Final Report
Project NS020

NATIONAL INSTITUTE FOR FOREST PRODUCTS INNOVATION

Solutions for the optimal use of dense, remotely acquired data by forest growers

2023

Mount Gambier Centre
Funded by the Australian Government, South Australian Government & Industry Partners.
nifpi.org.au

Solutions for the optimal use of dense, remotely acquired data by forest growers

Prepared for

National Institute for Forest Products Innovation

Mount Gambier

by

Dr Jim O'Hehir

Publication: Solutions for the optimal use of dense, remotely acquired data by forest growers

Project No: NIF073-1819 [NS020]

ISBN: 978-1-922718-24-2

Researcher/s:

Jim O'Hehir, Anthony Finn, Pankaj Kumar, Stefan Peters, Jiuyong Li, Jixue Liu, Liang Zhao, University of South Australia
Arko Lucieer, Darren Turner, University of Tasmania
Christine Stone, NSW Department of Primary Industries
Mitch Bryson, Lloyd Windrum, University of Sydney
Michael Watt, Scion
Susana Gonzalez, Interpine

This work is supported by funding provided to Forest and Wood Products Australia (FWPA) to administer the **National Institute for Forest Products Innovation** program by the Australian Government Department of Agriculture, Fisheries and Forestry and the Government of South Australia in partnership with the University of South Australia.

Australian Government
Department of Agriculture, Fisheries and Forestry

Government of South Australia
Department of Primary Industries and Regions

Researchers:

Jim O'Hehir
University of South Australia
GPO Box 2471
Adelaide SA 5001
jim.ohehir@unisa.edu.au

Anthony Finn
Director
Defence and Systems Institute
University of South Australia
GPO Box 2471
Adelaide SA 5001
anthony.finn@unisa.edu.au

Pankaj Kumar
University of South Australia
GPO Box 2471
Adelaide SA 5001
pankaj.kumar@unisa.edu.au

Stefan Peters
University of South Australia
GPO Box 2471
Adelaide SA 5001
stefan.peters@unisa.edu.au

Jiuyong Li
University of South Australia
GPO Box 2471
Adelaide SA 5001
jiuyong.li@unisa.edu.au

Jixue Liu
University of South Australia
GPO Box 2471
Adelaide SA 5001
jixue.liu@unisa.edu.au

Liang Zhao
University of South Australia
GPO Box 2471
Adelaide SA 5001

Arko Lucieer
University of Tasmania
Newnham Drive
Newnham TAS 7248
arko.lucieer@utas.edu.au

Christine Stone
NSW Department of Primary Industries
Level 12
10 Valentine Avenue
Parramatta NSW 2124
christine.stone@dpi.nsw.gov.au

Darren Turner
University of Tasmania
Newnham Drive
Newnham TAS 7248
darren.turner@utas.edu.au

Mitch Bryson
Australian Centre Field Robotics
University of Sydney
J04 - Rose Street Building
The University of Sydney
NSW 2006 Australia
mitchtjbryson@gmail.com

Lloyd Windrum
Australian Centre Field Robotics
University of Sydney
J04 - Rose Street Building
The University of Sydney
NSW 2006 Australia

Michael Watt
Forest Geomatics
Scion
Te Papa Tipu Innovation Park
Private Bag 3020
Rotorua NZ 3046
michael.watt@scionresearch.com

Susana Gonzalez
Interpine
PO Box 1209
Rotorua NZ 3010
susana.gonzalez@interpine.nz

Executive Summary

This collaborative, multi-objective, multi-year project was jointly funded by the NIFPI South Australian and Tasmanian Regional Committees. A feature of this project was the communication with all stakeholders which included 22 seminars, 4 workshops, 4 newsletters and packages of software tools. This approach ensured the outcomes of the project were progressively transferred to industry.

The project addresses three high priority themes identified at a Forest and Wood Products Australia Estate Planning and Modelling Interest Group meeting held in Launceston, December 2017. The three research themes included:

1) Optimising remotely acquired, high resolution data to improve resource assessment by plantation growers;
2) Applying remote sensing technologies to map the health and nutritional status of stands and individual trees, as well as mapping weeds in plantations;
3) Provide recommendations for the management and analysis of remotely acquired 'big' datasets.

The rapid developments in data resolution and precision acquired by sensors mounted on UAVs, airborne and satellite platforms now present novel opportunities to deliver on these three themes. Systems now exist that can be used as survey or sampling tools or for obtaining a total census of trees across the estate.

However, while there existed a myriad of potential remote systems, only those tools that were demonstrated to add value (i.e. were cost-effective, accurate and could be integrated into existing management systems) were adopted by the forestry sector. The trade-offs between accuracy, reliability and costs was evaluated in all the applications evaluated in this project.

