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Current and emerging techniques and technologies for Single Tree Inventories

Lee Stamm

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The Trust is the living legacy to honour Bill (Joseph William) Gottstein - who died in a tragic field accident in 1971. He was an exceptional, innovative man and was internationally respected. He was a scientist and a leader in the CSIRO forest products division.

The Gottstein Trust invests in capacity building. The Trust strives for the pursuit of excellence in people, processes, and products. And, in so doing, contributes to the evolution of Australia's wood products and forestry industry.

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About the author

Lee Stamm has a background in Plantation and Native Forest Resource Information and Planning. Having graduated with a Bachelor of Forestry (Hons) in 2004, Lee has been working in the forest industry in Tasmania, Queensland and New South Wales with Inventory Systems, Resource planning, Valuation, Remote Sensing and Spatial Analysis.

Lee is particularly interested in the use of remote sensing to conduct full inventory surveys of the forests of Australia, to map and describe every tree. A centralised and continuously measured national inventory system across multiple tenures is crucial to understand long term trends across Australia's forest ecosystems. Lee believes this information will enable forests to be managed more effectively to mitigate natural disasters and monitor vegetation change in response to climate change and land use types.

This Gottstein Fellowship was awarded to Lee in late 2023.

Acknowledgement

I would like to personally thank the Gottstein Trust and Forestry Corporation of NSW, my employer, for supporting my research trip.

1. Executive Summary

A Single Tree Inventory (STI) is a method by which individual trees in the forest are measured and described. The method results in a description of every single tree, commonly called a Census, in a forest area of interest. A STI is typically generated using LiDAR point clouds, combined with ground measurements and machine learning.

Notwithstanding the high level of detail about the forest that an STI provides when first generated, further benefits of STI are that once a tree's location is known and the attributes of that tree is calculated, future remote sensing measurements can easily track each trees growth, whether a particular tree has been harvested, relative canopy health, competition surrounding that tree (i.e. what are the characteristics of proximal trees relative to this tree).This opens up a huge realm of possibilities in measuring and managing forest as well as predicting and monitoring change.

STIs are generating interest and are utilised in several countries. As part of my Gottstein Tour, I visited several current users of Single Tree Inventories (STI), technology providers with potential to contribute to STI and academics in the field of dense point clouds and machine learning related to Forestry.

One of the limiting factors to the implementation of STI is the fact that until recently, most of the input to STIs, are lower density Linear Mode Airborne LiDAR of between 4 and 30 points per square meters, and do not penetrate and delineate all stems or structures in all but the simplest, most open forests.

In early iterations, because of the omission of smaller subdominant stems, use of simple individual tree detection algorithms and lower density LiDAR for generating STIs have led to biased predictions of volume in some contexts, which has deterred practitioners from implementation. Recently, more complex algorithms and systems have been developed to counteract this bias.

Sub-tree log product descriptions are not catered for very well in most STI systems used today. Most of the application in the northern hemisphere are tailored to simple allometric stem volume calculation based on the estimated Diameter at Breast Height (DBH) and height of the tree. In Australian native forests or pruned *Pinus* forests, stem form is more variable and the simple individual tree detection approach using standard density LiDAR is not fit for purpose for predicting the potential range of log products and their values in the standing tree.

If implementing STI, highly penetrative and higher density LiDAR is required to segment out most if not all stems in a stand and define stem shape and quality. A simple to moderately complex forest which was densely measured with LiDAR, would deliver a very accurate STI for describing stem quality attributes of interest to forest managers.

Large scale dense, highly penetrative LiDAR (reminiscent of high-density UAV LiDAR) have, to date, not been able to be easily or cheaply achieved and are beyond the budget of most land management organisations especially forestry.

However, the latest generation Geiger Mode LiDAR and advanced processing techniques provide real promise for the efficient and affordable capture of highly penetrative, dense LiDAR that delineates all stems in most forest types. The cost of data capture using the new Geiger Mode LiDAR sensors, should be much lower than Linear Mode LiDAR for collecting high density LiDAR at large scales, being 10 times more efficient at collection and more sensitive to lower light conditions within the subcanopy.

The latest techniques for single tree inventory rely heavily on Deep Learning techniques, a subcategory of Machine Learning. Groundbreaking work has been applied recently to derive an 'automated' inventory framework, in which Deep Learning models are trained using sample point clouds of ground checked individual trees known as a tree reference library. This library is built by manually labelling points within a point cloud, as belonging to individual tree instances, and classifying the tree points as stems, branches or foliage. This framework, once trained, can segment individual trees out of large point clouds including the semantic classification of stems, branches, foliage, ground, along with attributes such as diameter of the stem points being calculated.

Several providers and non-commercial institutions in Scandinavia and North America routinely serve up web-based inventory display systems over 10s of millions of hectares using commercial off the shelf software or proprietary web-based applications as part of Digital Twin systems. The issue of storage of derived single tree points and display of derived mapping products to end users (Foresters) has been found to be one that forestry organisations could implement easily.

STI is very suitable base level data for input into advanced Digital Twins. Digital Twins rely on detailed input data from the real world, methods of modelling and simulating responses to real world changes, coupled with visualisation of the Digital Twin in a meaningful way to gain maximum benefit.

One use case for Digital Twins in Native Forest subject to forestry operations, is the ability to temporally and spatially visualise larger habitat trees that are legislated to be retained in perpetuity within NSW native forests under the Coastal Integrated Forestry Operations Approval (CIFOA) process. Within a Digital Twin, defining their existence before harvest, and monitoring their persistence during and after harvesting ensures regulatory compliance. There is a need to develop a framework in which STI fits into Forest Digital Twins to maximise value.

To conclude, a successful STI implementation in eucalypt forests in eastern Australia, has two important requirements. Firstly, the supply of highly penetrative, and dense LiDAR data at scale, and secondly an appropriately sampled and relevant set of tree reference libraries and Deep Learning algorithms. This will generate a meaningful LiDAR derived STI.

To enable this, the following step should be taken by Industry-led research groups in Australia:

1. Invest in studies to validate the effectiveness and efficiency of Geiger Mode LIDAR systems for mapping of individual trees.
2. Invest in field work to capture the necessary training and validation data that will support building a Deep Learning process that will segment out individual trees from a dense Geiger Mode LiDAR derived point cloud.
3. A digital tree reference library needs to be created from field data, as none exists currently in the NSW native forest case. This is required to build a STI, being the input to train models to classify species and segment trees from dense LiDAR.
4. Validate the accuracy of a dense LiDAR derived STI for predicting forest attributes spatially such as total stem volume, and sub tree product volumes.
5. Trial the set up and demonstration of a digital twin for viewing STI data and other spatially relevant data for the improved digital-based planning of forest operations in NSW.

This report is presented with a generalised presentation of the project topic with a focus on the non-technical reader.

The Appendices contain details of the Gottstein Tour, more technical descriptions of the various technology seen and discussed, and more detailed recommended outcomes.

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Glossary

3D CNN
They are particularly useful in fields where understanding the relationships and patterns across multiple dimensions is crucial. In a 3D CNN, the convolution operation extends to three dimensions. Instead of using 2D filters, 3D CNNs use 3D filters (also called kernels) that slide through the data cube. This allows the network to capture spatial and temporal patterns or relationships in volumetric data. For example, in a video, 3D convolutions can learn features that span across both spatial dimensions (width and height) and the temporal dimension (time).

Allometric
In the context of trees, allometric refers to the study of the relationships between different measurements of a tree's size and its other characteristics. This often involves creating mathematical equations to estimate difficult-to-measure attributes, such as tree volume or biomass, from more easily measured ones, like diameter at breast height (DBH).

Augmented Reality (AR)
Augmented Reality (AR) is a technology that overlays digital information, such as images, sounds, or other data, onto the real world through devices like smartphones, tablets, or AR glasses. This creates an enhanced version of reality where virtual elements interact with the physical environment. An example in the forest might be pointing your device at a tree to show its species, age, and height.

Airborne LiDAR Scanning (ALS)
This is a broad term to describing LiDAR captured from Manned Aerial Vehicles such as light planes and is agnostic to the type of LiDAR system attached to the plane.

Area based imputation (ABA)
Area Based Inventory describes a LiDAR derived Inventory where; individual reference plots are measured; remote sensing is conducted over the entire forests; statistical models are develop to relate the field measurements to the remote sensing data and predict forest attributes; the forest is divided into grid cells, usually of 20m x 20m in size; and the models are used to predict the values in each grid cell by imputing the values of the plots to each grid cell, thus creating a prediction coverage over all grid cells in the forest.

Digital Twins
A digital twin is a virtual representation of a physical object, system, or process. This digital model mirrors the real-world counterpart in real-time, allowing for simulation, analysis, and control. Digital twins use data from sensors and other sources to reflect the current state of the physical entity. They enable testing and optimization of processes without affecting the actual system and by analysing the digital twin, potential issues can be identified and addressed before they occur in the real world.

DBH

Diameter at Breast Height of a tree stem. In the case of this report, it refers to the diameter over bark.

Deep learning (DL)

Deep learning is a subset of Machine Learning that teaches computers to process data in a way that is inspired by the human brain. DL models can recognize complex patterns in pictures, text, sounds, and other data to produce accurate insights and predictions. DL methods can automate tasks that typically require human intelligence, such as describing images or transcribing a sound file into text.

DL that is Convolutional Neural Network based, uses artificial neural networks in which multiple layers of processing are used to extract progressively higher level features from data.

F-score and mean IoU

Both F-Score and Mean IoU are statistics that respectively measure how well individual trees are segmented out from a point cloud, and how well stem points can be classified into different classes such as stem, branch, foliage.

F-Score is a way to measure how well a classification model is performing. It combines two important metrics: Precision and Recall. Recall is the stat that describes how many of the objects were correctly classified, for example, 30 out of 100 actual trees were called a tree (i.e. 0.3), whilst Precision is the number of correct predictions, for example the algorithm predicted there were 10 trees, and 8 out of the 10 predictions were, actually, trees (i.e. 0.8). F1 score then is a balanced harmonic mean of these two metrics, to give a balanced view of the overall performance of the classification model.

IoU is a metric used to evaluate the accuracy of an object detector or segmentation model. It measures the overlap between the predicted region and the ground truth. It is represented by the equation: IoU = Area of Overlap / Area of Union. In simple terms it means how much two shapes overlap, with Intersection between the two shapes being the Overlap area, and Union being the total area of both shapes combined. A perfect score would be 1 (100% overlap) and in a tree stem example, predicted stem points would be aligned perfectly with the actual stem points. Mean IoU is the average IoU across all classes, for example stem, branch and foliage.

Gaussian Splatting

Gaussian splatting is a newly developed volume rendering technique used to create high-quality images for 3D scenes. It involves representing 3D points as overlapping Gaussian distributions, which enhances image quality. Gaussian Splatting is particularly useful in fields like virtual reality, digital twins, and the metaverse, where accurate and efficient colour and textural rendering of complex environments is crucial. For example, a tree stem showing defect, or bark that enables species recognition and potential log product evaluation in a virtual environment.

GPU

A GPU (Graphics Processing Unit) is a specialized electronic circuit designed to accelerate the processing of images and videos. Originally developed to render graphics in video games, GPUs are now widely used for a variety of tasks, including Machine Learning.

Geiger Mode LiDAR (GML)

Geiger Mode LiDAR is an advanced type of LiDAR technology that uses a highly sensitive array of avalanche photodiodes (APDs) to detect single photons. It is much more sensitive than LML, detecting objects with up to 10 times lower light levels than LML.

Hyperspectral Imagery

Hyperspectral imagery is imagery that collects and separates electromagnetic radiation into hundreds or thousands of narrow spectral bands. This can be used for analysing the spectral properties of objects such as foliage of a tree to discriminate between tree species.

Internet Of Things IOT

The Internet of Things (IoT) refers to a network of physical devices, vehicles, appliances, and other objects embedded with sensors, software, and network connectivity. In Forestry these can capture information from the real world and feed this data into Digital Twins and are a key part of the conceptual framework of Digital Twins of natural environments.

LAS/LAZ Files

LAS files are used to store LiDAR (Light Detection and Ranging) data, which consists of 3D point clouds representing the scanned environment. They consist of a standard binary format that is optimal for storing LiDAR point cloud data. LAZ files are simply compressed LAS files.

Linear Mode LiDAR LML

LML is known as the conventional LiDAR systems that have dominated LiDAR capture over the last 20+ years. This technology emits a laser pulse and typically collects up to 7 measurements of objects that each of the laser pulses interact with.

Machine learning (ML)

Machine learning is a subset of artificial intelligence that focuses on developing algorithms and statistical models that allow computers to improve their performance on tasks through experience, without being explicitly programmed for each specific task.

Mobile Laser Scanning (MLS)

MLS is simply laser scanners that can capture ground, or near ground, point clouds with similar densities to Terrestrial Laser Scanners, albeit, whilst moving. Most MLS systems utilise Simultaneous Location and Mapping (SLAM) algorithms to align and co-register points within the point cloud. Emesent's HoverMap is an example of MLS that is commonly used by inventory foresters.

Multispectral Imagery

Multispectral imagery is imagery that, like Hyperspectral, separates electromagnetic radiation into bands, however, the difference is that multispectral has fewer bands, with 100 bands being the generally agreed separation between multispectral and hyperspectral imagery.

PointNet++

PointNet++ is designed to process and learn from point cloud data. It captures local features at different scales and combines them to form global features. PointNet++ is used in applications such as classifying 3D objects and segmenting point clouds into meaningful regions. For example, in forestry it can segment stems from foliage and ground points.

Pulses and PPSM

A LiDAR laser pulse is a brief burst of laser light emitted by a LiDAR system to measure distances and create detailed maps of the environment. A typical Linear Mode LiDAR system emits pulses and measures the time taken for the laser pulse to be reflected off target objects and return to the sensor. Multiple pulses are emitted over a target to build up a measurement of the object or ground. PPSM is equivalent to Pulses emitted per square meter of the target by the LiDAR sensor.

Raster

A raster is a type of data representation that uses a grid of cells (or pixels) to store information about the environment. Each cell in the grid contains a value representing a specific attribute, such as elevation, temperature, or land cover.

RGB

RGB pertains to a typical photographic imagery that we see and use in everyday life in regular digital cameras. In an RGB digital image, each pixel's colour is defined by a combination of red, green, and blue values, typically ranging from 0 to 255. In addition to regular cameras, RGB format is used for forest characterisation, often captured from above using Planes and Satellites to capture imagery at scale.

Terrestrial Laser Scanning (TLS)

TLS is the scanning of objects using stationary LiDAR sensors such as the Reigl VZ-400i. This is not typically used for large scale area scanning but rather highly detailed scans of forest plots or individual trees, with the highest quality accuracies and point densities available. These are typically tripod mounted and require multiple relocations within a forest plot or around a single tree to capture all surfaces of trees in the plot, or the tree.

Semantic Segmentation

Semantic Segmentation is the classification of objects within images or point clouds into a specific category. With point clouds, Deep Learning models are used, trained on large datasets of examples, to semantically segment the point cloud into objects. In Forestry, these would be things such as stems, foliage, branches, coarse woody debris, and ground.

Voxel

With respect to LiDAR, a voxel represents a three-dimensional unit of volume, also referred to as pixels, and can be a combination of any three dimensions of height, width, and length. Typically, Voxels are used to segment the volume into regular cubes and summarise LiDAR points that are located within each voxel. For example, number of points, average location or intensity of the points located within each voxel. Voxels are a useful way to summarise LiDAR data structure and properties.

2. What is Single Tree Inventory

A single tree inventory involves the detailed recording of all individual trees within a specific area. This type of inventory is crucial for effective forest management and conservation. Attributes required include the species of each tree, diameter at breast height (DBH), total height, crown width, and sometimes age. Volume of log products are required by forestry practitioners. Health attributes are useful, such as physical damage from fire, drought, storm damage or pests, crown vigour and disease indicators.

This detailed data helps to make informed decisions about thinning, harvesting, and reforestation and managing carbon stocks. The individual tree characteristics measured can assist in identifying and protecting rare or endangered species and managing habitats for wildlife.

STI comes in a range of flavours. At the simplest end a practitioner will assign spatially located points to estimated locations of tree canopy tops, and these can be based on:

- Algorithms that look at Red Green Blue imagery using machine learning approaches to put a dot on each tree.
- Analysis of low to moderate density airborne LiDAR or photogrammetry point cloud to find trees based on canopy shape, or machine learning approaches to assign points to locations representing the tops of trees.
- Analysis of low to moderate density airborne LiDAR or photogrammetry point cloud combined with field measured reference plots to assign points to locations representing the tops of trees.

However, these are not fit for purpose for forests with a high level of variability in stem form where that stem form affects the type and value of log products arising from that stand.

To describe log product within each stem, a dense point cloud that describes the understory features such as stem shapes, branches, and understory shrubs and structures is required. These algorithms go beyond simply putting a point on a surface or modelling tree height and DBH.

Currently these models can take a dense point cloud and:

- Use algorithms to find shapes in the point cloud corresponding to circular or elliptical shapes that represent tree stems. These algorithms can be manually tuned to the type of forest captured in the point cloud.
- Deep learning algorithms are used with training data whereby dense point clouds have been manually segmented into individual tree instances and semantic classes such as stem points, foliage points, branch points, ground points and low vegetation points. The deep learning models are then applied to point clouds of similar density to extract tree instances and classify points in the point cloud into semantic classes.

- Finally, emerging techniques utilising dense point clouds are used to 'measure' the stem taper and volume of each stem directly, where each stem has been extracted from the point cloud and just the stem points isolated. This approach utilises all the information collected within the point cloud to model stem taper and calculate individual tree volumes.
- A combination of the above 3 examples can be used to both extract trees from a point cloud and describe the diameter, volume and type of products tree.

This approach means that a good quality, dense point cloud over large areas provides the most promise in terms of accurately describing the trees in the landscape. This is especially true when there is a large amount of variability in tree sizes and shapes that are not accounted for with simple taper models.

3. LiDAR technology

Geiger Mode LiDAR

The first step in creating a good STI is to collect a dense point cloud that delineates the structures of the trees in the canopy and sub canopy of the forest.

As part of the Gottstein study, I visited 3DEO, a manufacturer and expert in Geiger Mode LiDAR (GML) systems.

3DEO's GML collects large scale point clouds economically with data densities commonly associated with drone LiDAR collections, but at a scale associated with larger aircraft. This high-density data has traditionally been too time consuming and expensive to collect over large scales.

GML is the term used to describe LiDAR systems that utilise Geiger-Mode Avalanche Photo Diodes (APD) Arrays to detect single photons interacting with the sensor. 3DEO produces a GML system that can detect 700 million photons per second.

The system works by emitting a pulse of light, currently at a wavelength of 1064nm and then 'listens' for returning photons reflected from target objects. The Geiger Mode sensors can digitise a photon time of arrival at the sensor in the order of hundreds of picoseconds.

Behind all this capability are highly technically advanced equipment consisting of nanosized components, high precision timing circuits and sensor chips.

The GML can detect and discriminate objects as close together as 18cm when capturing data from several thousand meters above the target. For example, two branches of a tree that are 18cm apart can be resolved. Compared to this range resolution, typically commercial Linear Mode LiDAR (LML) can detect objects around 60cm apart. GML can also detect objects with a precision equal to most commercial LML systems.

Part of the advantage of GML over LML, is the sensitivity of the sensors to photons. The number of photons required for the GML to reliably detect an object is about 30 photons. For LML this figure is closer to 300 photons. This means more measurements can be made, especially in low light environments, like the subcanopy of a forest.

Figure 1 below shows a single tree captured with 4 different specifications:

A. tree captured with traditional 6ppsm LML and shows little data that could be used to describe the tree stem, and a vague description of the crown volume could be generated.
B. GML captured from High Altitude at 4,000m. Here the stem can be seen as not being perfectly straight, the crown base, shape, asymmetry and volume is well captured.
C. GML captured at a typical capture height for LML ALS, of 1,100m and shows that the stem structure is well defined, and branch stubs can be seen, as well as an accurate

location of a 'kink' in the stem. This point cloud is suitable for describing the location and size of straight sections in a tree suitable for sawlog production.

D. is included for reference and is the result of Mobile Laser SLAM capture at ground level using a Emesent Hovermap device at about 4-15 meters from the stem.

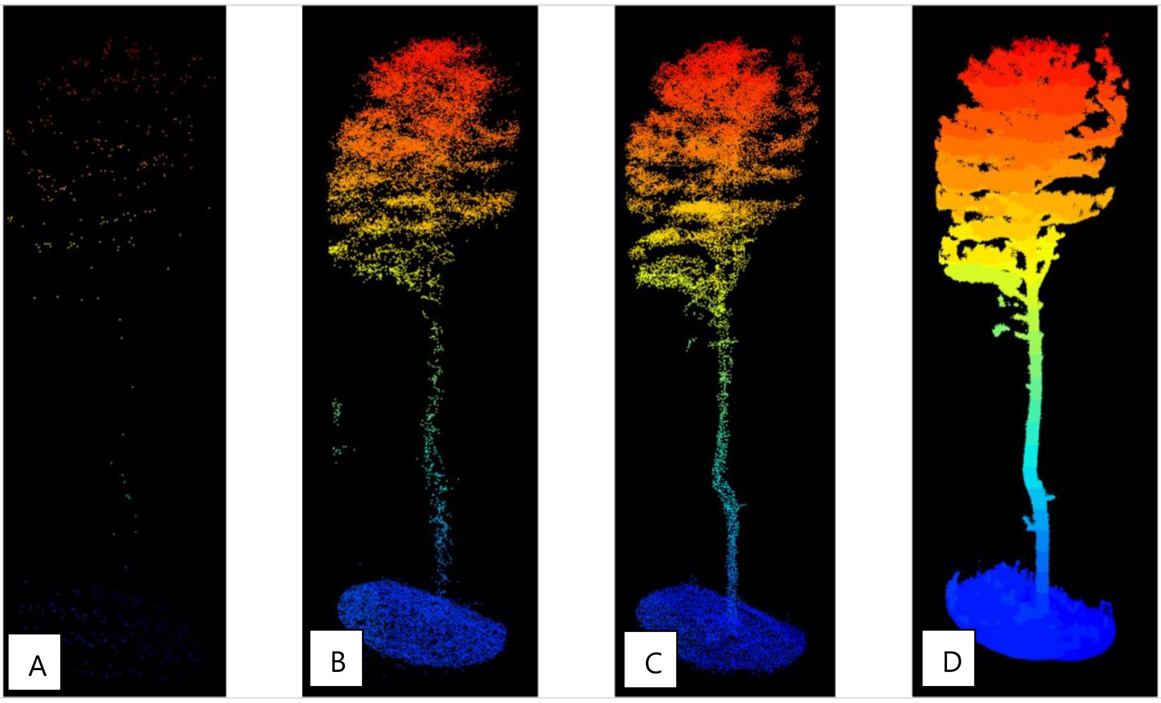

Figure 1: The same tree from four LiDAR collects. A). Traditional ALS 6ppm. B). GML high altitude (~4000m AGL). C). GML low altitude (~1100m AGL). D). Hovermap SLAM LiDAR mounted on backpack.

What does it enable us to do?

Capture of GML across a production forest estate as per figure 1C above, and combined with a reference tree dataset would enable the development of a high quality single tree inventory.

The GML makes it possible to:

- Capture/Fly at a level appropriate for segmenting single trees from raw LiDAR captured wall to wall over an entire estate at the level of detail shownin Figure 1C
- Fly at lower elevation and capture data that is as close to terestrial laser scanning datasets (TLS) as possible and capture reference plots/trees without having to visit the field on the ground. Fusion of the GML with RGB imagery would be necessary.

This means it is possible, with a bit of experimentation, from a plane, to capture both the wall to wall data and the highly detailed training datasets that could be used for tree segmentation and describing each tree. This could potentially be very cost effective.

4. Tree segmentation and classification

What is Tree Segmentation

Tree segmentation involves separating a dense point cloud into individual trees by labelling each point in the point cloud by the tree instance that point belongs to. Each point can be given a semantic label as well, such as stem, branch and foliage.

An example of tree segmentation technology: ForAInet

As part of visiting Norwegian Institute of Bioeconomy Research (NIBIO), I was introduced to ForAInet, a stem segmentation model, which shows the most promise for extracting single trees from large areas of dense point clouds.

ForAInet is an end-to-end deep learning model that can segment point clouds into trees and was trained using the FOR-instance dataset. The FOR-instance dataset is a dataset of 1,130 dense point clouds of labelled trees from Norway, Czech Republic, Austria, New Zealand, and Australia.

The tree point clouds were manually segmented into single tree instances and five semantic categories: low vegetation, ground, stem points, live branches and dead branches. Five different forest types were sampled, in coniferous, dry sclerophyll eucalypt forest and deciduous alluvial forests.

This dataset was used to train ForAInet to segment trees. It achieves over 85% accuracy (F-score) for individual trees, respectively over 73% accuracy (mean IoU) across five semantic categories: ground, low vegetation, stems, live branches, and dead branches, and is applicable to many forest types.

In addition, a suite of forestry-related biophysical variables at the per-tree and per-stand levels are generated such as tree height, crown diameter, crown volume, live crown volume and DBH.

Dense GML data captured in Delaware, USA was used as input into the ForAInet and performed very well (Figure 2), segmenting all the visible stems and trees into individual instances.

Appendix 1 provides more detail of Tree Segmentation and Classification, and data explorations conducted.

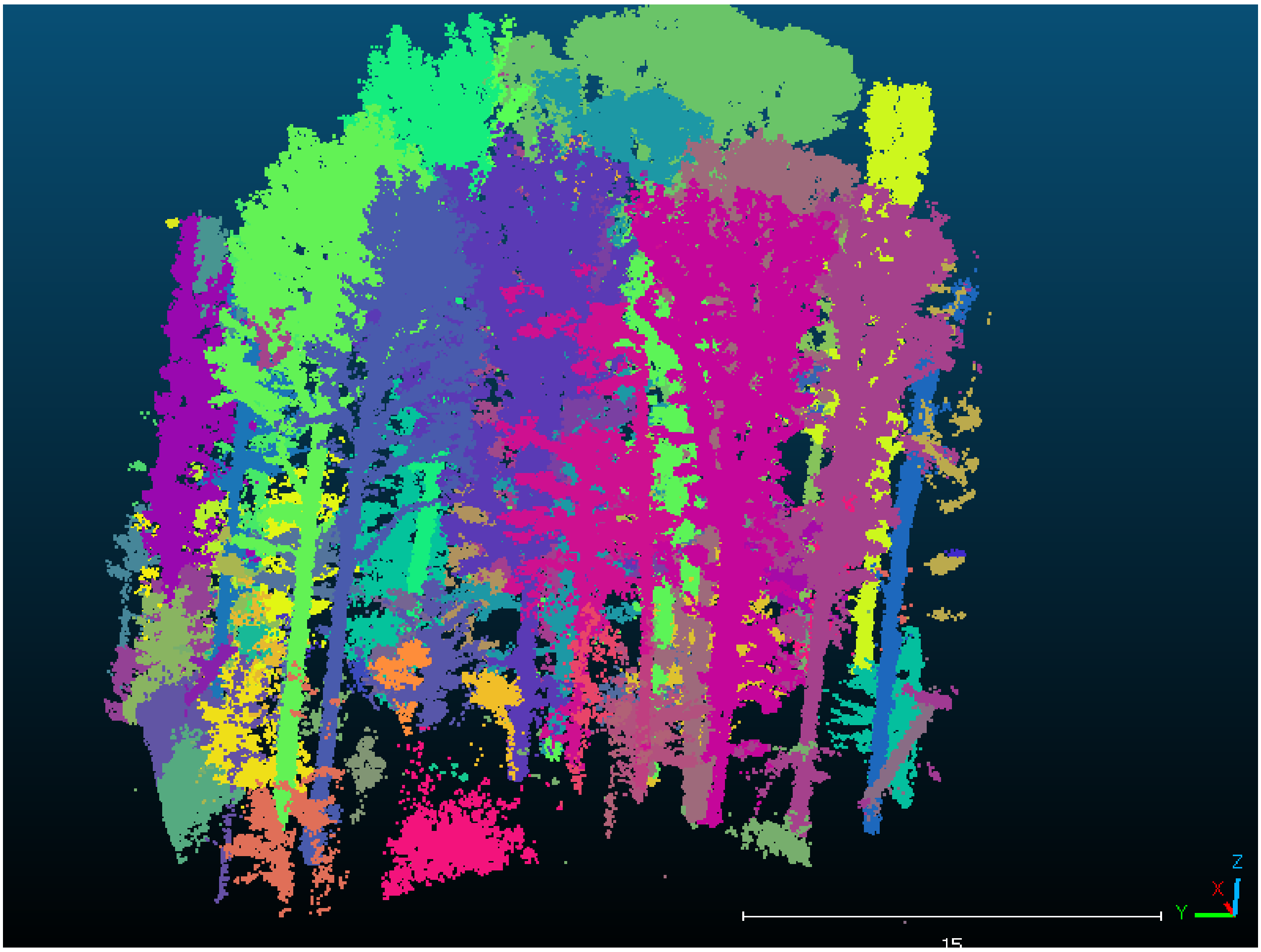

Figure 2: Visual example of single tree segmentation of Geiger mode LiDAR.

