser scanning in ecology and forestry. Adapted from Lang et al. (2023).

5 Global Models

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

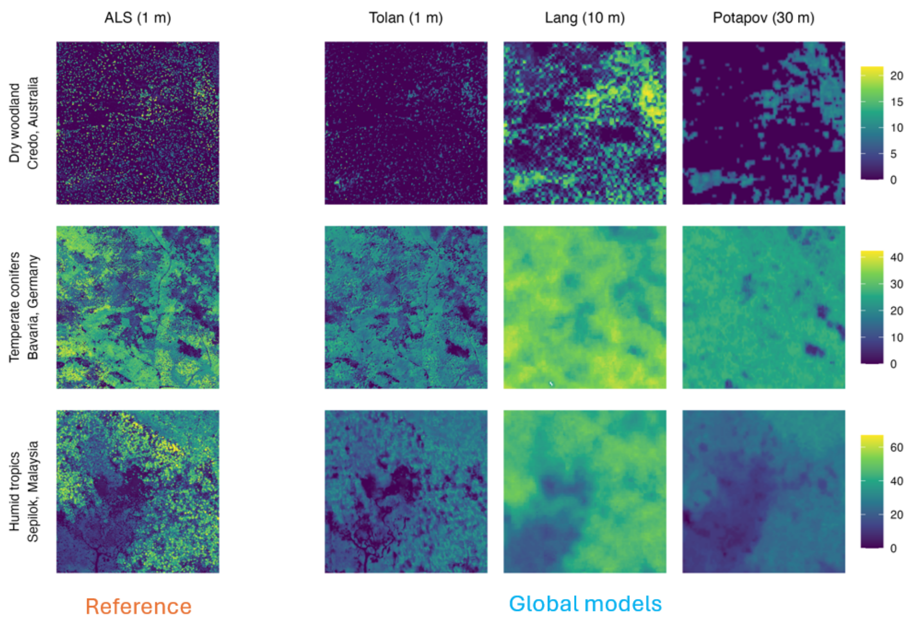

Figure 6: Figure 6: ALS as reference data for global models. Source: Fischer et al. (in preparation).

