A Prototype servIce for fOrest inventory and health moNitoring using EndurancE dRones and citizen science (ForestPIONEER)

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Forest PIONEER

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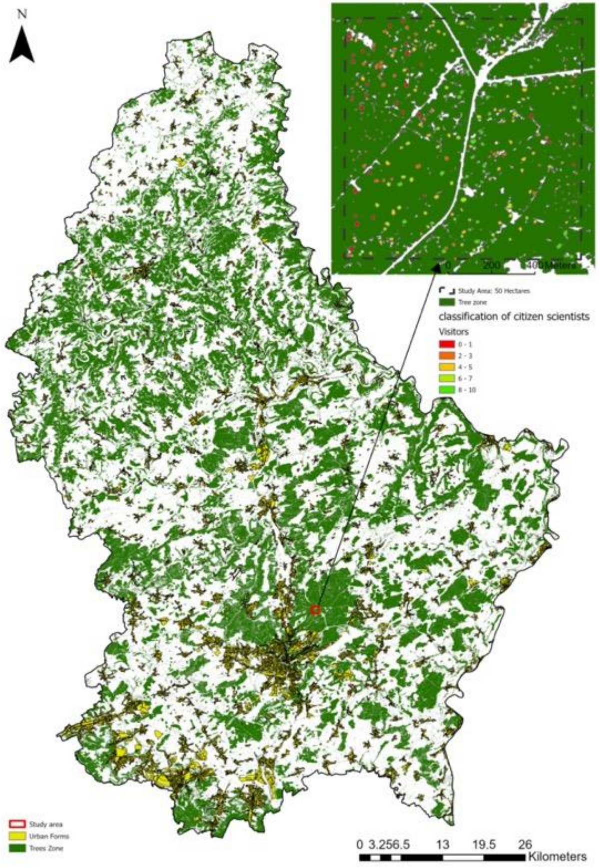

N
0
200
400 Meters
Study Area: 50 Hectares
Tree zone
classification of citizen scientists
Visitors
0 - 1
2 - 3
4 - 5
6 - 7
8 - 10
Study area
Urban Forms
Trees Zone
0 3.25 6.5 13 19.5 26
Kilometers

Geodesy and Geospatial Engineering

State of health of Luxembourg's forests

As of 2022

- **15.4 %** of trees undamaged (class 0)
- **22.9 %** slightly damaged (class 1)
- **61.7 %** clearly or severely damaged / dead (classes 2–4)
- Dieback driven by extreme weather, bark beetle, and browsing in a self-reinforcing loop.
- Current monitoring: ~1 100 trees → just **0.06 %** of 90 000 ha, updated only every **4 years**

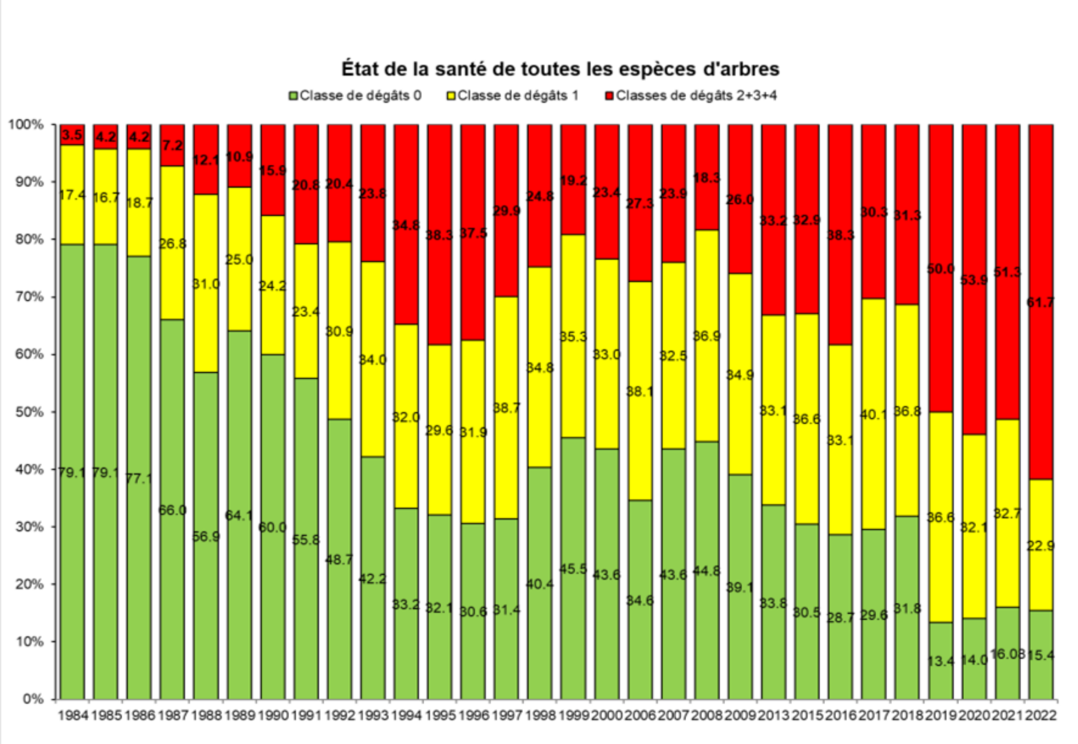

Fig: Evolution of the state of health of Luxembourg's forests, all species combined (Source: ANF, 2022)

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The ForestPIONEER Project

- **Objective:**
  Contribute to the development of an innovative, feasible and cost-effective participatory monitoring system that anticipates monitoring requirements on forest ecosystem restoration targets

- Project funding by the Institute for Advanced Studies at Uni.lu (2024-2026)
- Interdisciplinary research between scientists in engineering and socio-ecological systems
- Uses geospatial technologies and citizen science to address urgent needs in monitoring forest ecosystems
- Explores what is feasible with cutting edge scientific methods in the social and governmental setting
- Engages volunteers including private forest owners in co-design and co-creation of evidence for a democratic approach to evidence-based forest management

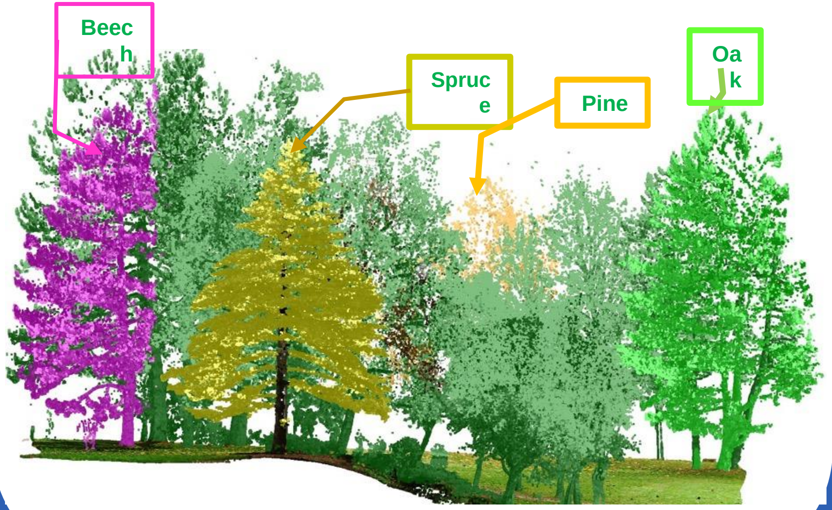
Problems and Proposed Solutions

- Satellite imagery with ≥0.5 m resolution is insufficient to resolve individual tree crowns and interconnected branches
- Aircraft imagery with ≥0.1 m resolution is insufficient to resolve interconnected branches or individual leaves

- Drone imagery can deliver ~1 cm ground-sampling distance, enabling leaf-level health indicators
- LiDAR + hyperspectral imaging + AI can produce 3-D, tree-level biomass and species maps
- Ground-truthing with citizen-science increases data legitimacy and accuracy amongst improving public engagement

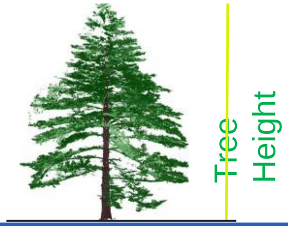
Method Developments for Automated Forest Inventories

