Research, development and extension investment plan

Research, development and extension priorities to achieve value gains through forest resource modelling and remote sensing.

2020

Adapted from *FWPA Resource Modelling and Remote Sensing Investment Plan: Research needs assessment*, prepared for FWPA by Authors: Braden Jenkin, Stefan Peters, Jim O'Hehir and Chris Chow

This version of the Investment Plan, adapted by FWPA in December 2020, removes the cost estimates from the original Investment Plan, *FWPA Resource Modelling and Remote Sensing Investment Plan: Research needs assessment*, prepared for FWPA by Authors: Braden Jenkin, Stefan Peters, Jim O'Hehir and Chris Chow, 2019.

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Author declaration of interest

The authors, Braden Jenkin, Stefan Peters, Jim O'Hehir, received income in the past year from research, development and extension carried in the technical areas addressed in this investment plan. The authors anticipate receiving income in the next five years from research, development and extension activities carried out in the technical areas addressed by this investment plan.

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Forest & Wood Products Australia

Acronyms

ABA		Area-based analysis
AGDC		Australian Geoscience Data Cube
ALS		Airborne laser scanning
CAD		computer assisted drawing
CEOS		Committee on Earth Observation Satellites
CSIRO		Commonwealth Scientific and Industrial Research Organisation
DEM		Digital Elevation Model
EO		Earth observation
ESA		European Space Agency
GBDX		The GBDX platform refers to a cloud-based satellite image library
GEDI		Global Ecosystems Dynamics Investigation LiDAR
GFOI		Global Forest Observations Initiative
GIS		Geographic Information System
GRAC		Grower Research Advisory Committee
IFA		Institute of Foresters of Australia
ISRO		Indian Space Research Organisation
ISS		International Space Station
ITD		Individual Tree Detection
LAI		Leaf area index
LiDAR		Light Detection and Ranging
MAPIZY		Deep tech company focused on change detection through image data
MODIS		Moderate Resolution Imaging Spectroradiometer
NASA		National Aeronautics and Space Administration
NIR		Near Infrared
NISAR		NASA-ISRO Synthetic Aperture Radar
NRTSR		Near Real-Time Surface Reflectance
RDE		Research Development Extension
RS		Remote Sensing
SAR		Synthetic aperture radar
SLSTR		Sea and Land Surface Temperature Radiometer
SPCD		Satellite point cloud data
SWIR		Short Wave Infrared
STBA		Southern Tree Breeding Association
TLS		Terrestrial laser scanning
UAV		Unmanned Aerial Vehicle
UAV-LiDAR		Unmanned Aerial Vehicle equipped with a Light Detection and Ranging sensor
WMO		World Meteorological Organization
RN		Research need
R&D		Research and development
RD&E		Research, development and extension
TC		Technical committee

Forest & Wood Products Australia

Executive summary

This investment plan addresses resource modelling and remote sensing areas of research development and extension for hardwood and softwood plantations at the request of Forest and Wood Products Australia (FWPA). FWPA administers and provides leadership to investment in research and development in support of Australia's forest and forest products industries. To ensure an efficacious allocation of funds to the best outcomes for the industry, FWPA operates within targeted research and development investment plans developed under the auspices of the Grower Research Advisory Committee (GRAC). GRAC has articulated a specific vision for Australia's commercial forests [1]: *'Our Vision is to double the value of Australia's commercial forests by 2040, by fostering an innovation culture in our enterprises, applying world's best practices, collaborating and investing into research and development as appropriate'* and it is intended that investment in research and development should support this vision. Resource modelling and remote sensing are specific tools utilised by forest managers to assist in the management of forest estates to achieve a range of objectives. Remote sensing technology captures data via a range of platforms and sensors for use by forest managers. With technology development (including data management), the role of remote sensing is evolving. Resource modelling seeks to take data and apply analytical tools to generate projected outcomes (e.g. wood and product flows, forest values). Currently the resource modelling systems in place are a mixture of bespoke and 'Frankenstein' in nature through to proprietary systems.

To ensure a fit for purpose research and development investment plan for resource modelling and remote sensing, a collaborative and participatory approach was developed and implemented (see Appendix 1: Stakeholders consulted commencing on page 27). A list of 17 resource modelling and remote sensing research needs were identified and documented (Table 1) and a narrative was developed for each and this is presented in Appendix 2: A short narrative of the identified research needs issues and opportunities commencing on page 28 and Appendix 3: The identified research needs issues and opportunities commencing on page 1. The research needs were drafted based on a literature review (presented in Appendix 4: Literature review resource modelling and remote sensing) direct industry consultation and an online survey. The development of the investment plan was overseen by a Technical Committee (commencing with an inception meeting) and a participatory scoring process was undertaken to objectively rate the different needs. The research needs are rated as highest, medium and lower priority (see Table 1) and a method and indicative timeframe has been suggested and an estimated benefit has been assigned to each cluster of projects (Table 2).

The highest priority research needs focus on systems development including the better integration of the components of systems and the potential for inclusion of remote sensing data. Data management was considered a high priority and would form an underlying issue for many systems. The development of research projects is likely to have a major focus on a high priority research need and include elements of the medium and lowest priority research needs.

Barriers to undertaking research related to resource modelling and remote sensing can be categorised as capacity, capability and business needs and priorities. Resource modelling and remote sensing is complex and requires specialised skills, experience and time to carry through to operational business systems. Often forestry organisations don't possess the in-house skills and expertise to undertake research in this area and if they do have the expertise in-house those quantitative skills will often be in demand in other areas of the business. Forestry can also be insular and unaware of developments in other disciplines which could be adapted for forestry applications. All the research priority needs can be subject to these barriers (see Table 1).

[1] Downloaded from https://www.fwpa.com.au/forwood-newsletters/1695-fwpa-grower-members-aim-to-increase-investment-in-rd-e.html on the 26/04/2019.

TABLE 1: A SUMMARY OF THE MODERATED RANKING OF THE IDENTIFIED RESEARCH NEEDS.

Higher priority research needs	Medium priority research needs	Lower priority research needs
Regularly updated wood-flow projections and actuals (estate-based)	Integration of resource modelling systems with wood flow modelling	A centralised approach applied to resource modelling
Potential applications of remote sensing in resource modelling	System interfaces between remote sensing and resource modelling	A centralised approach to remote sensing data capture and supply
Remote sensing replacement of traditional inventory data capture	Precision requirements: the scope of systems down to the individual tree	The non-resource modelling needs of forestry in regards to remote sensing
Remote sensing options for use in forestry	The use of remote sensing in forest monitoring	Integration of the components of resource modelling systems
Platforms and integrated approach with combined sensors	Development of improved growth models	Analytical capacity and the speed of data analysis and timeliness
Data sources and management		On the horizon options and systems

The imperative for improvements to resource modelling and remote sensing systems can often rely on the recognition of senior management of a critical business need to attract the necessary priority for funds to be assigned. These imperatives are often time critical which can result in the development of expedient solutions when in fact a completely new but less timely development may have been more strategically appropriate. Although usually budgets anticipate licencing costs it is less likely they will allow for ongoing systems research and improvement, especially where a priority business need has not yet been identified.

TABLE 2: A SUMMARY OF LOGICAL RESEARCH PROJECTS RELEVANT TO IDENTIFIED RESOURCE MODELLING AND REMOTE SENSING NEEDS.

Broad category of research	Code	The identified research need	Method	Time (indicative)	Benefit (indicative total across 10 companies)
Better integration of all elements of resource modelling systems	A1	Integration of the components of resource modelling systems	Systems analysis of existing forestry and non-forestry systems to identify best practice. Scan of available technology including application in other industries and assessment of applicability to forestry.	12-24 months	+5-10% in net log value recovery through better matching of log characteristics with customer requirements
	A2	Integration of resource modelling systems with wood flow modelling			
	A3	Regularly updated wood-flow projections and actuals (estate-based)			
	A4	Potential applications of remote sensing in resource modelling			
	A5	System interfaces between remote sensing and resource modelling			
A centralised approach	B1	A centralised approach applied to resource modelling	Scan of organisations that provide these services potentially in other industries. Options for cooperative structures including cost, benefit, risk assessment.	6 months	-$1.5M cost of internal remote sensing services through elimination of duplicate effort
	B2	A centralised approach to remote sensing data capture and supply			
Growth models in resource modelling	C1	Remote sensing replacement of traditional inventory data capture	Scan of what models are currently used, their current performance and potential for replacement.	12-24 months	-50% cost of inventory through reduced field work
	C2	Development of improved growth models			
Resolution of forestry	D1	The non-resource modelling needs of forestry in regard to remote sensing	Survey of industry needs with regard to precision of management.	6 months	+5-20% in log value recovery through better matching of log characteristics with customer requirements
	D2	Precision requirements: the scope of systems down to the individual tree			
An evaluation of remote sensing options and opportunities	E1	Remote sensing options for use in forestry	Scan of what models are currently used, their current performance and potential for replacement with remote sensing. What system changes would be required.	12-24 months	-5-10% in cost due to multipurpose surveys and reduced fieldwork
	E2	Platforms and integrated approach with combined sensors			
	E3	On the horizon options and systems			
	E4	The use of remote sensing in forest monitoring			
Data	F1	Data sources and management	Understanding of current and future data sets, security arrangements and storage, potentially cooperative, options and costs.	6 months	+5% operational efficiency through better data management and analysis
	F2	Analytical capacity and the speed of data analysis and timeliness			