To test this on Australian forests applied the model to a dense point cloud collected in a growth-plot (PNB116) located in the Bulahdelah region of NSW, within dense moist eucalypt forest.

This point cloud has an approximate density of 2,500 pulses per square metre within a 25-metre radius circular plot. Figure 3 shows an image of the growth plot segmented into individual trees. This worked well and is worth developing further by training the model with local data from that forest type.

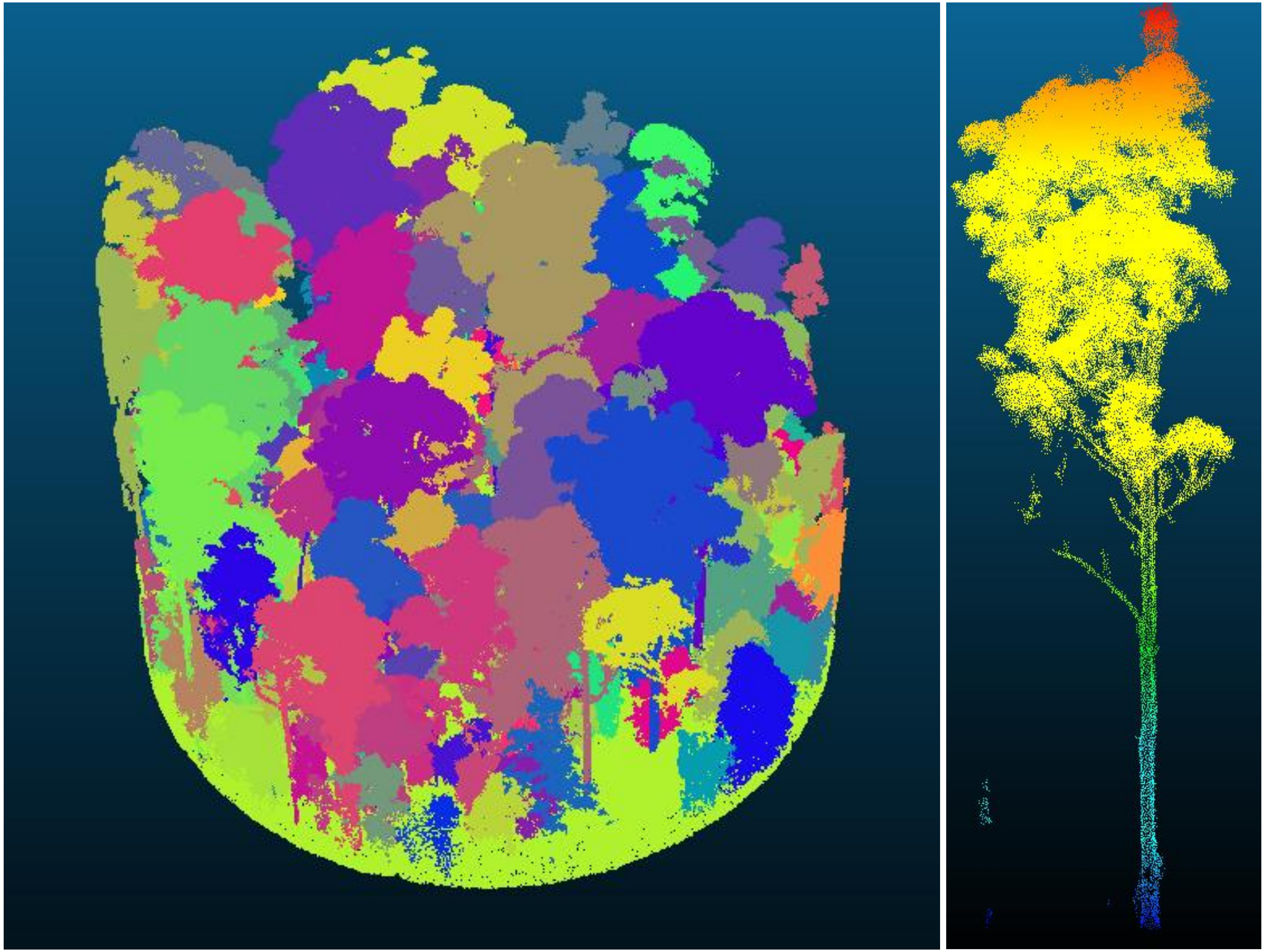

Figure 3: a). Plot PNB118 having been segmented into tree instances. B). A single tree extracted from the plot, coloured by height above ground.

A test of how the algorithm performs over a large dataset was conducted. A dataset of 270ppsm over 32ha of mixed conifer forests was processed with ForAInet. The ForAInet processed this data easily, and a conclusion was reached that this algorithm would be suitable for processing large areas of high density point clouds. Obviously this would require the algorithms to be installed on a scaleable instance with GPU architecture for processing. **Error! Reference source not found.** shows a section of the point cloud coloured by tree instance, and Figure 55 shows just the points labeled as stem points for the same area.

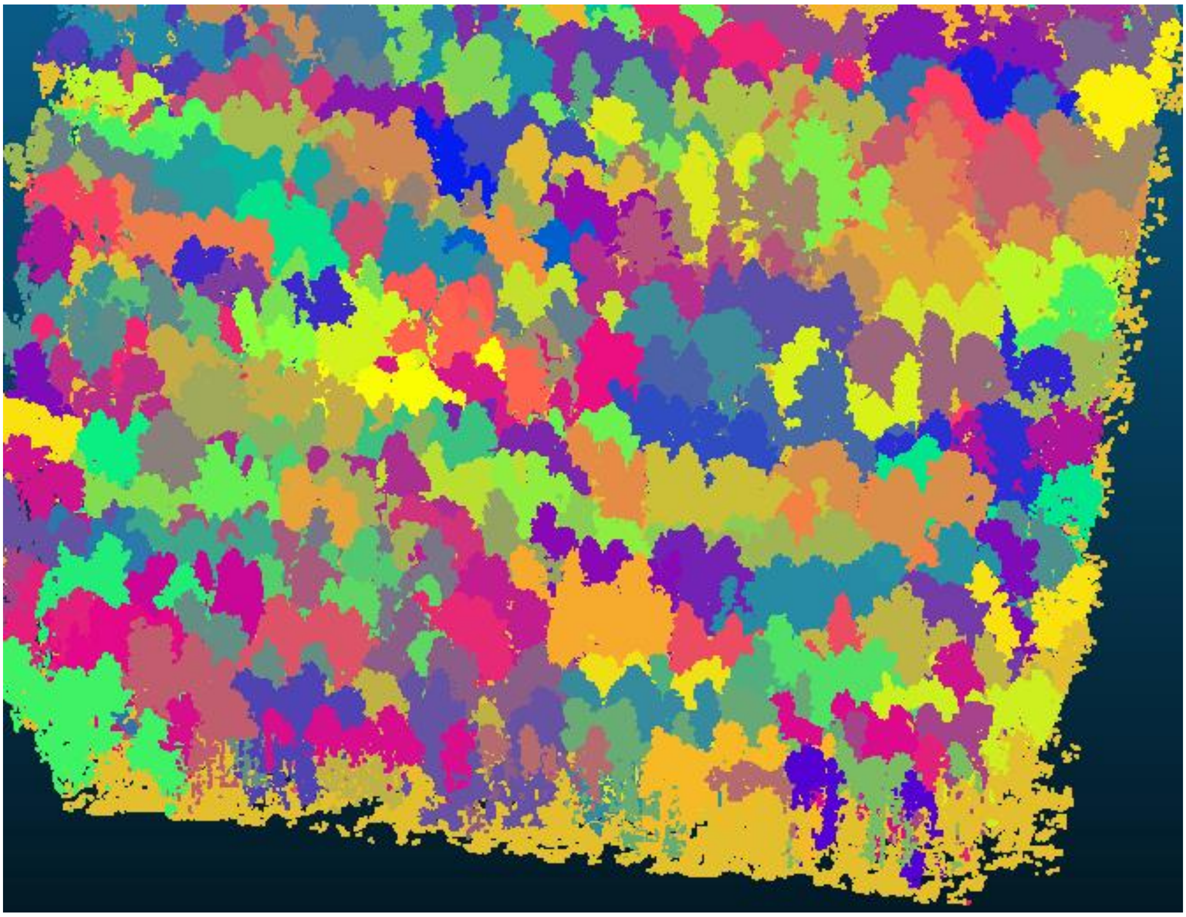

Figure 4: A closeup of a section of the point cloud segmented into individual stem instances.

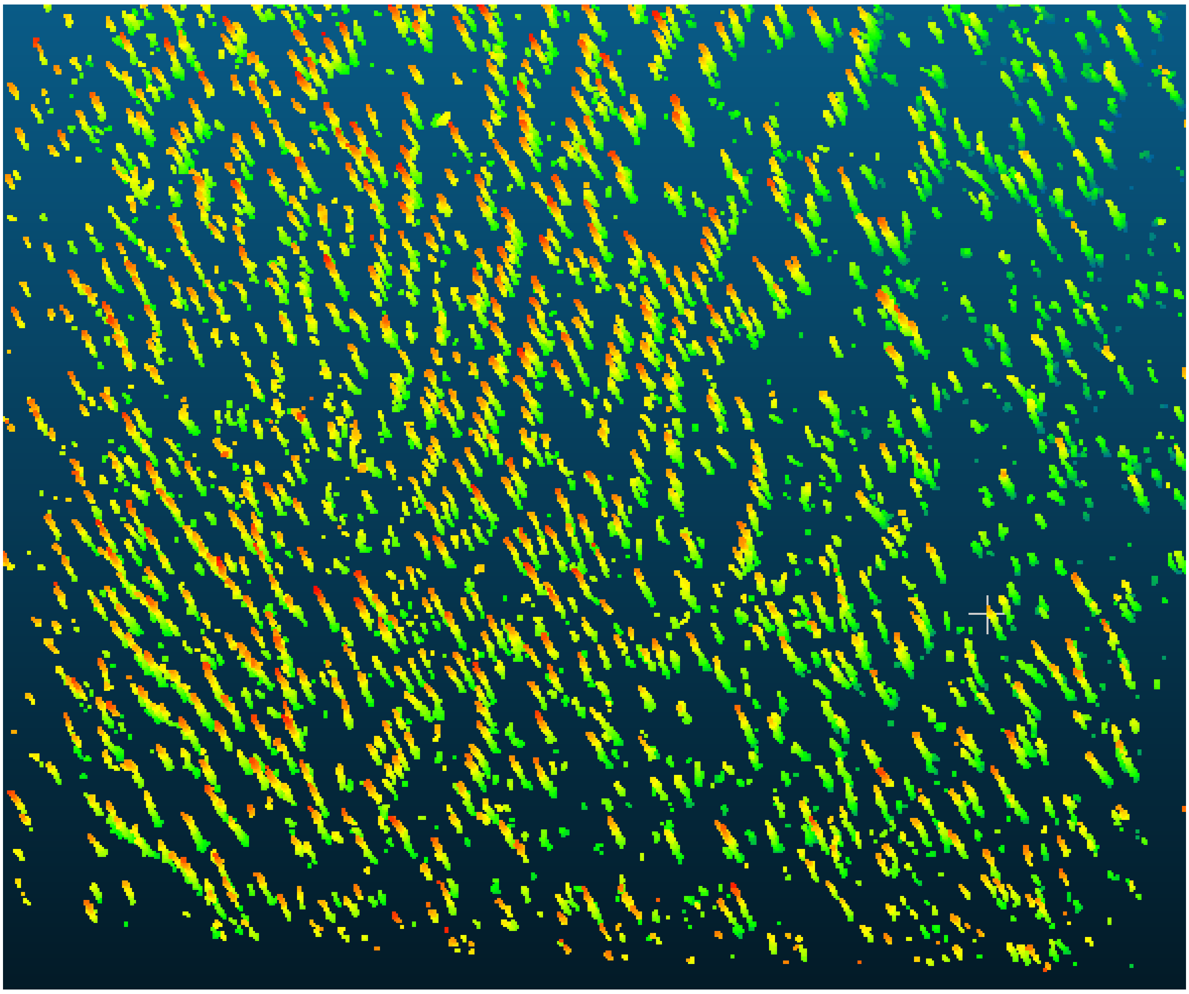

Figure 5: The above example from Figure 4, just showing the classified stem points, coloured by height above ground.

5. Reference Tree Library

Integral to the training of DL models for both species' detection and STI is the collation of point cloud-based tree libraries. A point cloud-based tree library is a reference collection of relevant trees captured using TLS or equivalent high-density LiDAR.

The data is usually generated by scanning with TLS with individual trees manually segmented into a stand-alone LAS file. The point cloud is sometimes classified into semantic classes such as stem, foliage or branch. A range of statistics is usually computed, such as crown area, volume, DBH, species, crown break height and so on and are combined with field-based assessments. Figure 6 shows an example of the attributes and point cloud for a single tree.

Attribute	Value
DBH	550 millimeters
Height	45 meters
Crown Diameter	9 meters
Crown Depth	18 meters
Crown Volume	50 cubic meters
Species	*Eucalyptus Pilularis*
Relative Local Position	Dominant
Hollows	None Visible
Hollow Potential	High
Dead Branches	@16m; @21m
Defects	Fire Scar: 0-1 meters
HQ Sawlog Volume	2 cubic meters
Salvage log Volume	0.8 cubic meters
Pulp Volume	1 cubic meters
Total Recoverable Volume	3.8 cubic meters
Total Stem Volume	4.1 cubic meters
Bole Height	25 meters
Bole Straightness index	3
Bole Branch index	2
Estimated Age	85 years
Age Confidence Index	1
Harvest History	2005 Light Selective
Fire History	2019/20 Moderate
Habitat Score	3

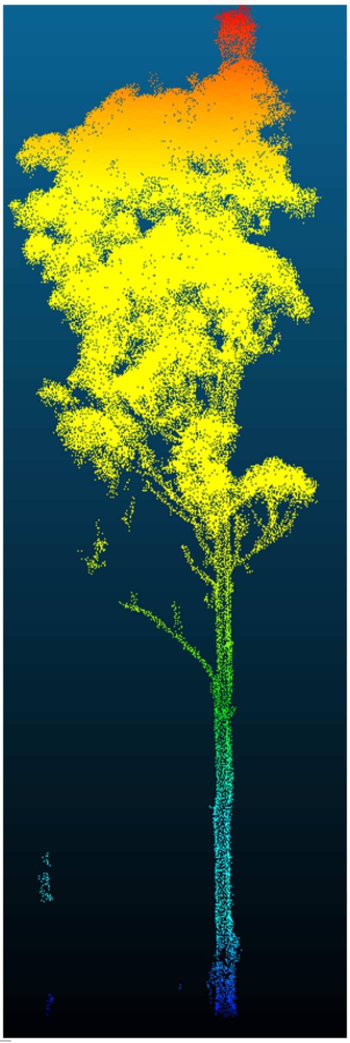

Figure 6: Example of Field Assessed Reference Tree Attributes and point cloud.

In the NSW native forest case, to build a STI and to train models to classify species, a reference dataset needs to be created, as none exists currently.

The process could be done in tandem with a statistically balanced sample of plots scanned using subcanopy MLS/TLS. This approach could potentially come up with a representative sample of stems to extract from the plots.

Careful collation of the plots and tree point clouds should be done with a focus on the ensuing coverage across the range of species, log types and volumes, habitat suitability, size classes and location in the landscape, such as position on slope, elevation and soil types. In addition, the coverage of reference trees should represent a range of past management activities given that this influences log products and habitat suitability. An example of this would be to sample in areas subject to past intensive harvesting practices (e.g. clear-felling) and areas where past selective harvesting has occurred.

6. Digital Twins

A digital twin is a virtual representation of a physical object, system, or process. This digital model mirrors the real-world counterpart in real-time, allowing for simulation, analysis, and control. Digital twins use data from sensors and other sources to reflect the current state of the physical entity. Globally across many professions, Digital twins are now becoming the tool for the job rather than a novelty.

Highly detailed Digital Twins (DT) promise to revolutionise the accuracy, planning processes, transparency, and education around forest management activities. A digital map of stems and their attributes is a core aspect of a detailed Digital Twin for forestry that used STI as input. Several providers I visited were starting on the process of building digital twins of their forests, also called a 'digital forest'. A few are listed below.

University of Idaho (UI) Digital Forest

University of Idaho is well advanced in setting up a digital forest centre, leveraging off the University of Idaho Experimental Forest (UIEF).

University of Idaho has captured and co-registered (spatially aligned):

- Field measured plots,
- Field measured stems mapped to Ground Based Mobile LiDAR plot datasets (Hovermap SLAM),
- Geiger mode LiDAR, flown at different elevations over a wider area.
    - This is in mixed native forest in the University of Idaho experimental forest (UIEF).

There is an ArcGIS Online page that shows the STI that has been generated over the UIEF with different sensors over time, Figure 7 shows an example of a tree map, coloured by tree height.

The digital inventory can be interacted with, and attributes of each tree viewed, or the data can be viewed by aggregated grid levels or stand levels. Once again, there is a common set of constructs/software systems that each ITD user/provider is using across the international industry, so there were no large differences between that shown by the different STI providers I visited on my tour.

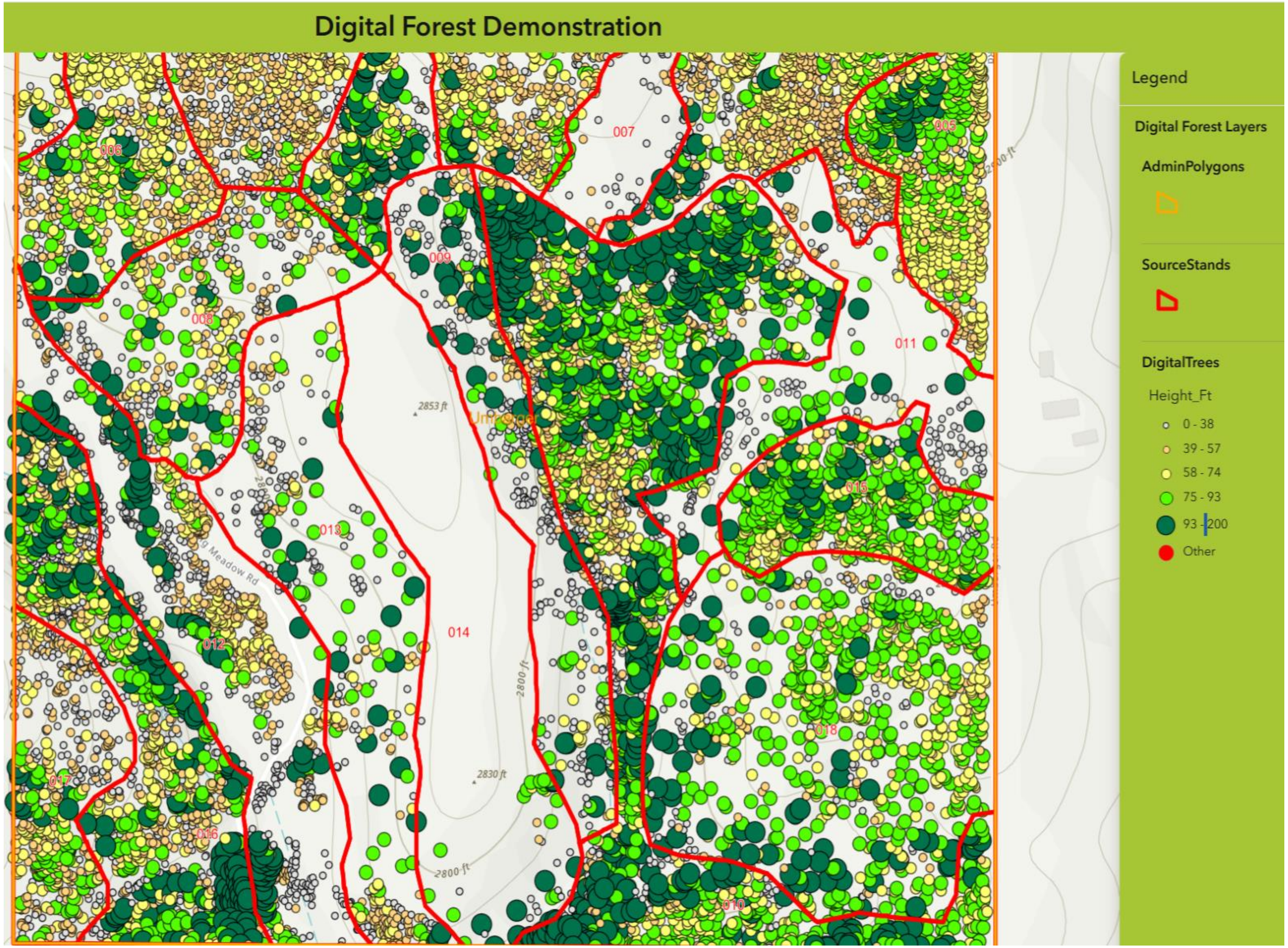

Figure 7: Digital Twin showing height of trees in forest within stands shown in ArcGIS Online.

Digital Twin provider: Northwest Management Incorporated (NMI)

A visit to NMI and discussions with the owner Mark Carrao, yielded very interesting discussions about Geiger Mode LiDAR, current sensors and helicopter-based LiDAR and NMI's general approach to STI.

NMI has performed STI across more than 10 million hectares in North America and are leading proponents. For Forest Management companies, NMI can host all the captured LiDAR data and supplementary data and provide hosted services. They deliver software such as ForestView® which is shown in this ForestView® example. ForestView is a mature and well-developed software that is very suitable to Foresters who want to understand the forest from the individual tree through to the estate level, with dashboards and tools that assist to make informed decisions.

The algorithms and methodologies utilised by NMI are proprietary, so a detailed description of these cannot be made here. However, comparisons between the digital inventory and intensively sampled and harvested areas of forests show that the predictions are very close to what was recovered from the forests.

Two videos below discuss this:

Forestview® and Digital Inventory® [1] [2]

Interestingly, and predictably, detailed subtree quality is not really required by the North American clients (due to the types of trees modelled), so allometric equations based on accurately predicted DBH and height is used to generate log product yield tables.

Further detailed information on Digital Twins is shown in Appendix 3.

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[1] URL Link: https://www.youtube.com/watch?v=j-qpO4x7qpw&t=153s

[2] URL Link: https://vimeo.com/906627662

7. The way forward

Required Research

There is a requirement for Industry to invest in several studies to facilitate the update of STI in Australia. Some broad topics are listed below and outlined in further detail in Appendix 4.

- Validate the effectiveness and efficiency of Geiger Mode LIDAR systems for mapping of individual trees.
- Field work to capture the necessary data that will support building a Deep Learning process that will segment out individual trees from a dense Geiger Mode LiDAR derived point cloud.
- Creation of a digital tree reference library, as none exists currently in the NSW native forest case. This is required to build a STI as input to train models to classify species and segment trees from dense LiDAR.
- Validate the accuracy of a dense LiDAR derived STI for predicting forest attributes spatially such as total stem volume, and sub tree product volumes.
- Set up and demonstrate a digital twin for viewing STI data and other spatially relevant data for the improved digital planning of forest operations in NSW.

Conclusion

A successful Single Tree Inventory in eucalypt forests in eastern Australia, would need to combine highly penetrative, and dense LiDAR data at scale with appropriate tree reference libraries and Deep Learning algorithms, to generate a meaningful LiDAR derived STI.

In Australia this is very achievable. Highly penetrative and dense LiDAR is becoming more and more available, for example with the advent of new Geiger Mode LiDAR sensors. Tree Reference Libraries currently exist for mostly northern hemisphere cooler climate species and are used to train Deep Learning algorithms and there is no reason the same cannot occur in Australia over the next few years. With these datasets, the Deep Learning algorithms will be able to segment trees across all tenures and state boundaries, and the application of STI in Australia would be very beneficial for measuring what is there now, and how it changes over time.

The Gottstein Fellowship enabled me to visit several researchers and practitioners in technology and research space in fields relevant to the topic of STI's. It has informed me that all the tools are currently present, and with a bit time and effort it is possible to implement fit for purpose STI's across the majority of Australia's forested landscape.

Appendix 1: LiDAR technology - Geiger Mode LiDAR

As part of visiting 3DEO, an in depth understanding of the characteristics of Geiger Mode LiDAR (GML) was gained.

3DEO's GML collects point clouds with data densities commonly associated with drone LiDAR collections, but at a scale associated with larger aircraft. This large-scale, high-density data is a critical input for applications such as wildfire prediction, forestry, urban mapping, and disaster response.

GML is the term used to describe LiDAR systems that utilise Geiger-Mode Avalanche Photo Diodes (APD) Arrays to detect single photons interacting with the sensor.

3DEO produces a GML system that can detect 130 million photons per second at a flying height of 3,200m.

The system works by emitting a pulse of light, currently at a wavelength of 1064nm. This pulse is emitted through the detector array, and then the detector array 'listens' for returning photons reflected from target objects. The Geiger Mode sensors can digitise a photon time of arrival at the sensor in the order of hundreds of picoseconds.

The detector arrays of the existing systems contain currently 4096 or 8192 pixels. Each one of these pixels has a circuitry fitted behind it that can detect the single photons. The number of detector arrays can be scaled up if necessary, leading to even higher photon detection rates if required. It was mentioned that a 128 x 256 (32,768 pixels) and larger arrays are in research and development.

Behind all this capability are highly technically advanced equipment consisting of nanosized components, high precision timing circuits and sensor chips. Also, the physics is fascinating, with concepts such as breakdown voltage, over-biased APD, run-away avalanche processes. In my opinion, these concepts are not necessary for, and are beyond the capability of the average user of LiDAR to understand. However, Figure 8 does show a schematic of the process for interested readers.

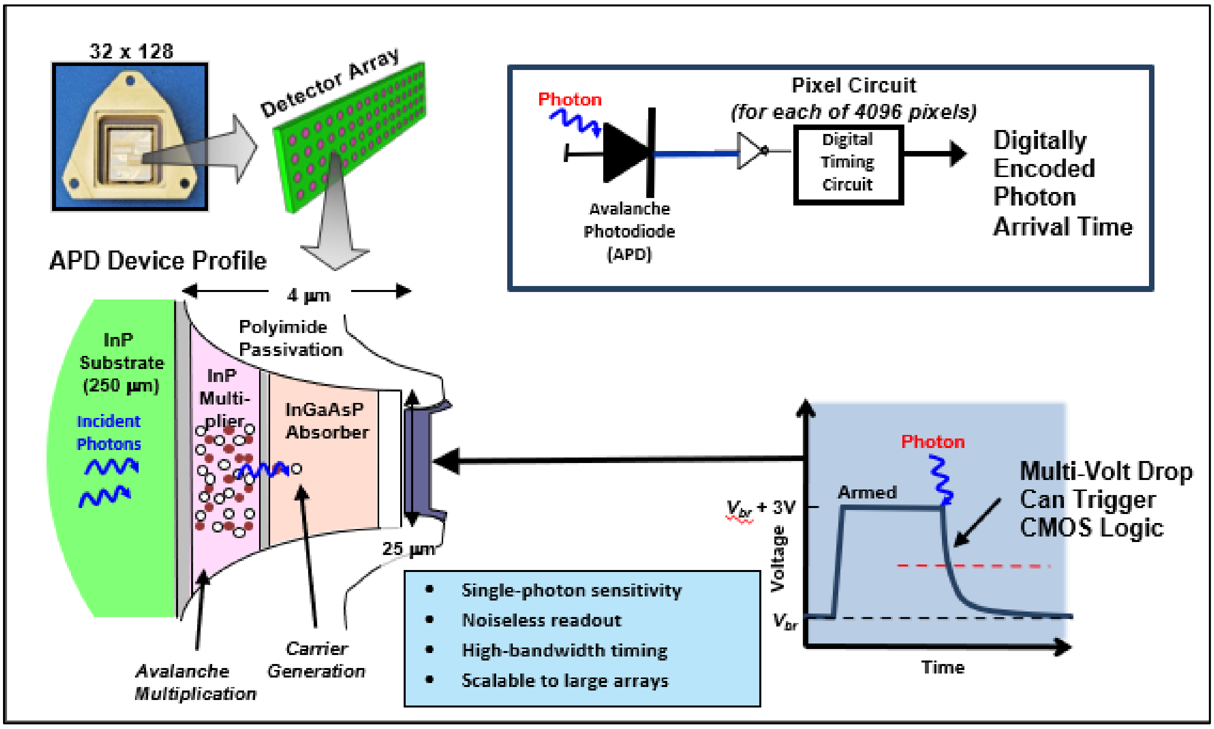


Figure 8: Schematic of the process and device used for single photon detection. Courtesy of MIT/LL/3DEO.