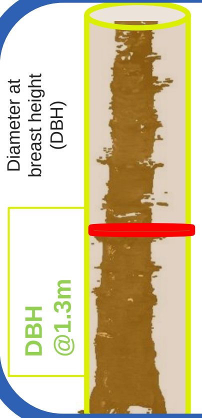
A part of a mixed forest



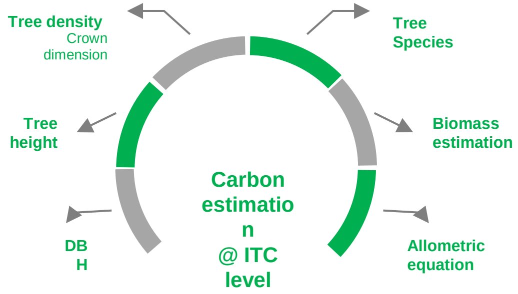
Tree metrics and Individual Tree Crowns (ITC) from LiDAR 3D point clouds

- **Crown dimension**
- **Diameter**
- **Height**
- **Volume**





Above ground biomass and carbon estimation



Geodesy and Geospatial Engineering

Hyperspectral Image and LiDAR Sensors

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Flight plans: selecting only straight lines

Straight flight lines uploaded to the AFX-10 hyperspectral mission planner. **Side overlap:** 25 – 45 %; **ground speed:** ≈ 5 m s^{-1}; **flight altitude:** ≈ 50 m AGL

Data processing workflow

Stage	**Key Actions**	**Output and checks**
RAW Acquisition	Capture sensor digital numbers (DN) or at-sensor radiance • Record dark frames / white reference panels for later calibration • Log GNSS + IMU data, sensor temperature, exposure, and integration time	Unprocessed image cube (DN).
Radiometric Processing	Pixel-wise non-uniformity / bad-pixel correction • Spectral calibration (wavelength assignment, etc) • Apply gain/offset	Calibrated radiance cube.
Georeferencing / Orthorectification	Align push-broom image lines with GNSS/IMU trajectory • Boresight angle estimation & correction • Orthorectify using a DEM (project to map grid)	Geo-tiff / ENVI image cube with map projection.
Mosaicking	Blend overlapping flight-lines (seamline optimisation)	Seamless hyperspectral mosaic
BRDF & Atmospheric Corrections	Atmospheric modelling (DROACOR) → surface reflectance • Topographic correction BRDF: Bidirectional Reflectance Distribution Function	Surface-reflectance cube
Machine-Learning Inference	Pre-processing: spectral indices, continuum removal, dimensionality reduction (PCA, MNF). Deploy model, generate thematic maps.	Class / regression map (GeoTIFF).

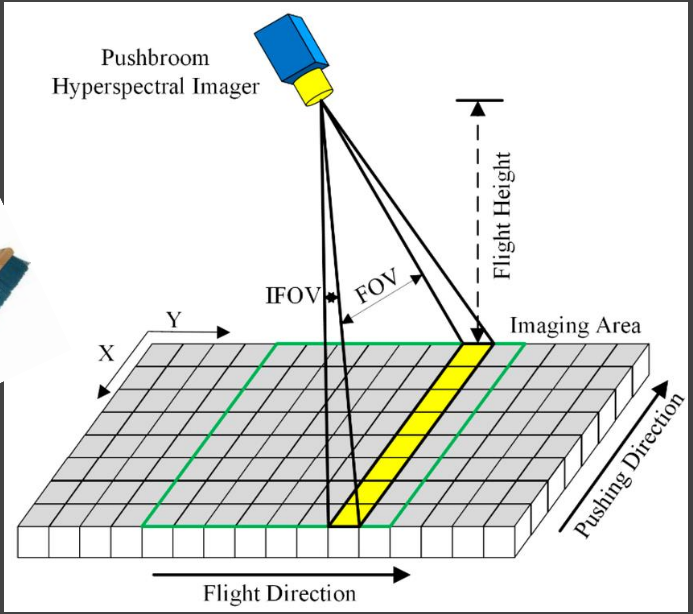
Hyperspectral Imagery

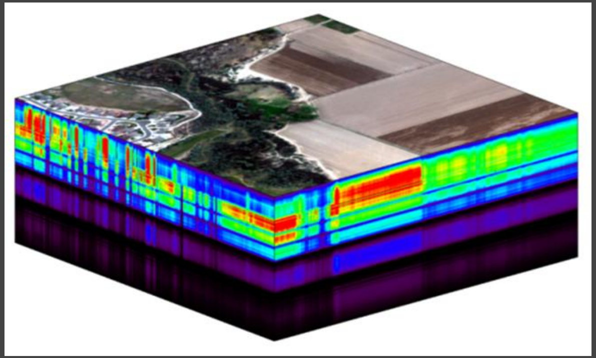
- **AFX10 line-scan sensor** – records one pixel row across all spectral bands; successive rows are mosaicked into full images.

- **Hyperspectral "data cube"** – two spatial axes + one wavelength axis.

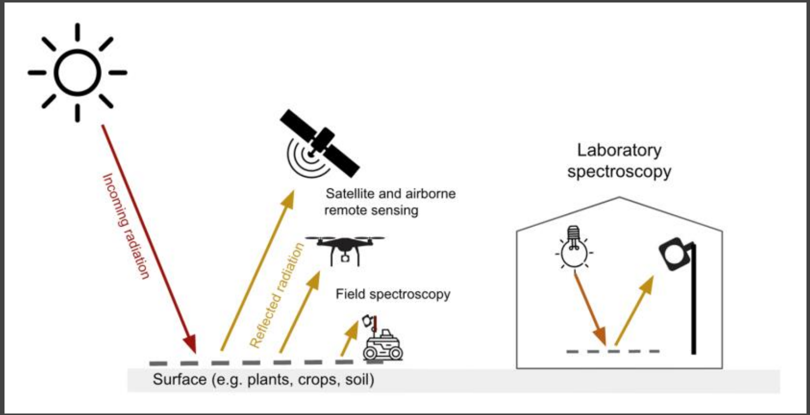
- **Radiance** – radiant power per unit solid angle·area·wavelength (W sr^{-1} m^{-2} nm^{-1}).

- **Reflectance** – fraction of incident light returned or transmitted.

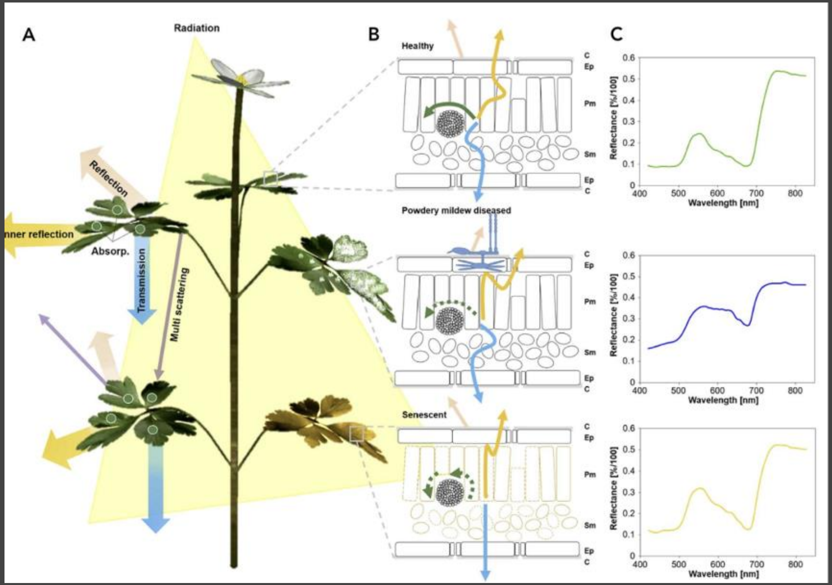




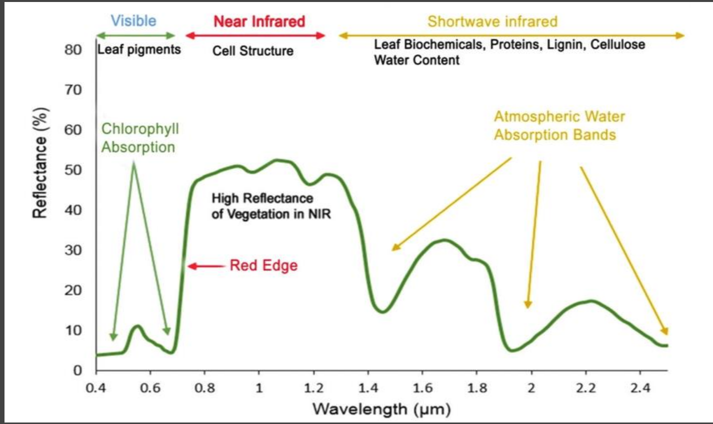
Hyperspectral Imagery: Measuring Reflected Radiation allows Detection of Surface Characteristics