Introduction

Australia's forest estate includes 131.6 million ha of natural forests and 1.9 million ha of plantations (0.9 million ha of hardwoods; 0.9 million ha of softwoods).[2] The total woodflow from Australia's forests was 33.2 million m^3 of logs harvested in 2016/17 with a gross value of $2.6 billion: 4.1 million m^3 of natural forests logs with a gross value of $0.4 billion; 11.4 million m^3 of plantation hardwood logs with a gross value of $0.8 billion; 17.7 million m^3 of plantation softwood logs with a gross value of $1.4 billion.[3] The logs harvested result from a combination of market pull and available supply. Market pull is in most cases based on contracted long-term supply obligations with specific processors and a minor component of short-term and spot market sales. Log supply results from forest and plantation growth and in the case of plantations, management interventions targeting specific log attributes (e.g. thinning). Quantification of standing resource stocks is based on resource modelling. Resource modelling in forest management is concerned with estimating the available timber resource for commercial management purposes (e.g. the total quantity, the characteristics of the timber, its location and a time series of availability). This information allows forest managers to estimate the woodflows available under assumed or alternative management regimes, and scenarios such as fertilisation and forest health impacts, and then estimate the value of the timber assets. The scale and stratified attributes of the forest estate is a fundamental input to resource modelling and more and more remote sensing is a fundamental tool. Remote sensing in forest management is concerned with the acquisition of information about the forest without making physical contact with it. Thereby, tree as well as stand wide information are obtained by sensors mounted on satellites, aircraft or drones. Remote sensing is undertaken by remote sensing systems. A remote sensing system is the combination of the technical components used to capture and store remote sensing data, including data analysis. The resulting output of resource modelling feeds into operational and tactical harvest planning systems. An operational harvest planning system schedules harvesting operations from weeks to several years to match short-term customer requirements and allocate harvesting and transport resources whereas a tactical cutting planning system schedules harvesting operations for the next 1-5 years to allow for preparation of operational harvest plans.

A wide range of resource modelling and remote sensing systems are in place and in use by the Australian industry and as with any system, there is a need to maintain and up-grade the capabilities of the systems. This is more important given the role of such systems supporting critical decision making and statutory requirements such as forest asset valuations and reporting. Forest and Wood Products Australia (FWPA) has developed a series of industry advisory committees and supporting research and development investment plans covering strategic elements of the industry (Box 1) and this document forms the Resource Modelling and Remote Sensing Research and Development Investment Plan.

BOX 1: THE FWPA SEGMENTATION OF RESEARCH AND DEVELOPMENT INTO A SERIES OF DISCRETE RESEARCH INVESTMENT PLANS. [4]

• Soils and nutrition • Damage agents (pests, disease, extreme climatic events) • Fire • Operations and supply chain	• Genetics and tree breeding • Plantation silviculture • Native forest silviculture • Resource modelling and remote sensing.

Objectives

An important element in research planning and priority setting that links the strategic context to priority activities is the industry's vision. The relevant vision for the development of the resource modelling and remote sensing research, development and extension (RD&E) investment plan is FWPA's vision and

[2] ABARES (2018: Table 3 & Table 4).
[3] ABARES (2018: Table 6 & Table 7).
[4] Downloaded from https://www.fwpa.com.au/about.html on the 13/03/2019.

mission (Box 2). FWPA's Grower Research Advisory Committee (GRAC) has articulated a specific vision for Australia's commercial forests[5]: *'Our Vision is to double the value of Australia's commercial forests by 2040, by fostering an innovation culture in our enterprises, applying world's best practices, collaborating and investing into research and development as appropriate.'* The specific objective of this Investment Plan is to enhance resource modelling and remote sensing capacity as tools to enable industry to meet its compliance obligations (e.g. contracted wood supply), statutory requirements (e.g. asset valuation reporting) and management objectives (e.g. thinning regimes) while reducing risk due to uncertainty around wood flows and forest value.

BOX 2: THE FWPA VISION AND MISSION STATEMENTS.[6]

*'**Our Vision:** The forest and wood products industry will grow as a result of increased demand for its market-oriented, sustainable and competitive products and services.*

***Our Mission:** FWPA collaborates with government and industry stakeholders to determine strategy and deliver programs designed to grow the market for forest and wood products, increase productivity and profitability across the value chain, and ensure positive environmental and social outcomes.'*

Background

The steps and elements of remote sensing and resource modelling systems are presented in Figure 1 and Figure 2. Historically, forest resource data were collected via ground-based surveys of forests and trees using manual methods and extrapolating the results to an estate level. Sometimes aerial photography provided a useful extension to the manual data collected. After a slow start, remote sensing methods have now supplemented manual methods and now provide a cost-effective replacement for some of these methods of data collection and provide derived forest biometric data that can be used as inputs to existing growth and yield modelling systems. However, in Australia and New Zealand the adoption of remote sensing for data collection has not led to a fundamental change in growth and yield modelling systems or the metrics that drive them. The full value of the remote sensing data collected is not being realised because the legacy systems only include biometrics that can operate on traditional forest inventory data metrics. Historic log supply agreements formalise this disconnection because the drivers of value do not underpin the pricing mechanisms which in turn results in incorrect pricing signals. There are several opportunities that should be investigated over the next 5 years to close the gap between the requirements of customers and the capability of the forest growers to meet their needs. In addition, not all the attributes of forests and trees that are important for timber processors are currently able to be collected from remote sensing or other methods. This can lead to a disconnect between the attributes and capacity of forests to meet the requirement of processors and customers of their products. In the assessment of tree and forest quality and condition there is a continuing reliance on manual assessment methods that have a large influence on forest merchantability estimates. Although some objective scanning methods exist, they have not been developed to operational status.

[5] Downloaded from https://www.fwpa.com.au/forwood-newsletters/1695-fwpa-grower-members-aim-to-increase-investment-in-rd-e.html on the 26/043/2019.
[6] Downloaded from https://www.fwpa.com.au/about.html on the 13/03/2019.

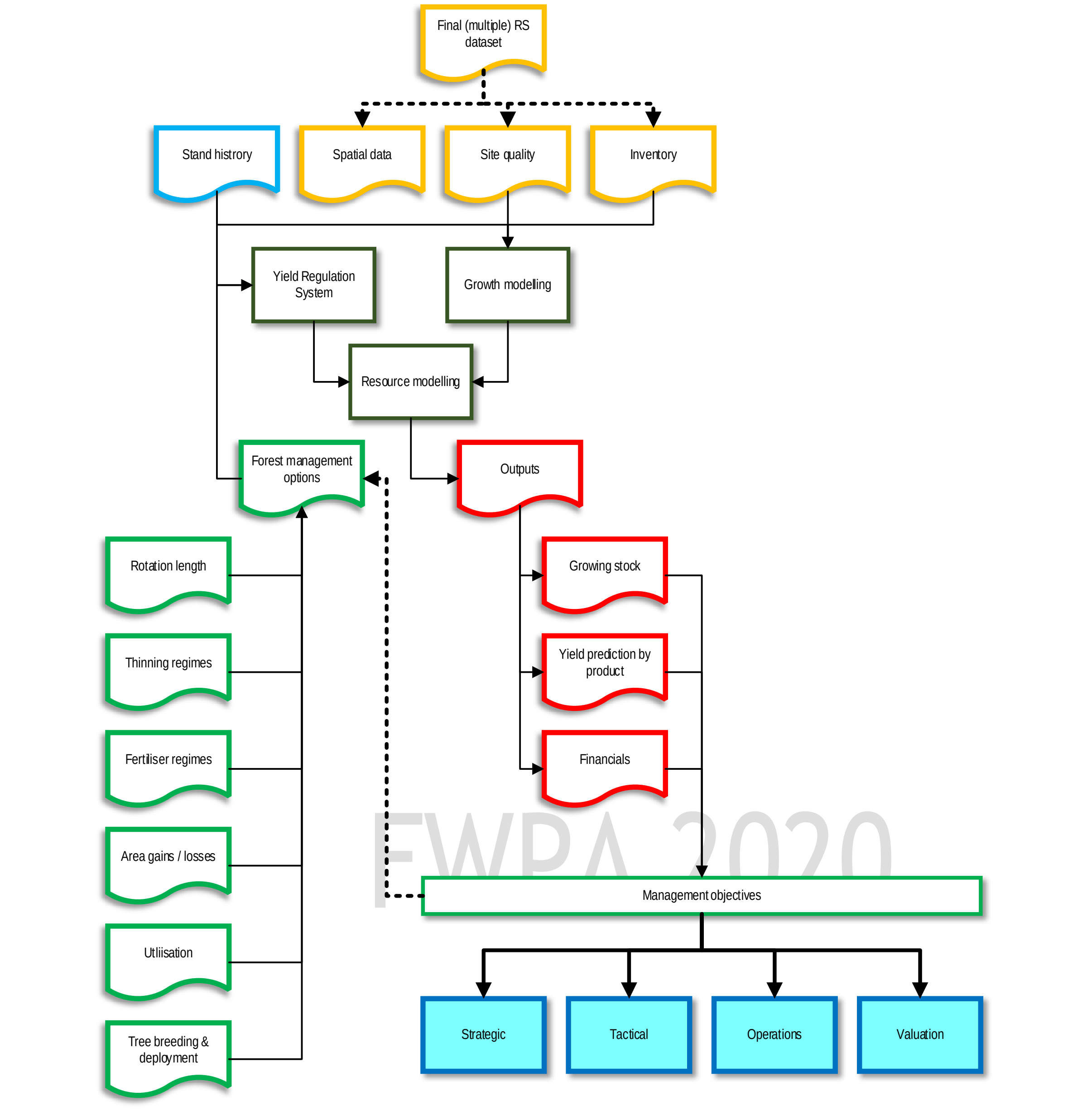

FIGURE 1: A SUMMARY OF THE ELEMENTS OF A RESOURCE MODELLING SYSTEM.