Accuracy specifications

The sensor has a range resolution of 18cm. Put simply, this means that the LiDAR can detect and discriminate objects as close together as 18cm whilst capturing data from several thousand meters above the target. For example, two branches of a tree that are 18cm apart can be resolved. Figure 9 shows an example of a point clouds range resolution demonstrated on a flat surface. Compared to this range resolution, typically commercial Linear Mode LiDAR (LML) achieves a range resolution of around 60cm.

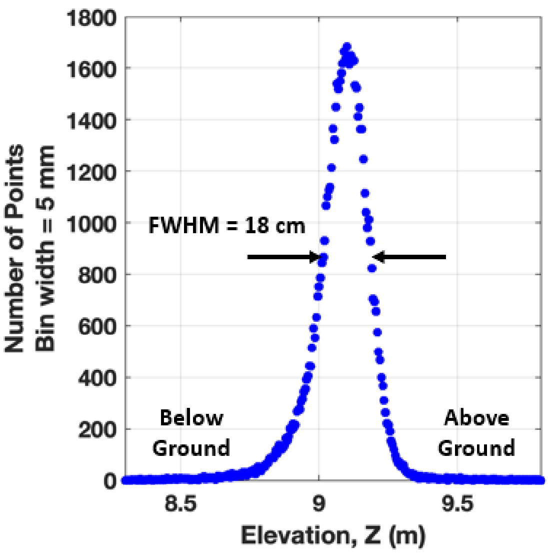


Figure 9: Illustration of Range Precision (FWHM)

Simply put, the range precision reflects the repeatability of an objects elevation (z) estimate as it increases with the number of detected photons. At a typical collection condition of 3,200m height and 10 photon detections per point generated, the RMSE of the elevation value is 3.5cm. As the number of photons increase however, the confidence in the elevation value increases. Figure 10 shows how Range precision can increase with collection rates. This is equivalent to most commercial Linear Mode LiDAR systems.

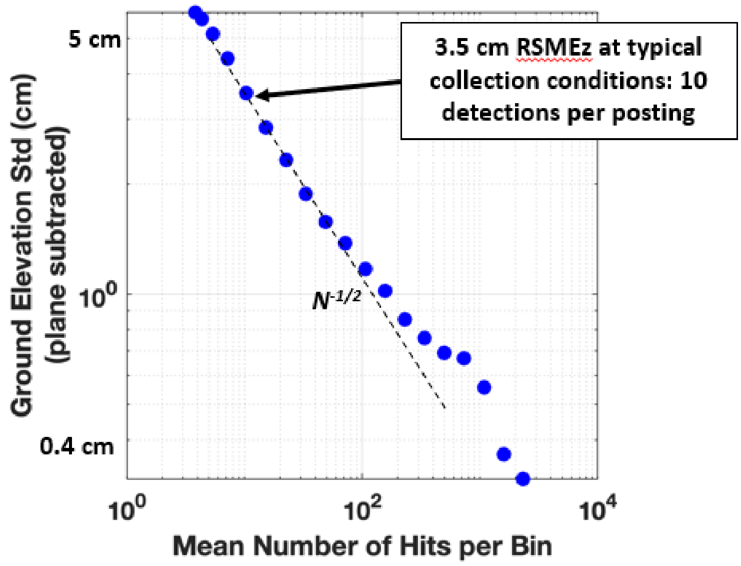


Figure 10: Illustration of relationship between Range Precision and collection rate.

Photon Sensitivity and counting.

Part of the advantage of GML over LML, is the sensitivity of the sensors to photons. The number of photons required for the GML to have a 95% probability of detection and a very small 'false alarm rate' is about 30 photons. For LML this figure is closer to 300 photons. Depending on the objects being scanned, these settings for processing could be adjusted to suit the objectives of the project.

For example, processing can require more photons per measurement for scanning objects that require good linear accuracy with low RMSE, say, an unobstructed rooftop. In this case, the collection of large amounts of data over the roof top in a flight using GML means that there is leeway to filter out all but the measurements with the highest confidence, whilst still retaining a high enough point density to describe the object accurately.

Conversely, a scan of a forest plot for fuel density, may mean that detecting as many fuel objects as possible is more important. In this case using all possible measurements that have been collected from all 'view angles' is important to minimise occlusion from objects surrounding the fuel (i.e. tree stems). This means that potentially individual objects have a bit less certainty in their shape, position, or size, but the confidence that all objects in the entire plot have been detected, is higher.

Additional attributes

Each measurement output from the processing of photons into measurements has a set of attributes other than the usual LML intensity metrics that also allows it to be described and filtered from final point clouds depending on the aspect of importance that the user is focused on. The section following briefly attempts to describe those that were demonstrated at 3DEO with some preliminary datasets.

One such attribute was a representation of the peak axis on the x, y or z, with the axis aligned with the signal peak tend to have more reliability. In this case the wall of the building was subject to GML captured at 3,200m, had several viewpoints from different look angles, and as such was covered comprehensively with many points. Each point had an peak axis on either the horizontal (x, y) or vertical (z) axis. Removing points with less reliability on the horizontal (x and y) axis visibly reduced the 'fuzz' in the point cloud, presenting a very clean and presumably more accurate point cloud describing the walls' vertical surface. This was also done with ground points on flat surfaces, by filtering out points with less reliability on the z axis, and creating a much cleaner surface, with very adequate point coverage due to the large initial density of points.

This has applicability to forest stem measurement, as, if density of capture is significant enough, filtering of less reliable points could lead to less 'fuzzy' vertical stem coverage by points, whilst retaining an adequate number of points to still describe the shape of the object, and hence perhaps better segmentation and diameter measurement results.

Another attribute of the processed measurements is the attribute of number of 'hits' per measurement within small voxels of 10 x 10 cm^3 or smaller. Objects with many hits tend to be larger objects that are more prominent from different look angles, such as a branch or stem or ground. Objects with a smaller number of hits could include foliage, given the small size and lower reflectivity, each collection of leaves or fine twigs return fewer hits from different angles. Figure 14 shows a point cloud, further described in the section below, where 3 hits in a 10cm voxel leads to a 'fuller' point cloud, with points representing foliage highly represented, but filtering to only include points with a minimum of 10 hits in a 10cm3 voxel seems to filter more of the crown area out of the point cloud, leaving proportionally more stem and branch structures. This is a potentially useful method that could be applied to improve the segmentation of stems from the point cloud.

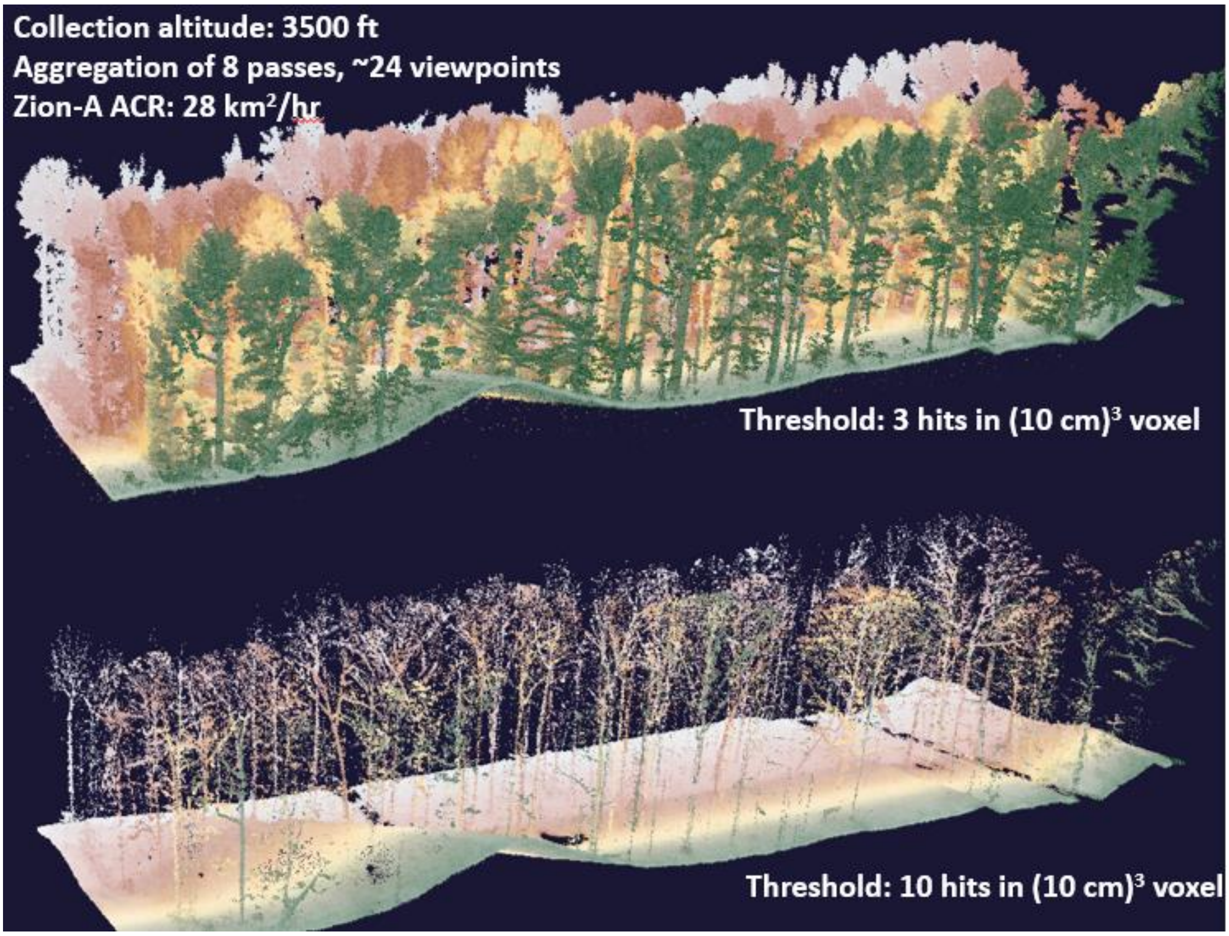


Figure 11:Example of filtering by number of hits in a voxel to remove points associated with finer structures.

Examples of Geiger Mode LiDAR

Example 1. Mixed Conifers Delaware

The visual example above (Figure 11), and Figure 12 and Figure 13 below, were captured in 2022 over mixed conifers in Delaware US, with 3DEO Geiger Sensor. The capture specifications for this are:

- 1,650m flying height and 8 passes.
- 24 viewpoints, or look angles, for each surface
- Ability to be captured at 6,000ha per hour with current sensors, but capacity to increase in future.

It can be seen in Figure 12 that the penetration of the foliage and forest structure is comprehensive. The shape, sweep and branchiness of individual stems is well defined right through the profile of the forest.

Figure 13 shows a cross section of the GML point cloud processed in ForestSens ForAINet and shows very good segmentation. The quality of segmentation shown here gives confidence that single tree inventory of a high quality could be produced using Geiger mode captured using the specifications above as a minimum.

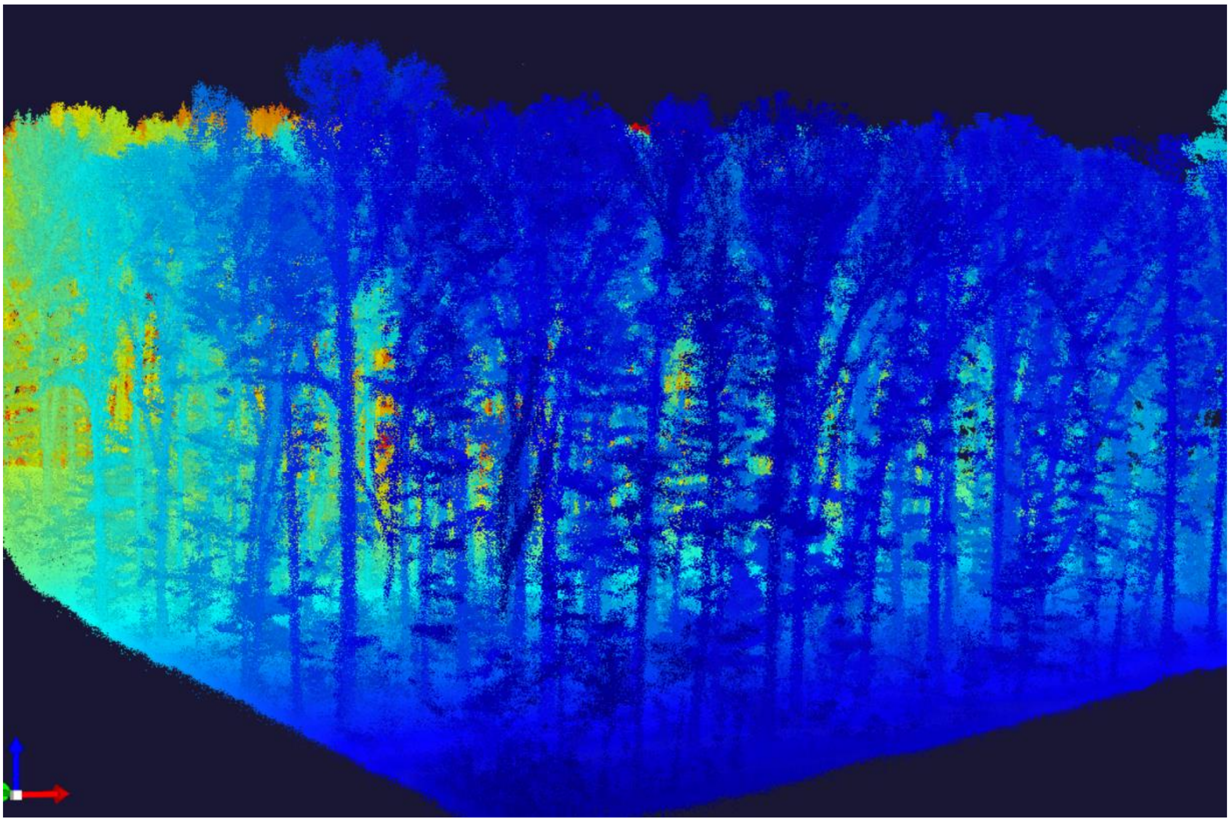


Figure 12: Visual example of a Geiger Mode point cloud showing detailed subcanopy structures.

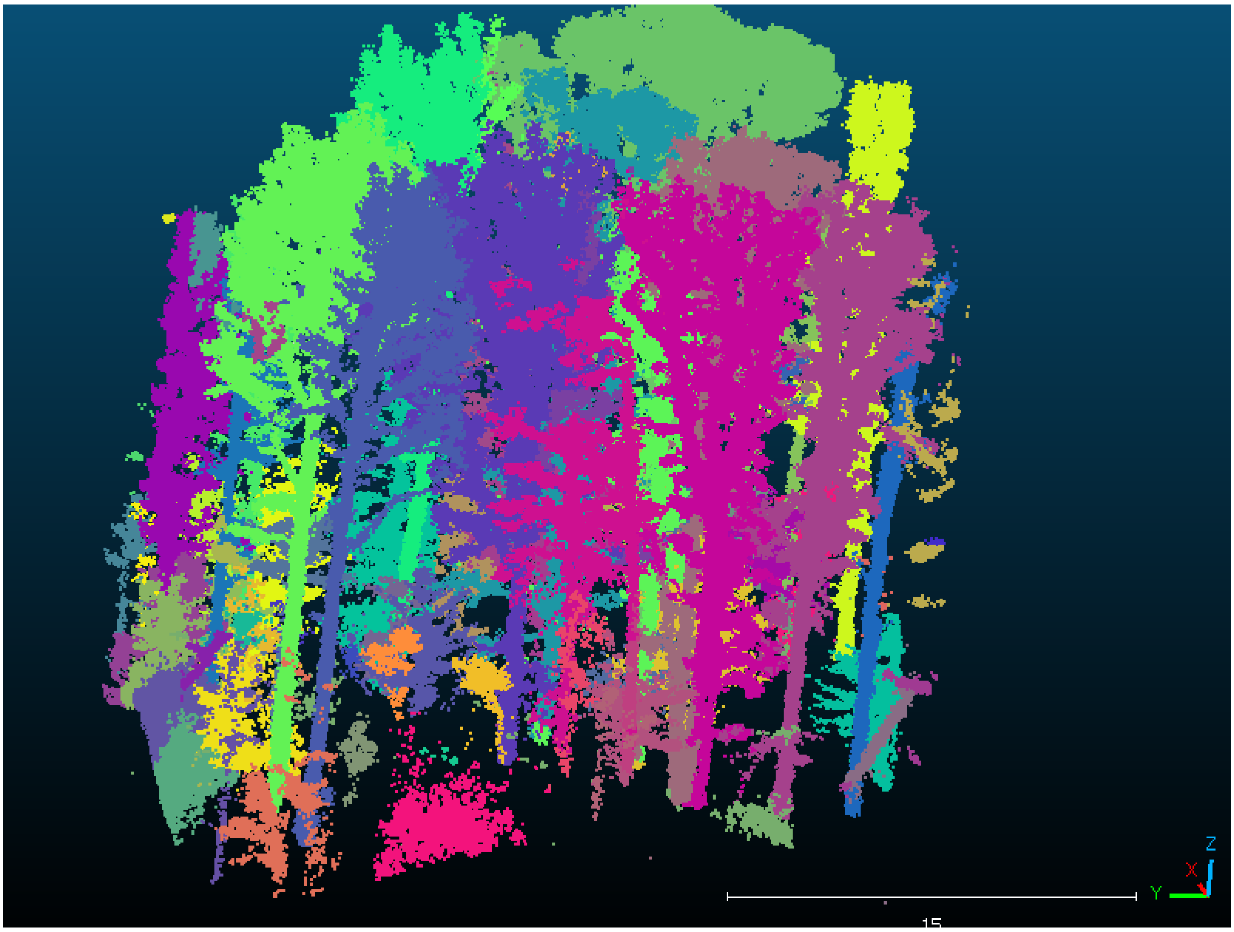


Figure 13: Visual example of single tree segmentation of Geiger mode LiDAR.

Example 2. Single Conifer

Figure 14 below shows a single tree captured with 4 different specifications:

A) tree captured with traditional 6ppsm LML and shows little data that could be used to describe the tree stem, and a vague description of the crown volume could be generated.

B) GML captured from High Altitude at 4,000m. Here the stem can be seen as not being perfectly straight, the crown base, shape, asymmetry and volume is well captured.

C) GML captured at a typical capture height for LML ALS, of 1,100m and shows that the stem structure is well defined, and branch stubs can be seen, as well as an accurate location of a 'kink' in the stem. This point cloud is suitable for describing the location and size of straight sections in a tree suitable for sawlog production.

D) is included for reference and is the result of Mobile Laser SLAM capture at ground level using a Emesent Hovermap device at about 4-15 meters from the stem.

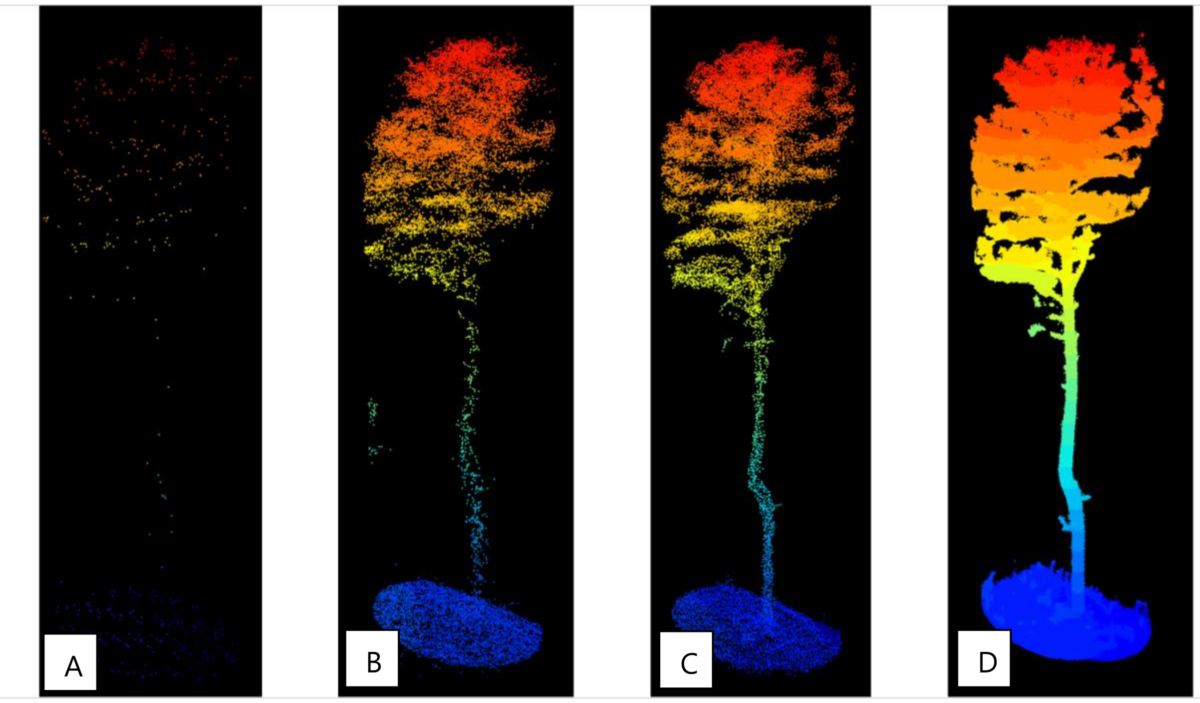


Figure 14: The same tree from four LiDAR collects. A). Traditional ALS 6ppm. B). GML high altitude (~4000m AGL). C). GML low altitude (~1100m AGL). D). Hovermap SLAM LiDAR mounted on backpack.

What does it enable us to do?

Capture of GML at, say, 1,100m across a production forest estate and combined with a reference tree dataset would enable the development of a high quality single tree inventory.

Broadly speaking, once the GML data was captured, DL methods for segmenting trees are the first step, using the reference tree dataset to train the DL model to segment trees and stems from the wall-to-wall GML. This would result in being able to segment out most trees in the estate into separate 'tree' point clouds. The resultant GML 'trees' could then be compared with a balanced and unbiased collection of reference trees that have been cruised in the field or in virtual reality for log products. The field-based cruising could potentially be done after GML capture, processing and segmentation, with field cruisers targeting specific 'tree' point clouds to visit and assess.

Once a statistically valid reference tree collection was curated and cruised, the assignment of the nearest neighbour reference tree for each GML tree should enable results that are suitable and fit for purpose for production forestry in NSW native forest.

Another possible approach is to directly measure the stems after the fashion of Hyyppä *et al.*described above in Direct Measurement of Tree Volumes. In native forest selective harvest operations, the most important contributors to sawlog volume are usually the largest 50% of stems between the heights of 0.3m to about 15m above the ground as these stems are viable for harvest. If these larger cohort trees can be measured directly, at the very least this would provide a baseline validation tool to compare log product predictions from other LiDAR and non-LiDAR inventory methods, such as ABA or traditional sampling respectively.

Acquisition of Geiger Mode LiDAR

There are a few differences with the 3DEO sensor that are worth exploring in the future. Below are some simple summaries of the functions that could be performed for the readers consideration.

Agile Georeferenced Scanning

A primary innovation is 3DEO's patent-pending agile geo-referenced scanning, which directs the full capability of the LiDAR into only specific areas of interest, such as a narrow winding corridor or a campus, and which enables high angular diversity to mitigate shadowing.

3DEO's Agile Geo-Reference Scanning (youtube.com) [3]

[3] https://www.youtube.com/watch?v=9saTWdozGsc

Wide Area Capture

Figure 15 shows an example of a flight plan to capture stem profiles across large areas of the estate. In order to prioritise diversity in view angles it is important to fly at a 2/3 overlap, in opposite headings in order to capture data from at least 6 flight passes and generate 12-18 view angles for each scanned surface. This multi view angle is crucial to penetration of the canopy to cover the subcanopy objects with points.