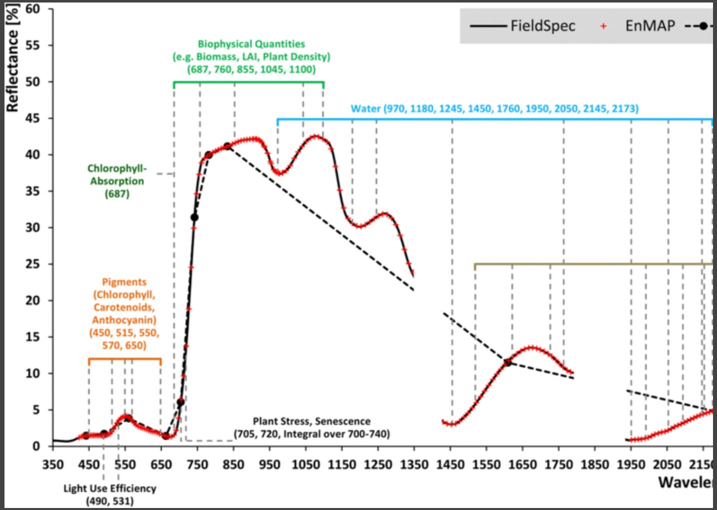


A surface's reflectance at any wavelength is set by how much incoming radiation it reflects, absorbs, and transmits—values that hinge on its physical and chemical makeup and therefore vary with wavelength



Spongy Mesophyll/palisade mesophyll layers





General Spectral response

Visible Light

- **Chlorophyll's Role**:Chlorophyll, the green pigment that powers photosynthesis, absorbs visible light chiefly in the blue (~ 450 nm) and red (~ 670 nm) bands, converting that energy into chemical form; reflectance dips at these wavelengths because the light is absorbed rather than reflected.

Near-Infrared (NIR) Reflectance:

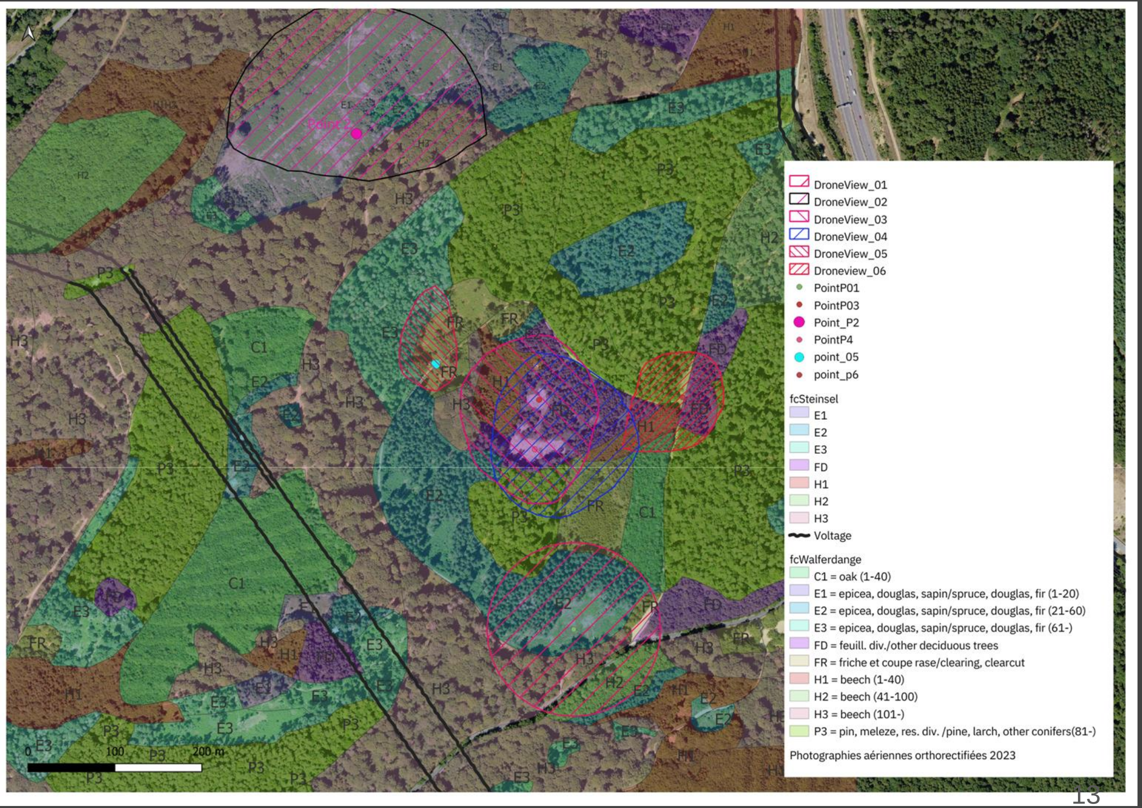
- Beyond ~700 nm chlorophyll barely absorbs, so healthy leaves strongly scatter and reflect NIR (≈ 700–1300 nm) thanks to their internal structure—high NIR reflectance is a hallmark of plant vitality.

Geodesy and Geospatial Engineering

Tree Species Classification over the Test Forest (Walferdange/Steinsel)

Figure : Classified Tree Species map . Background: orthorectified aerial 2023 © ACT.

- **Campaign** : Airborne HIS/Lidar survey (DroneView_01–06),
- **Ground reference**: Forest inventory points collected by ANF,
- **Legend** – classes harmonised with ANF forest-management categories (C1, E1–E3, H1–H3, FR, etc.), with the **age class** of each individual tree



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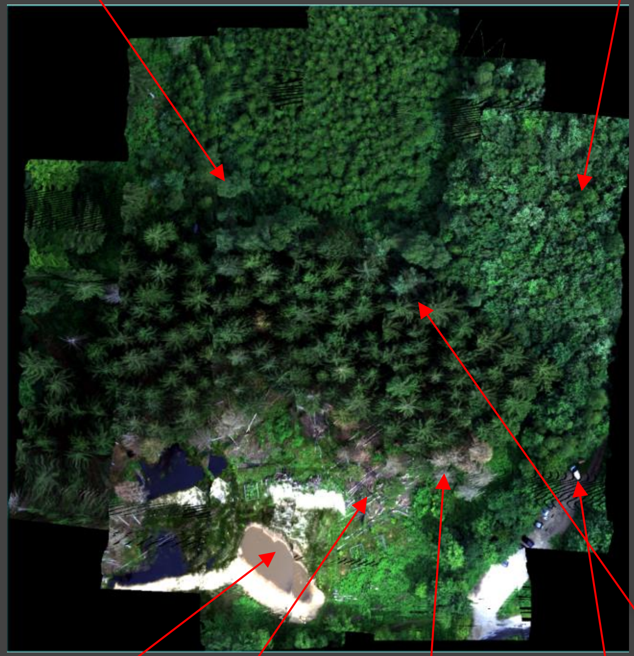
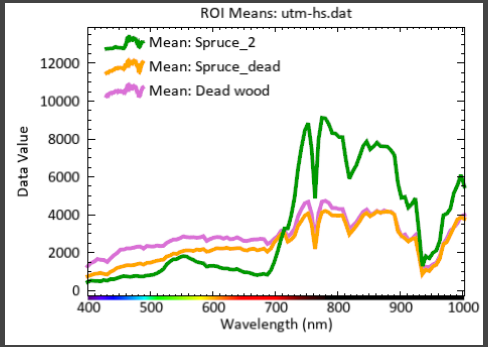
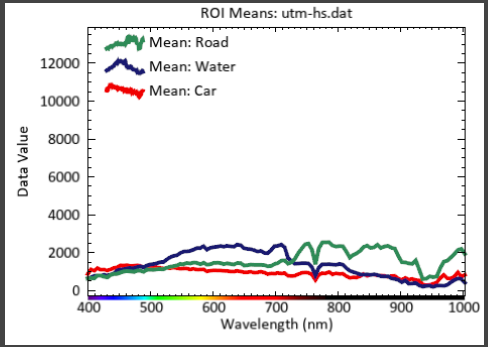
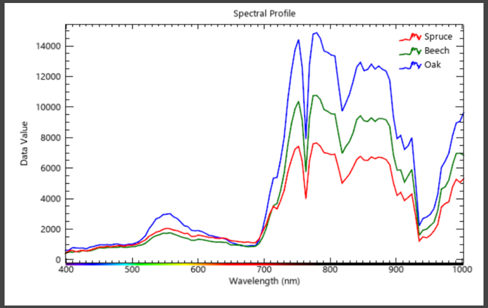
Location: Walferdange