Remote sensing has not generally found application in nutrition and health applications in Australian forestry compared with the rate of adoption in in agriculture and horticulture for these purposes. There are opportunities to consult remote sensing experts in agriculture and horticulture to understand the drivers that led to the use of remote sensing in these industries and to consider opportunities for adaptation of some of this remote sensing to forestry. To date a clear barrier to forestry applications of remote sensing for nutrition and health assessment has been the extensive scale of forestry activities compared with agriculture and horticulture, and the lack of precision of the available remote sensing data from satellites. The cost of calibrating remote sensed data with on ground measurements has contributed to a lack of application. In both agriculture and horticulture fixed wing aircraft and drone technology can provide cost effective platforms for various remote sensor deployment across the relatively small areas under management. Resource modelling and remote sensing can contribute to better understand the factors that influence growth and different productivities through the integration of climate and management time series data related to pest and disease incidence and other disturbances.

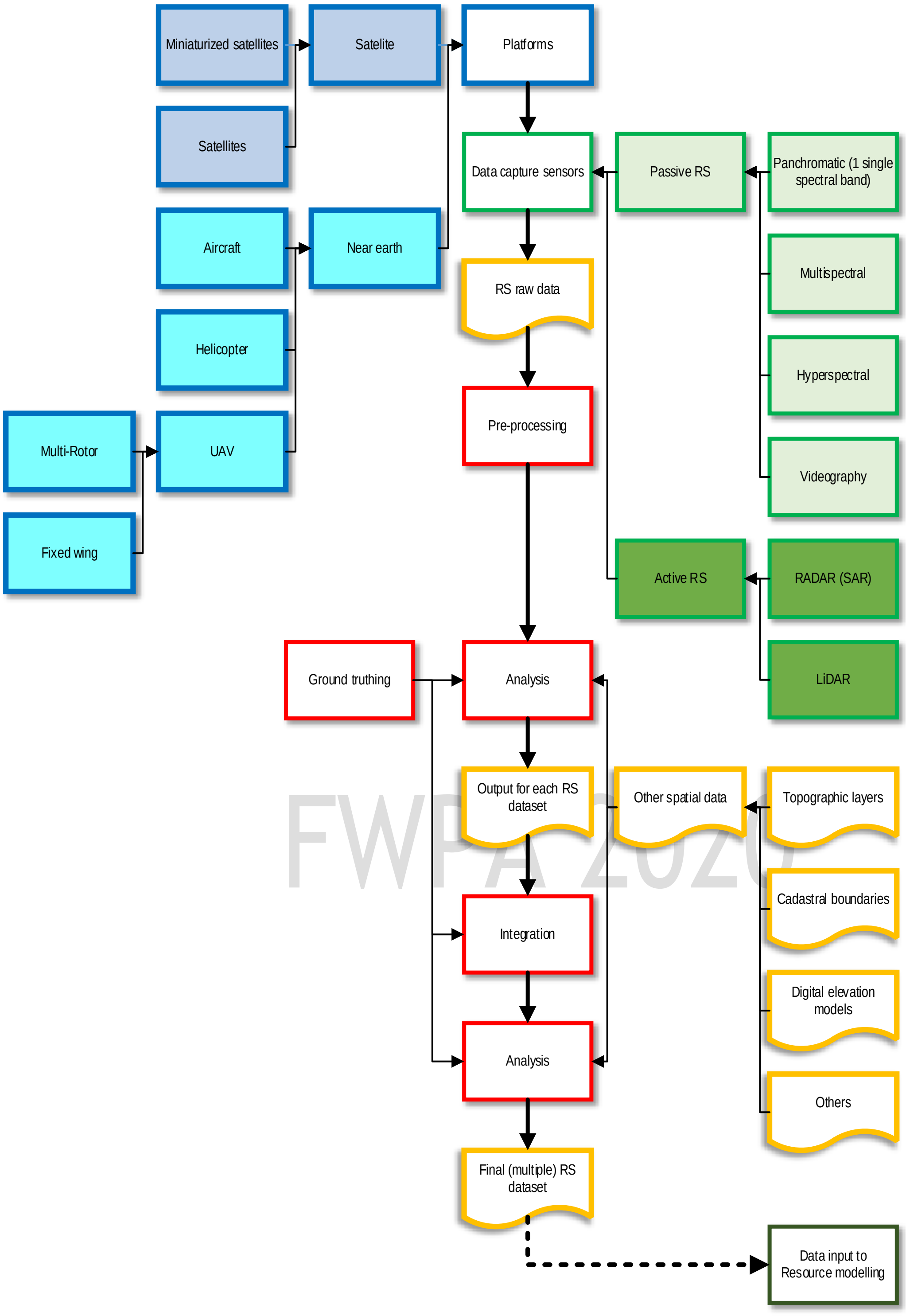

FIGURE 2: A SUMMARY OF THE ELEMENTS OF A REMOTE SENSING SYSTEM.

There may be opportunities for forestry applications of the latest remote sensing technologies such as full-waveform, multispectral, and Photon (airborne) LiDAR. However, specific nutrition and health detection applications may be more feasible with hyperspectral satellite sensors announced to be launched in 2021 or later (e.g. HyspIRI, HypXIM). It is to be expected that cloud-based big data sharing/processing/deep learning libraries will boom in the next decade and strongly shape the remote sensing data processing market. Forest companies' remote sensing and associated costs may reduce as cloud-based computing may lead to reduced geographic information systems and remote sensing (GIS/RS) software licenses, less GIS/RS skilled staff, less data, software and hardware infrastructure, and less data acquisition as satellite sensors increase in spatial/spectral/temporal resolution.

Based on discussions with the FWPA, the industry vision is to double its value by 2040 across both natural and planted forests which equates to a real annual compounded interest growth rate of 3.5% from 2020 to 2040. It is recognised that value can be improved by changing financial considerations (e.g. costs and returns) and product mix outputs (e.g. volume and different products). The value of the estate can be defined based on accounting standards as interpreted in '*A standard for valuing commercial forests in Australia*' (version 2.1).[7] The methods developed by the proposed investment plan will contribute to robust and defendable forest estate valuation.

Methodology

The aim of the methodology developed was to facilitate a participatory process to develop the R&D investment plan for resource modelling and remote sensing. The process included seven broad stages and as outlined in Figure 3. A three-step process was undertaken: 1) Identifying the research needs; 2) Scoring the research needs; 3) Moderating the scores and assigning priorities. The development of a R&D investment plan commenced with an inception meeting held on 1/11/2018 with participants joining the meeting either in person or remotely. The inception meeting participants formed a project Steering Committee and included the FWPA's GRAC Executive representatives and other interested parties. This commenced the participatory nature of the project and was under-pinned by a short pre-meeting survey to gain an understanding of the needs of the industry. The meeting outcome was a sign-off on the proposed methodologies and direction of the investment plan. A range of information was collected via industry consultation, a literature review process and an industry survey. A formal literature review was undertaken of the resource modelling and remote sensing literature. Industry consultation was ongoing throughout the process commencing with the project inception meeting. The information collected by each method was collated and aggregated and distilled into a series of research needs. The insights and research needs were then combined in the one document and further distilled and collated to a list of 17 research needs. It should be noted that there are links and overlap between the research needs.

A narrative and a succinct statement of the research needs was prepared for each of the 17 identified research needs. To determine the relative priority of each research need, a two-stage process was undertaken. In the first stage the Technical Committee members independently assessed each research need for each of the impact (potential benefits and ability to capture the benefits) and capacity (research capacity and delivery) (see Box 3 and Table 3) and recorded their scores on a score sheet. The score sheets were collected, and the scores were entered into an overall spreadsheet. Aggregated average scores were determined and a preliminary overall priority assessment was prepared. This preliminary assessment provided a basis for discussion and debate. An online workshop was held (09/04/2019), where members of the Technical Committee reviewed the aggregated results of each research need.

[7] A publication of the Institute of Foresters of Australia Limited, Association of Consulting Foresters of Australia Division, July 2012.

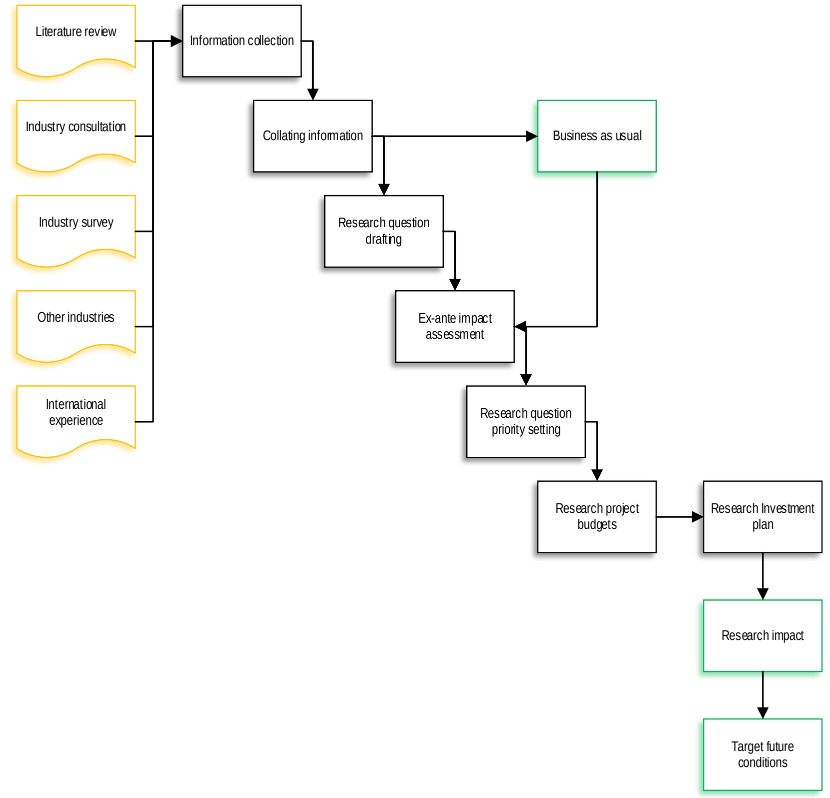

FIGURE 3: AN OVERVIEW OF THE RESEARCH METHODOLOGY TO GENERATE THE RESEARCH INVESTMENT PLAN.