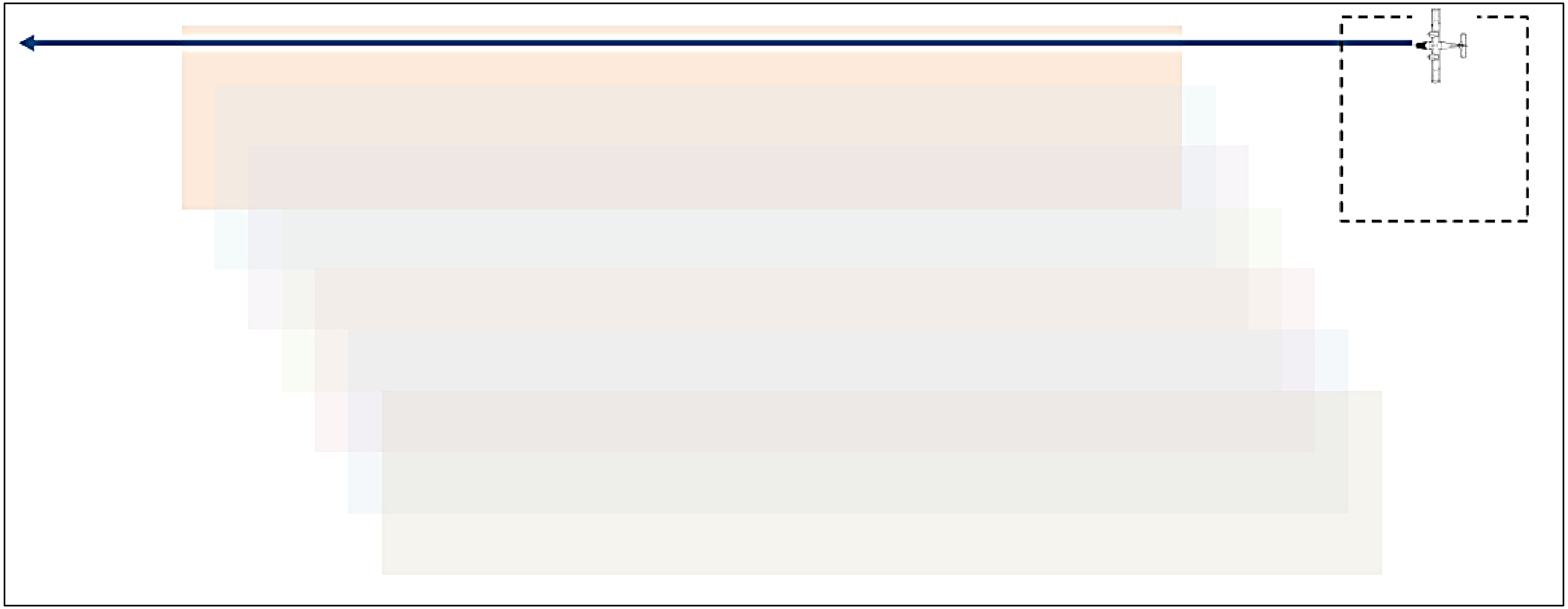
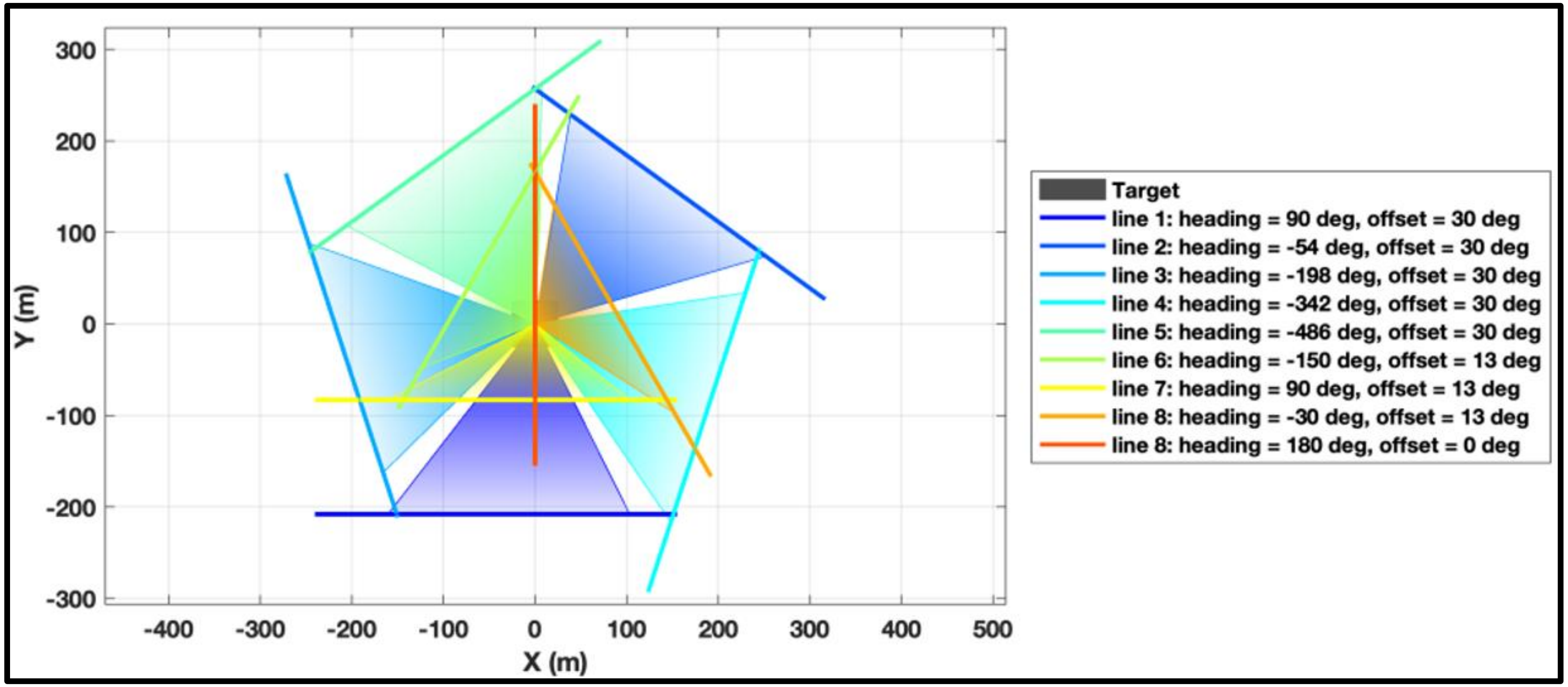


Figure 15: Flight Patterns associated with capture of large area GML.

Targeted 'Plot/Strip' high density capture

For targeting individual 'Plots' for calibration purposes and comparison with TLS data,



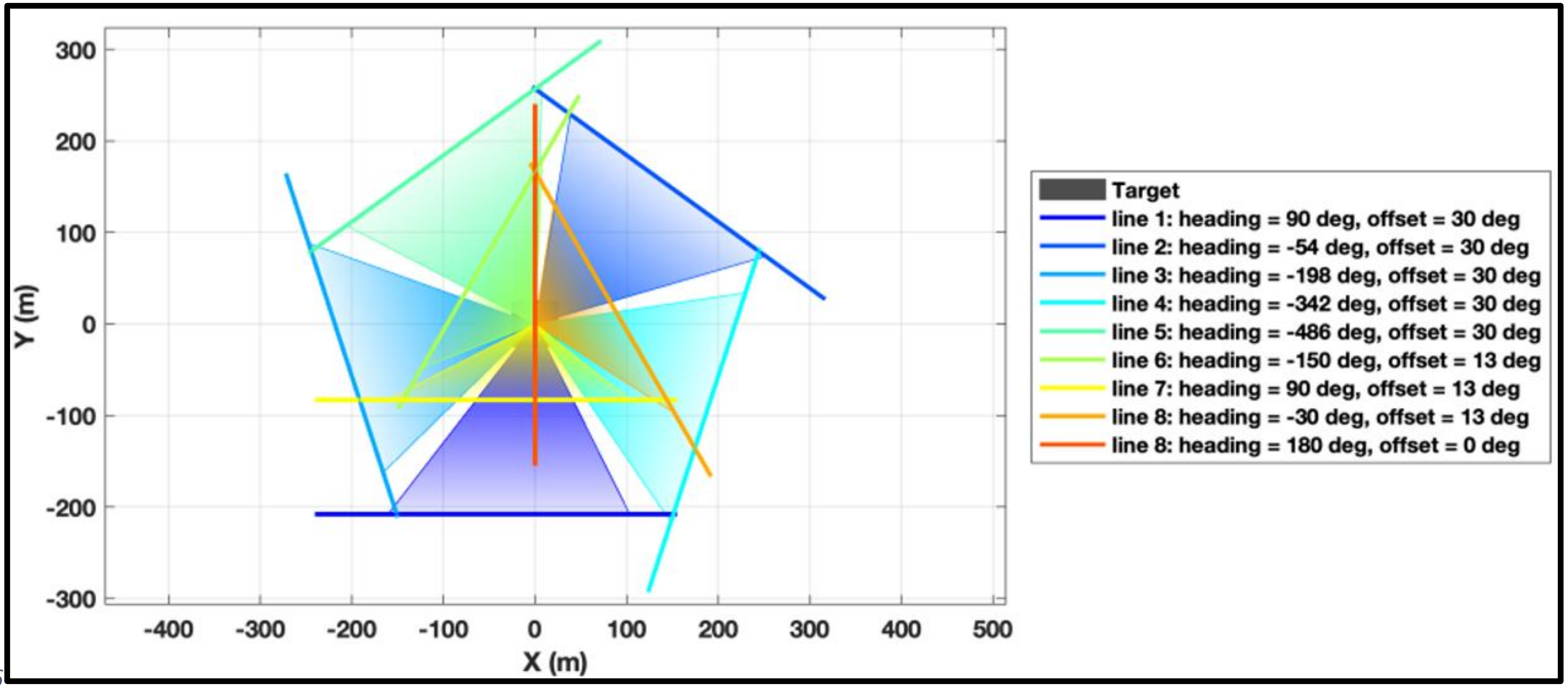


Figure 16

Figure 16 shows a potential flight plan that could achieve superior angular diversity of capture. This flight plan could cover an area of 50 x 50m, capture 10 scans per pass from different angles, contain a 30 degree offset off nadir to target stem and subcanopy strikes, and resulting in a point cloud of approximately 2,500 ppsm, once denoised. This dataset would be equivalent in stem coverage to a Hovermap SLAM dataset captured at sub canopy and could be captured from a light plane at 360m AGL, with multiple plots captured per day.

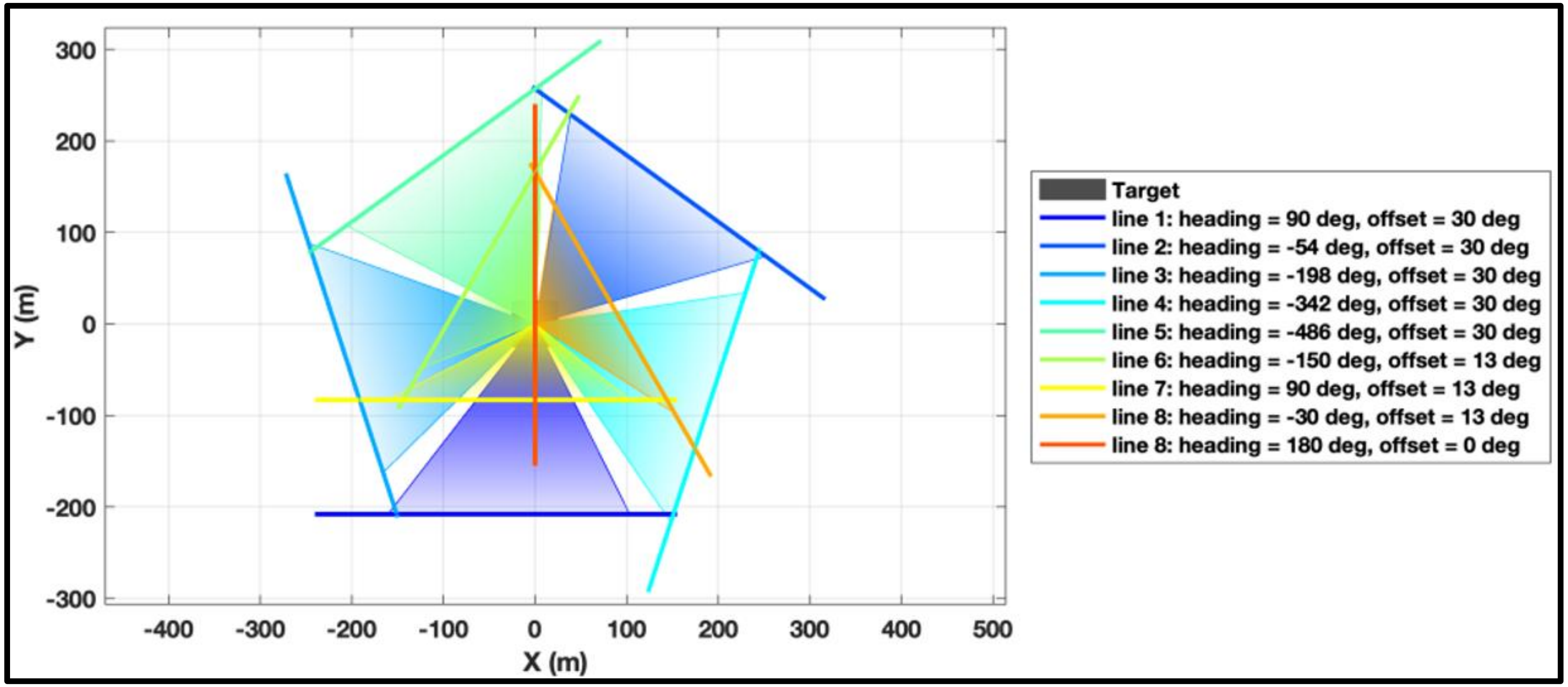


*Figure 16: Capture design for flying a 50*50m plot.*

Appendix 2: Tree segmentation and classification system – ForestSens.

ForestSens, FOR-Instance and ForAInet

As part of visiting Norwegian Institute of Bioeconomy Research (NIBIO), described in Appendix 6, I was introduced to ForestSens a platform that hosts ForAInet, a stem segmentation model, built from the FOR-Instance reference dataset and DL, which shows the most promise for extracting single trees from large areas of dense point clouds.

Description of ForestSens

NIBIO hosts the ForestSens Application, an Oracle platform that houses a range of useful implementations of open-source algorithms that could be used by foresters for seedling detection, species detection and other tools.

There are several tools on this site, which can be demo-ed by the user, with the opportunity to test them. The interface consists of simple drag and drop or file upload interfaces that allow sample data to be uploaded to the Oracle cloud to test the algorithms with user data. Presumably, whilst the platform is relatively young, it is designed as a testing place, before users migrate the underlying open-source code into the users' systems for processing larger datasets. Access to the application can be requested by applying to register at ForestSens.[4]

To encourage its uptake and use it would be good if ForestSens allowed a paid subscription-based approach that enabled users to pay to process larger datasets as datasets are limited to 2GB in size, and hopefully that functionality exists in the future. There are no plans to create a standalone piece of software.

There are several useful tools apart from the Tree Segmentation tools which are shown below in Figure 17Figure 17, and are not assessed or discussed further. I note this platform could be useful source of tools for foresters to test in due course.

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[4] https://forestsens.com/

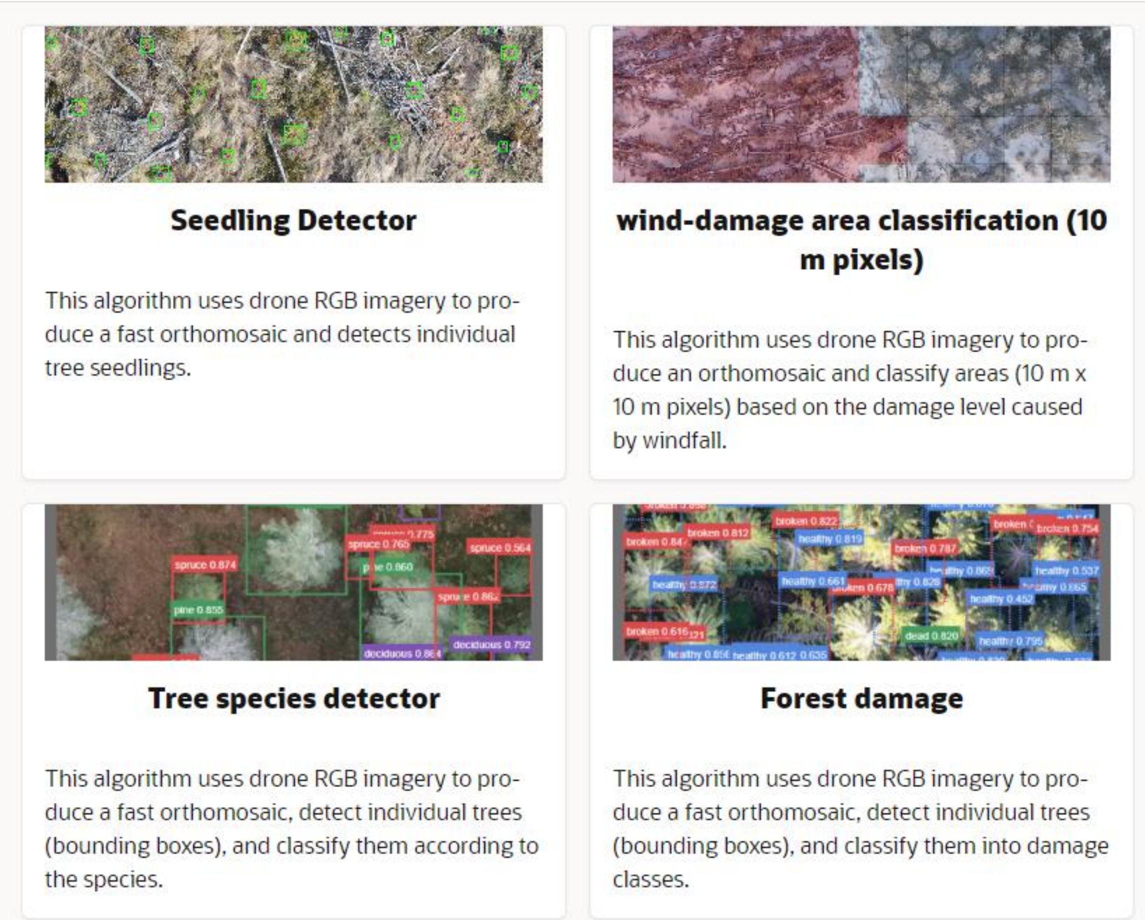

Figure 17:A selection of tools that could be utilised by foresters in due course. The code is open source.

Figure 18 shows the interface for the ForAInet and its precursor SegmentAnyTree.

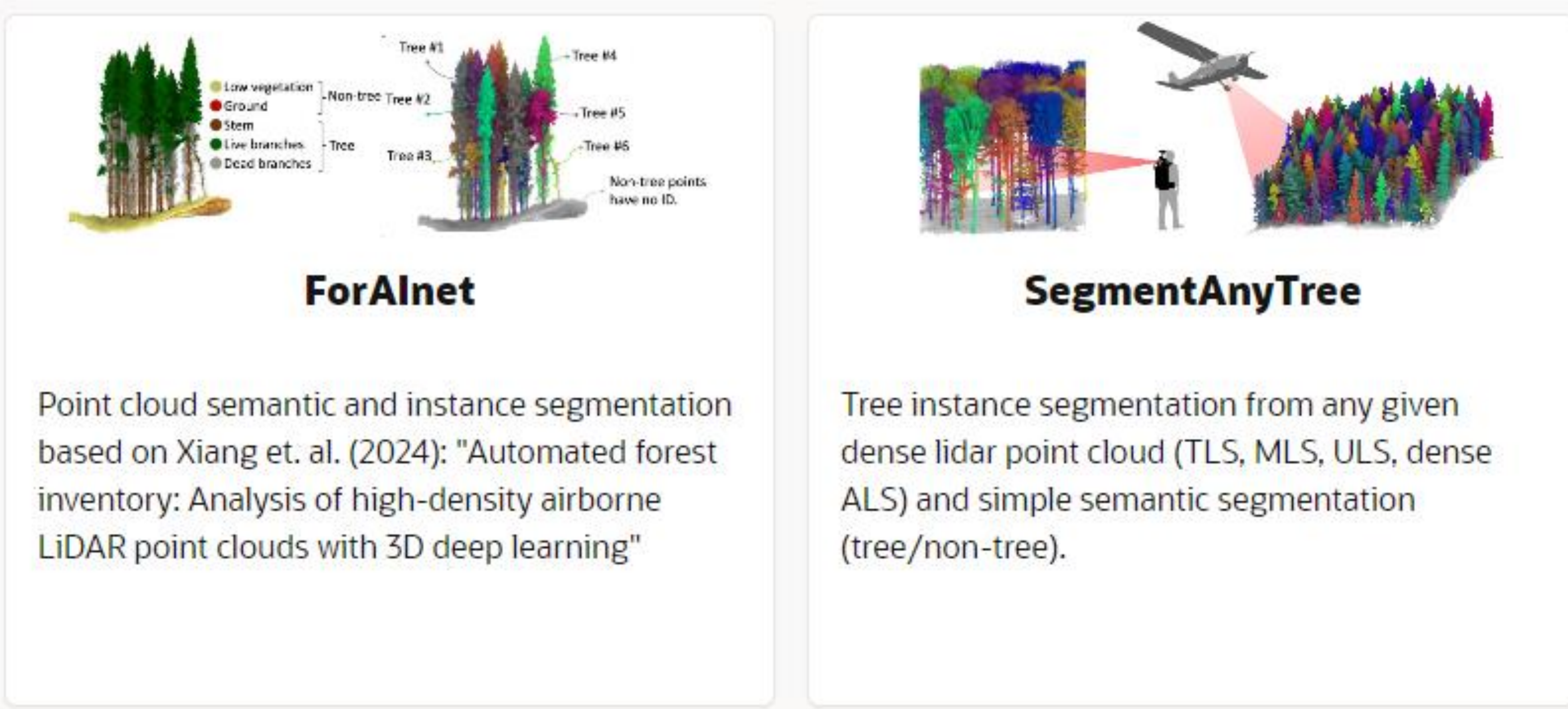

Figure 18:Interface for the Forest Automatic Inventory Neural Network (ForAInet) and its precursor, SegmentAnyTree algorithm within the ForestSens Application

A brief overview of the study and software is provided here:

FOR-instance dataset

The FOR-instance dataset is a dataset of 1,130 point clouds of trees from Norway, Czech Republic, Austria, New Zealand, and Australia. The point clouds were collected from unmanned aerial vehicles (UAV) using Riegl laser scanners and were manually segmented into single tree instances and five semantic categories: low vegetation, ground, stem points, live branches and dead branches. Five different forest types were sampled, in coniferous, dry sclerophyll eucalypt forest and deciduous alluvial forests.

ForAInet

ForAInet is an end-to-end deep learning model for forest panoptic segmentation (semantic and instance segmentation) described in the following paper: *Xiang, Wielgosz, Kontogianni, Peters, Puliti, Astrup, Schindler. 2024 Automated forest inventory: Analysis of high-density airborne LiDAR point clouds with 3D deep learning, Remote Sensing of Environment* https://www.sciencedirect.com/science/article/pii/S0034425724000890.

The critical step that this method focuses on as the most important, is that of segmenting trees. To measure the properties of each tree, one first needs a sufficiently accurate and transferable method to segment the raw scan data into individual trees. Comprehensive labelled datasets like FOR-Instance are an important prerequisite to enable 3D deep learning in support of forest inventories.

The FOR-Instance data set was split into 42 training plots, 14 validation plots and 11 test plots. The training plots were used as input to a 3D convolutional neural network (3DCNN) to label the individual 3D points, simultaneously assigning semantic labels and instance IDs.

The segmentation back-end achieves over 85% F-score for individual trees, respectively over 73% mean IoU across five semantic categories: ground, low vegetation, stems, live branches, and dead branches.

In addition, ForAInet includes learning-free geometric methods that operate on the segmented data to retrieve a suite of forestry-related biophysical variables at the per-tree and per-stand levels. Tree height, crown diameter, crown volume, live crown volume and DBH.

ForAInet was originally trained on drone laser scanning data but is applicable to terrestrial laser scanning data (TLS/MLS) and seems to work well on higher density Geiger Mode LiDAR samples that I have tested.

Examples of usage

To use the software, simply drag a LAS or LAZ file into the location provided in the ForAInet ForestSens interface, give a name and press submit. This file is uploaded to the cloud-based processor and is processed. The model outputs a single zip file with the uploaded point clouds in laz format that in addition to the original fields will include two fields, PredInstance, a field defining the individual tree identifier and PredSemantic which defines the semantic class shown here:
0: Low vegetation
1: Ground
2: Stems
3: Live crown/leaves
4: Branches.

Testing the ForAInet on different Datasets

Example 1: Moist Coastal Eucalypt (Bulahdelah NSW)

Dataset description

This Dataset was captured using a helicopter mounted Optech Galaxy prime+ in 2023 by AAM for forestry corporation of NSW in the growth-plot PNB116 in the Bulahdelah region of NSW, within dense moist eucalypt forest. The point cloud has an approximate density of 2,500 pulses per square metre within a 25-metre radius circular plot.

Results from processing dataset with ForAInet

Despite the structural characteristics of this forest being very different to any datasets in the FOR-instance dataset that the ForAInet was trained on, the segmentation seems to have segmented the plot into tree instances and foliage and branching with moderate accuracy. This is promising since it is a good starting point, from which a model trained with data from this forest type will improve upon when added into the training dataset.

Figure 19 below shows the plot segmented into individual trees, coloured by PredInstance. Visually it looks like most crowns are segmented well, however there are some understorey crowns fused with larger trees, and some stem points are incorrectly classified when there are understorey shrubs/foliage surrounding those stem points.

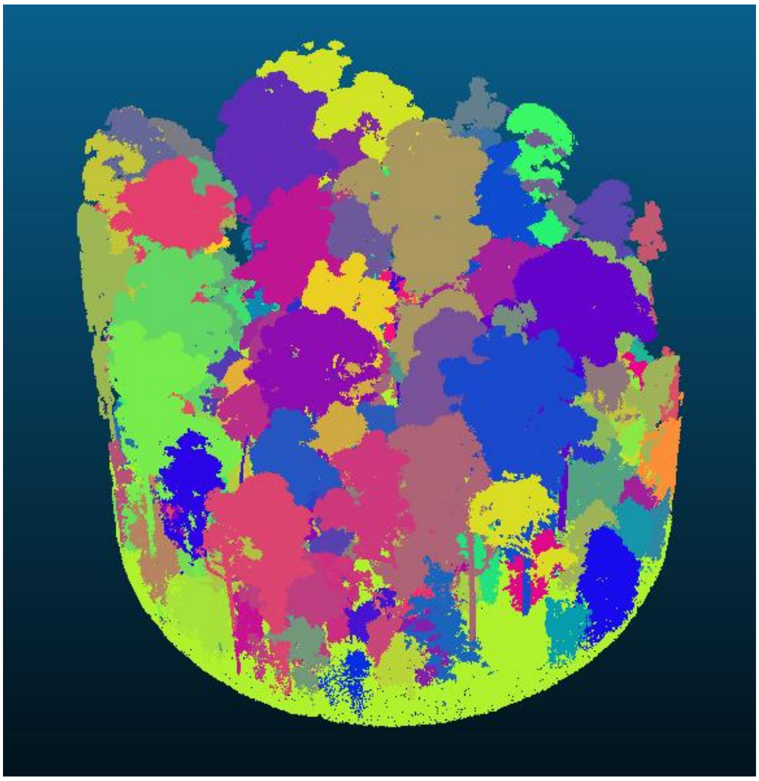

Figure 19: Plot PNB118 having been segmented into tree instances.

Example of individual trees processed.

Tall Eucalypt tree

Extracting an individual dominant eucalypt tree, of about 35 meters in height, figure 4a shows it coloured by elevation, the PredInstance did a reasonable job of assigning points to that tree. There are some strange artifacts however, several meters away from the tree which are not related to the tree but are assigned that trees' pred-instance.

Looking at the classification into stem, branches, and foliage (figure 11b) and then looking at the bole (Figure 11c), it did a very reasonable job of classifying the commercially important part of the stem. From a wood production perspective, this is a reasonable outcome for this tree. The stem volume could have volume and quality metrics applied to it with a level of accuracy that is appropriate for native forest inventory requirements.

In terms of the crown and branch separation, Figure 4d shows that the branches on the bole were well classified. However, there are branches further up into the canopy that are classified as canopy/foliage and not branch, meaning there is some room for improvement. However, to reiterate, it seems a reasonable job was done of not including branches as part of the main bole (the commercially important section of the tree for forestry inventory purposes).

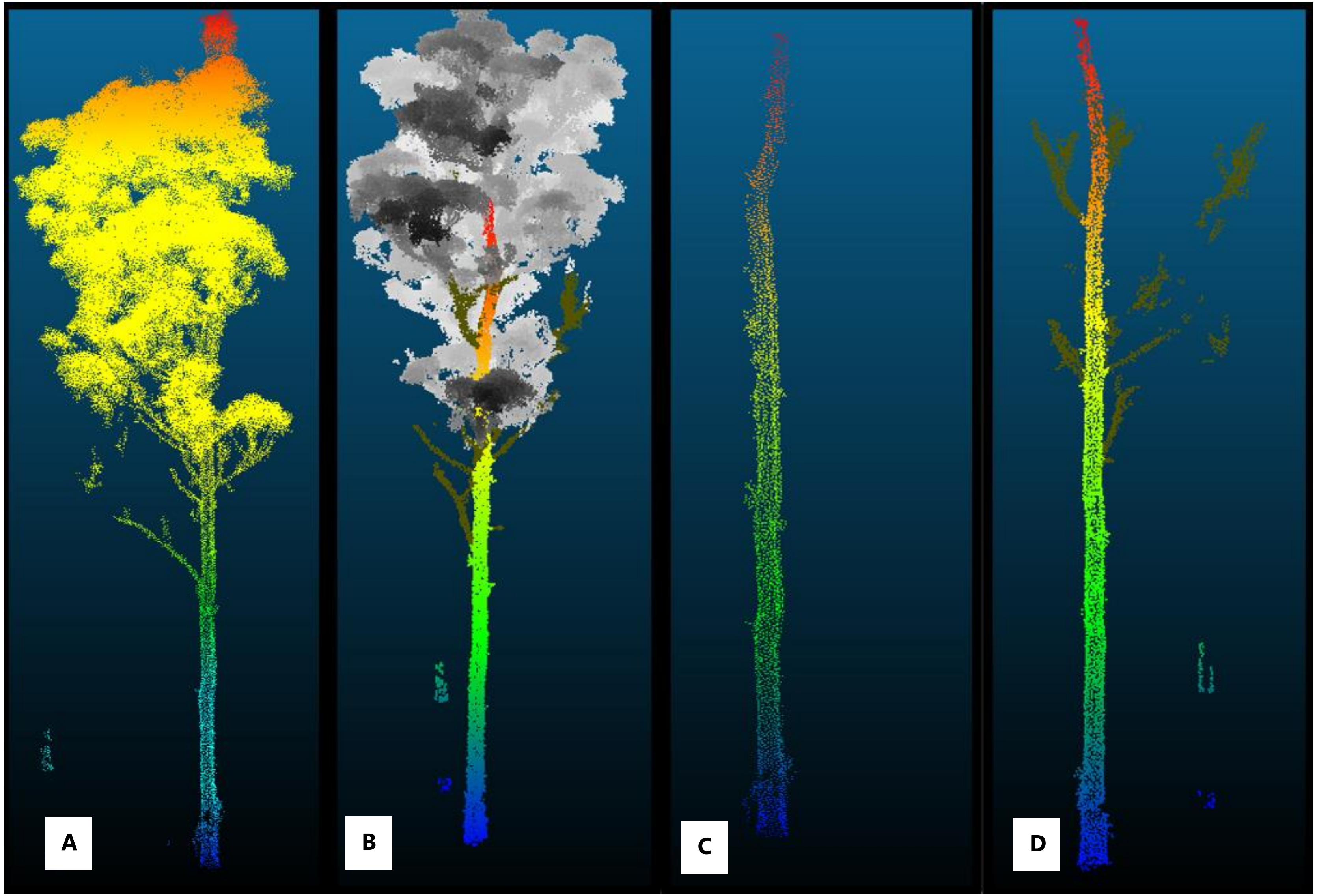

Figure 20: a). A single tree coloured by height above ground; b). The tree segmented into stem (coloured by height above ground), branches (olive colour) and Foliage (greyscale); c). Just the bole; d). the bole and branches

Dead Tree

A dead tree with no foliage was present in the plot, and the PredInstance assigned all the points correctly to that tree, albeit a few foliage points were present which may not be accurate. Interestingly **Error! Reference source not found.** shows that the semantic classification thought there was foliage on the tree, but only a small number of points relative to the tree. I consider this reasonably successful, once again it is not clear without reviewing all the FOR-instance data, whether dead trees were used in the training dataset. Most of the commercial (log shaped) bole is classified as stem.