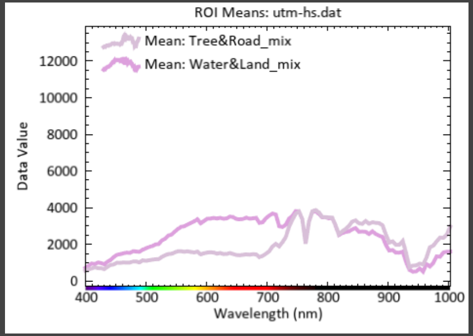


Radiance value of Spruce, Oak, Road, Water, Car, and some mixed spectra



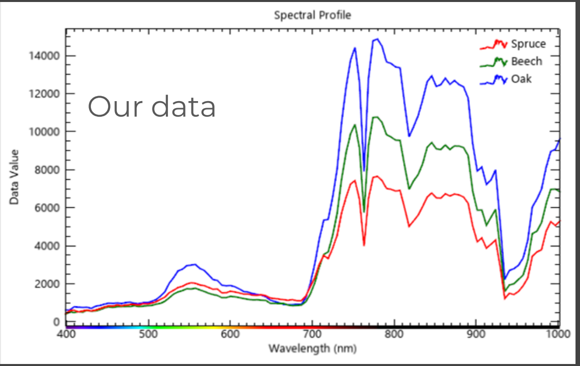


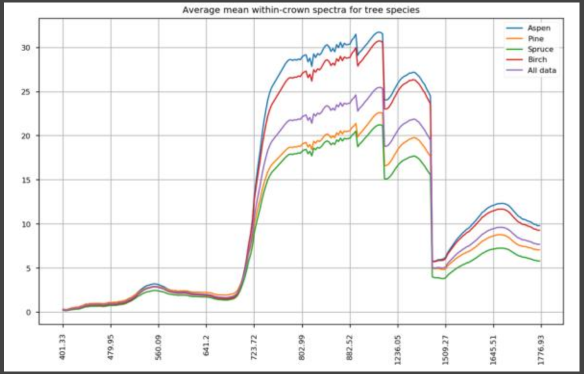




Cross-validation of Radiance as Function of Wavelength

Panel	Our data	Literature
Unit	Sensor-level radiance. No atmospheric or BRDF correction	Canopy-level reflectance
Spectral range	400–1 000 nm (VNIR)	400–1 750 nm (VNIR + SWIR-1)
Target	Individual tree crowns extracted from HSI flight line: Spruce, Beech, Oak	Crown-averaged spectra reported by Viinikka et al., 2020 for Aspen, Pine, Spruce, Birch





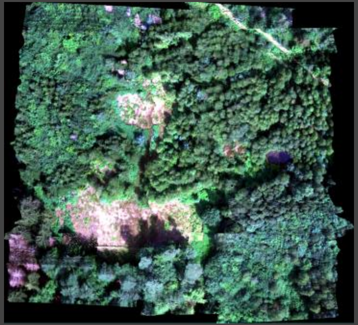
Viinikka et al., 2020

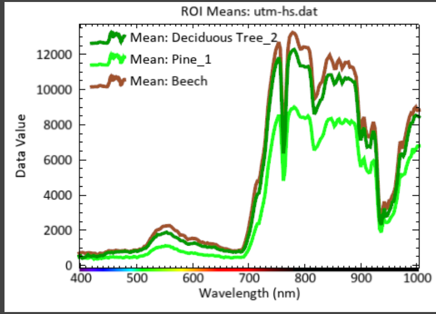
Cross-Validation of Radiance as Function of Wavelength

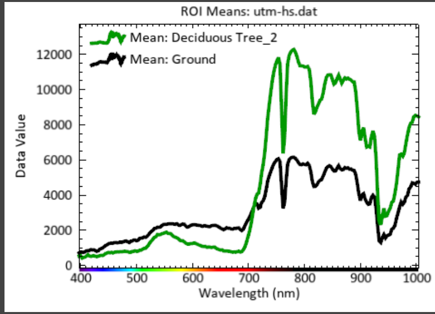
In every physiologically important region, the *shape* and *relative* ranking of species in our radiance data match what canopy-level studies report. That is strong evidence that:

- Our sensor radiometric calibration is behaving as expected
- Crown segmentation is largely correct
- Species-specific spectral differences are preserved even before reflectance conversion
- Most of the remaining discrepancies (overall scale, minor spikes) are exactly what one expects before radiance-to-reflectance conversion and atmospheric / BRDF correction

Drone flight over Test Forest - Spectra in Radiance



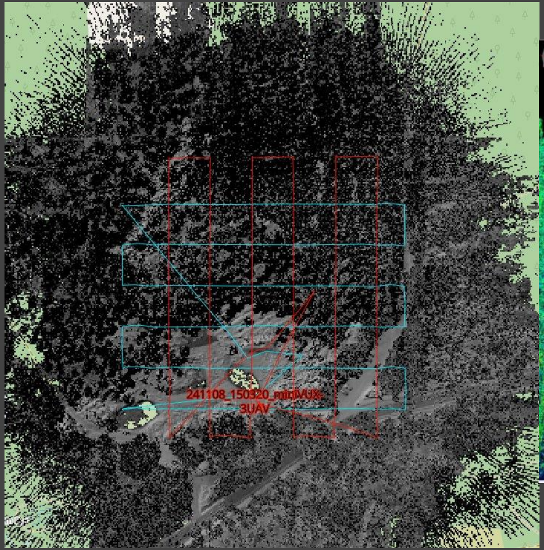


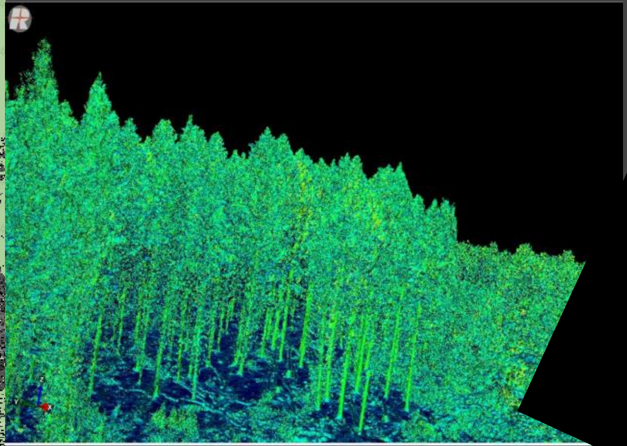


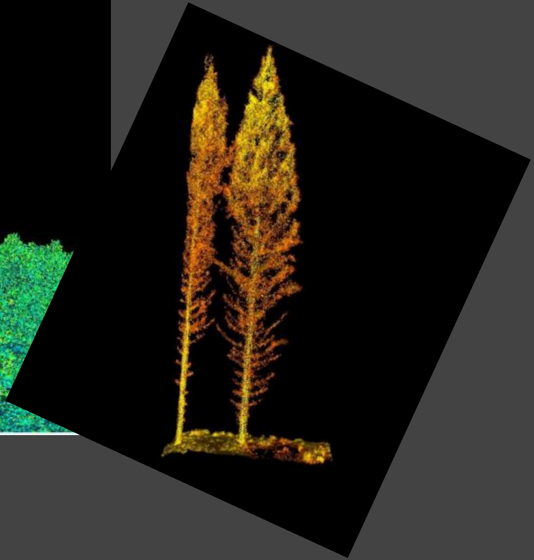
See, Raczko & Zagajewski, 2018

Feature	Pine	Beech	Deciduous
Physiology	Evergreen; 2-needle fascicles	Broad-leaf Canopy-level	Broad-leaf mix
VIS (400-700 nm)	Lowe reflectance - darker green line	Slightly higher VIS due to flat leaves	Similar to beech but varies with species mix
Red edge	Steepest slope ~705 nm	~710 nm	~710-715 nm
Atmospheric O_2-A dip	Atmospheric feature, not species-specific (759–770 nm)	759–770 nm	759–770 nm