BOX 3: THE DEFINITION OF IMPACT AND CAPACITY AS USED IN THE ANALYSIS AND PRIORITY SETTING PROCESS.

Impact is based on assessment of two criteria – *potential benefits* and *ability to capture* (Table 3). Impact combines assessment of the potential economic/financial, environmental/ecological, social and knowledge benefits from investment in R&D in each research need with assessment of the ability to capture or realise those benefits. Realising potential benefits can be influenced by physical conditions, institutional factors, access to resources to assist adoption (human, physical, financial, knowledge), cultural factors and the attitudes of those who could utilise or benefit from (improvements associated with) the research need. These influences may be positive or negative.	**Capacity** is based on assessment of two criteria – *research and development capacity* and *delivery capacity*. Assessment of R&D capacity accounts for the scientific and technology capabilities and the knowledge and technology transfer capabilities of relevant R&D providers, to make a positive difference for a research need within a reasonable time-frame and budget. Capabilities comprise skills, experiences and competencies as well as the quality of R&D infrastructure, equipment and services. It also includes continuing collaborations and partnerships with external organisations and established knowledge networks. Capacity assessments must also consider the ease of mobility of capabilities (between organisations) and the factors influencing collaboration and integration. It is not sufficient to consider research capacity alone to make valuable improvements in a particular R&D area but the capacity to deliver research outputs in a time frame must also be considered in the overall assessment of capacity. Assessment is made of the effectiveness and efficiency of the use of skills, facilities, networks and services to deliver or disseminate the outputs from improvements in a particular research need in a series of time frames.

TABLE 3: A SUMMARY OF THE IMPACT AND CAPACITY ELEMENTS.

Criteria	Element	Narrative
Impact:		A measure of the likely economic, community or social, environmental and scientific/knowledge benefits from successful technology advances within a particular research and development area.
	Potential benefits	Maximum additional benefits (economic, social, environmental and knowledge) for your industry from investment in R&D for the particular research and development area.
	Ability to capture	Likelihood of your industry capturing the estimated benefits from successful R&D for the particular research and development area.
Capacity:		Capacity is a measure of the competitive position of the R&D provider(s) to generate scientific and technical progress for the industry, environment and community.
	Research capacity	Ability to conduct research competently and efficiently for the research and development area by Australian researchers and their collaborators
	Delivery capacity	Ability to deliver research outputs in set time frames to the satisfaction of users and beneficiaries by Australian researchers and their collaborators.

Analysis of current state of RDE, operational practice and gains (avoided losses)

Summary of resource modelling and remote sensing literature review

Figure 4 presents the outcomes of a Web of Science search and analysis[8] of the topic keywords "Remote Sensing", "LiDAR", "UAV", and "multi-spectral", published in the last 5 years with 53 100 records identified. There were 958 forestry 'hits' (related papers) and 544 for agriculture and 71 for horticulture. However, publications in environmental sciences (6058) and water resources (2150) were significant and potentially relevant to forestry research. A key point is that remote sensing advances are most likely in other sectors rather than in forestry.

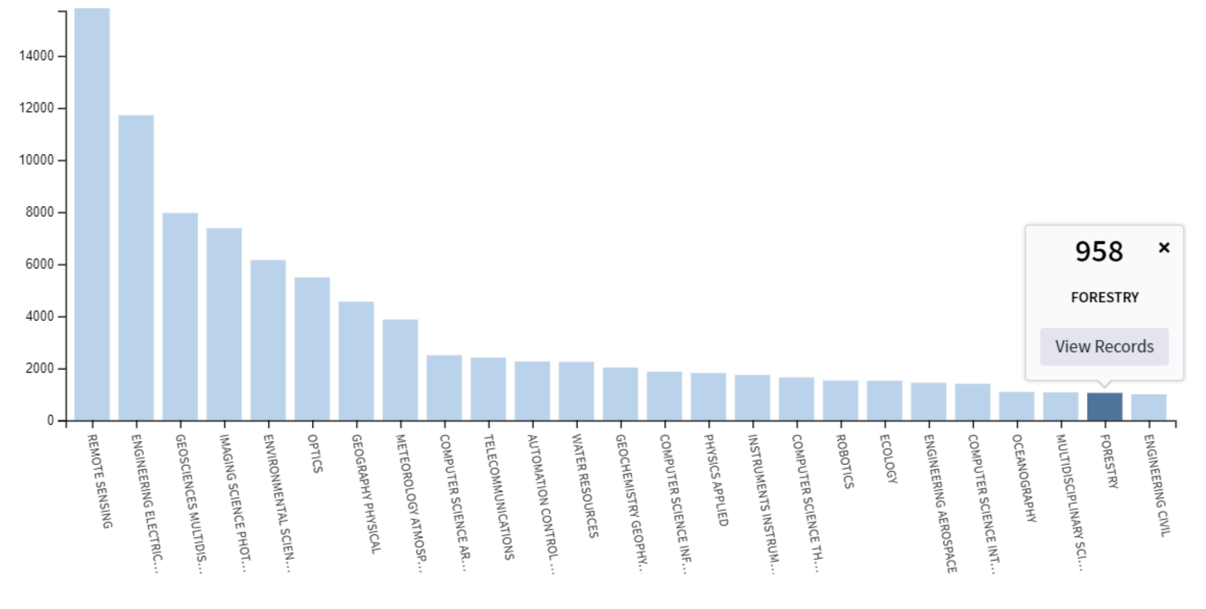

Figure 4: Web of Science results analysis for publications listing "Remote Sensing", "LiDAR", "UAV", and "multi-spectral".

Overall, future advances in remote sensing and associated technologies will enhance forest resource management as well as forest inventory and monitoring solutions. These solutions will be more detailed and sophisticated, more reliable, quicker and more efficient, more focused and more accurate. A literature review of resource modelling and remote sensing is included as an appendix (see Appendix 4: Literature review resource modelling and remote sensing) and a summary of the trends are presented. In summary several remote sensing trends relevant for future forestry research are expected including:

- Freely available Satellite data
- Development of miniaturised satellite platforms
- Advances in customisable systems and flexible frequencies
- Advances in sensor technologies improving frequency, quality and quantity of remote sensed forest data
  - Miniaturisation and integration of electronics
  - Progress in large apertures and larger antennas

[8] Web of Science: http://login.webofknowledge.com/error /Error?Src=IP&Alias=WOK5&Error=IPError&Params=&PathInfo=%2F&RouterURL=http%3A%2F%2Fwww.webofknowledge.com%2F&Domain=.webofknowledge.com

  - Increases in transmitter power for active systems
  - Miniaturisation of optics
  - Enhancements of on-board storage technology
  - Better batteries
- New sensors (e.g. Photon LiDAR, Multispectral LiDAR, Acoustic Tomography)
- Further development of UAV-based data acquisition systems
- Advances in techniques for processing and analysing “Big remote sensed Data”
  - Increases in computational power such as quantum and biological computing
  - Cloud processing of remote sensing data
  - Customised browser-based forestry applications based on (free) satellite imagery
  - Integrating multiple sensors sources
- New/advanced remote sensing data analysis methods:
  - Investigation of SAR data for forest monitoring
  - Combining datasets e.g. multi-temporal LiDAR datasets
  - Machine Learning

These remote sensing trends will lead forestry research towards:

- Decreased/replacement of ground measurements
- Improved reliability of collected data
- Individual tree-based forest management through individual tree detection and classification of tree features (stem position, tree crown, 3D-model: textured and classified point cloud)
- Satellite remote sensing for area-based analysis of forest stands
- Improved imputation models
- Improved (more precise, more frequent, at higher spatial resolution) estimates of forest features e.g. wood volume, biomass, tree health information, etc.
- Smart forest data systems / Forest phenotyping platforms

The survey outcomes

A detailed online survey was conducted to seek information on current resource modelling and remote sensing systems in place and the needs of the industry. A total of 61 individual responses were received providing significant information and insights. A key question asked the respondents to list the top five research needs for resource modelling and the top five research needs for remote sensing. The respondents to the survey provided key insights to specific research needs in a narrative format. Each response was analysed and the issues raised categorised (e.g. a single sentence may include a number of areas of interest). The frequency of reference data was captured for resource modelling and remote sensing and an analysis indicated the frequency of reference as a proxy to interest and importance of a topic: the results are presented in Figure 5 and Figure 6. The most frequently referenced needs for resource modelling were growth models, system integration, yield modelling, operational planning tools and data management. For the remote sensing needs, accuracy, timeliness, data capture speed, data costs and data access where the most referred to issues.