Significant progress was made in the operational adoption of dense LiDAR and photogrammetric data (e.g. FWPA PNC326-1314 and PNC377-1516). However, less attention was given to the application of high resolution spectral data for a range of potential management applications. In addition, airborne and UAV platforms were built with capacity to carry multiple sensors, in particular optical sensors (including hyperspectral) with LiDAR sensors. While LiDAR provided detailed three-dimensional data on forest structure and the sub-canopy ground surface elevation, high spectral resolution data can provide information on vegetation composition and condition. Fusing the data streams from two co-aligned sensors greatly increases the dimensionality of the acquired data. Novel processing methods were evaluated to optimise the extraction of both structural and spectral features for modelling stand attributes of interest. These datasets were acquired from a series of softwood and hardwood plantations, as well as from native forests, with the study sites identified through consultation with collaborating companies.

Coincident with the development of these remote systems were the advances in automated analytical methods and the development of cloud-based processing engines. New analytical techniques such as active machine learning was customised to deliver tree-level information. In all cases the objective developed efficient processing workflows. Each solution was accompanied by recommended specifications and procedures, which in some instances was provided as "Best practice" guides.

Table of Contents

Introduction

The purpose of this project was to improve the capacity of forest growers and forest service providers to apply current and novel remote sensing systems for a range of operational practices including: tree level assessment of structure, crown condition & foliar nutritional status, weed mapping, use of multi-temporal LiDAR datasets for growth and yield modelling and, provide advice on the management and storage of data derived from these remote sensing systems.

Background

It is now established that remote sensing technologies provide spatially explicit information that more accurately quantifies resource yield estimates than the conventional plot based estimates (e.g. FWPA PNC326-1314 and PNC377-1516). Awareness of the benefits derived through the application of Airborne Laser Scanning (ALS, also known as LiDAR), typically via the process of imputation using ground-measured reference plots, has been reinforced through industry meetings such as ForestTECH. Less attention has been directed towards the benefits derived from high spatial resolution spectral imaging from manned and unmanned aircraft systems. High spatial resolution sensors enable the measurement of individual trees, potentially over large areas. However, to keep pace with the scale and resolution at which data is becoming available, new automated processing methods are needed to be able to exploit this data and extract robust and accurate information at the tree-level.

This project focussed on three high priority themes identified at a FWPA Estate Planning and Modelling Interest Group meeting held in Launceston in December 2017. The three research themes included:

1) Optimising remotely acquired, high resolution data to improve resource assessment by plantation and native forest growers.
2) Application of remote sensing technologies to map the health and nutritional status of stands and individual trees, as well as mapping weeds in plantations.
3) Provide recommendations for the management and analysis of remotely acquired, 'big' datasets.

Participating forestry companies were: Australian Bluegum Plantations, FCNSW, Forico, FPC WA, Green Triangle Forest Products, HQPlantations, HVP Plantations, Midway Plantations, OneFortyOne, PFOlsen, Sustainable Timber Tasmania and Timberlands Pacific.

To ensure that there was sufficient research capacity to address the research and development themes the research collaboration included the University of Tasmania, the Australian Centre for Field Robotics at University of Sydney, Scion (New Zealand) and the University of South Australia; and Terra Drone Australia (C4D Intel), Esk Mapping & GIS, Australian UAV.

Methodology

The project was structured into seven subprojects such that each research partner and team could identify the workstream that they need to undertake and report on:

1. Ultrahigh-resolution imaging from unmanned aerial systems for detection of weeds and tree health assessment (Arko Lucieer and Darren Turner, University of Tasmania)
2. Automation of forest inventory (Mitch Bryson and Lloyd Windrim, University of Sydney; Interpine)
3. Monitoring forest properties at the individual tree level using UAV-borne Sensors (Anthony Finn and Pankaj Kumar, University of South Australia)
4. Growth and yield modelling for the future (Stefan Peters and Pankaj Kumar, University of South Australia)
5. Hyperspectral detection of nutrient deficiencies in radiata pine (Michael Watt, Scion)
6. Investigation of data management and processing options forest industry (Jixue Liu and Jiuyong Li, University of South Australia)
7. Remotely sensing native Jarrah forests (Arko Lucieer, Uni Tas and Mitch Bryson (University of Sydney)

Shared, Cloud-Based Directory for the Project

Protocols for data storage and sharing were established for all project participants acquiring data. All the datasets were secure but access to certain datasets was additionally restricted depending on the requirements of their owners. This was particularly an issue where company data has been made available for specific research. Table 1 below shows the agreed arrangements for data storage that were followed.