Morphological Parameters from LiDAR



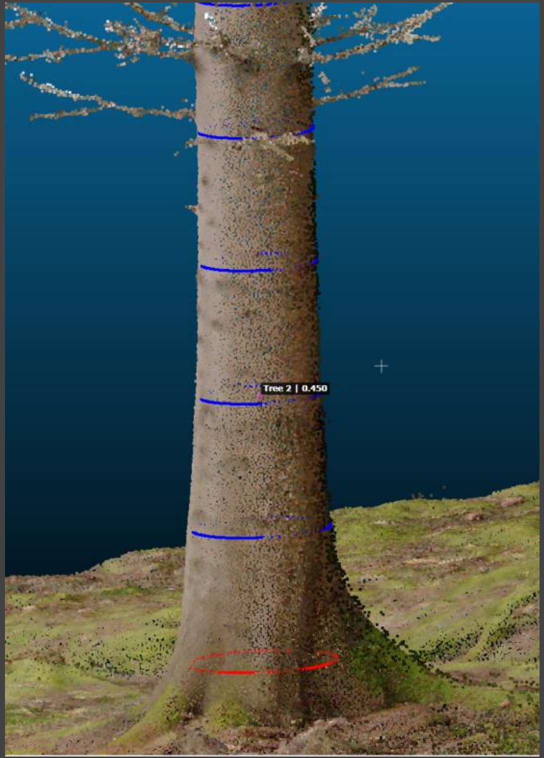




- Flight-line grid on raw cloud
- Intensity-coloured stand
- Isolated twin spruce

- The LiDAR mission captures centimetre - scale 3-D structure, enabling precise, tree-level morphology and biomass that traditional methods cannot match

Mobile Mapping System: Tree diameter at DBH and Height: Walferdange forest



Individual tree height and tree diameter modelled from point clouds

Automated Classification of Wood and Leaves

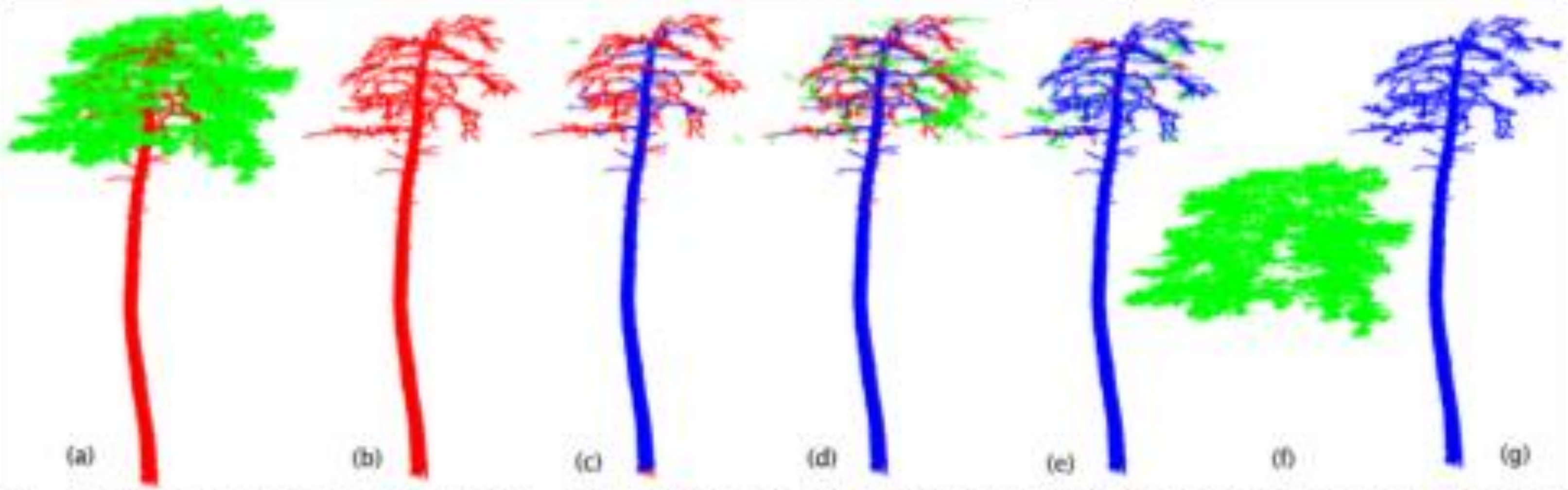


Figure 3. Classification results (wood and leaves) for the Scots pine tree: (a) manually classified point clouds, (b) manually classified wood points, and classified points by: (c) LeWoS, (d) GBS, (e) ours; blue are classified wood points, red and green points are failed to identify as wood and leaf points, respectively, (f) identified leaf points by our method, (e) our extracted tree-wood structure.

A Workflow for Automated Tree Stem Estimation

Steps. Ground points elimination, clustering and denoising, finding 3D stems disks, generating 2D point clouds and use of DBSCAN, circle fitting and stem diameters estimation, stem curve derivation and cylinder parameters estimation, and stem volume estimation.