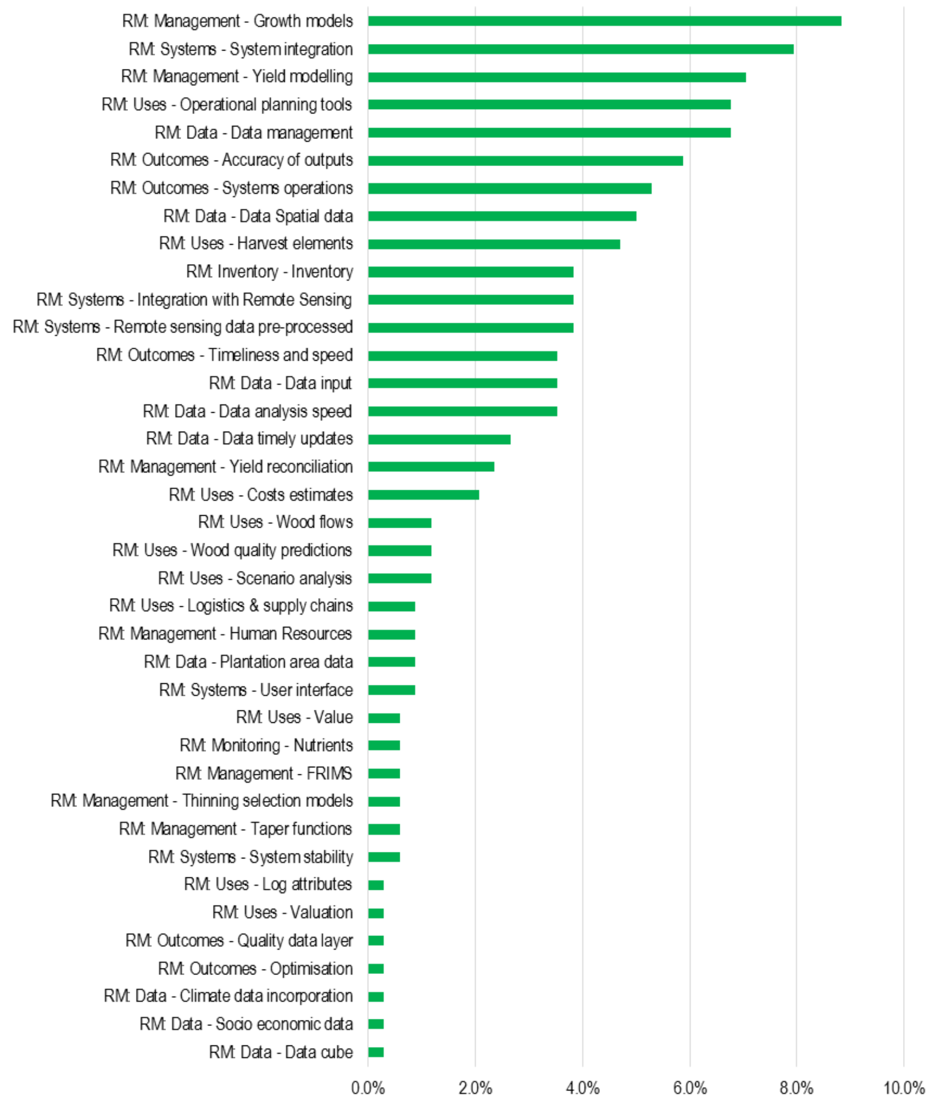

FIGURE 5: A COLLATION OF THE SURVEY STATED UNMET NEEDS FOR RESOURCE MODELLING.

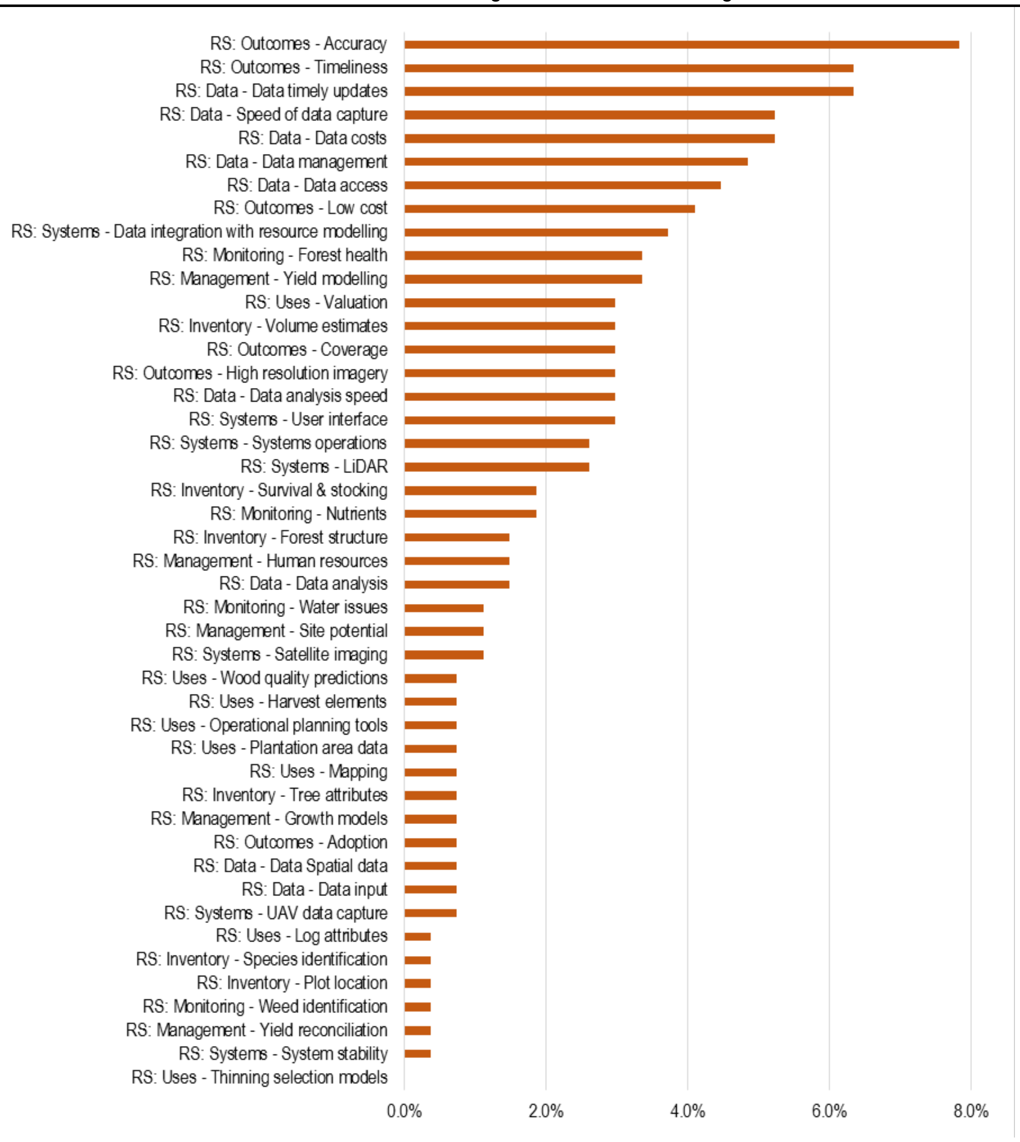

FIGURE 6: A COLLATION OF THE SURVEY STATED UNMET NEEDS FOR REMOTE SENSING.

The identified research needs

While the data presented in Figure 5 and Figure 6 was of use, the single points collated required details and narrative. The outcomes of all consultations was combined into the narratives presented in Appendix 2: A short narrative of the identified research needs issues and opportunities commencing on page 1 and Appendix 3: The identified research needs issues and opportunities commencing on page 1. Table 4 presents the titles to each research need.

The outcomes of the priority setting process

The priority setting process achieved the outcome of a transparent and participatory assessment of the 17 research needs presented in Table 4. The four-stage process (individual scoring; aggregated scores for impact and capacity – see Figure 7; the combined impact and capacity scoring – see Figure 8; the Technical Committee review) resulted in a clear priority order for the 17 research needs. In the development of actual research projects, it is highly likely that research needs could and will be combined from the high, medium and lower ranked cohorts.

TABLE 4: A SUMMARY OF IDENTIFIED RESEARCH NEEDS AND THE CODES APPLIED.

Code	Broad category of research	The identified research need
A1	Better integration of all elements of resource modelling systems	Integration of the components of resource modelling systems
A2		Integration of resource modelling systems with wood flow modelling
A3		Regularly updated wood-flow projections and actuals (estate-based)
A4		Potential applications of remote sensing in resource modelling
A5		System interfaces between remote sensing and resource modelling
B1	A centralised approach	A centralised approach applied to resource modelling
B2		A centralised approach to remote sensing data capture and supply
C1	Growth models in resource modelling	Remote sensing replacement of traditional inventory data capture
C2		Development of improved growth models
D1	Resolution of forestry	The non-resource modelling needs of forestry in regard to remote sensing
D2		Precision requirements: the scope of systems down to the individual tree
E1	An evaluation of remote sensing options and opportunities	Remote sensing options for use in forestry
E2		Platforms and integrated approach with combined sensors
E3		On the horizon options and systems
E4		The use of remote sensing in forest monitoring
F1	Data	Data sources and management
F2		Analytical capacity and the speed of data analysis and timeliness