6 Open Data Access

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

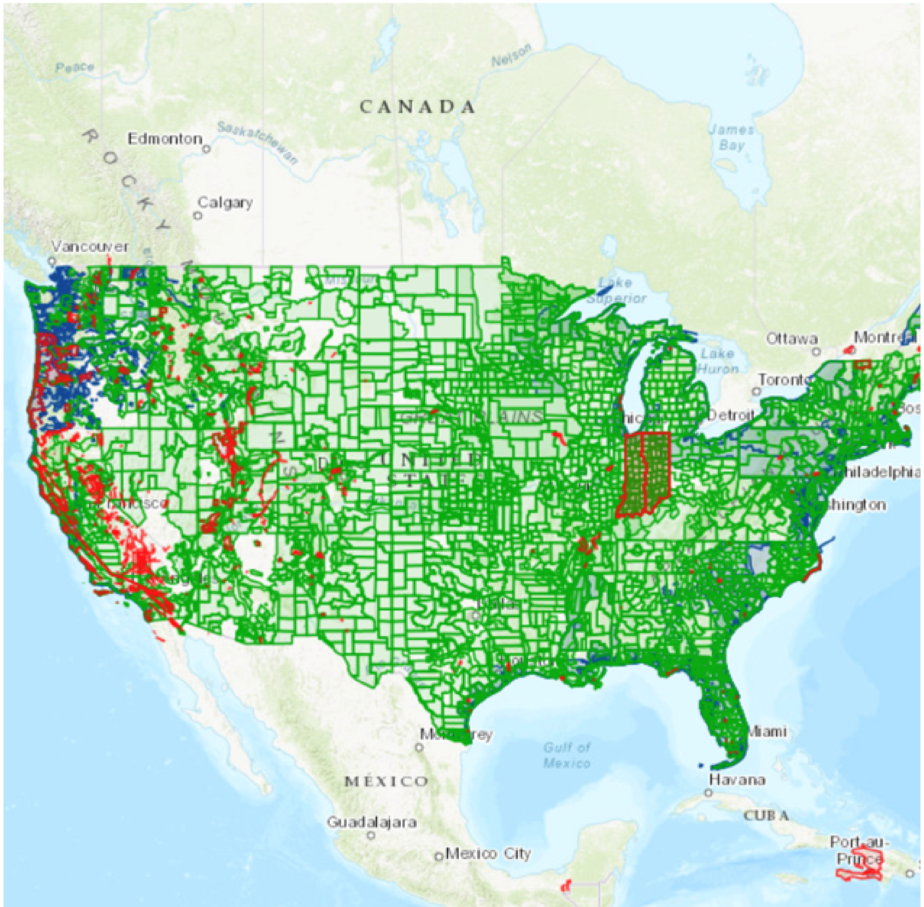

Figure 7: Figure 7: OpenTopography platform for accessing lidar data. Source: OpenTopography (2024).

7 Forest Monitoring

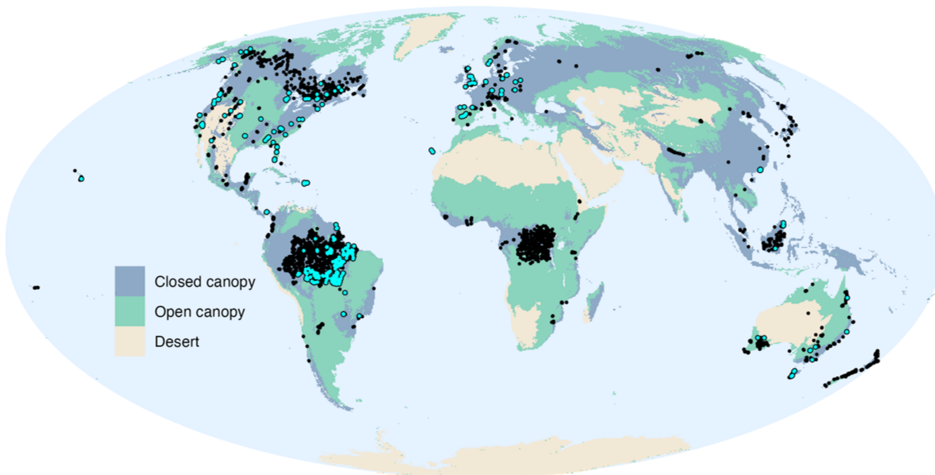

Figure 8: Figure 8: ALS applications in forest monitoring and research. Source: Fischer et al. (in preparation).

8 Ecosystem Studies

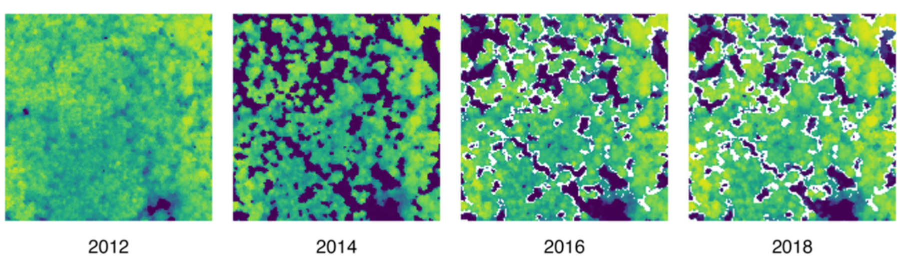

Figure 9: Figure 9: Ecosystem-level applications of ALS technology. Source: Fischer et al. (in preparation).

> ⚠ A Critical Warning About Global Canopy Height Models
>
> Recent years have seen the emergence of global-scale canopy height models that combine satellite LiDAR (GEDI) with optical imagery. While these represent important progress, **users should exercise extreme caution when using them for ecological analyses at present.**

Current limitations of major global models:

- **Meta/Facebook model** (high resolution, ~30m): Consistently underestimates canopy height, has substantial artifacts (e.g., clouds mistaken for gaps in tropical regions)
- **Lang model** (10m resolution): Overestimates canopy height and smooths out landscape-scale variation
- **Potapov model** (Landsat-based, 30m): Better estimates of mean height but loses fine-scale resolution

While these models capture general trends between biomes, they are **not operationally useful for most ecological studies at present.** For local to landscape-scale research, high-quality ALS data remains essential.