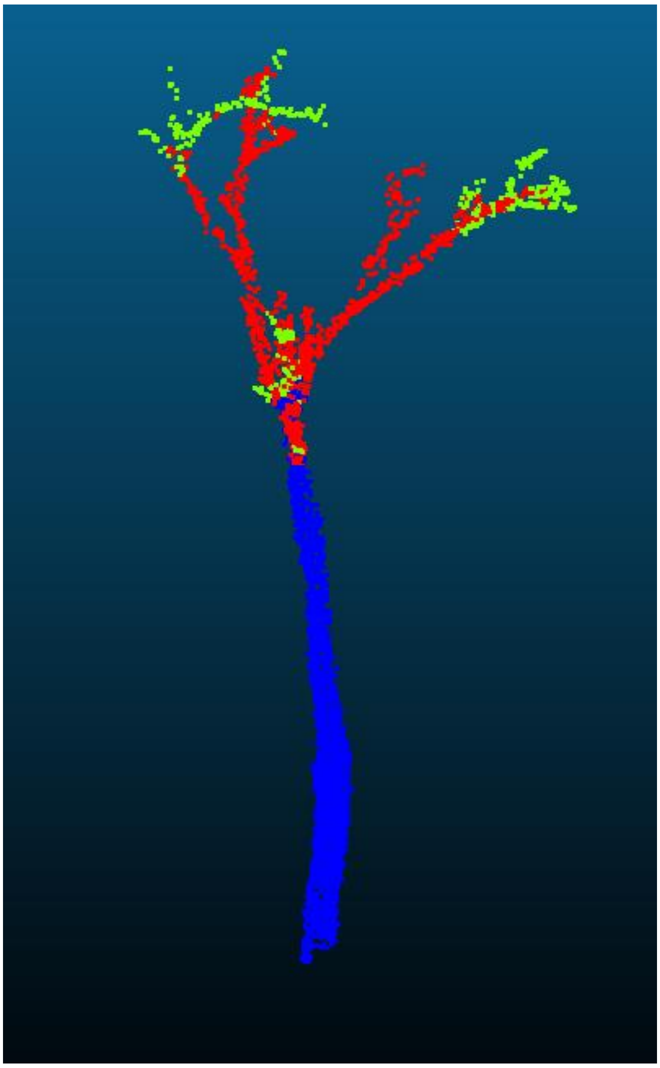

Figure 21: A dead tree of about 15meters in height.

Small understorey tree

A small sub canopy tree close to other trees was selected out of the dataset, and Figure 13 shows that the bole was well segmented out, albeit with a bit of noise around the base of the tree that would need to be filtered out in a second stage classification. Also, given the lack of branch like structures in the canopy (either due to poor penetration of the canopy, or actual lack of good-sized branching in the canopy, the foliage and branching definition is reasonable, with obvious branching at the base of the canopy classified correctly (Figure 13c).

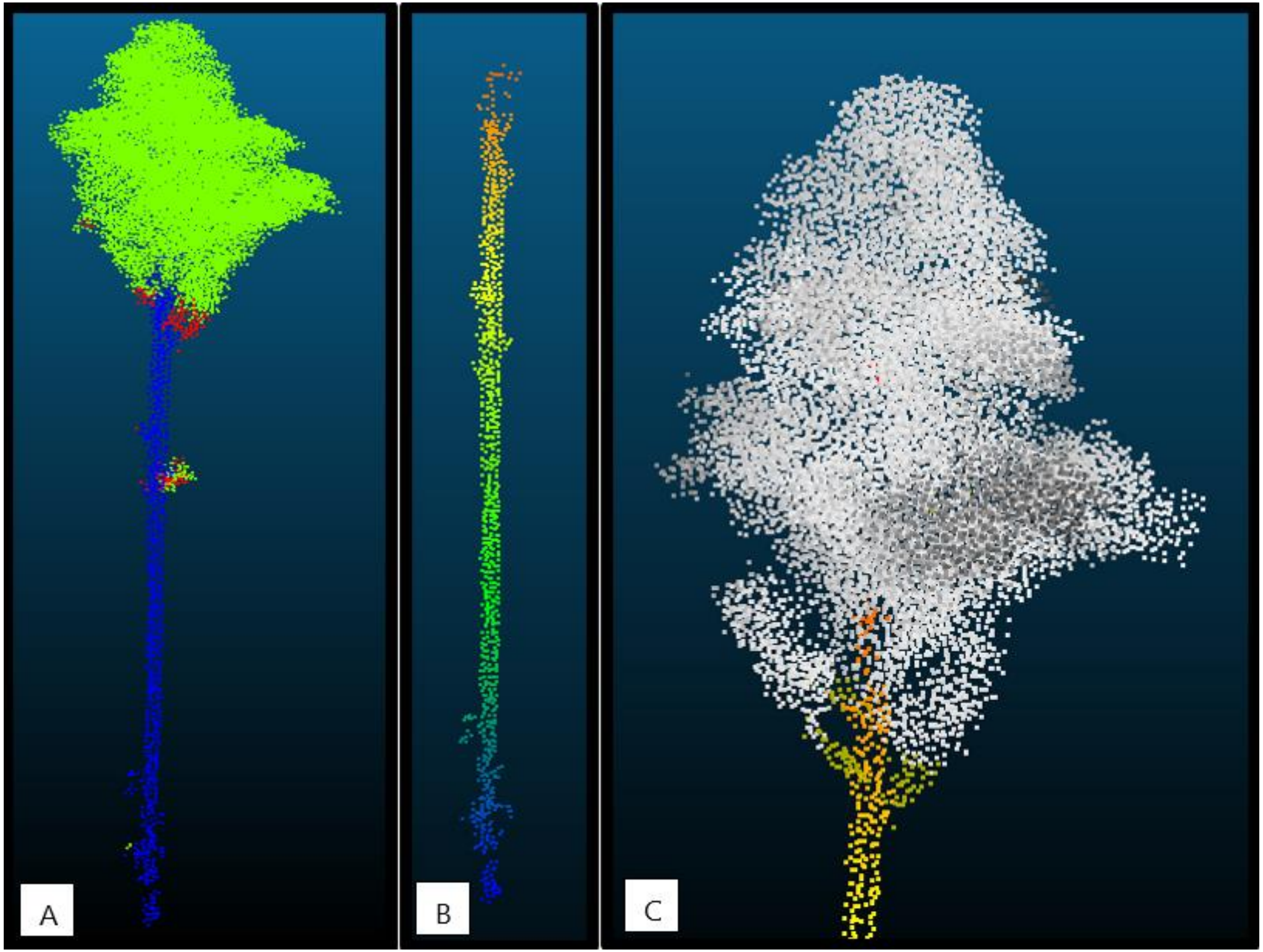

Figure 22: Examples of a small understorey tree, a). bole (blue), branches (red), foliage(green); b). Just the bole highlighted by height above ground; c). a closeup of the canopy.

Segmentation Issues

Grouping of trees into one PredInstance

Several examples of segmentation inaccuracies were observed in the datasets processed, especially the lower density datasets. Figure 23 shows an example of a 22-meter tree (blue) with a 13-meter smaller tree (also in blue to the left side of Figure 23) also classified as part of that PredInstance (i.e. Same tree instance). This data set is lower in coverage and quality compared to the helicopter dataset with a density of approximately 270ppsm. So, it is obvious that high coverage and point density is key to getting a good result.

Assigning Crowns points incorrectly

The example below also shows that the olive-coloured points are assigned incorrectly to the right side of the larger blue tree.

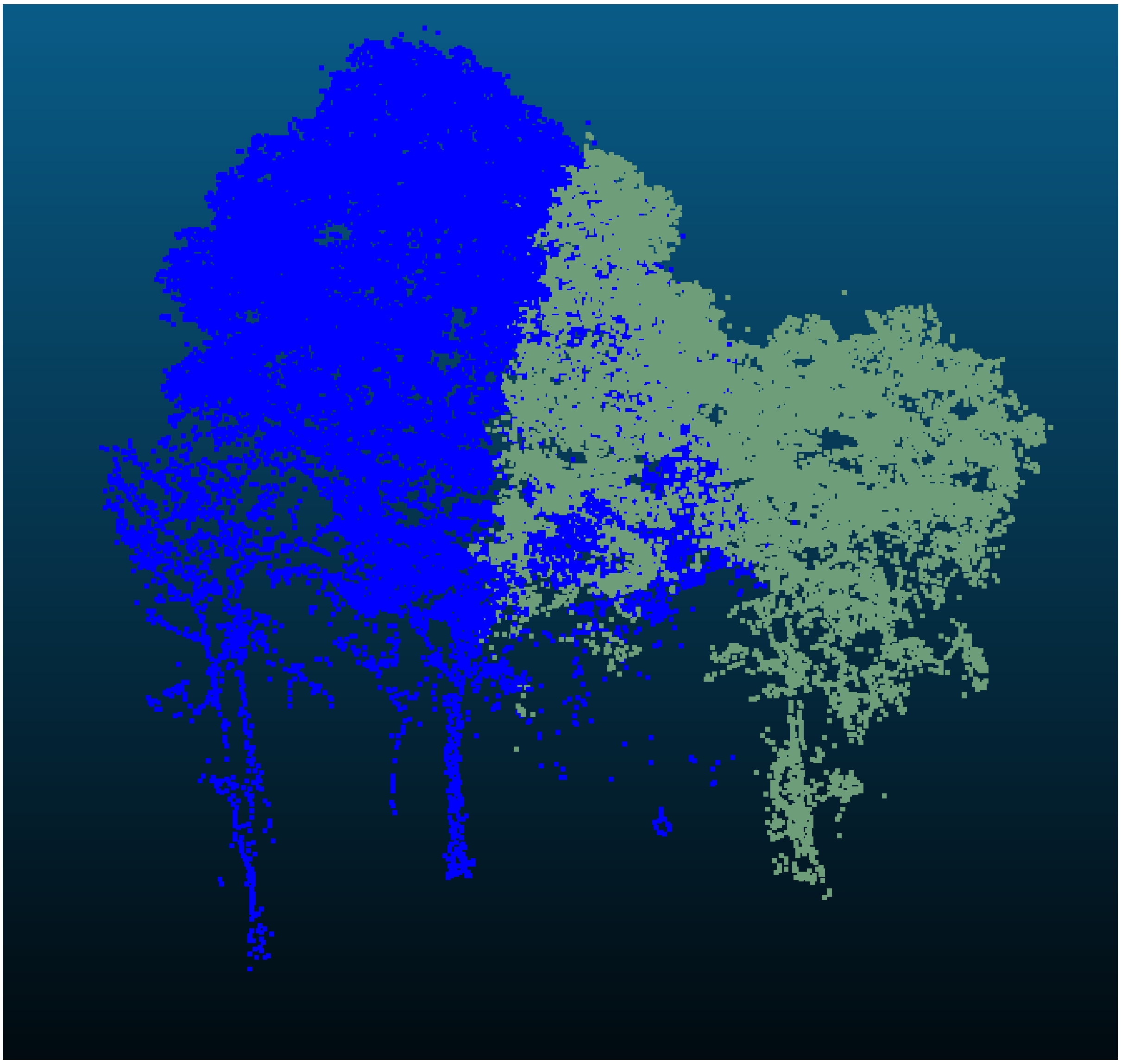

Figure 23: Example of poor segmentation results.

Processing of large datasets

A large dataset of 270ppsm over 32ha of mixed conifer forests was processed in the ForSens application. Figure 24 and Figure 25 below show an example of this point cloud segmented into individual instances and also the assigned stem points.

The ForAInet processed this data easily, and a conclusion was reached that this algorithm would be suitable for processing large areas of high density point clouds. Obviously this would require the algorithms to be installed on a scaleable instance with GPU architecture for processing.

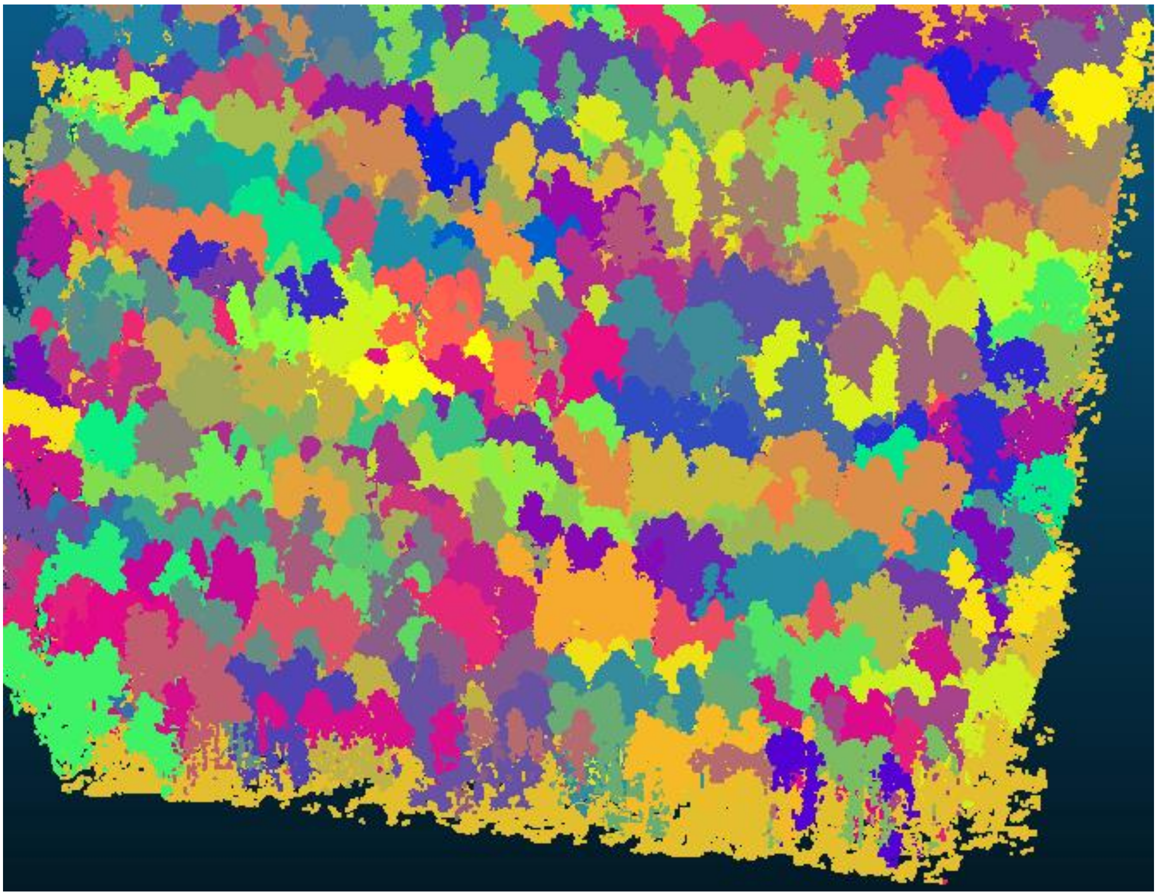

Figure 24: example of the large extent point cloud.

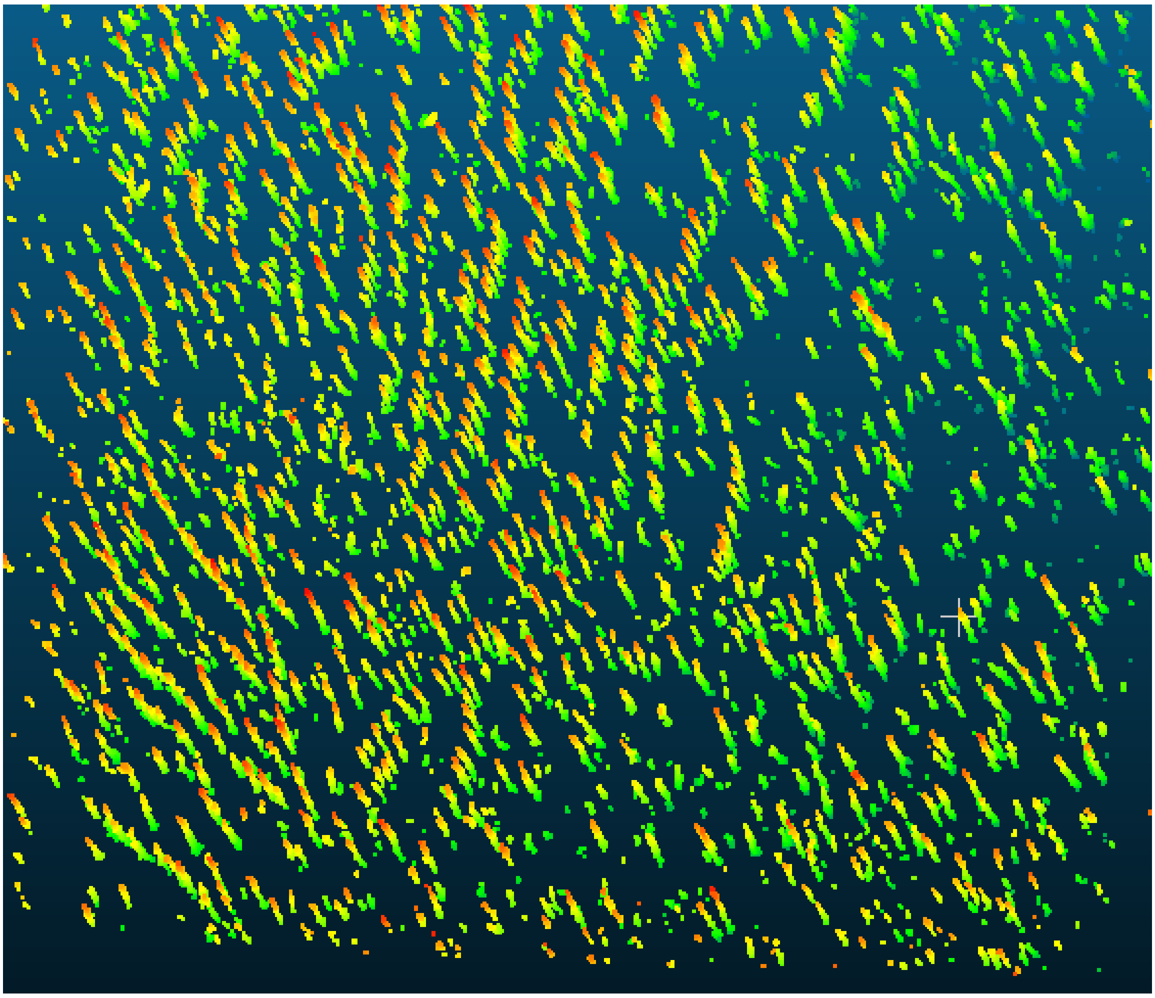

Figure 25: the stem boles highlighted by height above ground.

Appendix 2 Conclusion

The ForestSens platform was used to test segmentation of large point clouds into tree instances and semantic classes. It worked well and is worthy of further investigation and exploration.

Appendix 3: Reference Tree Library

Integral to the training of DL models for both species' detection and STI is the collation of point cloud-based tree libraries. A point cloud-based tree library is a reference collection of relevant trees captured using TLS or equivalent high-density LiDAR.

Globally there are a few examples of open-source reference sets such as FOR-species20k, FOR-Instance and SYSSIFOSS. These are referenced in Appendix 3. The data was generated by utilising TLS mainly, and individual trees were manually segmented into a stand-alone LAS file. The point cloud is sometimes classified into semantic classes such as stem, foliage or branch. A range of statistics is usually computed, such as crown area, volume, DBH, species, crown break height and so on.

The FOR-species20K dataset was used along with a variety of ML and DL techniques to predict species, the FOR-instance dataset was used to train a DL model to segment trees in point clouds, and classify point clouds into semantic classes, whilst SYSSIFOSS has been used for a variety of uses, including in the generation of synthetic point clouds using Helios++.

In the NSW native forest case, to build a STI and to train models to classify species, a reference dataset needs to be created, as none exists currently.

The process could be done in tandem with a statistically balanced sample of plots scanned using subcanopy MLS/TLS. This approach could potentially come up with a representative sample of stems to extract from the plots.

Careful collation of the plots and tree point clouds should be done with a focus on the ensuing coverage across the range of species, log types and volumes, habitat suitability, size classes and location in the landscape, such as position on slope, elevation and soil types. In addition, the coverage of reference trees should represent a range of past management activities given that this influences log products and habitat suitability. An example of this would be to sample in areas subject to past intensive harvesting practices (e.g. clearfelling) and areas where past selective harvesting has occurred.

Once the stems are extracted manually, the attributes of importance to yield prediction should be associated with each tree LAS file. These include diameter in 20cm rings up the stem, DBH, field or VR based classification of log products up the stem, including defect, distance dependent stocking densities, crown break height, crown depth, width, and volume. A range of standard LiDAR metrics should be generated such as max height, bincentiles *etcetera*. This range of tree metrics and attributes will be utilised later in model building to create a STI.

SYSSIFOSS uses a python software package to provide a python library for the storage and sharing of single tree-based point clouds and all relevant inventory and tree measurements.

An example web front end to the dataset is shown at pytreedb (uni-heidelberg.de)[5] and enables any person to search and download LiDAR point clouds for trees by species or other attributes. Figure 20 shows an example of the interface with a map showing the data collection location of the filtered trees. This would be a desirable format to utilise to create an accessible publicly available dataset.

[5] https://pytreedb.geog.uni-heidelberg.de/

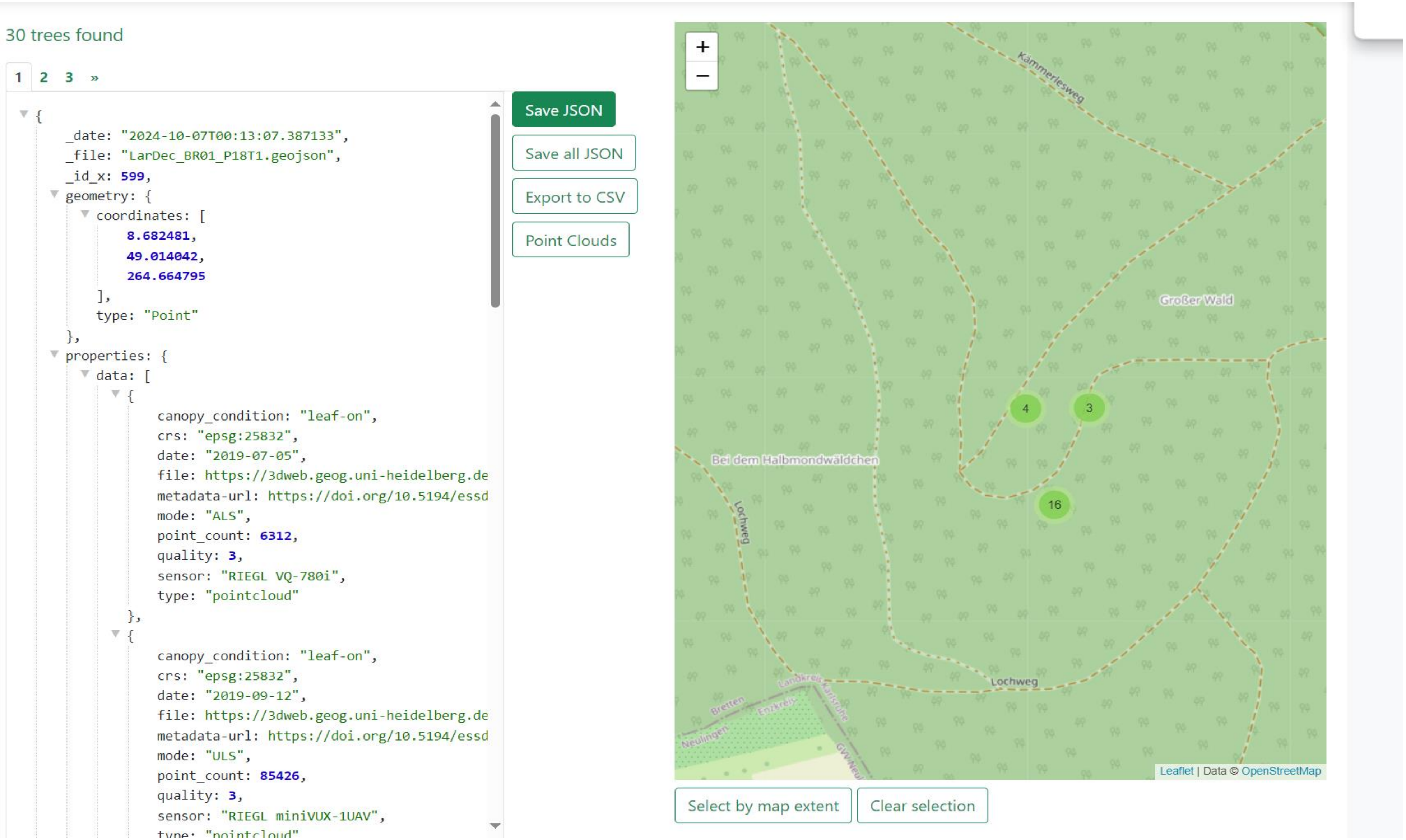

Figure 26: Web front end to access single tree point clouds and attributes.

Appendix 4: Hypothetical trial for progressing a single tree inventory in NSW native forest.

As a result of the Tour and discussions with providers and other industry staff I devised a list of steps required within a hypothetical trial that would expand our knowledge of the accuracy and limitations of STI in eucalypt native forests in Australia. Ideally a substantial FWPA or AFWI supported project or similar would be initiated to explore this, in the same way that a landmark FWPA report PNC305-1213[6] delivered outstanding results and guidance to the forestry industry in 2015.

Field Trial of STI using GML, MS Imagery, TLS.

Figure 27 shows an outline of the main components and actions required to collect, compare, and analyse data to generate confidence in single tree inventory. The broad steps are described below the figure.