Data Storage Protocols

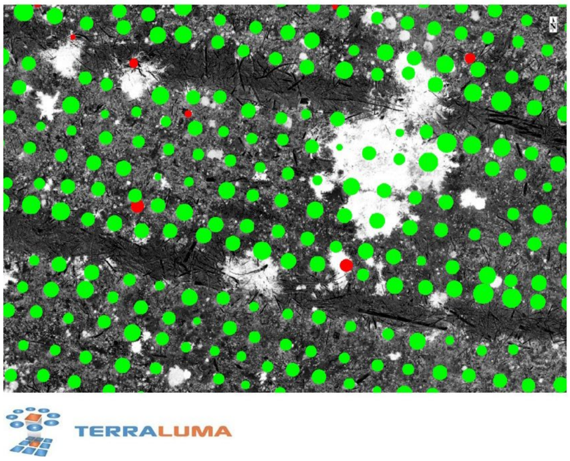
Data set description	Example	Solution
Very large data sets	Very high-density LiDAR ex UAV etc	Local hard drives or Cloudstor
Company supplied data with security caveats	OFO, Timberlands and GTFP specific LiDAR and plot measurements which the companies have said they only want shared with their specific approval	UniSA Research Data Storage - Nextcloud (allows external access).
Data sets already on Cloustor from previous projects	LiDAR data from the RieglVUX1 inside of Tumut_Oct2016 and from the RieglVUX1LR inside Carabost_Feb2018.	Data remains on Cloudstor
Project documents	Workplans, Newsletters	Onedrive

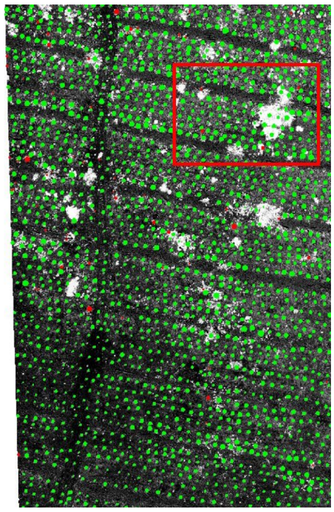
Results

The detailed results for the individual projects are included in the relevant reports, workshops and seminars. A brief summary of the results is included below.

1) Ultrahigh-resolution imaging from unmanned aerial systems for detection of weeds and tree health assessment.

Data was collected at three pine plantation sites in Northern Tasmania using a range of sensors: hyperspectral; multispectral, visible and thermal, with the aim of testing which sensors are best at detecting weeds.



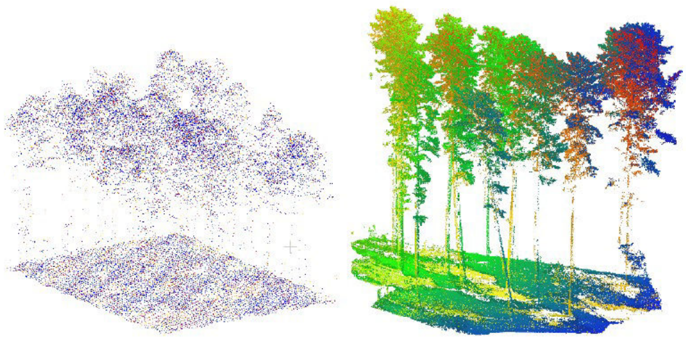


2) Automation of forest inventory

The sub project has progressed development of workflows and algorithms for tree-level census using point clouds, deep learning and human-machine interaction. Research indicated tree detection methods developed for high resolution Airborne Laser Scanning (ALS) data based on deep learning object detection could also be applied effectively to low resolution ALS data. The implication for forest companies is that using this method, cheaper data can be used to obtain more tree attribute information.

3) Monitoring forest properties at the individual tree level using UAV-borne Sensors

Two approaches have been developed to undertake survival counts of young radiata pine plantations from pre-processed Hyperspectral and Phantom UAV images. Both methods work but the second approach has been found to be more accurate and cost-effective in terms of estimating tree survival counts. Most plantation companies already have the equipment to capture the necessary data and allow the companies to estimate replanting costs to make more informed decisions.



(a) low res data (HQP)   (b) high res data (Tumut)

4) Growth and yield modelling for the future

The sub project has incorporated ground truth data into plot imputation models and shown that potential to increase the efficiency, and lower the costs, of ALS surveys by reusing calibration plot data both spatially and temporally.