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

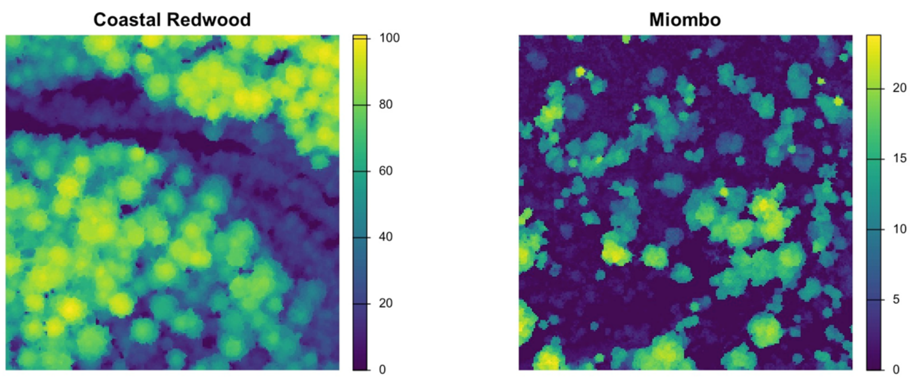

Figure 10: Figure 10: Example of coniferous forest: a lot of methods have been developed and work well in conifer forests or open systems (ground detection, tree segmentation, understory assessments).

! 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

Note on AI and deep learning approaches: Even advanced AI techniques struggle with individual tree segmentation in closed-canopy forests. A fundamental limitation applies here: **if human experts cannot reliably delineate individual tree crowns, AI methods are unlikely to perform better.** This is not a temporary technical limitation but rather reflects the physical reality of overlapping, intertwined canopies in dense forests.

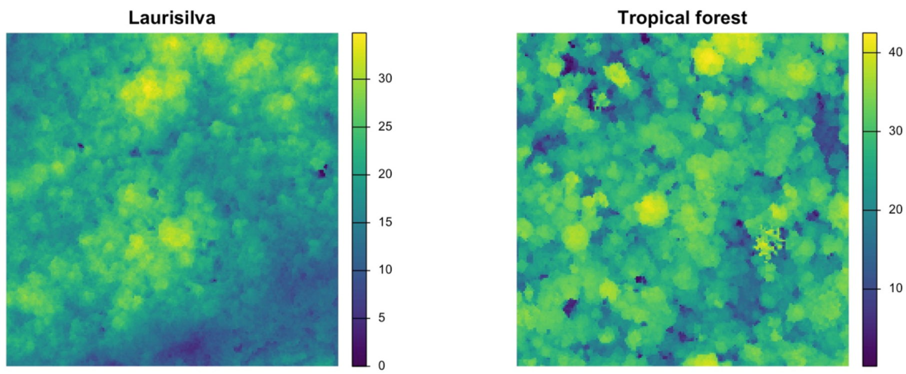

Figure 11: Figure 11: Dense tropical forest: a lot of methods do not work so well in dense, closed-canopy deciduous forests (especially in the tropics and subtropics).