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[6] Rombouts J, Melville G, Kathuria A, Rawley B, Stone C. 2015. Operational deployment of LiDAR derived information into softwood resource systems. Project No: PNC305-1213. Prepared for Forest & Wood Products Australia. Available from: https://fwpa.com.au/report/operational-deployment-of-lidar-derived-information-into-softwood-resource-systems/

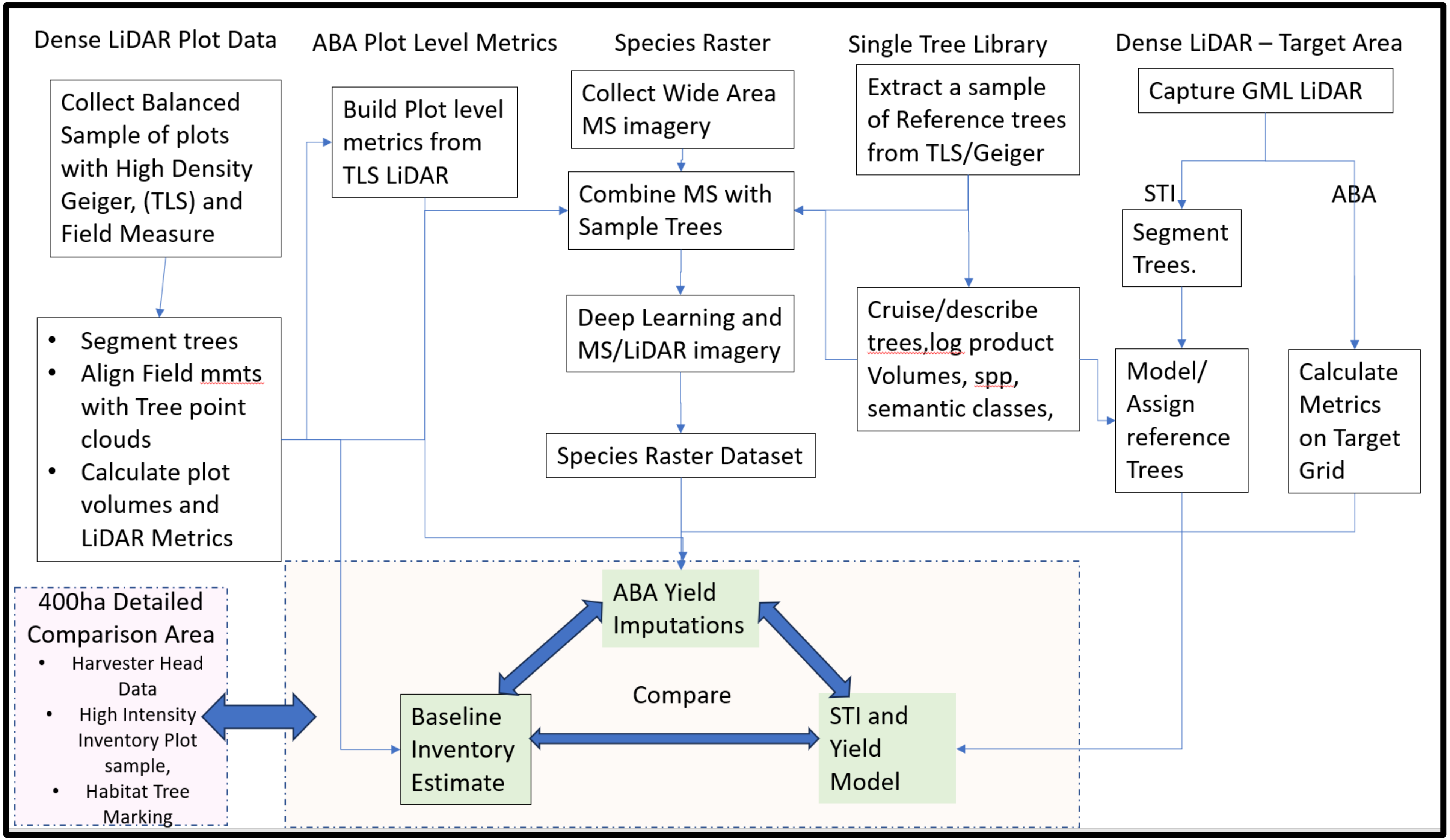

Figure 27: Broad outline of hypothetical steps to conduct a trial to assess accuracy of STI.

Capturing Dense GML over Target Area

Geiger mode LiDAR has the potential to capture UAV-like data that delineates sub canopy structures with the potential for extracting individual arrays from that data set. This GML, based on observed point clouds, should be captured at an approximate density of around 400 points per square metre (or more!) with a high level of view angles. The flying height should be somewhere around 1000 metres above ground.

This data has a size of approximately 60GB -75GB per 1,000ha in a LAZ file.

Generating a sample strategy

A sampling strategy for collecting a sample of high-density LiDAR plots could be generated utilising LiDAR point clouds across an area of interest. Packages are available that can take a point cloud and stratify according to structural and other non-structural metrics to create a new sample or augment an existing sample of plots. An example of this is sgsR a structurally guided sampling (SGS) tool implemented in R (see Appendix X). To do this, a LiDAR coverage needs to exist.

Due to the need for efficient sampling based on *a-priori* information from a point cloud, this step needs to be undertaken after GML has been collected.

The sampling strategy should be designed in such a way that a sample of plots within that strategy are a statistically representative sample of the area of interest and measures of volume, stocking, and basal area, for example, represent a statistically unbiased point to compare other yield generation methods with.

Capturing dense plot data for creating single tree library

Once the sampling strategy and intensity has been calculated, then dense plot data can be collected at these points. The locations should be field measured, with the precise location of the trees recorded. The Geiger mode LiDAR already captured over these areas could easily be segmented into individual trees using existing algorithms to, along with providing their coordinates, height crown size and DBHOB as calculated from the Geiger mode LiDAR, to inform field operators on mobile devices, to assist with measurement in the field.

Once the plots are field measured for forestry and other attributes relevant to an inventory, the field plots should be scanned utilising mobile laser scanning equipment such as Emesent Hovermap.

Collecting multi spectral imagery at each plot and over the target area.

ideally as part of the dense GML capture over the target area, multi-spectral imagery would be captured at the same time at a resolution of 10cm GSD. This capture would cover each plot measured, enabling the clipping of the multi-spectral imagery over each plot and ultimately extracted tree.

Due to the coincidence of the multi-spectral imagery and the GML, only multi-spectral pixels coinciding with the two-dimensional location of crown vegetation need be utilised. The GML can simply be crudely classified into tall vegetation, excluding low vegetation, and the multi-spectral pixels clipped based on this extent.

This means that only multi spectral signals from the actual tree canopies are utilised at a later stage for species mapping.

Generating ABA Plot Level Metrics

From both the wide area GML and the plot level dense LiDAR a series of metrics can be generated representing typical metrics utilised to generate an area-based imputation.

From the plot measured field data, volume and other field measured metrics can be generated. From this combination of metrics an area-based imputation can be performed. Area based imputation methodologies have been well documented, for example, in FWPA project number PNC305-1213[7] and will therefore not be described here.

Generating Single Tree Library

The next step is to generate a library of single trees as extracted from each plot. The trees within the plots will need to be extracted semi-manually, perhaps initially via ForAInet with subsequent tidying an editing of individual point clouds. Ideally, all the trees within all the plots would be segmented out. For a small sample of plots of interest, associated with a smaller or more homogenous error, this may be feasible.

However, for a larger area of interest where there were 300 plots across the area of interest, each plot containing an average of ~40 trees would mean 12,000 trees representative of the area of interest would be extracted. In this instance a balanced sampling of the trees within the plots would be required to select a subset, being representative examples of each size species and log volumes, in a way that maintains an unbiased view of the resultant area of interests. The original representative sample should be used as a benchmark to ensure that the selected subsample of trees is still representative of the entire area of interest.

The points within each tree would need to be assigned to semantic classes of alive stem points, dead stem points, foliage, live branches and dead branches, and linked to the field measurements. The location of trees within each plot should be preserved to enable reconstruction of the plot.

Generating Species Raster

From the extracted point clouds of trees, which contains species labels via matching with field measurements, the foliage element should be matched with the multispectral pixels to associate species multi-spectral pixels to a species label. From this point machine learning techniques could create a species raster. The literature shows many examples of species classification techniques, and this is not described further, not being a novel topic.

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[7] Rombouts J, Melville G, Kathuria A, Rawley B, Stone C. 2015. Operational deployment of LiDAR derived information into softwood resource systems. Project No: PNC305-1213. Prepared for Forest & Wood Products Australia. Available from: https://fwpa.com.au/report/operational-deployment-of-lidar-derived-information-into-softwood-resource-systems/

The resultant species model should be applied to the wider area multi spectral capture to classify pixels into species groups. For the most part in native forest eucalypts, the most important objective is to distinguish non eucalypt from eucalypt species and into subgroups of eucalypt: such as *Eucalyptus*, *Corymbia* and *Angophora* genera. This is low hanging fruit, and the potential to utilise existing aerial photography interpreted yield association group mapping as input could facilitate the classification of trees even further into stringy bark, iron bark, spotted gum and blackbutt species for example.

Extracting Tree instances from the Target area point cloud

The Single Tree reference datasets for the forest in question, should be used to retrain the ForAInet models (on local instances obviously), and then the model should then be applied to the point cloud to extract stems from the wide area point cloud. For 400ha this task would not take very long given the experience of the author if the LiDAR tile sizes were appropriate. This is a topic/ research project on its own.

Generating STI

Combining the Single Tree reference point clouds, along with the attributes and metrics generated for each, models could be built based on this data, in order to apply to the single tree, point clouds that were extracted from the Wide area point cloud. This is also a topic/research project on its own.

Comparing Standard Inventory, ABA Yield Imputation and STI Yields

Comparison of the different yield profiles from Standard, ABA and STI are relatively straight forward. The difficult question is how you conclude that an inventory is fit for purpose. In NSW public native forests, the current inventory and yield generation processes result in very low accuracy volume predictions, albeit, potentially not biased. The comparison of the three inventories with recovered volumes from the 400ha detailed study area would be a good start in evaluating the fitness of purpose of the different yield generation methodologies. It may well be that the STI could be accurate for certain forest types, and ABA based yield profiles need to be generated for forest types that are not well suited to STI, thus creating a hybrid inventory. This is recommended as another topic/research project that should be undertaken.

Appendix 5: Outline of Digital Twin concepts

Highly detailed Digital Twins (DT) promise to revolutionise the accuracy, planning processes, transparency, and education around forest management activities. The following section attempts to describe DTs and how they might apply to forest management in Native Forests. It is simply intended to provide a means for readers to think about how they might interact with a DT and how they might start to resource the construction and maintenance of a DT.

A DT could mean many things to many people. The focus here is on DTs in relation to forestry, STI and remote sensing.

Key Concepts of a Digital Twin

A key concept of a DT is that it is not just a digital representation of a forest. A spreadsheet of inventory volumes assigned to forest stands on its own, is a digital representation of the forest. A dense point cloud collected at a single point of time that describes the diameters and sizes of trees is also just a digital representation.

What makes a DT different to a digital representation of a forest is the following:

- It is not about technology or product, but reconstructing reality in as high accuracy and detail as possible/suitable for end uses.
- It has a level of detail both spatially and temporally, that ensures that the real world is represented accurately.
    - It must be to scale and of a known precision.
    - If one is concerned with individual tree assets, then the spatial accuracy needs to be accurate enough to locate trees.
    - If you are concerned with logs in tree, then spatial accuracy needs to be able to describe location and size of logs in trees.
    - The growth of trees and logs in trees occurs over long-time frames and needs to be tracked, so temporal coverage of the entire life cycle of each tree asset is required.
- A concerted effort to connect the real world to the virtual environment via data connections is required to ensure that the physical and digital versions stay in sync over time. For example:
    - IOT sensors feedback the real time condition of the forest environment such as soil moisture, temperature, tree diameter growth and this is updated in the virtual representation.
    - Accurate measurements of tree and log locations and sizes from harvesters in the field update the tree and log asset data of the tree, to continuously improve data accuracy.
    - This process is reliable and is part of the design framework of the DT.
- Changes in the real world are used to update what happens in the virtual environment. For example:

    - Increases in soil moisture, nutrient status result in increased growth of the stand.
    - Actual harvested stems are removed from the DT and the effects of the harvesting on the surrounding environment, such as light availability, water use, competition is updated.
- Changes in the DT influence what happens in the virtual world. For example:
    - A planner using a virtual Interface could specify a harvest operation.
        - Specify which trees are harvested.
        - Specify the retained trees.
        - Harvest machine/s follow the digital plan.
- An advanced DT responds to environment and makes systematic changes automatically:
    - Monitoring via IOT might indicate nutrient deficit, which triggers an automated application of fertiliser via unmanned robotic vehicles.
- Positional data of moving assets interact with DT assets of interest – e.g. trees, watercourses, for:
    - Integration of real time machines, field workers into the DT
    - Viewing in real time.
    - DT assets interacting with each other can trigger an action. For Example:
        - Worker moving within 10meters of a dead tree asset triggers a warning on the workers personal device.
        - Unauthorised worker moving within 40meters of a working harvest machine triggers the machine harvest head to shutdown via remote shutdown protocols.
    - Delivers advanced health, safety, and productivity monitoring.

Digital Twin Forest Example

An example of a DT for a forest asset is described below.

There are usually three main components or layers that DT can be broken down to:

1. Underlying Data
2. Computing and Analysis Layer
3. Visualisation and Interaction Layer

Layer 1: Underlying Data

For a forest asset this involves the following examples of data:

1. LiDAR Data describing
    a. Terrain,
    b. Vegetation
        i. Shape and size of stems, branches, and crowns.
2. Spectral Imagery describing

        i. High level imagery (human readable context/information)
        ii. Spectral signatures
3. Modelled Data
    a. LiDAR/imagery/data modelled:
        iii. Terrain models
            1. Hillshades, digital Elevation Models
            2. Slope,
            3. Watercourses and drainage lines
            4. Soil
                a. Types
                b. Fertility/Quality
                c. Erodibility/compaction
        iv. Trees
            1. Locations
            2. Species
            3. Stems
                a. sizes
                b. shapes
                c. Derived 'cylinders' within stems describing log products.
            4. Non-Stem components
                a. Type (leaves, branches)
                    i. Component qualities
                    ii. Nutrient status
                    iii. Wood Stiffness
                    iv. Flammability
        v. Fuel
            1. Size
            2. Flammability
            3. Location/stratum
            4. Continuity
        vi. Visual Models
            1. Gaussian Splatting models showing detailed texture rendering of objects.
                a. Enables remote sensed description of defects and features within stems/trees that are shown via surface colouring rather than structural shape properties.
4. Climate data (past, current and future)
    b. Rainfall
    c. Temperature
    d. Evaporation
    e. Wind
    f. Humidity

   g. Evaporation potential
   h. Weather 'Events'

Layer 2: Computing and analysis Layer

1. Growing trees
   a. Input neighbourhood competition.
   b. Input weather/climate variables.
   c. Respond to tree removal due to disturbance.
   d. Predict effect of individual tree removal in growth model
   e. Simulate ingrowth of seedlings
2. Event based modelling.
   a. Responding to harvester-based tree removal Via sensors, GPS and feedback to DT (remove tree in DT)
   b. Post Fire seedling regeneration.
3. Simulate snig based soil compaction.
   a. Based on machine tracks, track types, soil type and weather conditions
4. Capture and represent fire effects. For Example:
   a. Remove fuel in DT in response to actual fuel reduction burning.
5. Simulate fuel levels and fuel metrics.
   a. In response to harvest, wildfire, fuel reduction methods

Layer 3: Visualisation and interaction layer

1. Stakeholder can view harvesting/regeneration.
   a. In real time
   b. As per predicted future growth and harvest
      i. At landscape level
      ii. Local level

      - See post-harvest stand conditions.

      iii. Tree level
2. Planners can simulate the harvest of a Harvest unit.
   a. Demonstrate harvest pre, during and post conditions to regulators.
   b. Regulators can sign off on digital twin plans and audit data captured within DTs post-harvest.
3. Complete visibility of all moving assets and stationary assets
   a. All authorised personnel within and outside of vehicles
   b. All vehicles and plant
   c. Fixed structures
4. Safety monitoring of assets
   a. Fire events.

   b. Within the context of an accurate representation of forest/fuel
      i. See escape routes and adjacent fuel loads.
5. Digital twin can guide users within forest.
   a. Using AR
      i. Visualise fuel around them as calculated in DT.
      ii. Directions to locations/escape routes
      iii. Visualise log products in trees.
      iv. Visualise assigned habitat retention trees.
      v. Guide Harvest operators to follow set plan as determined by planners via in-cab screen or AR.
   b. Gaussian Splatting
      i. Highly detailed visual model of the forest for intuitive interpretation.

Appendix 5 Conclusion

The non-exhaustive structure of digital twins with examples as set out above is simply a guide for readers to think about how they would interact with a digital twin, and even, start the process of building one.

The current model of managing native forest harvesting in NSW could be described as a digital twin, however it is not necessarily at the level of detail and connectivity that could deliver an advanced digital twin and the commensurate benefits.

Capture of high-resolution LiDAR and Imagery is the first step. However, this data should be captured, processed, and stored within the bounds of a Digital twin context.

From discussions with various researchers and practitioners on the Gottstein tour, it became apparent to me that the future of forest management will rely heavily on highly detailed digital twins.

Appendix 6: Gottstein Project tour details

Foresttech (2023 New Zealand) and Remote Sensing Cluster Conference

Key learning points

- *Good quality STI can successfully be done right now if the density of the data collected is high enough.*
- *Drone LiDAR using DJI L1+ Sensors are a great place to start to test STI on smaller extents*
- *Accurate results in Eucalypt Plantations are already being produced in Pulp Regimes- more work required to apply to pruning regimes.*

Several presentations were relevant to STI at this conference. I met and discussed STI and species detection with a range of conference delegates.

Two presentations were particularly relevant:

1) Sam West from Interpine presented on thinning inventory, where RGB was captured via drone to create accurate Individual Tree Detection (ITD) points and heights for a young age pine plantation. It showed what capturing high resolution data could achieve. The tree height measured was used to impute diameter of trees and essentially grow on as an STI and simulate when/where to prune and predicted pruning costs.

2) Perry Han from Interpine presented a drone and hovermap based single tree inventory. A relatively cheap DJI L1 drone-based LiDAR scanner scanned a eucalypt plantation and then scanned with Hovermap and extracted 455 trees from the point cloud and matched them with field measurements. Trees were segmented from the point cloud and a single tree imputation was performed, which was shown to be within 6.5% of the actual recovered yield for two individual stands compared. This is a great study and should be replicated in Australian plantations and Native forests.

Skylab Global – Hamburg, Germany

Key learning points

- *Perfection in every 'square meter' of a seedling/stem map raster is not required, as it is overcome by the advantages of census style measurement as opposed to sampling theory.*
- *Perfection is the enemy of the good when it comes to changing practices from a sample theory method of measuring to census style approaches.*
- *Foresters need to accept imperfection at the grid cell level and focus on understanding trends and patterns.*

Skylab Global is a software company based in Hamburg Germany. For several years Skylab has been developing fast turnaround mapping and data products that cover the full growth cycle. The company was awarded the "Best Forest Management AI & Aerial Data Analytics Specialist 2021".

The analyses that they specialise in include:

- Forest damage mapping
- Multi-Temporal Forest Health monitoring,
- Seedling stocking counts,
- Stand density maps.
- Species mapping.

I am interested in Skylab Global for their ability and experience in machine learning to harness imagery from drones or satellites, along with reference plots to create relevant mapping and data solutions for Foresters.

One of the questions that was raised during discussions with Skylab, was the required level of detail. One of the challenges is that forestry staff often don't understand the difference in accuracy of having a whole of plantation map versus plot sampling in the field.

For example, with seedling maps there are often some areas where seedlings are obscured by weeds within a plantation and it is the tendency of foresters to focus on the five to 10% of a plantation where this stocking count isn't as accurate relative to the rest of the plantation without realising that traditional plot sampling, very often would not likely have even sampled these areas.

A key challenge to face is the ability to convince Foresters that early versions of STI may be sometimes less accurate in some specific spatial locations (i.e. where there is thick vegetation etc) but having wall to wall coverage could be superior to sampling if overall it is unbiased.

Norwegian University of Life Sciences (NMBU), Oslo Norway

Key learning points

- *Norway has a national inventory system that is shared with lots of stakeholders. A data sharing platform that shows the volume, value, harvestable areas, ownership a new other mapping products for all forest stakeholders in society is an enviable position, which would deliver many benefits in Australia.*
- *The technology and modelling focus in Norway Forestry Cooperatives is satisfied with the current level of technology and do not see a need for more intense measurement with LiDAR yet. That is, they have a fit for purpose approach that suits their forest types and industry needs. This approach is different to that to that which I am interested in focusing on going forward for modelling single trees inventories in Australia which is for largescale dense LiDAR collection*
- *Harvester head data is a very important part of the puzzle which can be used to retrain models based on measured data, validate your tables, and new systems can collect extra information about trees/property boundaries without necessarily chopping them down such as habitat trade status or forest stand boundaries.*

NMBU is the Norwegian University of Life Sciences. I visited the Forest and Renewable Energy Section where I met with Terje Gobakken, Hans Ole Orka and Erik Naesset. These researchers pioneered the implementation of LiDAR based inventories. The local forest grower's association also attended a brief discussion.

Discussions in Oslo centred on my presentation of single tree inventory and dense LiDAR data capture performed in Australia to date and what type of LiDAR Inventory systems Norway conducts.

Currently in Norway, most of the forests are privately owned with an average property size of 30 hectares.

The government collects 2-5 pulse per square meter LiDAR, and this is used to do localised stratification and applying regression models to the strata to produce estimates of total harvestable volume.

There is little segregation of volume that occurs in this forest, and harvesting is mostly heavy cutting (akin to clear cutting) and replanting.

There is a data sharing approach where the maps of the landowners' volumes, harvest boundaries, and so on are publicly available and shared between the different levels of landowners, wood purchasing entities, and forest grower's organisation. This is impressive and enviable to have such open data shared among stakeholders.

The forest grower's organisation is only one part of the government that decides on what density of LiDAR is generated, and LiDAR is multiuse across different government functions.

When discussing single tree inventory, large datasets, feature extraction and so on, it became clear that the organisation, and indeed the researchers in NMBU were not anticipating that it would give them any further benefit and were satisfied with the current approach of regression modelling of volumes and yields.

Single tree inventory is rarely utilised. From what I could understand, the reason for that is because it has been shown to underestimate volume in studies done in Norway forests.

Norwegian forests are completely differently structured than Australian native and plantation forests where there are large price differences for different products in the trees. In Norway, there is only a small price difference between small logs and large logs. Most trees are relatively small anyway. Therefore, a simpler and easily explainable process is fit for purpose.

It is interesting to think that there may be future requirements for prediction of habitat trees, identifying future natural forest set asides, and perhaps a transition to selective harvesting. These may be imposed on the forest owners from external political pressures, both domestic and from other countries in the EU and may necessitate more detailed and nuanced data and models than currently exists.

As an example, one topic studied in NMBU is focused on predicting habitat trees using remote sensing. It became clear that using denser LiDAR to do this may not be on the horizon. Why? because the government only collects 2-5ppsm LiDAR, and all studies seem to be guided to try and utilise the available data rather than designing a more optimal approach using different, higher density data sources. From looking at the studies predicting the probability of habitat trees at a broader level, it could be done using the coarse LiDAR, but more precise modelling of future Habitat tree retention requirements and current habitat tree locations, would require more dense data at least as a bridging model to scale to broadscale lower density data.

Additionally, discussions centred on future laser scanning technology such as Geiger Mode LiDAR and the ability to acquire more dense point clouds. However, the interest of the forest growers and researchers was still focused on collecting at the same density of data but for a lower price per hectare.

All in all, NMBU was interesting to look at the history of STI as researchers there pioneered the STI methods, however, there was little research immediately applicable to my topics of interest.

Other topics discussed

Harvester data as a source of validation and training data

Harvested data is being used to collect more and more information about the forest in Norway. Rather than just rely on plot level measurements by inventory crews to train models to perform imputation, there was discussion about how harvested stands could be used.

The sampling strategy is not 100% clear but as harvest age stands are cut, the relationship between the log products recovered, the size of the trees all collected by the harvester (GPS is submeter accuracy on harvester) can be related to the point cloud that was collected over that location and this data used to retrain models.

This is an excellent Idea when clearcutting is practiced, however in Australian native forests, clearcutting is not practiced (in any scale). If only part of the forest is cut, and the harvest prescriptions are changed to suit the forest type, it was unclear how this methodology could provide meaningful predictions.

Another interesting discussion was around the use of the harvest machine, which is always in the forest, to collect more information about the forest and boundaries.

The harvesting machine standard for data (StanForD) has been modified for the user to be able to record non log production data without having to make a machine cut. This means that putting the harvester head against a tree or object allows the attributes of that tree/object to be recorded (by the harvester operator) and the location of that tree/object recorded.

For example, harvest machine operators could record object locations such as retained habitat trees, or boundaries to properties where the harvester notices a difference between the mapped boundaries on the GIS and the actual boundaries that the harvester is seeing "on the ground". This could be fencing lines, private property boundaries and stream side retention boundaries. Natural hazards such as stags or dangerous terrain could be recorded as well.

This data can be fed back to the managing organisation to update various spatial datasets.

Norwegian Institute of Bioeconomy Research, Oslo Norway

Key learning points

- *End-to-end deep learning processes in ForAInet system, are much more efficient at processing larger amounts of data than existing algorithms used to segment stems from point clouds that the author had used before and can be used across many different forest types.*
- *It was conjectured that it would be quite possible to feed in huge areas of dense point clouds across hundreds of thousands of hectares, and the process would be able to generate individual tree instances and perform semantic segmentation on the point cloud. This was exciting, as it was an example of a positive step on the way to using a dense point cloud captured across an entire estate, and directly derive a complete census of the forest from that point cloud.*
- *Fully automated tree-level forest inventories based on remotely sensed data are within reach.*
- *There is a database of single trees (n = 1,130) that have been scanned using High density UAV LiDAR called FOR-Instance. This was used to train the deep learning algorithms, and that any single tree inventory using dense LiDAR data requires a library of single trees.*

I visited Stefan Puliti from the Norwegian Institute of Bioeconomy Research (NIBIO). NIBIO's stated aim is to contribute to food security and safety, sustainable resource management, innovation and value creation through research and knowledge production within food, forestry, and other biobased industries. Stefano is a research Scientist in the Division of Forest and Forest Resources in As, Norway.

We discussed the examples of Virtual Reality tree measurement software, and segmentation of stems using the segmentation algorithms at a plot level. The discussion centred around the relative challenge of segmenting the point cloud into trees and then segmenting further into branches and foliage and stems.

The other issue that was discussed was the relative slowness of the process and the fact that tree segmentation was currently limited to relatively small plots, thus limiting the ability to segment stems, branches, and foliage for whole forests.

Stefano introduced the ForestSens.com platform, which is an Oracle hosted platform that houses a range of useful implementations of open-source algorithms that could be used by Foresters for seedling detection and species detection. There are several tools on this site including seedling detectors, tree species detectors and other modules.

Stefano introduced the Segment Anything, later evolving into ForAInet algorithms that were developed by (Xiang *et al*. 2024) which are hosted on the platform for demonstration purposes.

Appendix 2 describes the ForestSens platform, the development and basis of ForAInet algorithm, and presents some output from using this tool on datasets that I have access to.

Natural Resources Institute Finland (LUKE) - Espoo, Finland

Key learning points

- *A centralised and continuously measured national inventory system is crucial to understand long term trends in the forests. Australia does not have a centralised and coordinated national inventory programme across its native forests and should invest in this.*
- *The centralised and continuous inventory shows that there is MORE forest volume in Finland now than 100 years ago. Imagine if Australia could point to data like that to contribute to debates around Native Forest harvesting.*
- *Point clouds collected prior to the harvest operation can guide thinning operations, whilst point clouds collected at the time of harvest, can potentially optimise harvest operator value recovery and provide a point cloud of post-harvest condition back to the office- this could then be used to improve future forest volume projections.*

Finland inventory NFI

A fascinating presentation was received based on the Finnish National Forest inventory (NFI). For the past 100 years Finland Forest Services have been diligently measuring all the forested land across the whole country. This has generated amazing indicators which unequivocally show long term changes to the forest state across the country.

This centralised data source has been utilised by several research institutes and groups of researchers to monitor forest condition, look at raw material potential, as input for planning and monitoring of forest policy and other forest related programmes as well as providing input data for carbon and greenhouse gas reporting.

The methodology for sample establishment, and field measure assessment is well documented and is reported on in published papers such as:

Korhonen K. T., Ahola A., Heikkinen J., Henttonen H. M., Hotanen J.-P., Ihalainen A., Melin M., Pitkänen J., Räty M., Sirviö M., Strandström M. (2021). Forests of Finland 2014–2018 and their development 1921–2018. *Silva Fennica* Vol. 55 no. 5 article id 10662. https://doi.org/10.14214/sf.10662

For example, some of the metrics show that the current productive forest area is 20.276 million hectares and that is larger than in the 1920s by more than two million hectares. This inventory also shows set the current growing stock is 1.7 times the growing stock present in the 1920s at 2500 million m^3 with an annual volume increment of 107.8 m^3. These are very enlightening statistics.