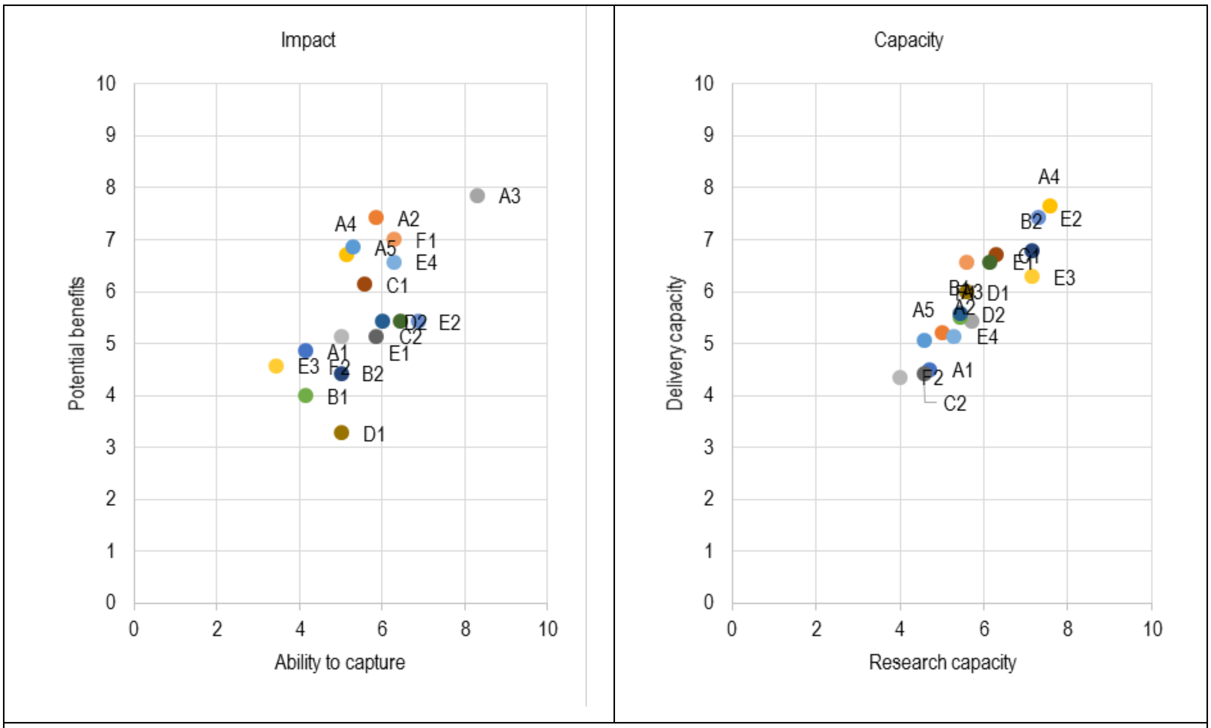

FIGURE 7: THE COLLATED SCORING OF IMPACT AND CAPACITY

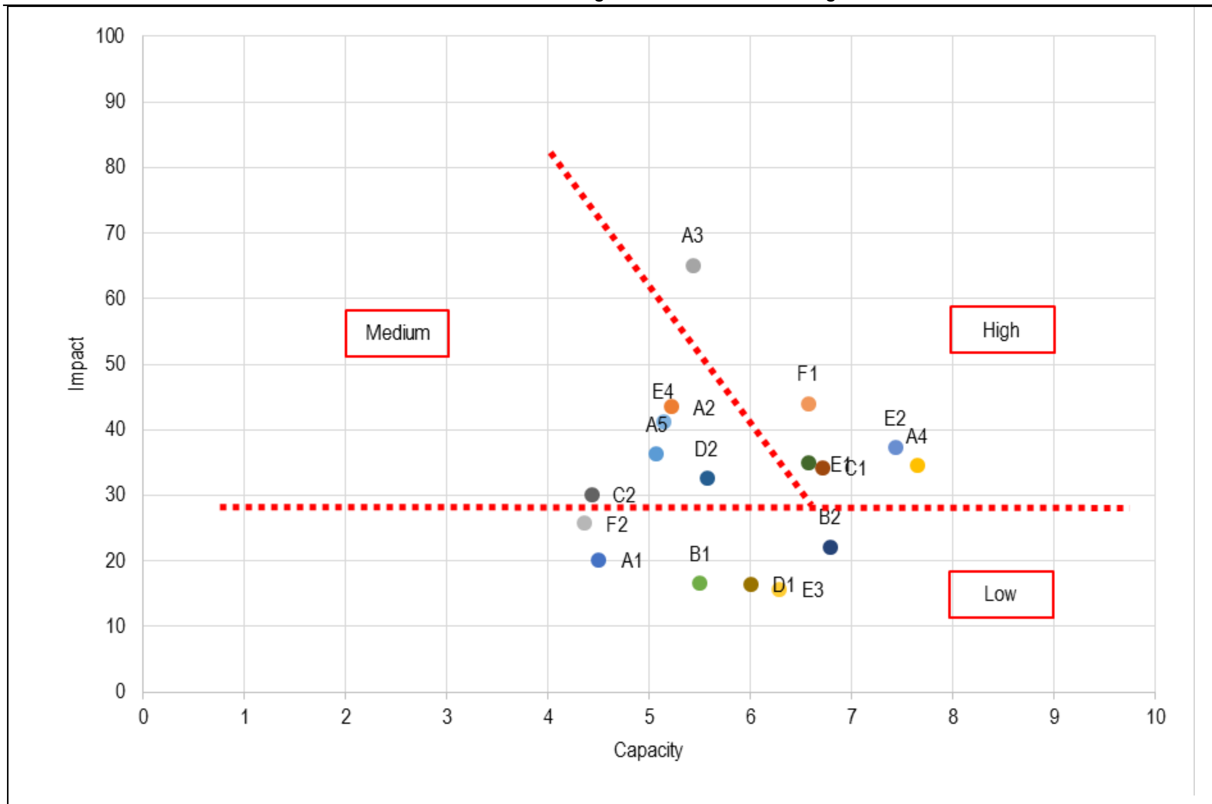

Figure 8: The priority setting outcomes for the 17 identified research needs – identified as 'High', 'Medium' and 'Low'.

Estimate of the quantum of gains achievable in Australia

From 2018 to 2023

The gains and avoided losses from enhanced resource modelling and remote sensing include:

Business risk

- A forest manager can achieve their legal and other required obligations at a lower cost per unit of forest managed and/or per unit volume of resource transacted;
- A forest manager can improve the cost-effective targeting of stands to customers and reduce the level of buffer stock held due to enhanced certainty in the estimate of both volume and product types available from a forest. This would allow either an increased volume of resource for sale on a long-term basis, via spot markets or into different product markets, and/or targeting of sales of specific products to higher value customers;

Biological risk

- The ability to model the business impact of a range of biological scenarios will assist with more informed due diligence and decision making;
- The biological risk associated with forest management is reduced by better access and incorporation of data (e.g. remote sensing data) identifying changes in the forest estate.

Beyond 2023 (an outlook)

A vision of beyond 2023 is access to a 'smart forest data' system allowing a greater reliance on real-time data and data analysis made available to decision makers in the field and in the office. In the field this would assist with specific decisions such as which tree to harvest to optimise the current market supply while maximising the longer-term value of a forest: it is possible that the best possible outcome may not be obvious. This vision is supported by the availability of very high resolution spatial / spectral / temporal remote sensing linked to individual tree data and browser-based visual analytical tools as a basis of decision making. While in the office, real time data from the field can be integrated into the business systems. Overall, there will be a greater integration of all workflows. There will be a continuous process of technology advancement in support of remote sensing and resource modelling and the challenge will be to maintain a watching brief particularly where the advancements are external to the forestry sector. It is highly likely that the forestry sector will become more and more an adopter and adapter of developments in other sectors. A key challenge and opportunity will be to realise the potentials particularly by addressing issues that all or part of the sector does not know that it has. Systems are likely to be much more modular allowing greater access to hardware and software upgrades, the various remote sensing platforms will have a higher degree of integration, including the potential to include data from bespoke company systems and capture, management, storage and use of big data will be the norm. With changing expectations (e.g. fewer staff in the forest), human actions and activity are likely to be replaced by real-time cloud-based processing of remotely sensed forest data and machine learning enabled technology undertaking a range of tasks such as stand attributes capture (e.g. a replacement of traditional inventory systems and a lesser reliance on ground truthing of data). The next 10 years will see significant change and opportunities and the key skill required by the forestry sector will be the ability to see the potentials and adapt and adopt.

Barriers to achieving potential gains

A primary barrier to achieving the potential benefits (either as avoided losses or actual gains) is predicated on forest manager's ability to justify the investment in improved resource modelling and remote sensing capacity. Systems development is complex, expensive and takes time to enact and implement. Legacy systems by their nature have existed in organisations for many years with a succession of people contributing to the developments. The issues that need to be addressed include the following.

Current systems

Current resource modelling and remote sensing systems are usually trusted if they have operated for many years. Organisations will not change these systems for the sake of doing so. Therefore, it is only where a current system is considered inadequate in supporting current business needs that enough justification is likely to exist to substantially upgrade or replace it. Circumstances that can lead to an imperative to a system change can be where:

- The costs of continuing to use and support the system are becoming prohibitive, perhaps due to a reliance on a diminishing pool of expert staff.
- The business needs change and cannot be supported by the current system; this maybe triggered by a change to the regulatory environment or ownership.
- Expertise required to maintain the system itself may be lost or assigned to other priorities.
- New technology becomes available which has a compelling opportunity for development.

Lack of in-house expertise

It might be that there is no single person in the organisation who understands all aspects of the resource modelling or remote sensing systems or of how the components interact. The longer systems are used in an organisation and the more changes made to them, the greater this risk. The complexity of these systems can be underestimated and therefore the expertise required to operate and improve the systems be discounted. This situation can become evident when a business imperative arises where change is required and then it is discovered that the expertise of the existing system custodians is insufficient to adapt the system to support the change. At this point a decision is often made to replace the bespoke system with a generic commercial system.

A lack of time to address issues

Business imperatives can often be short-term and need to be addressed in a shorter timeframe than structured system development or replacement can allow. This means that ad-hoc solutions and 'work-arounds' may be implemented that are not later replaced and become incorporated into the legacy system. This is risky because shortcuts are likely to have been taken in the ad hoc development which may not have been fully tested and documented. The risk increases when a person other than the developer uses the system. The cycle of business information requirements can be so short that those responsible for supporting it may simply have no time to design and make necessary system improvements.