5) Hyperspectral detection of nutrient deficiencies in radiata pine

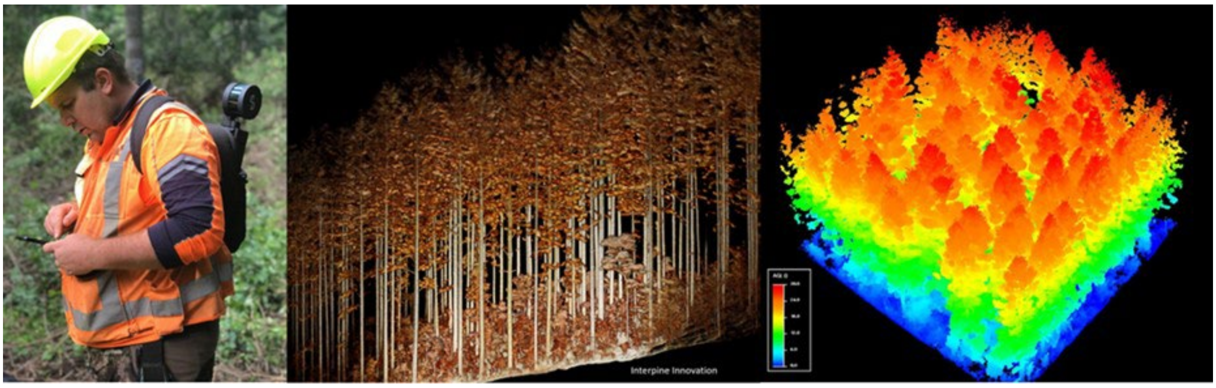
This sub project has demonstrated that generalised field predictions of photosynthetic capacity can be made using only remote sensed reflectance data. This will benefit the industry by improving the assessment of plantation nutrient status at a fraction of the cost and complexity of manually collected and analysed methods.

6) Investigation of data management and processing options forest industry

This sub project has resulted in the development of a report which draws on the literature to compare options for forestry data management with an emphasis on large data sets.

7. Ultra-Dense Point Clouds for Inventory (Interpine)

Interpine have continued working on implementing forest inventory using a backpack LiDAR scanner. The resulting scans are being incorporated in a virtual reality application (VRForest) and these results are then available for use in forest resource planning software.



As part of the knowledge transfer process, four workshops were delivered via ZOOM with good attendances to ensure the findings were communicated into partner organisations:

1. 4 August 2021: NIFPI NS020: Forest3DApp: Software tools for tree inventory using point cloud data virtual workshop – Mitch Bryson - 35 attendees https://unisa.au.panopto.com/Panopto/Pages/Viewer.aspx?id=6cfe9a75-f88e-471d-a906-ad7a004975ee
2. 18 August 2021: NIFPI NS020 PINT, a Program for Identifying Nursery Trees (included seedlings) virtual workshop – Anthony Finn – 35 attendees https://unisa.au.panopto.com/Panopto/Pages/Viewer.aspx?id=be1eb7a8-b84f-45e4-900d-ad880038f16c
3. 1 September 2021: NIFPI NS020 UAS imagery over forests – collecting, processing, and analysing multispectral and RGB data virtual workshop – Darren Turner – 27 attendees https://unisa.au.panopto.com/Panopto/Pages/Viewer.aspx?id=b7f3d1e3-ca72-4923-a283-ad960047a4da
4. 15 September 2021: NIFPI NS020 Growth and Yield Prediction of trees at plot and individual level using Imputation Modelling virtual workshop – Pankaj Kumar – 31 attendees https://unisa.au.panopto.com/Panopto/Pages/Viewer.aspx?id=c543dac1-6fe6-460d-b9a0-ada4002c6fe8

Attendances reported are based on video connections so do not include situations where multiple people are in the same location. In addition to the workshops, 22 seminars were delivered via ZOOM to further reinforce the communication of findings into partner organisations:

Mini seminars delivered:

1. 15 April - NIFPI Presentation - young plantation age survival counts from pre-processed Hyperspectral & Phantom images (low cost) - Anthony Finn – 34 attendees – not recorded
2. 22 April - NIFPI Presentation - Estimating N and P and photosynthetic capacity in N and P limited radiata pine using hyperspectral imagery - Mike Watt - Scion – 26 attendees https://unisa.hosted.panopto.com/Panopto/Pages/Viewer.aspx?id=d9ee0004-68a2-4605-a630-aba700271caa
3. 29 April - NIFPI Presentation - High resolution LiDAR data in Forest inventory - Susana Gonzalez - Interpine – 39 attendees

https://unisa.hosted.panopto.com/Panopto/Pages/Viewer.aspx?id=a429e44d-5fbe-442a-aacc-abac0049cb90