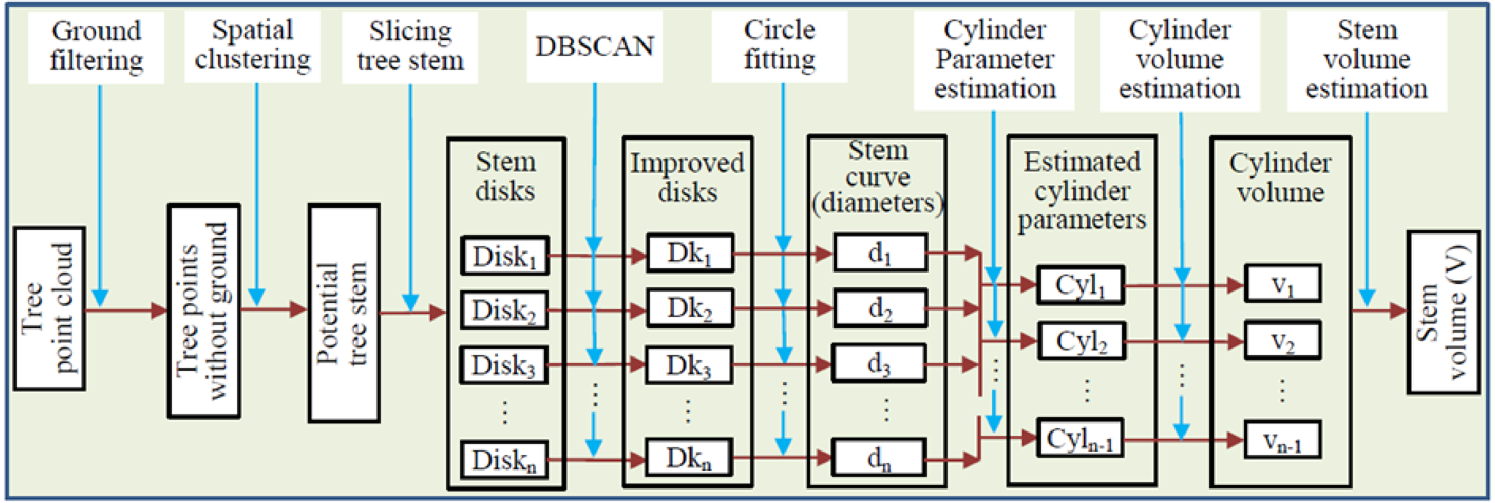


Figure. Workflow of the proposed stem curve and stem volume estimation method

Experiment 1

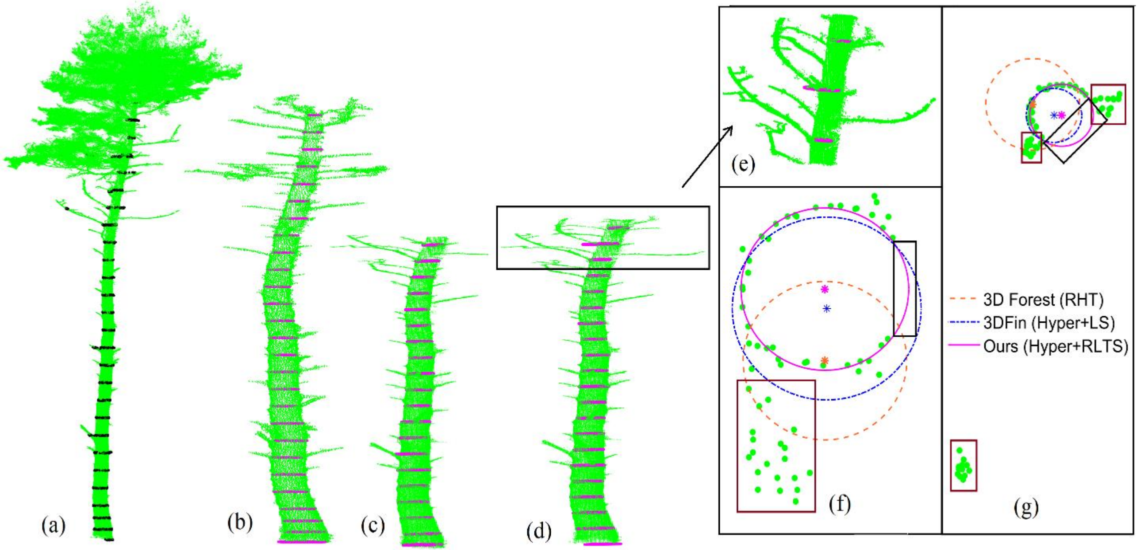


Figure. (a) Scots pine tree point cloud, black rings indicating stem disk-circles to be fitted at those heights, (b) the stem segment obtained through spatial clustering, magenta rings representing the fitted circles (stem curve; our method) at defined heights, (c) stem curve derived by 3DFin (d) stem curve derived by 3D Forest, (e) a part of the stem curve from Fig. (d); with fitted circles (magenta rings) at 18m, 19m, and 20m, (f) fitted circles at 18m height; the blank space in the black box represents an incomplete circular arc, (g) fitted circles at 19m height, points in the maroon rectangles showing the presence of clustered and scattered outliers.

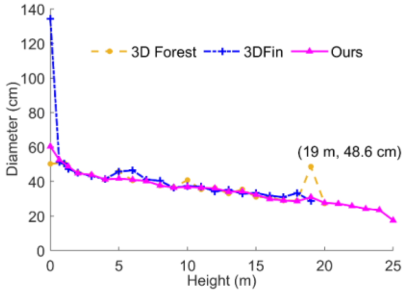


Figure. Line diagram for estimated diameters versus different heights along the stem for the Scots pine tree.

Table. Estimated diameters w. r. t. the corresponding heights of the stem curves at Fig. 4(b), (c), (d). Ground truth DBH is 48.5cm.

Height/position at (m)		0	0.65	1.0	**1.3**	2	3	4	5	6	7	8	9	10	11
Dia-meter (cm)	3DForest (RHT)	50.2	-	50.8	**48.6**	45.2	43.8	41.0	45.8	40.6	40.4	37.6	36.6	40.8	35.4
	3DFin (Hyper)	55.0	51.3	50.5	**47.1**	45.1	43.1	41.4	45.7	46.4	41.2	40.4	36.3	37.3	36.9
	Ours	60.3	52.5	50.5	**48.7**	44.7	43.8	41.1	41.6	41.0	40.2	37.7	36.4	36.8	36.3
Height/position at(m)		12	13	14	15	16	17	18	**19**	20	21	22	23	24	25
Dia-meter (cm)	3DForest (RHT)	36.2	33.0	35.4	31.0	30.8	29.0	28.8	**48.6**	27.2	-	-	-	-	-
	3DFin (Hyper)	34.3	35.1	32.8	33.4	31.6	30.9	33.2	**28.7**	-	-	-	-	-	-
	Ours	36.0	34.0	34.2	32.3	29.8	28.9	28.5	**30.9**	27.5	27.1	25.7	24.1	23.4	17.5

Experiment 2

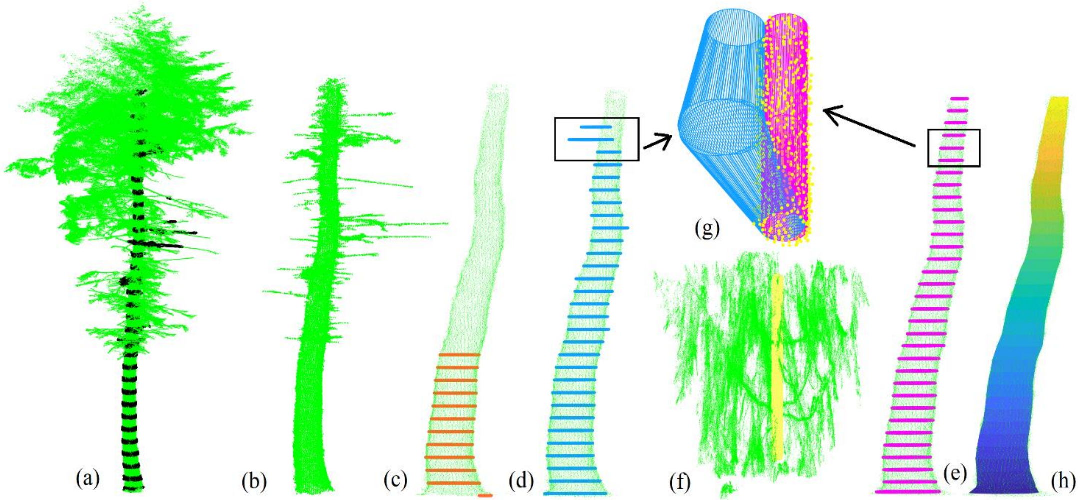


Figure. (a) Douglas-fir tree point cloud, black points (look rings) indicating specific positions where circles to be fitted for getting stem diameters, (b) extracted stem segment obtained by using spatial clustering, (c) stem curve (orange rings) using 3D Forest; rings representing the fitted circles at different heights, (d) stem curve (blue rings) by using 3DFin, (e) stem curve (magenta rings) by using our method, (f) tree point cloud between 27m to 29m, (g) two fitted cylinders by using 3DFin and our method for the stem part (yellow points) in Fig. (f), (h) reconstructed stem using the fitted cylinders based on our method.