A lack of available technology

The forest industry tends to be an adaptor of existing technology rather than a developer of new technology. Sometimes the forest industry has been a fast adopter of new technology, such as with GIS beginning in the 1980s. The generally large scale and geographic diversity of forest management and spatially related decision making required meant this technology was immediately useful to the industry allowing better characterisation and quantification of the assets it managed. Similarly, Global Positioning Systems (GPS), originally developed for military use, were quickly deployed in the forest industry. However, precise and reliable positioning under forest canopies remains a difficult challenge with no obvious technical solutions yet. In addition, in many forest areas, digital communications are beyond the range of mobile phone and other civilian networks. This represents a constraint on systems in the timeliness with which activity reporting can be logged and therefore the timelines of corporate reporting that is reliant. A key potential barrier to the use of technology is data transfer and communications between the forest and the data processing centres. While batching or caching of data may work in some circumstances (e.g. log truck data for download at a sawmill), realising the potential of technology will be underpinned by the ability to transfer and receive data remotely.

Inadequate support

Inadequate technical support can be a barrier to improvement of resource planning and remote sensing systems especially where those responsible for making the improvements are assigned substantial resource modelling and remote sensing development projects without being relieved of operational and other responsibilities. Like all substantial project management an essential requirement for success is to ensure the necessary resources in terms of human resource expertise and time is allocated commensurate with the complexity and importance of the project.

Not knowing how to address an issue

The forest industry can be isolated from mainstream technical developments; which can lead to a lack of awareness of potential solutions to problems that may be already be solved, for example, in military, mining and agriculture. Sometimes this lack of connectedness can result in unawareness that a problem even exists and the chances of this increase as more technology is adopted without the necessary due diligence being done to understand the full risks. Aspects such as data quality, user requirements, data representativeness (time series and spatial distribution) and understanding of environmental factors affecting growth all need to be understood when considering the adoption of new technology.

The priority RDE needed from 2018 to 2023, and beyond

The participatory process of development of this R&D investment plan has resulted in three levels of research priorities (see Table 5). The five highest priority areas are more about the systems, systems integration and the management of data around the systems. It is likely that the development of research projects will include elements of the medium and lower research priorities.

TABLE 5: A SUMMARY OF THE MODERATED RANKING OF THE IDENTIFIED RESEARCH NEEDS.

	Code	Combined			Time until impact		Ability to capture		
		Low	Medium	High	Short-term	Long-term	Low	Medium	High
Regularly updated wood-flow projections and actuals (estate-based)	A3			1	1				1
Potential applications of remote sensing in resource modelling	A4			1	1			1	
Remote sensing replacement of traditional inventory data capture	C1			1	1			1	
Remote sensing options for use in forestry	E1			1	1			1	
Platforms and integrated approach with combined sensors	E2			1	1			1	
Data sources and management	F1			1	1			1	
Integration of resource modelling systems with wood flow modelling	A2		1		1			1	
System interfaces between remote sensing and resource modelling	A5		1		1			1	
Development of improved growth models	C2		1			1		1	
Precision requirements: the scope of systems down to the individual tree	D2		1		1			1	
The use of remote sensing in forest monitoring	E4		1		1			1	
Integration of the components of resource modelling systems	A1	1				1	1		
A centralised approach applied to resource modelling	B1	1			1		1		
A centralised approach to remote sensing data capture and supply	B2	1			1		1		
The non-resource modelling needs of forestry in regards to remote sensing	D1	1			1		1		
On the horizon options and systems	E3	1			1		1		
Analytical capacity and the speed of data analysis and timeliness	F2	1				1	1		

Table 6 presents the identified broad categories of research. Each research need will require development of a full proposal with detailed costings. It is likely that some of the identified research needs can be addressed in parallel.

TABLE 6: A SUMMARY OF LOGICAL RESEARCH PROJECTS RELEVANT TO IDENTIFIED RESOURCE MODELLING AND REMOTE SENSING NEEDS.

Broad category of research	Code	The identified research need	Method	Time (indicative)	Benefit (indicative total across 10 companies)
Better integration of all elements of resource modelling systems	A1	Integration of the components of resource modelling systems	Systems analysis of existing forestry and non-forestry systems to identify best practice. Scan of available technology including application in other industries and assessment of applicability to forestry.	12-24 months	+5-10% in net log value recovery through better matching of log characteristics with customer requirements
	A2	Integration of resource modelling systems with wood flow modelling			
	A3	Regularly updated wood-flow projections and actuals (estate-based)			
	A4	Potential applications of remote sensing in resource modelling			
	A5	System interfaces between remote sensing and resource modelling			
A centralised approach	B1	A centralised approach applied to resource modelling	Scan of organisations that provide these services potentially in other industries. Options for cooperative structures including cost, benefit, risk assessment.	6 months	-$1.5M cost of internal remote sensing services through elimination of duplicate effort
	B2	A centralised approach to remote sensing data capture and supply			
Growth models in resource modelling	C1	Remote sensing replacement of traditional inventory data capture	Scan of what models are currently used, their current performance and potential for replacement.	12-24 months	-50% cost of inventory through reduced field work
	C2	Development of improved growth models			
Resolution of forestry	D1	The non-resource modelling needs of forestry in regard to remote sensing	Survey of industry needs with regard to precision of management.	6 months	+5-20% in log value recovery through better matching of log characteristics with customer requirements
	D2	Precision requirements: the scope of systems down to the individual tree			
An evaluation of remote sensing options and opportunities	E1	Remote sensing options for use in forestry	Scan of what models are currently used, their current performance and potential for replacement with remote sensing. What system changes would be required.	12-24 months	-5-10% in cost due to multipurpose surveys and reduced fieldwork
	E2	Platforms and integrated approach with combined sensors			
	E3	On the horizon options and systems			
	E4	The use of remote sensing in forest monitoring			
Data	F1	Data sources and management	Understanding of current and future data sets, security arrangements and storage, potentially cooperative, options and costs.	6 months	+5% operational efficiency through better data management and analysis
	F2	Analytical capacity and the speed of data analysis and timeliness			

Appendix 1: Stakeholders consulted

The project Steering Committee members

Resource Modelling and Remote Sensing Investment Plan Steering Committee				
Person	**Company**	**State**	**Forest type**	**Climate zone**
Glen Rivers	OneFortyOne	SA	Plantation pine	Temperate
Tony O'Hara	HVP	Vic	Plantation pine	Temperate
Suzette Weeding	Sustainable Timbers Tasmania	Tas	Natural forests	Temperate
Jodie Mason	FWPA	National	Research	All
Ernst Kemmerer	Forico Pty Ltd	Tas	Plantation hardwoods	Temperate
Jan Rombouts	OneFortyOne	SA	Plantation pine	Temperate
Mark McRostie	Australian Bluegum Plantations	Vic, SA, WA	Plantation hardwoods	Temperate
Ben Peirce	Midway	Vic	Plantation hardwoods	Temperate
Sharon Occhipinti	HVP	Vic	Plantation pine	Temperate
Rob Musk	Timberlands Pacific Pty Ltd	SA & Tas	Plantation pine	Temperate
Murray Lawrence	VicForests	Vic	Natural forests	Temperate
Henry Howsen	FPC	WA	Natural forests & plantation pine	Temperate
Auro Almeida	CSIRO	All	Research	All
Christine Stone	DPI NSW	NSW	Research	Temperate

The survey respondents

A total of 61 people responded to the survey with representations of each State but none from the ACT. The respondents included 8 people with interests in natural forest management, 34 people with interests is hardwood plantations and 35 people with interests is softwood plantations (note: parties could nominate more than one area of interest)

Appendix 2: A short narrative of the identified research needs issues and opportunities

Area of interest	Research topic	Research need
Better integration of all elements of resource modelling systems	Integration of the components of resource modelling systems	Research need 1: Forest managers are required to make decisions regarding resource modelling systems up-grades and/or replacements. The requirement to up-grade systems could be delayed by the development and deployment of systems integration tools that better allow communications between the components of a system (in particular where a system has developed over time on a bespoke basis). The approach to development of recommendations can be informed by experience in other industries and sectors. Research is required to consider and document the current and potential replacement systems, the options for 'patches' to better integrate the current systems. The options and outcomes require costing and documentation.
	Integration of resource modelling systems with wood flow modelling	Research need 2: A review is required to define the need for and options to better integrate resource modelling systems to strategic and tactical planning systems and inclusion of other assets such as water and carbon. This should include consideration of seamless data integration, output generation and the ability to undertake scenario modelling.
	Regularly updated wood-flow projections and actuals (estate-based)	Research need 3: A review is required to define the needs of operational planning as it relates to the underlying information required for decision making. The review should define the harvest data required by management and associated reporting systems. The research should then consider the ability to integrate actual (outcome) data to inform the planning process and the ability to integrate actual (outcome) data. The outcomes would include a statement of requirements, the options to address the requirements and the process to make decisions as to which solution is fit for purpose.
	Potential applications of remote sensing in resource modelling	Research need 4: The broad range of potential remote sensing data and applications in resource modelling need to be determined. The research required includes a review of the current options, documentation of the known needs and un-known opportunities. A series of options and recommendations would be developed. This will allow the development of potential development needs.
	System interfaces between remote sensing and resource modelling	Research need 5: Based on the identified specific needs of resource modelling which could be satisfied by remote sensing, options to implement such systems require definition, sourcing and/or development. Research is required to determine options for data integration, systems components required and overall fungibility of data between remote sensing data and resource modelling. There is potential to gain valuable insights from other industries, particularly an insight into cutting-edge systems and protocols available.
A centralised approach	A centralised approach applied to resource modelling	Research need 6: Given the options, opportunities and needs, there is a requirement to research and develop cost-effective and secure options to address the resource modelling needs of companies. This should include consideration of centralised management of data and software combined with a secure user interface back into the companies. Analysis is required of the human resources required under the different options, current and on the horizon options.
	A centralised approach to remote sensing data capture and supply	Research need 7: Companies must make a range of decisions on how best to access the required outputs of remote sensing: this will include a range of trade-offs (e.g. automation vs human actions, the sophistication of the technology and the costs associated). An analysis is required of the potential for a centralised approach to supply of data on a fit for purpose basis by a centralised service provider.
Growth models in resource modelling	Remote sensing replacement of traditional inventory data capture	Research need 8: Remote sensing data has significant potential to replace much of the traditional data captured by traditional inventory. There is a need to research the current and on the horizon options to make use of remote sensing as a replacement and/or complimentary inventory tool. There is also potential that future growth models will include a broader range of input data (e.g. water use) and generate a broader range of outputs (e.g. wood properties). The process and need to calibrate remote sensing systems is an important consideration which must be researched. Consideration is required of the trade-off of cost and precision, the technology needed and the approaches required to be undertaken.