4. 6 May - NIFPI Presentation - Multispectral sensors for drone remote sensing and generation of orthomosaics and 3D multispectral point clouds for applications in forestry - Arko Lucieer - University of Tasmania – 39 attendees https://unisa.hosted.panopto.com/Panopto/Pages/Viewer.aspx?id=484a6cd7-fbd4-4481-b44f-abb3002b30ec
5. 14 May - FWPA - Virtual reality technology with dense point cloud data in forest inventory - Winyu Chinthammit - University of Tasmania – 38 attendees https://unisa.hosted.panopto.com/Panopto/Pages/Viewer.aspx?id=aab08cd1-6d7d-4dd3-ab94-abbb0047f325
6. 20 May - NIFPI Presentation - Point cloud analysis for inventory using machine learning and automation - Mitch Bryson & Lloyd Windrim - University of Sydney – 37 attendees- https://unisa.hosted.panopto.com/Panopto/Pages/Viewer.aspx?id=a3466b6e-68ae-4b2b-8477-abc1002711a4
7. 3 June - NIFPI Presentation – A Report of LiDAR data management Solutions in the Forestry - Jixue Liu - University of South Australia – 31 attendees - https://unisa.hosted.panopto.com/Panopto/Pages/Viewer.aspx?id=9b2df209-53fe-44c6-a806-abcf0066bfcc
8. 10 June - NIFPI Presentation - Mapping weeds in young radiata pine plantations using multispectral UAV imagery - Arko Lucieer, Darren Turner - University of Tasmania – 34 attendees - https://unisa.hosted.panopto.com/Panopto/Pages/Viewer.aspx?id=97cd613b-c08d-4939-a053-abd6002596e6
9. 17 June - NIFPI Presentation: Remote sensing for harvest planning in native Jarrah forests - Hans Blom - Forest Products Commission – attendees 33
10. Presentation - https://unisa.hosted.panopto.com/Panopto/Pages/Viewer.aspx?id=6b614324-8b6d-4d24-99dd-abdd0025701b
11. Flythrough 1 - https://unisa.hosted.panopto.com/Panopto/Pages/Viewer.aspx?id=a9a634d1-fb89-4432-a089-abdd017bfa3c
12. Flythrough 2 - https://unisa.hosted.panopto.com/Panopto/Pages/Viewer.aspx?id=1a3d2663-71fb-4d07-8175-abdd017bfa6e
13. 1 July - NIFPI Presentation - Imputation models in spatio-temporal domain - do forest growers benefit from sharing ALS & inventory datasets for yield modelling ? - Pankaj Kumar, Stefan Peters – UniSA – 40 attendees
14. https://unisa.hosted.panopto.com/Panopto/Pages/Viewer.aspx?id=d1426742-171a-4c2c-b642-abeb002f5463
15. 8 July - NIFPI Presentation - Drone Based - Post Thinning Inventory – David Herries – Interpine
16. https://unisa.hosted.panopto.com/Panopto/Pages/Viewer.aspx?id=2e432ca8-c423-4a7a-a42f-abf20042b67a – 41 attendees
17. 15 July NIFPI Presentation - Mapping a forestry area with a drone: advice on how to get it right first time! - Darren Turner - University of Tasmania
18. https://unisa.hosted.panopto.com/Panopto/Pages/Viewer.aspx?id=009f59a9-76a2-4a01-a02e-abfc000a63f4

19. 26 August NIFPI Presentation - Eagle Eye - Applying the Internet of Things to landscape scale Wedge-tailed eagle management - Dean Williams – STT – 44 Attendees
20. https://unisa.hosted.panopto.com/Panopto/Pages/Viewer.aspx?id=f5e94de4-fbe8-404a-afb5-ac2300303d2a
21. 20 October NIFPI Workshop - Geo-spatial Precision seminar
22. https://unisa.hosted.panopto.com/Panopto/Pages/Viewer.aspx?id=96f1590e-1fb5-47a2-ad74-ac5a007d1e0e

Software developed as part of this project and available from the developers on request:

- Forest3DApp: Software tools for tree inventory using point clouds – Mitch Bryson
- PINT, a Program for Identifying Nursery Trees (including seedlings) – Anthony Finn
- Growth and Yield Prediction of trees at plot and individual level using Imputation Modelling – Imputation scripts – Stefan Peters/Pankaj Kumar

Automated software tools have been developed for:

- Several methods of survival count estimation of seedlings from UAV based point cloud data. Some of these methods are designed to work with cheap/low precision data collected from low-cost UAVs and sensors.
- Differentiating seedlings from weeds and weed type identification from UAV based point cloud data.
- Tree health assessment from point cloud data, including detecting nutritional deficiency, tree condition following wildfire, water stress or insect attack.
- Hyperspectral detection of nutrient deficiencies in radiata pine.
- Automation in an app (Forest3DApp) of forest inventory using machine, active learning and other methods to identify trees, construct tree stems and other structural features from remote sensed point cloud data.
- Improved methods for predicting and imputing plantation growth and yield modelling over space and time using remote sensed data from multiple sources.

Reports published/provided as part of this project and made available to project partners:

- Interpine - Guide to PlotSafe Data Collection - LiDAR Reference Field Inventory_2017 Survey.
- Scion – Watt. M.S. 2021 Using hyperspectral data to predict N and P limitations in radiata pine. 2pp
- University of South Australia – Kumar P (2021) Imputation Modelling for Growth and Yield Prediction of Trees at Plot and Individual Tree Level. 12pp.
- University of South Australia - Zhao Liang, Jixue Liu, Jiuyong Li (2020) A Review of Data Management Solutions in the Forestry Industries. A report reviewing large data set management and processing options for the forest industry.
- University of Sydney - Windrim L and Bryson M (2021) Final report on sub-project - Workfows and algorithms for tree-level census using pointclouds, deep learning and human-machine interaction. 45pp
- University of Sydney - Windrim L and Bryson M (2021) User_Guide Forest 3D App: inventory from pointcloud data. 16 pp.