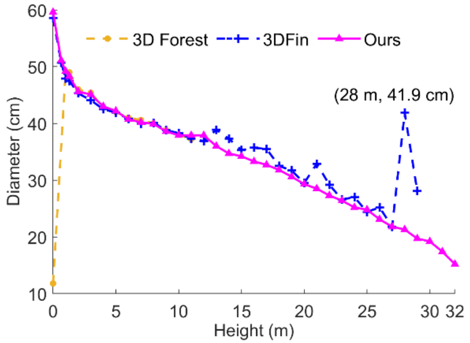
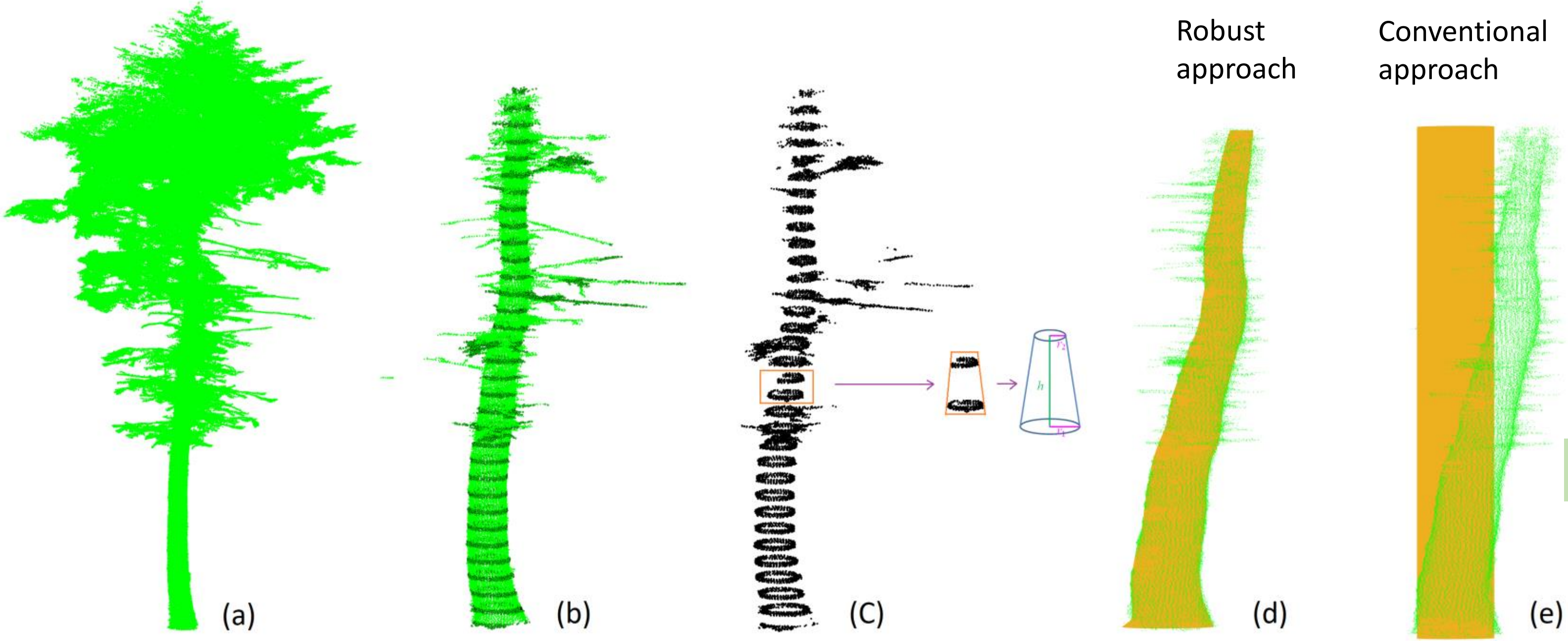


Figure. Line diagram for estimated diameters versus different heights along the stem for the Douglas-fir tree.

Table. Estimated diameters w. r. t. the corresponding heights of the stem curves at Fig. 6(c), (d), (e). Ground truth DBH is 48.2cm.

Height/position at meter (m)		0	0.65	1.0	1.3	2	3	4	5	6	7	8	9
Dia-meter (cm)	3D Forest (RHT)	11.8	-	49.0	**49.0**	46.0	45.4	42.8	42.0	41.0	40.6	40.0	38.8
	3DFin (Hyper)	58.6	50.7	47.9	**47.5**	45.3	44.1	42.5	41.9	40.8	39.9	40.1	38.8
	Ours	59.6	51.1	49.2	**48.3**	45.6	45.1	43.0	42.2	40.7	40.2	39.9	38.6
Height/position at(m)		10	11	12	13	14	15	16	17	18	**19**	20	21
Dia-meter (cm)	3D Forest (RHT)	38.0	37.2	-	-	-	-	-	-	-	-	-	-
	3DFin (Hyper)	38.3	37.3	36.9	38.9	37.2	35.3	35.7	35.5	32.5	**31.7**	29.5	32.9
	Ours	37.9	37.9	38.9	36.0	34.7	34.2	33.3	32.7	31.8	**30.6**	29.3	28.5
Height/position at(m)		22	23	24	25	26	27	**28**	**29**	30	31	32	
Dia-meter (cm)	3D Forest (RHT)	-	-	-	-	-	-	-	-	-	-	-	
	3DFin (Hyper)	29.2	26.6	27.0	24.4	25.2	21.8	**41.9**	**28.1**	-	-	-	
	Ours	27.3	26.4	25.2	24.8	23.1	21.8	**21.3**	**19.7**	19.2	17.4	15.2	

Impacts of Precise Diameter and Height Estimation on Tree Stem Volume Estimation



$V_c \approx 200\%$ of V_R

Fig. (a) Individual tree (Douglas-fir) point cloud, (b) tree stem, (c) tree stem curve, (d) fitted tree stem; robust method, (e) fitted tree stem (cylinder); classic method.

$$v = \pi h\left(\frac{r_1^2 + r_2^2 + r_1 r_2}{3}\right)$$

Robust Volume, $V_r = v_1 + v_2 + \cdots + v_{n-1}$

$V_r = 2.89\ m^3$

Conventional Volume,
$V_c = \pi r^2 h$

$V_c = 5.84\ m^3$

TLS (Terrestrial Laser Scanning), MLS comparison on UL data

UL tree TLS point cloud data,
MLS (14,493,004 Pts),
TLS (35, 259,546 Pts)

- Point density:
  TLS (1,13,011/m2), MLS (43,133/m2)
- Roughness
- Completeness

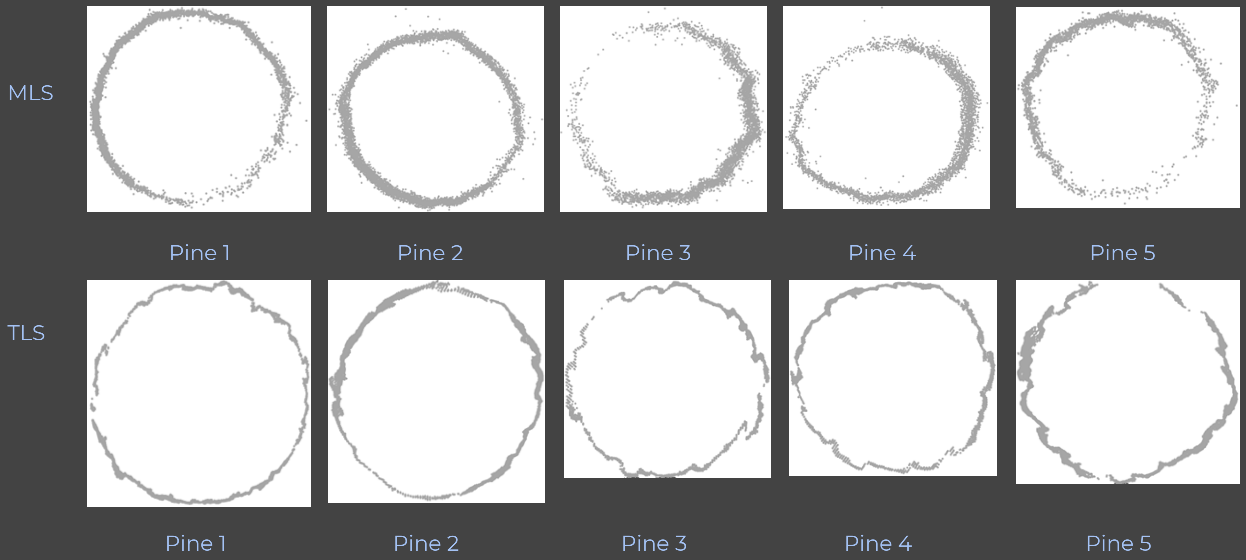


Fig. 2D circular arcs, extracted @ 1.3 m

	Pine 1 (66.4)		Pine 2 (45.5)		Pine 3 (36.9)		Pine 4 (36.3)		Pine 5 (46.8)	
System	MLS	TLS	MLS	TLS	MLS	TLS	MLS	TLS	MLS	TLS
DBH(cm)	64.95	64.37	44.86	43.51	37.22	35.24	36.38	35.23	46.64	45.58

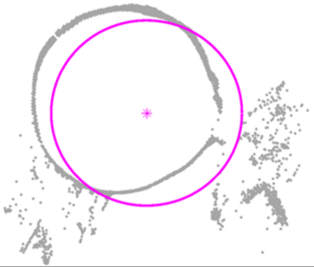
Table: Estimated DBH

Results of Spruce data: Impacts of outliers and data gaps

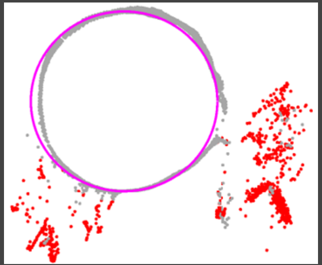
TLS data, Spruce
(7,556,807 Pts;
DBH, 46.1)

10cm 3D vertical slice @1.3m

2D Points



Circle fitted with outliers, DBH = 44.13 cm

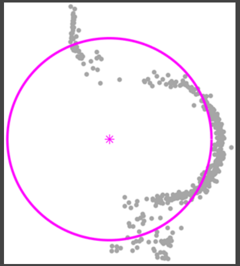


Circle fitted without outliers, DBH = 44.22 cm

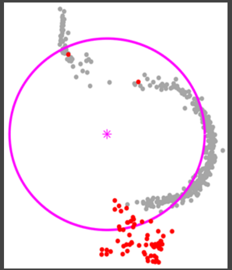
MLS data, Spruce,
(401,470 Pts)

10cm 3D vertical slice @1.3m

2D Points



Circle fitted with outliers, DBH = 73.57 cm



Circle fitted without outliers, DBH = 69.45 cm

Concerns

Outliers %

Data gap (how much ?)