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

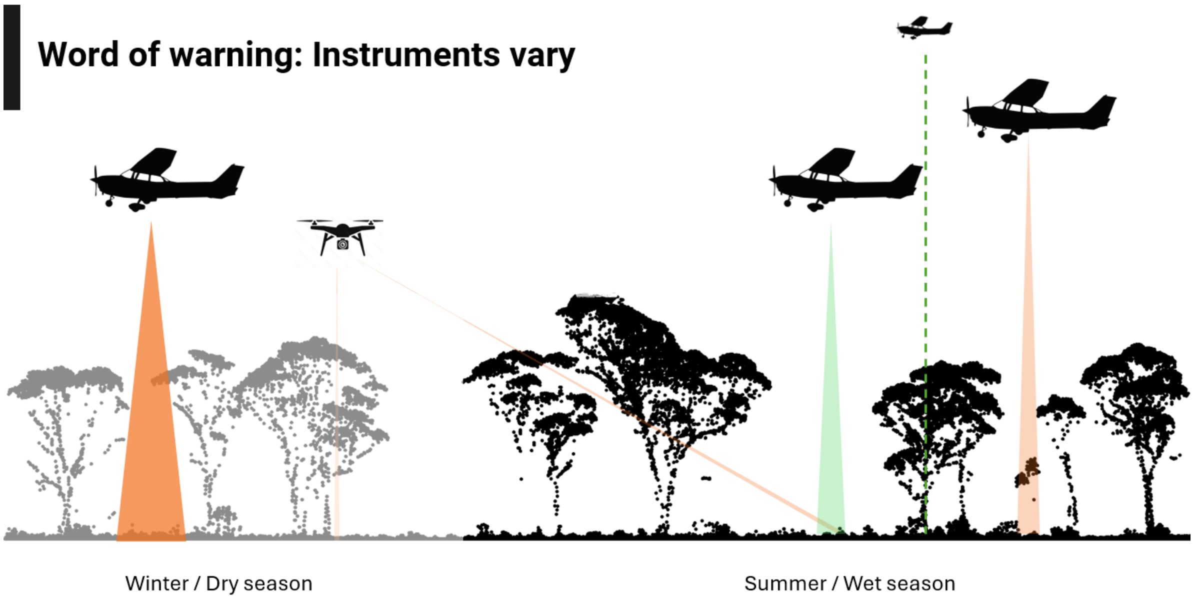

Figure 12: Figure 12: Comparison of winter/dry season (leaf-off) versus summer/wet season (leaf-on) acquisitions. Leaf-off conditions provide better ground penetration, while leaf-on better represents canopy structure

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

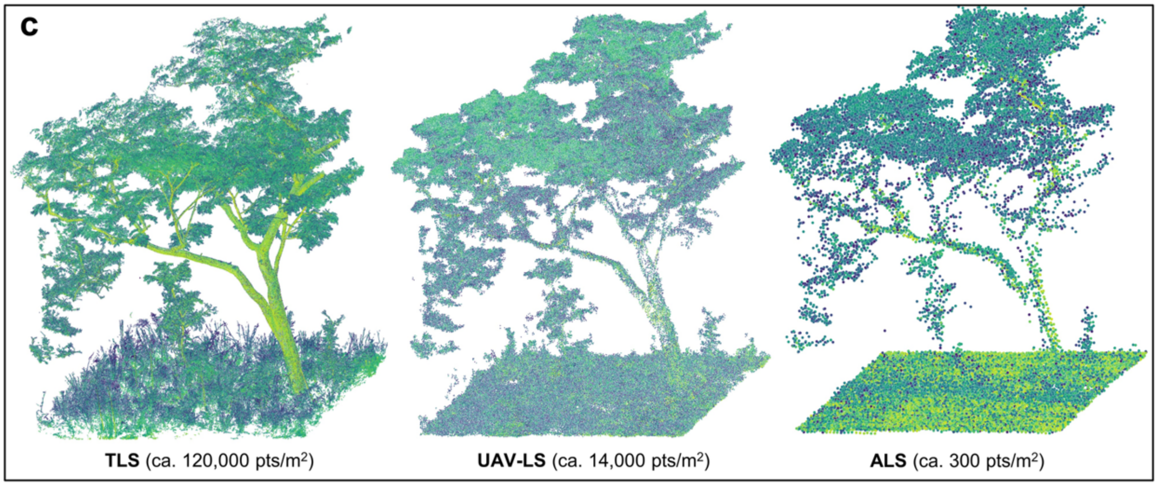

Figure 13: Figure 13: Impact of different sensor characteristics on forest structure retrieval. Adapted from Demol et al. (2024)

Key sensor parameters affecting data quality:

- **Pulse density**: Higher is generally better (5-15+ pulses/m² recommended)
- **Wavelength**: Near-infrared (1064 nm) vs. green (532 nm) - different wavelengths interact differently with vegetation and water
- **Beam divergence**: Affects footprint size and penetration. Wide beams are more sensitive to upper canopy elements (hitting something at the top), while narrow beams can penetrate small gaps more easily
- **Scan angle**: Central scan (nadir) vs. oblique angles
- **Flight altitude**: Trade-off between coverage and resolution

⚠ Cross-Sensor Comparisons Require Caution

Within a single study area scanned with the same system, you can use relatively complex structural metrics safely. However, **when comparing across different sensors or acquisition campaigns**, you must be much more careful:

- **Simple metrics** (e.g., mean canopy height, percentile heights) are generally comparable across sensors
- **Complex structural metrics** (e.g., entropy, fractal dimension, box dimension) can be problematic when comparing different scans
- **Risk**: You may inadvertently measure differences between sensors rather than

differences between environments

Recommendation: When working across multiple sensors or platforms, prioritize simple, interpretable metrics over complex ones. If you use structural complexity metrics, ensure you understand exactly how they work and validate that sensor differences don't drive your results.

Commercial Software for Ground Classification

For ground point classification specifically, commercial software (such as LAStools) often still outperforms open-source alternatives. If you receive point clouds that have been pre-classified by a company, **use those classifications rather than re-classifying** with your own tools. Commercial providers often employ manual corrections and have refined their algorithms over many years, making their ground classifications more reliable.

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 product from airborne laser scanning** and what ALS analysis historically started with.

The basic concept: Imagine draping a cloth over your point cloud. The cloth falls and settles onto the points, creating a continuous surface. You can control how far the cloth drops into gaps by adjusting weights - strong weights let it fall into small gaps, while lighter weights create a smoother surface that bridges over gaps.

This same process is applied to: - **All returns** → creates Digital Surface Model (DSM) representing the top of the canopy - **Last returns** (ground points) → creates Digital Terrain Model (DTM) representing the terrain

The difference between DSM and DTM gives you the Canopy Height Model (CHM).