- University of Tasmania – Turner D. and Lucieer A. (2021) Ultrahigh-resolution imaging from unmanned aerial systems (UAS) for detection of weeds and tree health assessment. 102pp.

Papers published as part of this project:

- Anthony Finn, Pankaj Kumar, Stefan Peters & Jim O'Hehir (2021, in review) Unsupervised Spectral-Spatial Processing of Drone Imagery for Identification of Pine Seedlings, ISPRS Journal of Photogrammetry and Remote Sensing.
- Kumar, P., Peters, S., Finn, A., Myers, B. & O'Hehir, J. (2021, in review). Examining the growth of plantation forests near wetlands using airborne LiDAR point cloud data.
- Kumar, P., Peters, S., Finn, A. & O'Hehir, J. (2021, in review). Spatial-temporal transferability of imputation models for yield prediction of forest plantations.
- Watt, MS., Buddenbaum, H., et al. (2020) Monitoring biochemical limitations to photosynthesis in N and P-limited radiata pine using plant functional traits quantified from hyperspectral imagery. Remote Sensing Environment 248: Article 112003.
- Watt, MS., Buddenbaum, H., et al. (2020) Using hyperspectral plant traits linked to photosynthetic efficiency to assess N and P partition. Journal of Photogrammetry and Remote Sensing 169 (2020) 406–420
- Windrim L and Bryson M (2020) Detection, Segmentation, and Model Fitting of Individual Tree Stems from Airborne Laser Scanning of Forests Using Deep Learning. Remote Sensing.

Data sharing:

- Sensor/point cloud data were available from multiple plantation species across multiple States.

Project Newsletters:

- Four project newsletters were circulated to update stakeholders during the project.

Discussion

Overall, forest growers will benefit from attaining improved, spatially explicit characterisation of their resource. A published benefit of moving to LiDAR from manual assessment methods (Maltamo, M, et al. 2014) in South Australian radiata pine plantations (reported by Rombouts, J. in this publication) demonstrated a reduction in overall site productivity assessment costs by 50–70 %, depending on the price of ALS data.

The derivation of innovative solutions using high fidelity, remotely acquired dense data will reduce the reliance on manual assessments, hence the costs of ground-based activities such as plot inventory. Reducing the need to traverse compartments will also reduce safety risks when working in difficult terrain or in stands supporting a dense understorey.

Reduced reliance on conventional field-based assessments through improved intra-compartment stratification for a range of attributes associated with stand structure, canopy condition including nutritional status (e.g. improved sampling efficiencies for nutrient analysis of foliage). An ability to map the understorey vegetation will improve the efficiency of accessing plots. This is important because while remote unmanned systems will reduce the reliance of manual on-ground assessments, there will always be a requirement for some ground-based reference/calibration data.

The ability to obtain estimates on many trees, at the tree level, will improve resource estimates, in part, through the derivation of a quantifiable systematic (machine) bias as opposed to the subjective assessment bias arising from visual plot assessments. The ability to correct for a systematic bias using algorithms for human-machine interaction will improve estimation accuracies.

This project further developed the research capability of a core of remote sensing scientists that have experience in the commercial forestry sector.

Project partners from this project have discussed opportunities for collaborators to engage in a joint development of forest resource management systems.

Mitch Bryson is undertaking a further project with University of Tasmania around extracting wood properties from individual tree scans.

Expected Benefits

Impacts of the research outcomes:

- Improved understanding and capacity to deploy unmanned airborne vehicles carrying different active (LiDAR) and passive (optical/spectral) sensors.
- Improved understanding of the optimal configuration (i.e. optimal spatial and spectral resolution) of these systems (UAS) for a range of operational tasks; this may include the opportunities of using UAS acquired data for training satellite imagery.
- Workflow solutions for acquiring, processing and analysing data acquired by these unmanned airborne systems.
- Recommendations of the requirements for sensor calibration for collection of high quality spectral data.
- Recommendations related to the management of ‘Big data’ including storage infrastructure, data transfer and communication networks.

Appendix 1 - Knowledge Transfer Plan

A major aim of the NIFPI projects is to ensure that the innovative outputs of the research are implemented within the forest industry. To facilitate this process requires a commitment between the industry partners and the researchers. The researchers undertaking the NIFPI project: Solutions for the optimal use of remotely acquired, high resolution data by the forestry sector, have developed many potentially valuable and useful outputs. The purpose of this paper was to identify each output to provide a basis for researchers and industry partners to discuss the appropriate methods for ensuring effective knowledge transfer to industry. For instance, industry partners have indicated an interest in workshops to ensure they understand and can operate software developed as part of the project. It may be appropriate for potential contractors to industry be present at the workshops.

However, in some cases a workshop was not necessary, and the required knowledge transfer had have already occurred e.g. the Review of Data Management Solutions was self-explanatory.