It really prompted thought on why the Australia does not have a centralised and coordinated national inventory programme across its native forests. Currently inventory is carried out by separate organisations in each state responsible for wood production. However, there is no coordinated multi tenure evaluation of forest volume and other attributes. For example, there is no highly accurate way to assess how national park forests are faring compared to surrounding forestry lands or how the forested landscape is changing over time.

Mauricio Acuna -Research Professor of Automation and AI in Forest Operations at LUKE.

Mauricio has been exploring the ability to take point clouds captured by a sensor on a harvesting machine and buck these 'point cloud stems' on the fly to determine the log products that a harvesting machine could generate. This is an interesting approach, as it focuses on the machine operator being guided to make the correct cuts at the time of harvest where lots of value is traditionally lost through suboptimal bucking practices.

The following papers are interesting and informative:

- Prendes C, Canga E, Ordoñez C, Majada J, Acuna M, Cabo C. 2023. Optimal bucking of stems from terrestrial laser scanning data to maximize forest value. Scandinavian Journal of Forest Research. https://doi.org/10.1080/02827581.2023.2215544
- Prendes C, Canga E, Ordoñez C, Majada J, Acuna M, Cabo C. 2022. Automatic assessment of individual stem shape parameters in forest stands from TLS point clouds: Application in Pinus pinaster. Forests 13(3): 431. https://doi.org/10.3390/f13030431

The other projects Mauricio is interested in is the use of STI to optimise which stems are removed during thinning of stands, and subsequent prediction of the optimal of the machine routes. This has the potential to save significant amounts of fuel and increase efficiency by reducing the distance machines must travel through the forest to harvest stems.

KELLUU, Joensuu, Finland

Key learning points

- *Continuously collecting near real time data over remote areas in response to events, such as fire, drought impact are a real possibility with Kellu Airships*

A visit to innovative startup Kelluu, based in Joensuu was undertaken.

Kelluu states that they design, manufacture and operate intelligent hydrogen safe airships for persistent aerial monitoring of forests and landscapes (See figures below).

The airship can operate in airspace for up to 12 hours at a time, flying up to 500km per day. One person can follow/manage multiple airships, this means the deployment of multiple airships over an area could mean coverage of huge areas, with minimal staff required to manage these areas.

The airships fly at lower earth altitudes from just above the forest canopy, through to a few kilometres above ground level.

Each Airship is fitted with a range of sensors, with the focus being on Passive sensors such as RGB and thermal sensors.

Kelluu is focused on Photogrammetry and hierarchical Gaussians (see Gaussian Splatting) for building digital twins of the landscape at varying levels of detail. The premise of the operation is to provide near real time data from the airship, with processing occurring as the data is collected.

Use cases for such a platform could include:

- Monitoring a fire with mounted thermal cameras and radiation sensors in real time, providing live updates of fire spread and temperature, as well as monitoring fuel moisture.
- Mounting an active sensor like DJI L2 LiDAR sensor and map large areas of forest from just above the canopy to achieve large area dense LiDAR that penetrates to the understorey with more efficiency than current drone-based solutions.
- Thermal cameras mounted could discretely monitor wildlife such as koalas, over large contiguous areas.
- Monitoring of powerline networks.

One limitation could be that the payload carrying capacity does not seem to be very high, so larger equipment like current generation Geiger mode sensors would not be able to be mounted.

It was amazing to view Kelluu's airships up close and discuss why they were doing this. A large benefit of this technology is that it essentially is a very low energy solution, being an environmentally friendly option for monitoring forests.

Below are some screen shots from Kelluu digital twin examples, showing photogrammetry point clouds collected from the Airship in a native forest area.

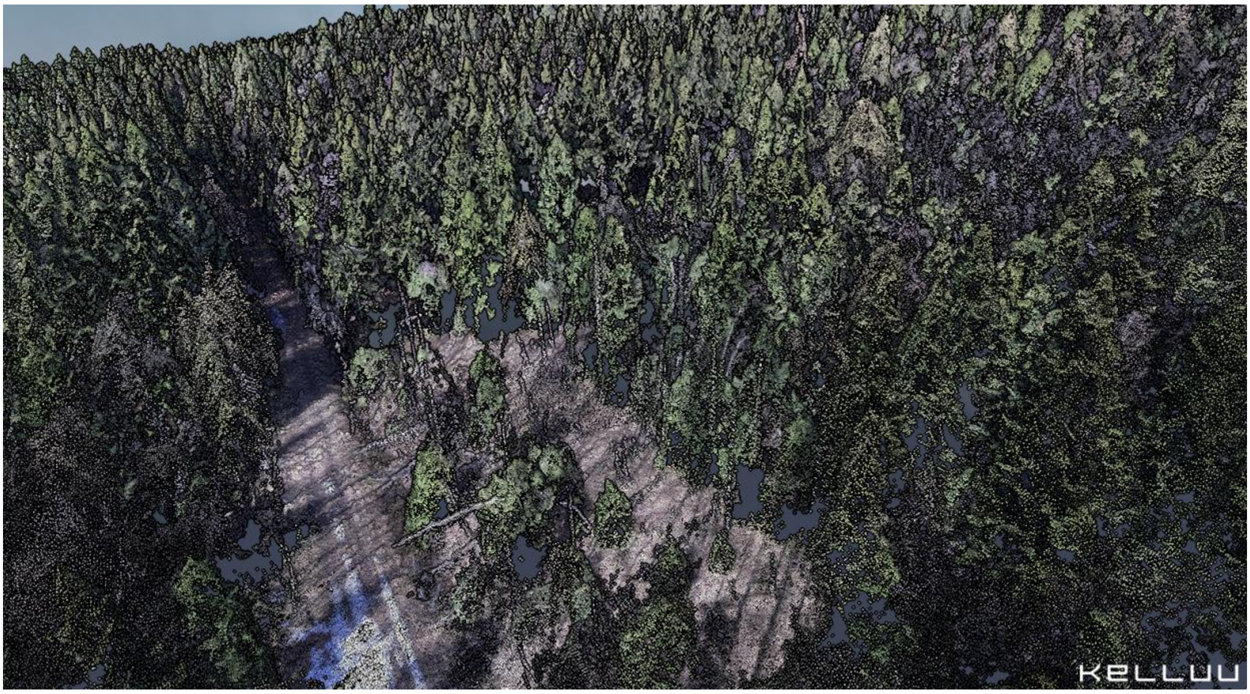

Figure 28: Photogrammetrically derived point cloud showing a forest in Finland captured from the Kelluu airship.

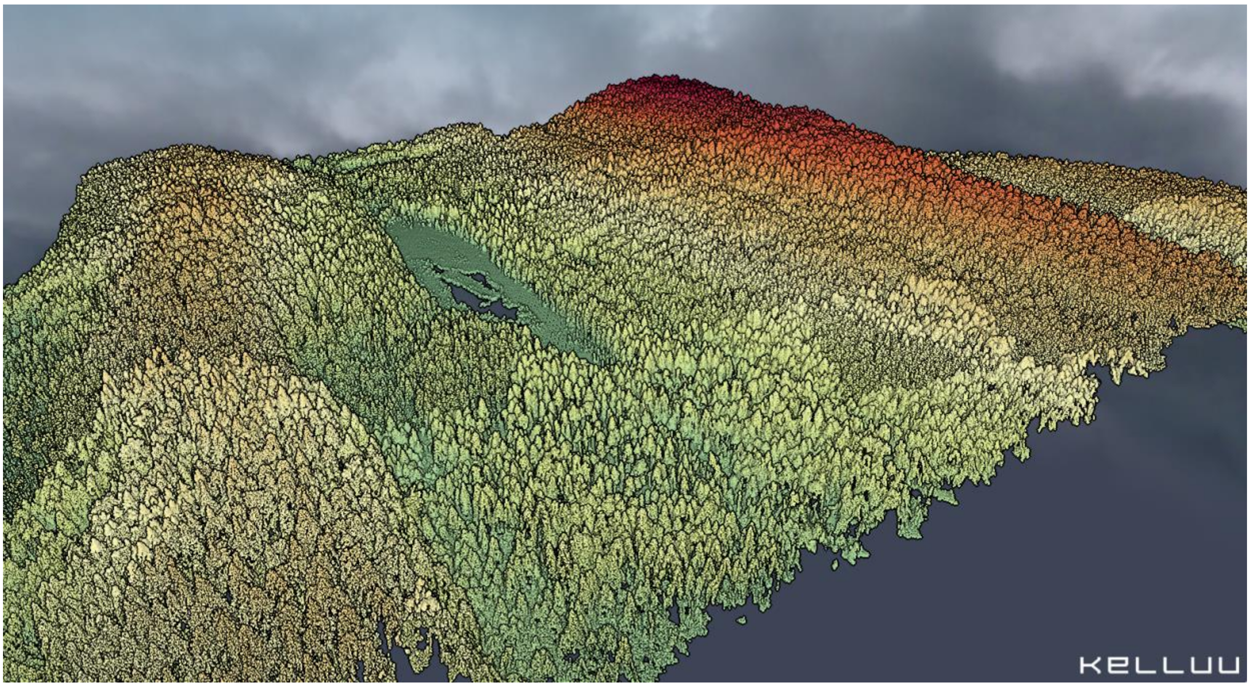

Figure 29: Large Scale view of the capture area point cloud generated by the Kelluu airship.

ARBORNAUT - Joensuu, Finland

Key learning points

- *There are some amazing systems available for viewing digital twins that are built for forestry organisations, and one does not necessarily need to build their own system, but rather utilize established systems and import your digital inventory to that system.*
- *Arbornaut have a focus on providing insights into more than just forest inventory, with one example being egress fire risk classification of road segments to determine which roads to treat to facilitate safe escape from fires along roads*

Arbonaut, based in Joensuu, Finland, have 30 years of experience with inventory and building digital twins of forests. They have built several products such as:

- ArboFiRM, a forest fire risk management tool,
- ArboFIS a decision support system for forest management, and
- ProMs a cloud-based forest information platform.

Arbonaut demonstrated some of their systems around single tree inventory and display of various spatial LiDAR derived systems. Arbonaut has conducted a LiDAR-based evaluation for over 15 million ha in natural, semi-natural, tropical forests, and plantations.

Of particular interest was their inventory display system in a web browser with their proprietary inventory viewing system. Inventory could be viewed in much the same way as all other providers of single tree inventory: at the single tree level, aggregated to cells and stand level values. The inventory system demonstrated was fast and informative.

Various inventory discussions were had around sub tree level quality assessment. However, like all other providers, no thought was really given to attempting to model subtree quality with the same level of attention required for native forests in Australia. This comes back to the density of point clouds that can commercially be captured over large areas. To effectively model subtree quality over large areas, denser LiDAR is required than is currently commercially available at an affordable price.

Also discussed was the approach of combining area based and single tree inventories together to get a robust estimate of log product volumes whilst acquiring high accuracy on stem count, species type and mean tree volume.

I concluded that Arbonaut would be a very capable partner for creating yield tables over plantation and simpler conifer forests such as Cypress pine forests in Western New South Wales.

Fire and Road access mapping

Access to forest areas and their resources is always a crucial factor in forestry and especially in prevention and suppression actions against forest fires. It demands knowledge of the specific location and thorough characteristics of each road, no matter the size, to plan and execute any action in forest fire management.

To assist with this, Arbonaut developed a LiDAR-based tool to map every existing road accurately and very precisely in an area of interest. Fuel mapping was incorporated adjacent to road segments to define the risk of traversing during fire. The segments with the higher danger rankings are highlighted for users of the system, to focus on these areas as a priority for fuel reduction.

Vehicle mobility

Arbonaut also demonstrated some impressive algorithms for mapping areas within stands that were less mobile for harvest machines than others and the concept of predicting snigging tracks for partial harvest and clear fall harvest was discussed.

Prediction of stems to be harvested in thinning

One of the things that can be done once a full census of trees in a stand is available is apply spacing algorithms combined with assessment of tree heights and diameters to determine which trees to remove to maximise a certain objective. This was discussed and demonstrated also.

Finnish Geospatial Research Institute (FGI) - Helsinki, Finland

Key learning points

- *Directly Measuring stem taper, DBH and stem volume using dense LiDAR can be done utilising algorithms developed by FGI.*
- *Millions of hectares of STI exist in Finland and are served up seamlessly by web-based interfaces. Serving up single tree inventory for smaller estates such as a 1million hectare estate is not a huge challenge in 2024.*

I had planned to visit the Finnish Geospatial Research Institute as their research on several topics is relevant to single tree inventory. Unfortunately, I came down with the flu and was bedridden during my time in Helsinki. Therefore, it was only possible to catch up over Teams for a brief meeting and discussion and sharing of ideas. I presented on what my aims were in terms of researching single tree inventory.

The FGI Is a core scientific institution in Finland and really focuses on delivering research, tools, and authority on all things geospatial.

FGI:
• Provides a scientific basis for Finnish maps, geospatial information, and positioning
• Carries out research and development on methods for the measurements, data acquisition, processing and exploiting of geospatial information
• Co-operates with industry, universities and governmental organisations nationally and internationally.

Professor Juha Hyyppä was the main contact, and FGI was very open to sharing what they are currently working on.

Key discussions focused on:

- How they measure trees from point clouds using novel algorithms. This is covered off in the section on direct measurements of tree volumes above.
- Development of life like trees in the real world within virtual digital twins' forests using photogrammetry and other methodologies.
    - The aim of this project is to give landowners, many of whom have never been to their forests, a digital representation of their forests that is very realistic.
- The accuracy versus point density for detecting smaller trees in single tree inventory, with the conclusion that obviously high point density improves detection of small trees.
    - Their view is that for a static view of forest value even, though small trees are under- estimated in STI, 99% of the value is within the trees 20 centimetres DBH or greater.
- The accuracy of species detection was discussed and there is more work to be done to improve these species detection accuracies in Nordic countries. This would improve with denser data and fusion of spectral and LiDAR data.
- The web based single tree inventory that is served up to the Finnish people called Metsakanta.com.
    - The aim is to map and represent the height, DBH, volume, fire mass, species, growth, and value of each of 2 billion trees across Finland.
    - This is open to any person who is interested in this information.

Direct measurement of tree volumes

An interesting topic of measuring tree stems directly was discussed as part of the Gottstein tour. The idea is that when you have very even coverage of stems up and down the upper and lower stem, using dense terrestrial, UAV based, or dense GML then a model of each stem profile can be relatively accurately constructed.

At the very least this could be used to calibrate allometric volume estimates generated from the DBH and height of each stem.

Hyyppä *et al.* did exactly this in their paper: Hyyppä E, Kukko A, Kaartinen H, Yu X, Muhojoki J, Hakala T, Hyyppä J. 2022. Direct and automatic measurements of stem curve and volume using a high-resolution airborne laser scanning system. Science of Remote Sensing 5: 100050. https://doi.org/10.1016/j.srs.2022.100050

And followed up this research in:

Muhojoki J, Tavi D, Hyyppä E, Lehtomäki M, Faitli T, Kaartinen H, Kukko A, Hakala T, Hyyppä J. 2024. Benchmarking under-canopy and above-canopy laser scanning solutions for deriving stem curve and volume in easy and difficult boreal forest conditions. Remote Sensing 16(10): 1721. https://doi.org/10.3390/rs16101721

To obtain high-quality stem volume estimates, they used the estimated stem curves and tree heights derived from the dense LiDAR, in order to compute the stem volume instead of using national allometric models for predicting the stem volume from the DBH and the tree height.

Essentially once they had found a stem in the point cloud, they grouped that stem into one metre height intervals finding a circular fit at each interval, calculating the diameter of the circle fitted where quality of the point cloud was good enough at that location. Given the combination of all these circles they fitted a simple parametric metric model to the stem diameters to extrapolate the stem diameters between the ground to the tree top. This essentially derives an individual taper for each tree from which the stem volume can be calculated, and bucking algorithms can be applied.

In the 1st paper, using these methods, they were able to estimate the stem curves with a root-mean-square error (RMSE) of 1.7–2.6 cm (6–9%). The RMSE of stem volume estimates was 0.1–0.15 m3 (12–21%). In the 2nd paper they refined the algorithms and applied a bias compensation method to reduce the overestimation of stem diameter arising from finite laser beam divergence. This reduced the diameter bias by up to 99% and resulted in a root mean square error of below 10% for DBH, stem curve estimates and stem volume on 'easy plots' with less than 500 stems per hectare. On harder, more densely stocked plots, the DBH and stem curve estimates had an RMSE still under 10 percent and the stem volume RMSE was below 20%.

Importantly, it was concluded that the techniques utilised in these studies were as good as manual field measurements or better when taking the localised taper modelling into account.

The relevant point that arises from this is that if GML can be captured with sufficient angular diversity and density to cover the stem profile of each tree then this methodology could be utilised and compared with field destructive sampling to assess the accuracy of GML derived taper for individual trees.

3DEO – Boston, Massachusetts USA

Key learning points

- *3DEO are an agile company that can greatly assist with downstream processing of GML into usable products if forestry companies and other users are willing to work with them.*
- *3DEO have a highly skilled team that could create good quality LiDAR products. One example to achieve efficiencies would be to produce all standard LiDAR derived mapping products as part of a 3DEO processing package.*
- *It could be possible to incorporate DL modules into 3DEO processing pipelines to spit out stem locations as part of processing the captured LiDAR into the product suite.*

A visit to 3DEO was informative. This company was spun-off from MIT. Detailed discussions were held regarding different attributes of Geiger mode LiDAR and how processing of the LiDAR is achieved. It was good to see the actual sensor as well and get an understanding of how it works firsthand. My presentation on the needs of Foresters was provided to 3DEO. It was fantastic to come away with an appreciation of how skilled the people in 3DEO at what they do.

University of British Columbia (UBC) - Vancouver, BC Canada

Key learning points

- *UBC is a leading research organisation in terms of utilising state of the art datasets and formulates research that is useful to forest management agencies.*
- *Large LiDAR and Imagery datasets and machine learning approaches can answer forestry questions, especially in terms of temporal change (i.e. repeated measurements)*
- *This visit to UBC reinforced the importance of a digital platform to tie all the results from these spatial and temporal analyses that will be done with increased frequency in the future.*

The visit to UBC was very informative. Several presentations were delivered by PhD candidates and also from Nicholas Coops. I also presented to about 20 students on what we are working on here in Australia re high density point clouds and forest inventory.

Overall, what was presented gave me a wealth of information to reference back to over time covering the following topics:

- Modelling height growth of temperate mixed wood forests using an age-independent approach and multi-temporal airborne laser scanning data.

- Framework for near real-time forest inventory using multi source remote sensing data.
- Modelling tree biomass using direct and additive methods with point cloud deep learning in a temperate mixed forest.
- Continuous monitoring and sub-annual change detection in high-latitude forests using Harmonized Landsat Sentinel-2 data.
- Characterizing forest fuel across mountain pine beetle attack mosaics.
- Quantifying Tree-level drivers of growth in high density managed stands with drone LiDAR.
- Estimating tree species composition from airborne laser scanning data using point-based deep learning models.
- Automated forest harvest detection with a normalized Planet-Scope Imagery time series.

This interaction really demonstrated the future of this field. UBC is a leading research organisation in terms of utilising state of the art datasets and formulating research that is useful to forest management agencies. It demonstrated that it is OK to demand good quality data, and solve forestry growth, yield and monitoring problems using more data, as opposed to using traditional methods relying on sparse data and simpler methods. In my opinion, other forest research organisations should look to UBC as a model for the type of relevant research they do.

FORSITE - Salmon Arm, BC Canada

Key learning points

- *ForSite has a well-developed methodology that is fit for purpose for conifer/Canadian/North American forest types.*
- *They often use a combination of STI and ABA data to arrive at a hybrid inventory.*
- *The interfaces and tools used are based on commonly available software and infrastructure- for example ArcGIS Portal.*

ForSite Canada provided me with a presentation on how their single tree inventory systems are built. This company/organisation is …. A link below shows a broad outline of the processes they utilise:

Remote Sensing Enhanced Forest Inventories - TreeID (forsite.ca) [8]

One key aspect of this approach is the acknowledgement that the STI process tends to underestimate volume. So, there is a strong focus by the company to utilise calibration

[8] https://maps.forsite.ca/portal/apps/storymaps/stories/b2078e0cdacf4da8b9e28eaa41cfa1b1

datasets to align the results with field verified data, such as sample plots and stand inventories. There are several ways to apply calibration, depending on what the focus of the organisation utilising the forest information is.

Another important point discussed was the fact that Allometric equations are used for bucking, based on the DBHOB and height of the trees, so does not consider defective stems. So, there is no 'sub-tree' information available in this process.

Western Forest Products – Vancouver Island, BC Canada

Key learning points

- *There are companies actively utilising the technology of STI to estimate woodflows and plan harvesting.*
- *General satisfaction and trust in the STI are high, but frustration that forestry governing bodies aren't up to speed with the new look inventory and don't trust it yet.*

A discussion with Western Forest Products, based on Vancouver Island, focused on the satisfaction of the company with single tree inventory. WFP's single tree inventory is built by ForSite, and as far as WFP are concerned, it performs very well.

In fact, although yield reconciliations show it is fit for purpose, one of the issues they face is the fact that it is different to the much coarser strategic inventory collected by the government land management agencies that set the sustainable yield constraints.

A challenge is there to convince the regulators to adapt more modern technology to derive sustainable yield estimates. Hopefully this would change as STI/Digital inventory becomes more widespread and data is collected to prove that predicted yields are fit for purpose with adjustment factors applied and informed by rigorous yield reconciliations.

University of Idaho (UI) - Moscow, Idaho USA

Key learning points

- *UI is leading the way in comparing Geiger Mode LiDAR with field inventory and will be a good research partner for companies that want to understand GML better.*
- *The UI Experimental Forest will continue to be a boon for research and industry to study implementation of digital twins*

University of Idaho is well advanced in setting up a digital forest centre, leveraging off the University of Idaho Experimental Forest (UIEF).

University of Idaho has captured and co-registered:

- Field measured plots,
- Stem mapped to Ground Based Mobile LiDAR plot datasets (Hovermap SLAM),
- Co-registered to Geiger mode LiDAR, flown at different elevations over a wider area.
    - This is in mixed native forest in the University of Idaho experimental forest (UIEF).

There is an ArcGIS Online page that shows the STI that has been generated over the UIEF with different sensors over time and below shows an example of a tree map, coloured by species.

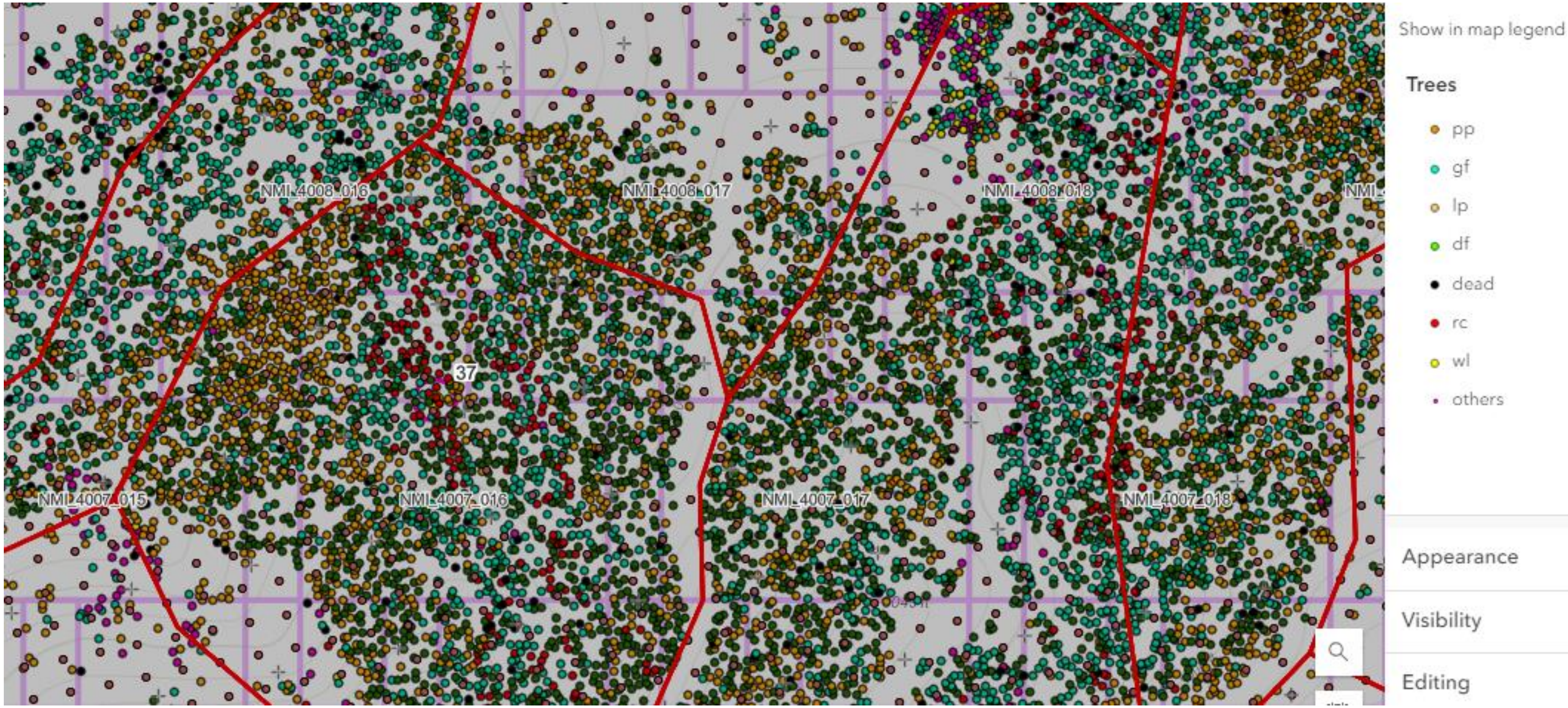

Figure 30: A view of tree instances within the UIEF in ArcGIS Online, by species.

The digital inventory can be interacted with, and attributes of each tree viewed, or the data can be viewed by aggregated grid levels or stand levels. Once again, there is a common set of constructs/software systems that each ITD user/provider is using across the international industry, so there were no large differences between that shown by the different STI providers.

Where UI is well advanced, though, is in their expertise in, capture and access to Geiger Mode LiDAR, coincident with Dense Mobile laser scanning and plots measured in the field and stem mapped to the LiDAR data. This should give a rich source of data for publications that will focus on comparing Geiger Mode LiDAR and assessing the accuracy and appropriateness of this technology performing STI, or even measuring stems directly.

Northwest Management Incorporated (NMI) -Moscow, Idaho USA

Key learning points

- *There are companies, such as NMI who are generating proven accurate STIs across millions of hectares in North America and have a mature process and products and are well worth approaching to assist with STI in Australian forests.*
- *NMI can generate STI over many millions of hectares and serve it up to clients responsively using* ForestView® or integrate into existing systems

A visit to NMI and meeting with the owner Mark Carrao, yielded very interesting discussions about Geiger Mode LiDAR, current sensors and helicopter-based LiDAR and NMI's general approach to STI.

NMI has performed STI across millions of hectares in North America and are leading proponents. For Forest Management companies, NMI can host all the captured LiDAR data and supplementary data and provide hosted services. They deliver software such as ForestView® which is shown in this ForestView® example. ForestView is a mature and well-developed software that is very suitable to Foresters who want to understand the forest from the individual tree through to the estate level, with dashboards and tools that assist to make informed decisions.

The algorithms and methodologies utilised by NMI are proprietary, so a detailed description of these cannot be made here. However, comparisons between the digital inventory and intensively sampled and harvested areas of forests show that the predictions are very close to what was recovered from the forests.

The video below discusses this:Forestview® and Digital Inventory® [9]

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[9] https://www.youtube.com/watch?time_continue=153&v=j-qpO4x7qpw&embeds_referring_euri=https%3A%2F%2Fnorthwestmanagement.com%2F&embeds_referring_origin=https%3A%2F%2Fnorthwestmanagement.com&source_ve_path=MTM5MTE3LDI4NjY2

Interestingly, and predictably, detailed subtree quality is not really required by the North American clients (generally due to the types of trees modelled), so allometric equations based on accurately predicted DBHOB and height is used to generate log product yield tables.