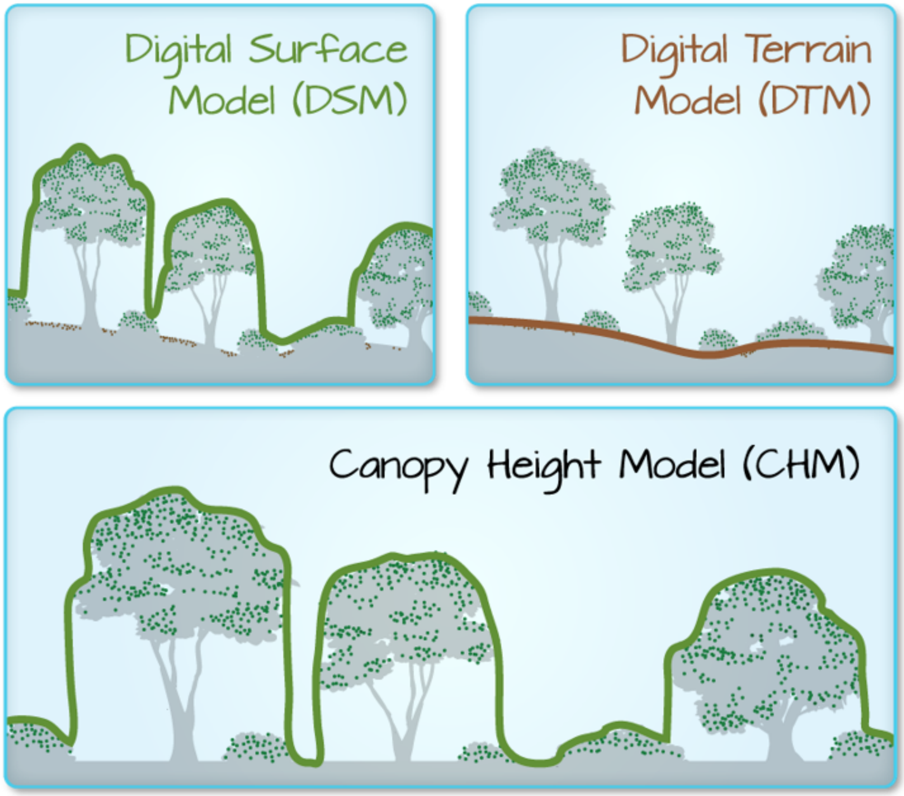

Figure 14: Figure 14: Example of pixel-based surface model approach. Source: NEON (2024).

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

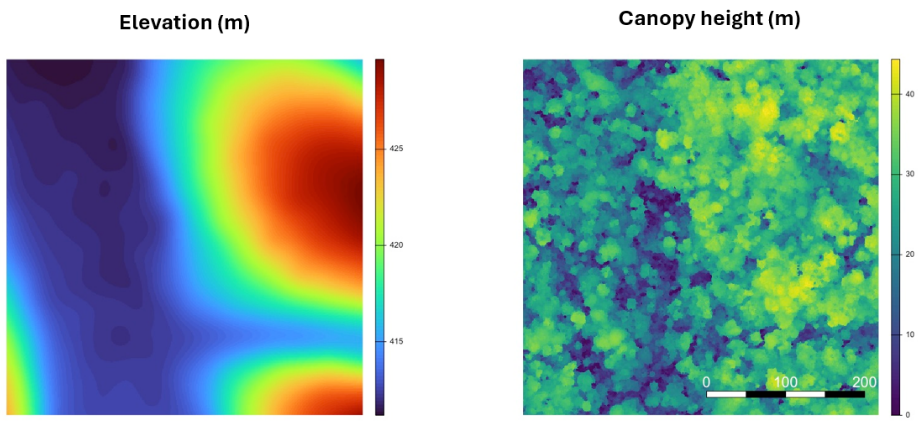

Figure 15: Figure 15: Example of elevation (left) and canopy height (right).

Ecological Patterns Visible in Canopy Structure

An interesting observation from processing ALS data globally: **you can often recognize terrain patterns directly from canopy height models**, even without looking at the elevation data. This is particularly evident in areas with subtle topography (like the Congo example above, with only 20-25m elevation change).

Why this happens: Forest structure is frequently determined by water availability. Trees grow taller and more vigorously in areas with better water access. As a result, you can sometimes trace: - River courses through taller forest - Valley bottoms with increased height - Ridge tops with lower canopy heights

This demonstrates that canopy height models capture not just structure but also underlying ecological processes and resource distribution patterns.

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

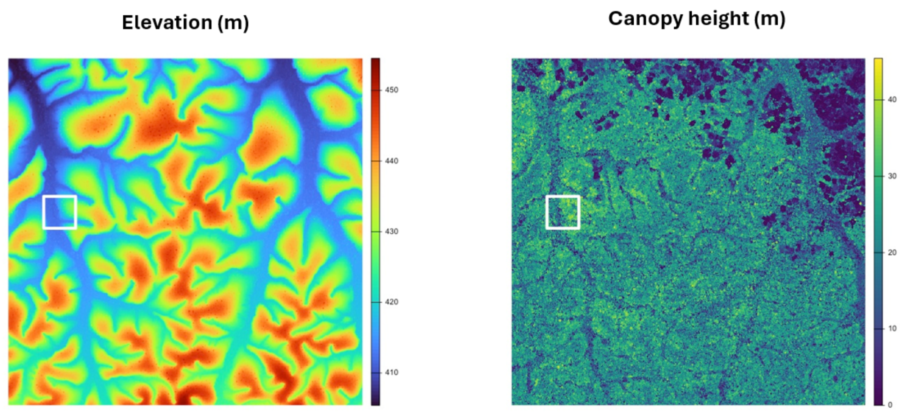

Figure 16: Figure 16: Detailed view of canopy height and elevation.