Below are two tables:

- Table 1: Workplan Areas, which was drafted soon after the start of the project which identifies the workplan areas for each project team, including Interpine and WA FPC.
- Table 2: Project Outputs, which identifies each sub projects outputs.

Process

1. In the first instance each researcher was asked to please consider the Project Outputs in Table 2 and provide any edits and additions. In the last row of Table 2, please indicate if you think a Workshop may be appropriate and some proposed dates and times. A shorter workshop for each sub project may be preferred to a single project workshop.
2. Table 2 below was finalised and shared with the Project Steering Committee for feedback, scheduling of agreed workshops and to ensure no aspect of the research outcomes was forgotten in the knowledge transfer process.

Table 1: Workplan Areas - Solutions for the optimal use of remotely acquired, high resolution data by the forestry sector

Assessment	Scion – Mike Watt	Sydney - Mitch Bryson	UniSA – Anthony Finn	UniSA – Stefan Peters	UTas – Arko Lucieer
Weed species and coverage In Pine & Euc plantations			√		√
Seedling survival In pine & Euc plantations			√		√
Young age plantation growth			√		
Foliar nutrient status	√				
Tree volume and product; tree census[1]		√			
Spatial and temporal effects on radiata stand parameters using ALS imputation				√	
Stand health (drought & herbivory) in Pine & Euc stands			√		√
Native forest inventory[2]		√			√

Footnotes

[1]Interpine are collaborating with HQP (Lee Stamm) and Mitch Bryson

[2]WA FPC are working with Terra Drone (C4D Intel), Arko Lucieer and Mitch Bryson for assessment of 2 stands of Jarrah Forest

Table 2: Project Outputs - Solutions for the optimal use of remotely acquired, high resolution data by the forestry sector

Sub Project	Scion – Mike Watt	Sydney - Mitch Bryson	UniSA – Anthony Finn	UniSA – Stefan Peters	UTas – Arko Lucieer	UniSA – Jixue Li	Interpine	WA FPC
Reports						A Review of Data Management Solutions in the Forestry Industries, Zhao Liang, Jixue Liu, Jiuyong Li (2020)		
Papers	Watt, MS., Buddenbaum, H., et al. (2020) Monitoring biochemical limitations to photosynthesis in N and P-limited radiata pine using plant functional traits quantified from hyperspectral imagery. Remote Sensing Environment 248: Article 112003. Watt, MS.,	Windrim L and Bryson M (2020) Detection, Segmentation, and Model Fitting of Individual Tree Stems from Airborne Laser Scanning of Forests Using Deep Learning		- Journal article on Individual Tree based Imputation Modelling	Scientific results in report may be converted into a paper after approval by steering committee.			

Sub Project	Scion – Mike Watt	Sydney - Mitch Bryson	UniSA – Anthony Finn	UniSA – Stefan Peters	UTas – Arko Lucieer	UniSA – Jixue Li	Interpine	WA FPC
	Buddenbaum, H., et al. (2020) Using hyperspectral plant traits linked to photosynthetic efficiency to assess N and P partition. Journal of Photogrammetry and Remote Sensing 169 (2020) 406–420							
Presentations/seminars	22/4/2020 - Estimating N and P and photosynthetic capacity in N and P limited radiata pine using hyperspectral imagery - Mike Watt 19/11/2020 Presentation at NZ Forest TECH 2020. Use of	20/5/2020 - Point cloud analysis for inventory using machine learning and automation - Mitch Bryson & Lloyd Windrim	15/6/2020 - Young plantation age survival counts from pre-processed Hyperspectral & Phantom images (low cost) - Anthony Finn	1/7/2020 - Imputation models in spatio-temporal domain - do forest growers benefit from sharing ALS & inventory datasets for yield modelling ? – Pankaj Kumar, Stefan Peters	6/5/2020 - Multispectral sensors for drone remote sensing and generation of orthomosaics and 3D multispectral point clouds for applications in forestry 10/6/2020 - Mapping weeds in young radiata pine plantations using	3/6/2020 - A Report of LiDAR data management Solutions in the Forestry - Jixue Liu - University of South Australia	29/4/2020 - High resolution LiDAR data in Forest inventory - Susana Gonzalez - Interpine 8/7/2020 - Drone Based - Post Thinning Inventory	17/6/2020 - Remote sensing for harvest planning in native Jarrah forests - Hans Blom