On discussion with Mark, the depth of knowledge and expertise was evident. NMI are investigating the use of denser LiDAR and assessing the benefits and costs of this approach compared to the traditional LiDAR that they utilise to generate an STI, which has is typically 20-40ppsm LiDAR.

Manulife Investment Management - Portland, Oregon USA

Key learning points

- *A large single tree inventory has been conducted successfully and implemented operationally across 3 million hectares in an organisation that relies heavily on accurate inventory for valuation purposes.*
- *ArcGIS online and ArcGIS Portal interfaces show great potential for managing and displaying subsets of billions of trees. That is, the storage and display of single tree points, whilst involving dedicated hardware and software, is, as shown elsewhere in the world, not a big challenge.*
- *Implementing a "Version 1.0" will provide a structure to further save money in inventory costs in the future, reduce processing time for determining harvesting and change to inventory, and enable much more functionality once LiDAR is captured in the future. This is also a much better option than 'doing it the way we always have'.*
- *Uncertainty still exists around smaller subdominant trees in more dense forests. However, this may change over time with more penetrative LiDAR technology measuring more of the understorey, and better segmentation techniques.*

A brief visit to Manulife was facilitated by Nick Blacklock, Managing Director, Global Timberland Resource Planning to discuss their experiences with single tree inventory.

Manulife Investment Management Timberland portfolio consists of USD $11.1 billion in assets spanning 5.4 million acres mainly in the United States, Australia and New Zealand

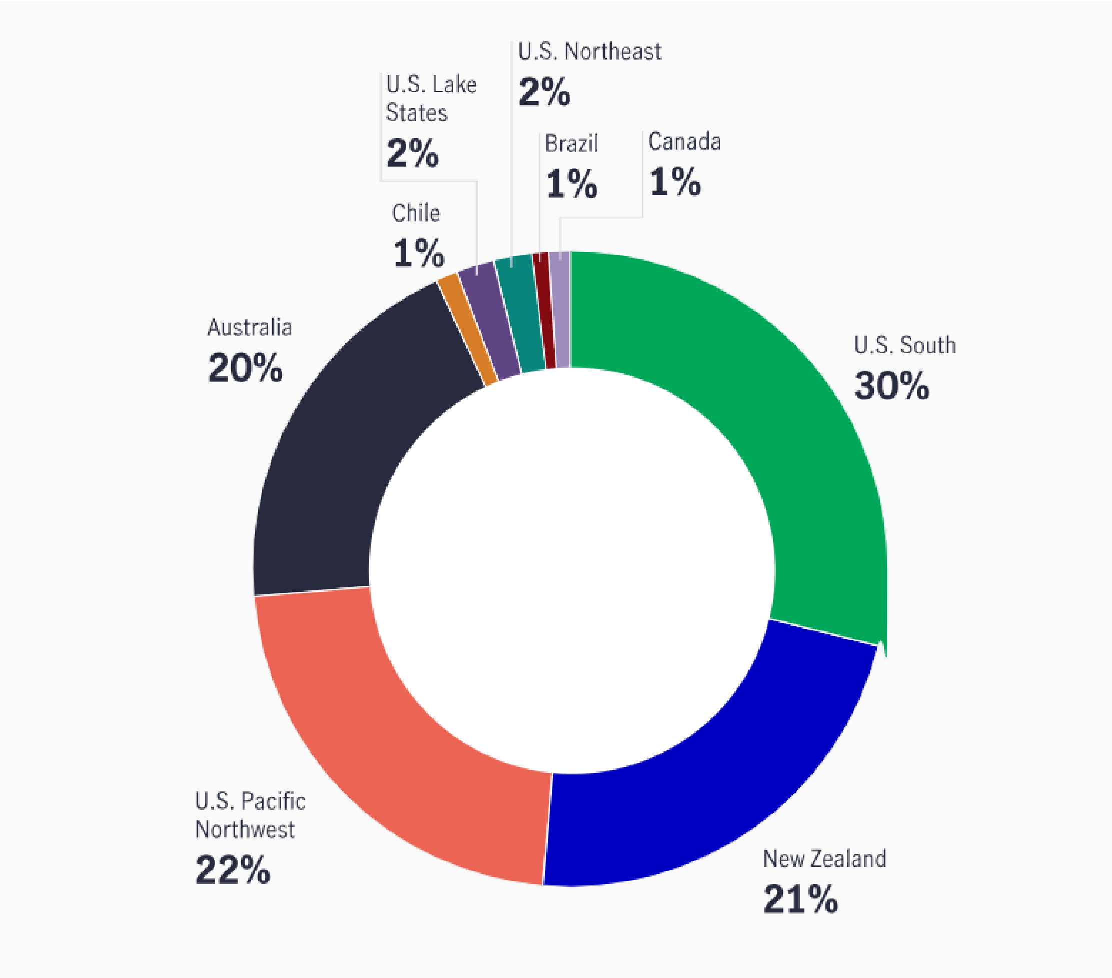

Figure 31: Manulife Timberland portfolio by location.

In the United States, approximately 3 million acres of forest land is managed, from hardwood forests in the north and north-east, hardwood in the Pacific north-west, and mostly *Pinus* species in the south-east.

There are many separate investment properties managed in the United States, which means that there are multiple valuations done across the portfolio, with many investors to report back to. Traditionally, this has meant there has been a large variety of systems employed to measure and model the volume of timber in each of these properties, which is one reason that Manulife embarked several years ago on a project to collect one set of inventories across the whole portfolio using a consistent methodology.

From approximately 2018, Manulife North America embarked on a project to capture aerial LiDAR and reference plots across the whole 3 million acres and develop a single tree inventory for the entire estate.

Manulife Single Tree Inventory

Data collection

The data was collected using 'normal' density LiDAR from 12ppsm to 20ppsm in approximately 2018 to 2020. Lots of reference plots were utilised (800-1000) in which tree locations were recorded, and cruising conducted on the trees.

Processing and serving up of data.

Manulife engaged Northwest Management Incorporated (NMI), to conduct the field inventory and the process of generating the single tree inventory, whilst Manulife coordinated the LiDAR capture. (NMI are described above)

The methodologies utilised by NMI are of a proprietary nature, and specific modelling and field measurement techniques used are not available.

The inventory is served up from NMI servers, rather than through Manulife, and ArcGIS online used to view the data.

Validation and Accuracy

The STI was conducted in such a way to ensure that on average for areas, the answer was unbiased. With any inventory, there are areas where the number of stems is under-estimated and other areas where stem numbers are over estimated. However, the thinking is, that due to the complete coverage of the estate, the overall answer is more accurate than traditional sampling.

Current Interaction with single tree inventory in Manulife

Manulife has an ESRI portal to view the individual tree locations, data about the trees such as size, DBHOB, dominance (i.e. subdominant, codominant, and dominant), species and volume. The interface renders individual tree locations rapidly when zooming in, using appropriate indexing and visible scale ranges. Volumes can be represented in grids, where the volume of individual trees are summed up in 20 by 20 metre grids for example or can be summed up at the stand polygon level. This also allows for the ability to draw a polygon and generate a yield summary for a custom area of interest.

Whilst the inventory is comprehensive, and tree locations are recorded and mapped in the viewer interface, utilisation of this detailed stem mapping, is for the moment, limited.

The outputs that Manulife currently utilise are simply the basic inventory outputs at the stand level to inform valuation of the crop, i.e. stand level volume per hectare by product, and generation of tree lists to input into growth models for projecting volume forward.

Future Interaction with single tree inventory in Manulife

Whilst the focus is currently on providing yield tables for valuations and summaries at the stand level, over time more value should be realised.

A key value associated with STI is the ability to track changes in individual stems or groups of stems over time. It is anticipated that a follow up LiDAR capture will prove the reason for STI to be well founded. For example, given most tree locations are already established, subsequent lower density LiDAR could be flown at low cost to give extremely accurate metrics around how many trees and acres have been harvested in the intervening period, and what the stocking change was for selective harvests. This could feasibly be done using a crude comparison and inventory update without having to conduct an extensive modelling project simply by comparing point cloud absence/presence in the vicinity of previously determined tree locations.

Inventory Issues/Perceptions of Staff

Issues with subdominant trees

Staff raised the issue of modelling of subdominant trees in denser forest. In some denser forest types, the lack of penetration of the Linear Mode LiDAR means that trees were 'inserted' into the stand to represent a group of trees that aren't explicitly measured by the LiDAR.

Staff commented that this means in some areas the approach doesn't really represent a single tree inventory but rather a complicated modelling process that is not really well understood. Why not just do a simpler ABA inventory instead? Staff didn't necessarily understand or trust this to have represented the smaller trees correctly.

Implementation issues

As mentioned, prior, Manulife North America has many portfolios across the United States, and managing the implementation of one set of LiDAR derived inventory has meant a lot of work. Reading between the lines, my personal impression was that some investors would have seen the value of their estates drop significantly, whilst others saw a significant increase.

Management of client expectations has created a large workload and possibly detracted from the exploration and leveraging of the extra information that might be gleaned from the single tree inventory. From an outsider perspective, I think a better approach would have been to implement the project in separate stages given the finite resources available to manage client valuation changes.

Moderating comments regarding Issues

With regards to the issue of missing subdominant trees, one point is that the smaller trees make up a much smaller fraction of the volume. If the modelled stem count is reasonably accurate, even if just based on a modelling exercise rather than clear signals from the point cloud, it should not significantly affect the volume and harvesting methods applied to each stand.

Another key point is that this approach applied what was amongst the first large scale implementations, and the algorithms and data combined means this approach could be considered as Version 1 of many refinements. This is one benefit of capturing LiDAR; you can re-use the data originally captured. Over time algorithms will improve, e.g. deep learning framework developments, and the modelling of smaller stems can be refined and retrofitted to older inventory plots to recast/improve the original capture.

The framework of modelling, storage and display is already in place for Manulife, so collection of subsequent LiDAR will be a lot easier to implement. The advent of newer ultra-high penetration LiDAR will ultimately improve the estimates of subdominant trees again within the next 5 years.

Regarding changes in valuation, implementing a consistent framework means that the next capture and update of LiDAR based STI will result in less variation from the original estimates than was found in the first implementation, given it is a continuation of the same/similar type of inventory.

Visual Forester, - Portland, Oregon USA

Key learning points

- *Public perception should drive stakeholders to use Digital Twins to visually represent landscape level forest changes associated with harvest or disturbance regimes.*

Visual Forester (see https://visualforester.com/development/) is a forest visualisation tool developer that works on the visualisation end of the digital forest. Visual forester can ingest STI, or just LiDAR, or other custom ways to build a forest, which is combined with the Digital Elevation Surface to create realistic scenes of the forests. The link below shows some examples:

Visual Forester: Digital Stands, Real Solutions - Forest Visualization Tools [10]

Given that public perception of native forestry is such a major issue in forestry globally, and particularly in Australia, it is surprising that more tools like this are not used by forest management companies to communicate the state of the forest across their tenures.

For example, it can be utilised to visualise harvesting, and then the subsequent regeneration of the stands over many years. Whole landscapes and catchments can be visualised, to give an overview of the landscape over 100 years for instance. If genuine forest opponents were able

[10] https://visualforester.com/

to see that the forest landscape would look pretty much the same in 100 years, it would be interesting to see how their general acceptance of the forest industry might change over time.

Fire effects of the landscape can also be simulated, showing the effects of wildfire versus alternative fuel reduction methodologies.

This links into the idea that a digital twin/inventory is not just a useful tool for getting volumes but also as an education tool, allowing people to see forest management virtually.

Since it's a VF digital twin rather than just a LiDAR viewer or other static 3D render, you will be able to click an asset and view data, show change over time, including growth, silvicultural treatments, and much more.

As Gaussian Splatting develops further, it will be interesting to see how this technology is leveraged to provide even more realism to the Visual Forester Platform.

Ironwood Forestry (Eli Jensen), Flagstaff, Arizona USA

Key learning points

- *Gaussian Splatting represents an amazing technological step that IronWood Forest is exploring to enable detailed realistic 3D scenes and models of single trees and forests.*
- *There is work to be done to come up with a methodology that enables stems and foliage right up to the crown to be captured in a way that ensures whole trees can be represented with Gaussian splatting reliably.*

A discussion with Eli Jensen was fruitful. Eli is what I would call a 'next generation' Forester, with his company leaning heavily into visualisation and virtual forest exploration.

Eli has a current project capturing large areas of relatively open forest utilising mobile laser scanners. What he has found is that walking open forests with Mobile laser scanners is feasible to capture large areas of more open forests until sub canopy drone tech catches up. This data is not being used solely for wood production, but also to establish what are the habitat qualities of certain areas.

Eli has an interest in Gaussian Splatting and is working hard on developing methodologies to be able to render whole standing trees consistently and clearly with Gaussian Splats. The images below show the capture of a Gaussian Splat over a patch of forest, and then digitally simulating the removal of stems. This is an extremely realistic view of the forest, which is different to current visualisation approaches using traditional geometric rendering.

As the saying goes, a picture tells a thousand words, so the trend in visualisation of harvest silviculture will probably be a key part in deciding how to manage forests in the future.

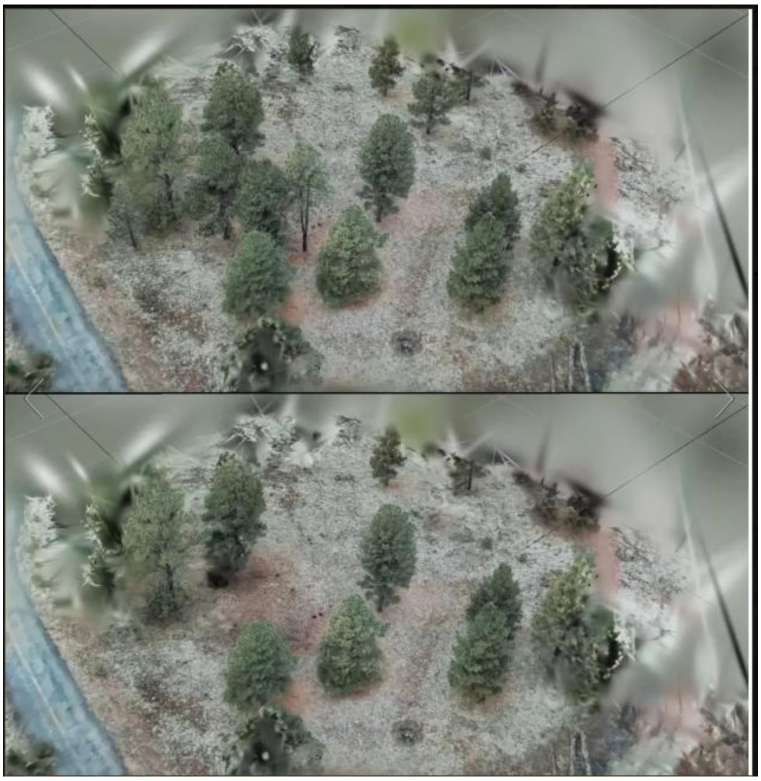

Figure 32: A Gaussian Splatting visualisation of a stand before (above) and after (below) digital thinning.

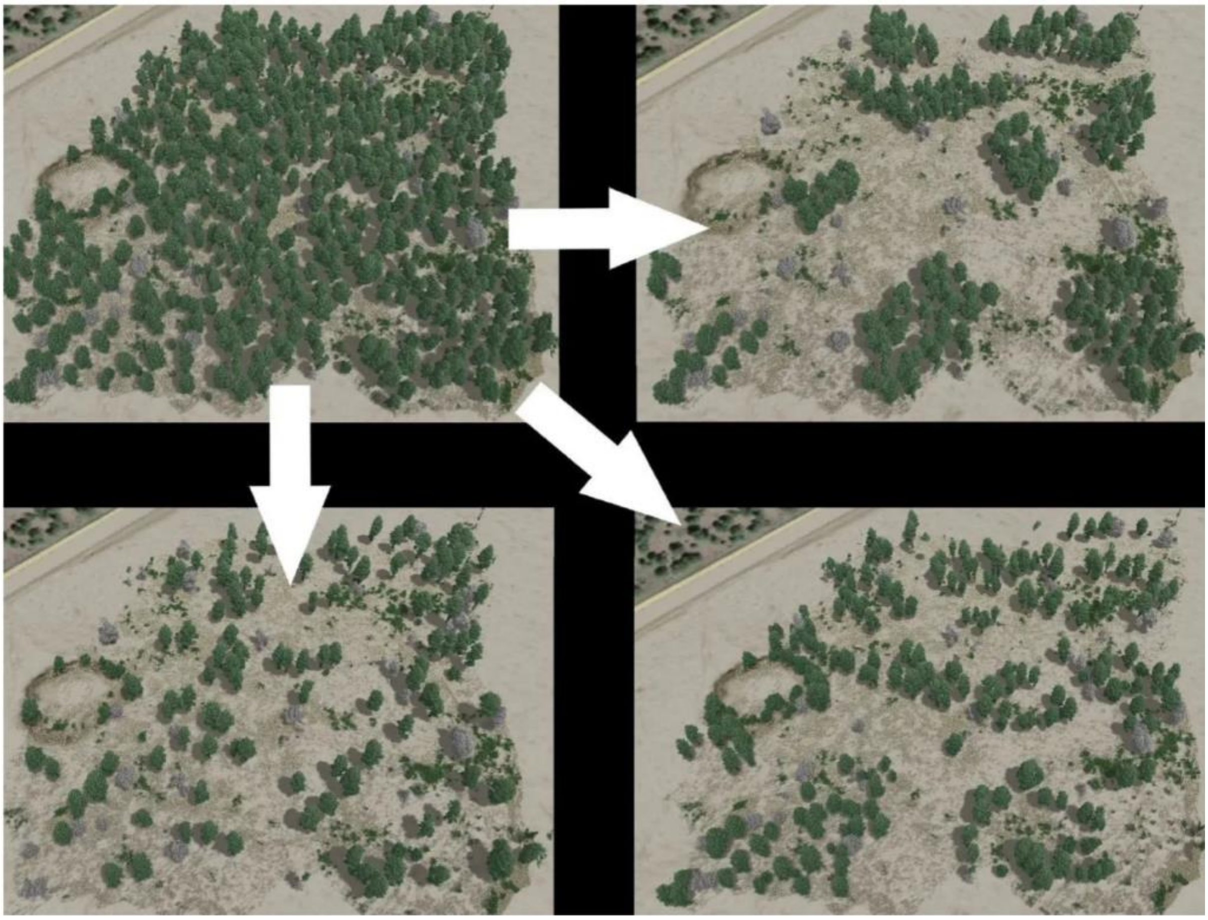

Figure 33: Visualising a scanned forest (top right) and three different spatial arrangements to the same residual basal area target.

Appendix 7: Review of select literature and data sources.

The following section is a selection of useful reading and data sources that could be of use to a forestry manager in Australia that may want to get a broad overview of topics related to individual tree inventory and species mapping for areas not already covered in the previous sections. It also would get a more technically minded forestry professional potentially started on mapping out a framework for developing a process to implement a LiDAR derived STI.

I have included pointers to areas of future importance to STI and that are relevant to future data capture technologies.

1. Species Mapping/prediction

FOR-species20K

- Topic: Using Several different Deep learning methods to get good results for species prediction using point clouds.
- Relevance: High. NSW/AUS should fund projects to start collecting point clouds that describe trees of different species and contribute to the FOR-species20K dataset. If Geiger mode LiDAR flown under specific capture parameters can provide similar coverage as TLS/MLS, then this may be able to be related to a TLS derived training dataset to classify tree species using DL approaches described in this research paper.
- Reference: Puliti S, Lines E, Müllerová J, Frey J, Schindler Z, Straker A, Allen MJ, Winiwarter L, Rehush N, Hristova H, Murray B, Calders K, Terryn L, Coops N, Höfle B, Krůček M, Krokm G, Král K, Luck L, Levick SR, Missarov A, Mokroš M, Owen H, Stereńczak K, Pitkänen TP, Puletti N, Saarinen N, Hopkinson C, Torresan C, Tomelleri E, Weiser H, Junttila S, Astrup R. 2024. Benchmarking tree species classification from proximally sensed laser scanning data: introducing the FOR-species20K dataset. arXiv preprint arXiv:2408.06507.

LiDAR and Deep Learning to predict Species.

- Topic: Using several different deep learning methods to get good results for species prediction using point clouds, explores different point cloud down sampling methods and a novel 'non uniform grid' down sampling.
- Relevance: High. As per the above paper, DL approaches in this paper could be applied to Australian collected datasets to test the accuracy of eucalypt species classification and relating to Geiger mode data.
- Reference: Liu B, Huang H, Su Y, Chen S, Li Z, Chen E, Tian X. 2022. Tree species classification using ground-based LiDAR data by various point cloud deep learning methods. Remote Sensing 14(22): 5733. https://doi.org/10.3390/rs14225733

Topic: Using Convolutional Neural Networks (CNN) Deep learning methods with 2cm RGB imagery to get good results for species prediction using point clouds.

Relevance: High. As per the above paper, DL approaches in this paper could be applied to Australian collected datasets to test accuracy of eucalypt species classification and relating to Geiger mode data.

Reference: Schiefer F, Kattenborn T, Frick A, Frey J, Schall P, Koch B, Schmidtlein S. 2020. Mapping forest tree species in high resolution UAV-based RGB-imagery by means of convolutional neural networks. ISPRS Journal of Photogrammetry and Remote Sensing 170: 205–215. https://doi.org/10.1016/j.isprsjprs.2020.10.015

2. Gaussian Splatting

Topic: LumaLabs.ai based DIY Gaussian splatting of different trees in different conditions

Relevance: Classifying and cruising LiDAR point clouds in VR or on the desktop, can be challenging, especially when separating foliage from branching, assessing defects like fire scars that are not represented by structural appearance in a colourless point cloud. Gaussian Splatting can bridge the gap between observers in the field, and desktop-based assessment. This is particularly useful in species discrimination.

Reference: The examples below were generated relatively quickly using low grade video and not any effort on the video personnel perspective. It is imagined that a high-quality Splat could be generated with a preplanned capture method using a high-quality camera mounted to a drone. No work I have come across to date has attempted to capture whole trees in a forest in high detail.

- A short video taken from an Iphone SE (2020 model), in tall moist blackbutt forest depicts a blackbutt tree. This was processed with Lumalabs.ai for free online, with the resultant 3D 'Splat' showing lots of detail from the side of capture: Blackbutt Tree (lumalabs.ai) [11]
- A short video of the immediate bole of a lillipilly (*Szygium* species) in low light rainforest conditions in the bunya mountains taken with the same low grade camera results in lots of detail of the bark, with surprisingly good 'Splat' considering the low light conditions. Lillipilly in low light Bunya Mountain Rainforest [12]
- Real time rendering of very large datasets:
  - Rendering Large datasets Gaussian Splatting [13]

[11] https://lumalabs.ai/capture/54fb2937-d23c-46ed-8aa8-9512625c3c6e?mode=sparkles
[12] https://lumalabs.ai/embed/6f62d886-cbed-4a2b-9555-b3002ae57b73?mode=sparkles&background=%23ffffff&color=%23000000&showTitle=true&loadBge
[13] https://www.youtube.com/watch?v=p-mb2TzVJZk&t=341s

3. Segmentation of Point clouds

Topic:

Semantic Segmentation of point clouds into different elements, such as stems, terrain, coarse woody debris.

Relevance:

This paper is a seminal paper that introduced the concept of sensor agnostic semantic segmentation using deep learning. Subsequent improvements and current approaches leverage the work reported here. It must be noted that Table 6 in the paper shows that processing times are quite long given the relatively small point clouds utilised, and as such the algorithm, as reported, would not be suitable for segmenting large areas of dense point clouds, say, larger than 0.5 hectares.

Reference:

- Krisanski S, Taskhiri MS, Gonzalez Aracil S, Herries D, Turner P. 2021. Sensor agnostic semantic segmentation of structurally diverse and complex forest point clouds using deep learning. Remote Sensing 13(8): 1413. https://doi.org/10.3390/rs13081413
- Link to Part 1 of Youtube showing examples associated with the paper [14]
- Link to Part 2 of Youtube showing examples associated with the paper [15]

Topic:

This paper and the associated processing platform – Forestsens.com represent the latest iteration of deep learning-based segmentation models. The open-source algorithms developed here cover individual tree instance generation, semantic segmentation into foliage, stem, and DBH and tree height generation.

Relevance:

As described in Appendix 1, implementation of this algorithm may be capable of segmenting large areas of forest captured with dense LiDAR point clouds. The development of a library of high quality segmented single trees from within Australian production native forest is required to train this collection of Deep learning models to arrive at good segmentation results for these forest types.

Reference:

Xiang B, Wielgosz M, Kontogianni T, Peters T, Puliti S, Astrup R, Schindler K. 2024. Automated forest inventory: Analysis of high-density airborne LiDAR point clouds with 3D deep learning.

[14] https://www.youtube.com/watch?v=MGRQDZZ1QBo
[15] https://www.youtube.com/watch?v=v0HwNu6SK6g

Remote Sensing of Environment 305: 114078. https://doi.org/10.1016/j.rse.2024.114078 Online platform for testing algorithms reported above: https://forestsens.com/

4. Remote sensing for detecting dead trees

Topic: Detecting dead standing Eucalypt trees in Australian native forests using LiDAR.

Relevance: As part of generating LiDAR derived inventory, processes for classifying 3D point clouds into Dead trees is an important input into the process of tree description. An independent assessment of tree status could be utilised to verify dead stems modelled using STI processes. Dead tree modelling using lower resolution LiDAR, as described in the paper below, could be a good post disturbance process that can be utilised to update STIs post disturbance.

Reference: Miltiadou M, Agapiou A, Gonzalez Aracil S, Hadjimitsis DG. 2020. Detecting dead standing Eucalypt trees from voxelised full-waveform LiDAR using multi-scale 3D-windows for tackling height and size variations. Forests 11(2): 161. https://doi.org/10.3390/f11020161

Miscellaneous Useful Papers relating to the Publication.

Ahola JM, Heikkilä T, Raitila J. 2021. Estimation of breast height diameter and trunk curvature with linear and single-photon LiDARs. Annals of Forest Science 78. https://doi.org/10.1007/s13595-021-01100-0

Brown R, Hartzell P, Glennie C. 2020. Evaluation of SPL100 single photon LiDAR data. Remote Sensing 12(4): 722. https://doi.org/10.3390/rs12040722

Call B, Fried D, Kelley D, Reichel-Vischi K, Reichert C. 2024. Assessment of foliage poke-through capabilities of an airborne Geiger-mode LiDAR. In: Proceedings of SPIE 13049, Laser Radar Technology and Applications XXIX, 130490I. https://doi.org/10.1117/12.3189877

Jiang Y, Liu B, Wang R, Li Z, Chen Z, Zhao B, Guo G, Fan W, Huang F, Yang Y. 2023. Photon counting LiDAR working in daylight. Optics & Laser Technology 163: 109374. https://doi.org/10.1016/j.optlastec.2023.109374

Marino RM, William R, Davis J. 2005. Jigsaw: A foliage-penetrating 3D imaging laser radar system. MIT Lincoln Laboratory Journal 1. Available from: https://archive.ll.mit.edu/publications/technotes/TechNote_ALIRT.pdf [accessed 12 March 2022]

Si S, Han D, Yulin Y, Xuekun J, Ying J, Yigao G, Xuming Z, Yeting C, Jie G. 2023. Multiscale feature fusion for the multistage denoising of airborne single photon LiDAR. Remote Sensing 15(1): 269. https://doi.org/10.3390/rs15010269

Wang D, Momo S, Casella E, LeWo S. 2020. A universal leaf-wood classification method to facilitate the 3D modelling of large tropical trees using terrestrial LiDAR. Methods in Ecology and Evolution 11: 376–389. https://doi.org/10.1111/2041-210X.13342

Yu X, Kukko A, Kaartinen H, Wang Y, Liang X, Matikainen L, Hyyppä J. 2020. Comparing features of single and multi-photon LiDAR in boreal forests. ISPRS Journal of Photogrammetry and Remote Sensing 168: 268–276. https://doi.org/10.1016/j.isprsjprs.2020.08.013