Verticality threshold, 60^0

Displaced fitting

Carbon estimation on Individual Tree

- Measure DBH (diameter at breast height, cm) and total tree height (m) in the field or from LiDAR.
- Assign species-specific wood density ρ ($g\ cm^{-3}$).
- Estimate above-ground biomass (AGB) using Chave 2014:
  $AGB = 0.0673 \times (\rho \times DBH^2 \times H)^{0.976}$ (kg).
- Convert biomass to carbon stock: Carbon = AGB × 0.47.

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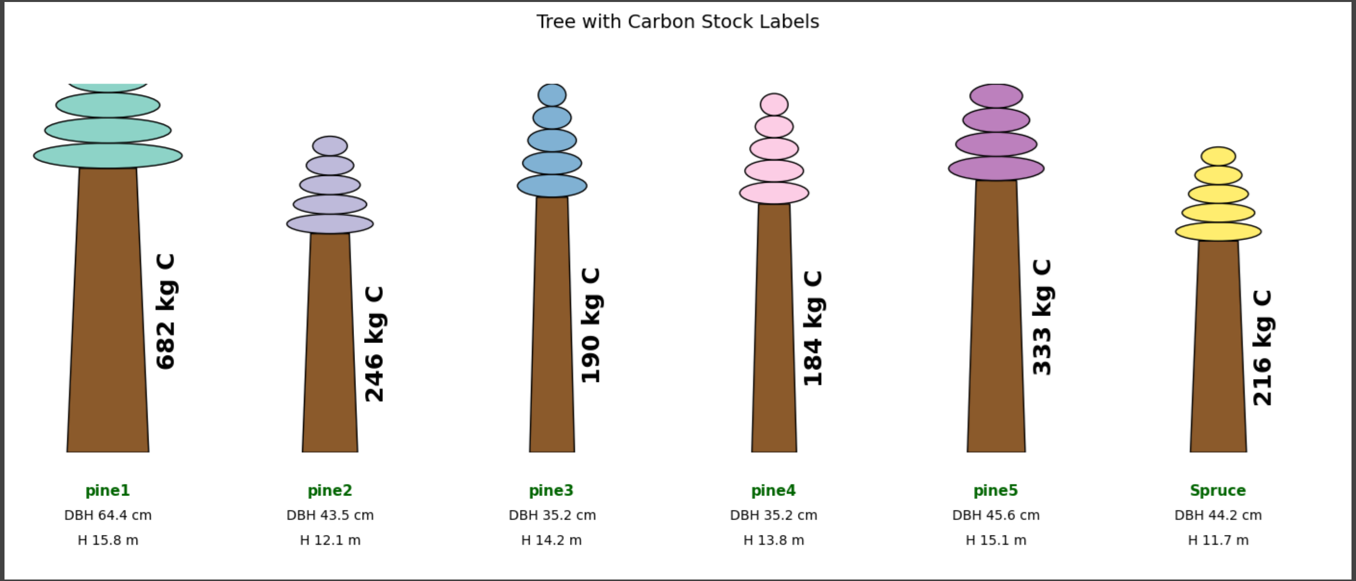
Tree carbon stock estimation



Total: 1 851 kg C ($\approx$ 6.8 t CO_2)

- Wood density (≈ 0.43 g cm^{-3} for pine, 0.38 g cm^{-3} for spruce)
- Carbon stock (C) $\approx$ 47 % of dry biomass
- AGB (above ground biomass) $= 0.0509 \cdot \rho \cdot DBH^2 \cdot H$ (Allometric equations from: Chave et al., 2014)
- $C = 0.47 \cdot AGB$

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Summary & key conclusions

Problem context – Luxembourg's forests are under stress

- Last health survey showed only 15 % of trees remain undamaged, while 62 % are clearly or severely damaged or dead; the current plot network samples just 0.06 % of the forest area and is updated every four years . (https://delano.lu) ANF technical annex 2022

PIONEER's integrated solution

- Centimetre-resolution **drone hyperspectral imagery** and **LiDAR** capture crown-level spectral and structural traits
- Development of automated analysis methods for these data are underway
- A **citizen-science mobile app** streams ground-truth records directly to the processing chain
- **Spectral validation** shows the shape and inter-species ranking of raw radiance curves for spruce, beech and oak match canopy-level spectra reported in the literature, confirming sound radiometric calibration
- LiDAR (MMS) delivers precise height and crown-shape metrics, enabling plot-independent estimation of 3-D structure and biomass
- **Limitations & open challenges**
  - Current products remain in **sensor-level radiance**; full atmospheric/BRDF correction is underway.

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Thank you for your attention!

- **PIONEER in Action – Saturday 10 May**
- **Tagged 400+ reference trees in test area** for ground truthing, attachment of QR-coded plaques
- **Ground Observations** of DBH, species, forest type, apparent health status
- **Initiated and uploaded records** live to the ForestPIONEER – ForestLinx database via a mobile app

AFX10-HSI Camera Features

- Spectral range (VNIR): **400 – 1 000 nm**
- Bands: **224** | Sampling: **2.68 nm**
- Spectral resolution: **≈ 5.5 nm**
- Field-of-view: **38 °**
- Weight (sensor head): **2.1 kg**
- Integrated GNSS/IMU: **Applanix 15**
- Uses the same in-house mounting case for the upcoming **AFX10 (NIR)**

Typical, height, swath and ground sampling for different spatial binning

Height	Swath	Spatial binning	GSD
50m	36 m	2	3.5 cm
50 m	36 m	**1**	**7 cm**
100 m	72 m	2	7 cm
100 m	72 m	**1**	**14 cm**

RIEGL miniVUX-3UAV: Key Specifications

- Laser Pulse Repetition Rate: 100 / 200 / 300 kHz (selectable)
- Max. Measurement Rate: up to 200,000 meas./s
- Range Accuracy: ±15 mm; Precision: ±10 mm
- Maximum Range: up to 330 m (reflectance ≥80 %)
- Field of View: 360° @ 100 kHz; 180° @ 200 kHz; 120° @ 300 kHz
- Multi-Target Capability: up to 5 echoes per shot
- Waveform-LiDAR Technology: echo digitization & online processing
- Weight: 1.55 kg (without fan); Dimensions: 243×99×85 mm

ForestPIONEER Publications

Year	Citation	Key contribution
2024	A. Nurunnabi *et al.*, “Robust estimation of tree diameter at breast height from point clouds,” *Proc. IEEE IGARSS*, pp. 5980-5983, Athens, 2024.	DBH algorithm (< ±1.2 cm error).
2024	A. Nurunnabi *et al.*, “Derivation of tree-stem curve & volume using MLS,” *Int. Arch. Photogramm. RS*, vol. XLVIII-2, pp. 81-88, 3D GeoInfo, 2024.	Full stem-volume reconstruction.
2024	A. Nurunnabi *et al.*, “Precise tree structure from LiDAR point clouds,” *Int. Arch. Photogramm. RS*, vol. XLVIII-2, pp. 301-308, ISPRS TC II, 2024.	Branch topology extraction.
2023	A. Nurunnabi *et al.*, “Detection & segmentation of pole-like objects in MLS,” *Int. Arch. Photogramm. RS*, vol. XLVIII-1, pp. 27-34, ISPRS GeoWeek, 2023.	Stem segmentation baseline.