Sub Project	Scion – Mike Watt	Sydney - Mitch Bryson	UniSA – Anthony Finn	UniSA – Stefan Peters	UTas – Arko Lucieer	UniSA – Jixue Li	Interpine	WA FPC
	hyperspectral imagery to characterise nutrient deficiencies in radiata pine – Mike Watt				multispectral UAV imagery 8/7/2020 - Mapping a forestry area with a drone: advice on how to get it right first time! - Darren Turner		– David Herries – Interpine	
Models	Predictive models of foliar Nitrogen (N), Phosphorus (P) have been developed from a set of measurements taken in October 2019.		Nursery Tree Survival Count Model (based on k-means clustering and morphological operations) Weed Detection Model (based on VoxNet architecture-based Convolution Neural Network). Processing workflow of Phantom, Hyperspectral and thermal datasets acquired using drone.	Processing workflow of LiDAR data and individual tree detection from them. Generation of standard and voxel-based metrics from LiDAR datasets. KNN and Random Forest models and how they can be used to impute response variables for spatial-temporal transferability (along with the recommendation of	Description and code (Python and R scripts) were provided such that machine learning models could be created, in particular, to classify tree species within a radiata pine stand. However, methods are generic and thus applicable to other forest types if further testing is undertaken.			

Sub Project	**Scion – Mike Watt**	**Sydney - Mitch Bryson**	**UniSA – Anthony Finn**	**UniSA – Stefan Peters**	**UTas – Arko Lucieer**	**UniSA – Jixue Li**	**Interpine**	**WA FPC**
				parameters in them).				
Software/location	Scion	Forest3DApp: machine-learning based software for analysis of trees from point clouds	Lidar3DMapApp PINT (Program for Identifying Nursery Trees) App	LiDAR processing batch files R-scripts for imputation modelling	Example code (Python and R scripts) and command line scripts will be provided for the various steps required to process and segment a photogrammetric point cloud of a forest coupe or stand.			
Workshops scheduled	No		Yes **13/5/21** ‘PINT, a Program for Identifying Nursery Trees (incl. seedlings)’ **Overview:** The workshop will cover how the program “PINT” works, how to use this program on your own data sets, and the results you can expect. For those who may have already started using PINT, the	Yes **18/8/21** ‘A Workshop on Growth and Yield Prediction of Trees at Plot & Individual Level using **Imputation** Modelling’ **Overview:** - Processing workflow of Airborne and UAV based LiDAR datasets (clipping,	**Date TBA** Playing to our strengths the best workshop to hold would be one on how best to collect quality UAS imagery over forests and then an overview of tools available to process and analyse this data. This would focus on the workflow			

Sub Project	Scion – Mike Watt	Sydney - Mitch Bryson	UniSA – Anthony Finn	UniSA – Stefan Peters	UTas – Arko Lucieer	UniSA – Jixue Li	Interpine	WA FPC
			workshop will contain a Q&A session on how to get the most out of the program. Note: PINT automatically identifies young trees in drone imagery. It has been tested on 700Ha replanted forest, comprising trees ranging from 9-months to 3 years old and growing in light and heavily weed environments. **Note:** Assume workshop will take a morning (or afternoon), including **Zoom** (but also happy to do in person presentation) **Preferred in person presentation venue:** Mount Gambier	noise removal, ground estimation, height normalization etc.) - Individual tree detection (CHM generation etc.) using various tools. - Generation of standard and voxel-based metrics from LiDAR datasets. - The use of KNN and Random Forest-based imputation models to predict the response variables using LiDAR metrics and ground inventory datasets. - Knowledge transfer on the use of these models to impute variables for spatial-temporal-sensor domain	to produce a photogrammetric point cloud, in particular a multispectral point cloud. Could be done over zoom, or in person. Anything from 2-3 hours to an entire day if Face to Face, could include some drone demonstration flying etc. Can be backed up with some instructional videos that we already have available in case the attendees cannot take it all in on the day.			

Sub Project	Scion – Mike Watt	Sydney - Mitch Bryson	UniSA – Anthony Finn	UniSA – Stefan Peters	UTas – Arko Lucieer	UniSA – Jixue Li	Interpine	WA FPC
			Alternate in person presentation venue: Mawson Lakes **Alternate Dates:** May 20th May 14th May 21st May 27th May 28th June 3rd June 4th June 10th June 11th June 17th June 18th	transferability. - The use of recommendable parameters in the processing of the LiDAR dataset and the use of imputation models. **Note:** As previously discussed and approved, project outcomes for the "imputation" project will be delivered with a 3-months delay as Pankaj is working Apr-June fulltime on another project. We will have further analysis results, findings and deliverable tools ready by August which are crucial for the workshop. Hence we propose to hold this workshop in August. **Zoom**				

Sub Project	Scion – Mike Watt	Sydney - Mitch Bryson	UniSA – Anthony Finn	UniSA – Stefan Peters	UTas – Arko Lucieer	UniSA – Jixue Li	Interpine	WA FPC
				Preferred in person presentation venue: Mount Gambier **Alternate in person presentation venue:** Adelaide **Alternate dates:** 25/8/21 31/8/21				
Alternative communication methods	Summary report provided.		Technical Report (on the use of delivered models and software)	Technical Report (on the use of delivered batch files and R-scripts)	Report on the case studies undertaken and their results. Detailed methodologies will be included such that industry partners can replicate if desired.			