10.2 Volume Models (Voxels)

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

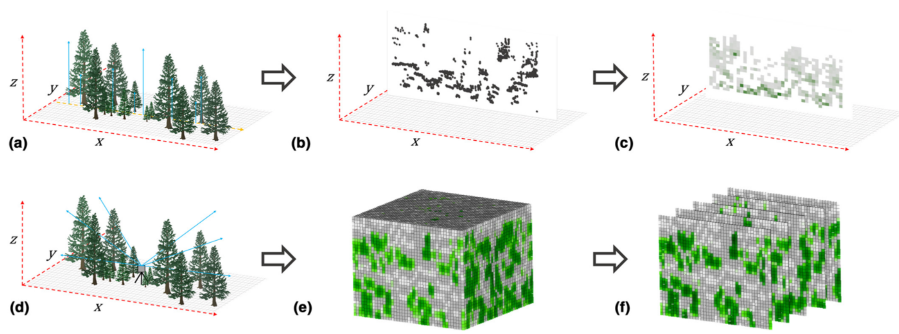

Figure 17: Figure 17: Voxel model example: example of voxel-based volume model approach. Source: Atkins et al. (2018)

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/

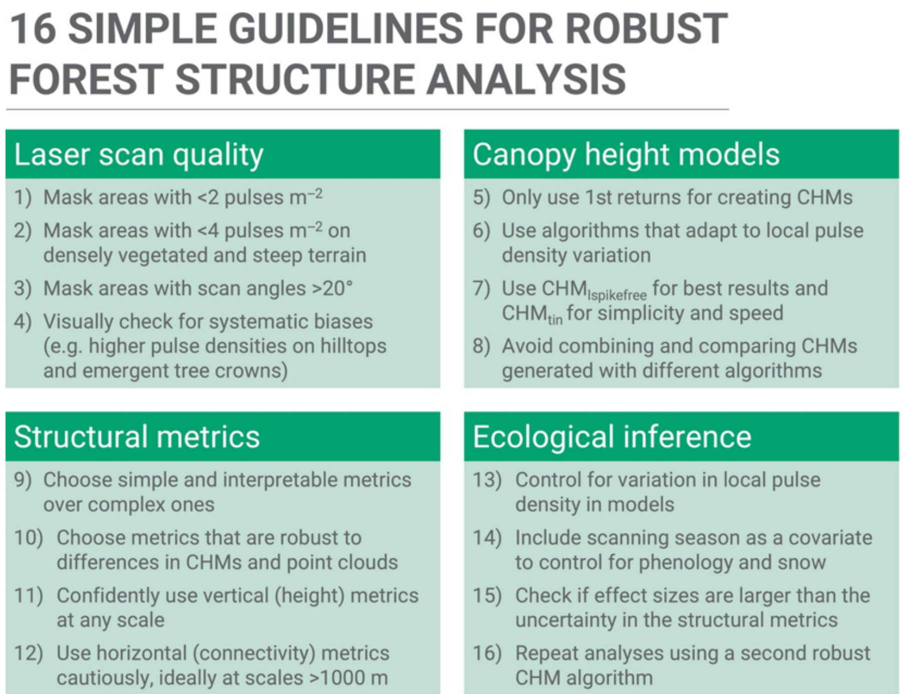

Figure 18: Figure 18: Key methodological paper on surface model approaches. Source: Fischer, Maréchaux, and Chave (2024).

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

Regional Coverage Notes:

- **United States**: Extensive coverage, with most areas scanned at least once. Many locations have multiple temporal acquisitions available through OpenTopography
- **Europe**: Variable - some countries like **Spain** provide excellent open access with multiple temporal scans, while others like **Germany** have mixed policies (some states provide open access, others do not)

- **Other regions**: Check national mapping agencies and research institutions for available data

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
- For multi-temporal studies, check if multiple acquisitions exist for your area

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.

19 References

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.

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

Earth Bridge · CZU Faculty of Environmental Sciences · Technische Universität Dresden · Universität Bonn · Alma Mater Studiorum Università di Bologna · CzechGlobe · Technische Universität München · Funded by the European Union