Area of interest	Research topic	Research need
	Development of improved growth models	Research need 9: The precision of the outputs of resource modelling is part of a function of the robustness of the underlying growth models. There is a need to understand the potential role of remote sensing in the development and calibration of growth models. Research is required into the range of combinations of remote sensing tools (platforms combined with sensors).
Resolution of forestry	The non-resource modelling needs of forestry in regards to remote sensing	Research need 10: There is a need to determine the drivers and options of the use of remote sensing in other industries with similarities to forestry. This should include development of an understanding of the needs of forestry (e.g. the different applications of remote sensing) with respect to resolution, accuracy, speed and analytics. The outcome would be a matrix of 'uses' and attributes.
	Precision requirements: the scope of systems down to the individual tree	Research need 11: While technology allows improvement of data resolution (with some difficulties, down to the individual tree), there is a need to understand the utility and purpose of such precision of management. This consideration should include the cost and technology required. Experience from other sections can be included in the analysis to better understand the options. It is likely that a combination of data and datasets, including tree data libraries would be required.
An evaluation of remote sensing options and opportunities	Remote sensing options for use in forestry	Research need 12: The full potential of remote sensing systems and the resulting data for application in forestry (beyond resource modelling) requires determination and documentation. The tools, technology and skills required to make use of each option needs to be documented to allow an informed decisions of a) which to use and when; b) the mechanisms to access such technology. It is possible that the technology can generate answers to questions as yet not considered by the forestry sector and insights can be gained from other industries.
	Platforms and integrated approach with combined sensors	Research need 13: On a fit for purpose basis, there is a need to develop a guide to combinations of remote sensing platforms and sensor options. Each option will have a cost profile, resolution, coverage and temporal profile which should be considered. This would assist companies to better understand the options and when to make use of each.
	On the horizon options and systems	Research need 14: A framework is required to document on the horizon technology developments. It is most likely that advances will originate from outside of the forestry sector (e.g. defence), hence a watching brief process is required.
	The use of remote sensing in forest monitoring	Research need 15: The options and strategies to make use of time series remote sensing data for forest monitoring needs to be determined. The requirements for effective implementation would include development of libraries of forest conditions data (e.g. the spectral imagery that captures species specific nutrient deficiencies in a region). The approach taken would also require consideration: is it to be an in-house tool or on a cooperative basis. A parallel consideration is what would be the responses to identified issues (this is beyond the scope of this investment plan).
Data	Data sources and management	Research need 16: Data once sourced, must be managed in a cost effective and robust (secure) manner often driven by legal and compliance obligations. There is a need to understand and document (methods, technology, costs etc) the options of data management to allow companies to best determine the option(s) that best meet their requirements.
	Analytical capacity and the speed of data analysis and timeliness	Research need 17: The use and associated benefits of access to remote sensing data either for use in resource modelling or stand-alone will be enhanced by the speed of delivery of results. There is a need to document the options for data analysis and the associated costs and time required. This should be compared to the required timeliness of data for use in different applications.

Appendix 3: The identified research needs issues and opportunities

Better integration of all elements of resource modelling systems

Integration of the components of resource modelling systems

In many cases the current resource modelling systems used by Australian forests companies have been developed on an *ad-hoc* basis in the absence of a single system solution. This has resulted in fragmented rather than integrated systems. Consideration is required of the requirements for seamless integration of essential business systems with resource modelling systems. There is a need to consider the fundamental question of at what stage it is prudent to seek a replacement for a patched system by a fully integrated system? The lessons from current reliance on bespoke resource modelling systems with add-ons can inform the development of new options. Consideration is required of current advances in technology, modelling, statistics and mathematics that can be used in current and future resource modelling systems. Regardless of the approach (repair or replace), there is a need to explore and develop mechanisms and tools to better integrate the components of resource modelling systems including integration of operational requirements. It is possible that technology and/or approaches used by other industries or in the forest industry in other countries to fully integrate systems supplied by different manufacturers for seamless integration could be applied to forest resource modelling.

Research need 1: Forest managers are required to make decisions regarding resource modelling systems up-grades and/or replacements. The requirement to up-grade systems could be delayed by the development and deployment of systems integration tools that better allow communications between the components of a system (in particular where a system has developed over time on a bespoke basis). The approach to development of recommendations can be informed by experience in other industries and sectors. Research is required to consider and document the current and potential replacement systems, the options for 'patches' to better integrate the current systems. The options and outcomes require costing and documentation.

Integration of resource modelling systems with wood flow modelling

There is a need for resource modelling systems to better link with operational planning and the tools used: this is a logical extension of the need for integrated resource modelling systems or to be considered as a stand-alone requirement. There is little value in developing precise strategic and tactical planning systems that integrate multiple information needs if this is can't be implemented operationally. Yet this is a difficult area of systems development because the user groups, by definition, are unlikely to have the skill sets to develop the systems to manipulate the resource management information and data into a form that allows clear implementation. Yet departure of operational plans from the tactical plans has a number of risks: sub-optimal outcomes; infeasible plans that lead to over or under log product availability or mismatched product specifications. There is a need for integration of resource modelling with all levels of harvest planning and the tools used, including harvest scheduling systems to be integrated into a single system to allow for better transparency towards achieving production targets. This includes the exploration and development of mechanisms and tools to allow the development of feedback to harvesting contractors and to supervisors of the harvesting contractors in a timely manner. Another need is the capacity of resource modelling systems to allow for scenario analysis. The desire of companies to have this information for decision making and recognising the value of integrated systems for delivering information will drive the need for these functional improvements to systems. This is a requirement because of the interdependence of decision making and asset management and the necessity for timely and consistent information on which to base decision making. For example, timber production may be driven by water availability and formation of timber drives carbon accumulation. The modelling of interdependent assets must be understood on a temporal and spatial scale to allow consistent and credible decision making. The need for this functionality sometimes exceeds the capability of the data, systems and modelling expertise to make these improvements.

RESEARCH NEED 2: A REVIEW IS REQUIRED TO DEFINE THE NEED FOR AND OPTIONS TO BETTER INTEGRATE RESOURCE MODELLING SYSTEMS TO STRATEGIC AND TACTICAL PLANNING SYSTEMS AND INCLUSION OF OTHER ASSETS SUCH AS WATER AND CARBON. THIS SHOULD INCLUDE CONSIDERATION OF SEAMLESS DATA INTEGRATION, OUTPUT GENERATION AND THE ABILITY TO UNDERTAKE SCENARIO MODELLING.

Regularly updated wood-flow projections and actuals (estate-based)

A tension exists between using the results of strategic woodflow planning to flow through to operational planning. While the strategic direction is set, it is the implementation of the operation plans that will have to deliver the outcomes. The tension arises where there is pressure to react to short-term needs by departing from the operational plans. One way to address this pressure is to ensure regular updating of the woodflow projections so that alternative operational decisions can be evaluated relative to the strategic plan. It is also important to be able to link back what decisions and outcomes have been made in a timely manner to keep operational plans on track and to monitor value recovery outcomes. Operational plans have to be defined spatially to ensure transport can be optimised and subsequent operations such as replanting can be undertaken efficiently. Updating of harvesting data in many companies is required monthly for reporting purposes. To maximise the relevance of the updates, data needs to be available as quickly as possible and in a form that allows systematic comparison with operation plans. All relevant attributes of harvesting operations need to be collated including volumes and values by product.

RESEARCH NEED 3: A REVIEW IS REQUIRED TO DEFINE THE NEEDS OF OPERATIONAL PLANNING AS IT RELATES TO THE UNDERLYING INFORMATION REQUIRED FOR DECISION MAKING. THE REVIEW SHOULD DEFINE THE HARVEST DATA REQUIRED BY MANAGEMENT AND ASSOCIATED REPORTING SYSTEMS. THE RESEARCH SHOULD THEN CONSIDER THE ABILITY TO INTEGRATE ACTUAL (OUTCOME) DATA TO INFORM THE PLANNING PROCESS AND THE ABILITY TO INTEGRATE ACTUAL (OUTCOME) DATA. THE OUTCOMES WOULD INCLUDE A STATEMENT OF REQUIREMENTS, THE OPTIONS TO ADDRESS THE REQUIREMENTS AND THE PROCESS TO MAKE DECISIONS AS TO WHICH SOLUTION IS FIT FOR PURPOSE.

Potential applications of remote sensing in resource modelling

Remote-sensing approaches can provide a wealth of data for the forestry sector. A specific use of remote sensing data is with resource modelling and includes growth and yield estimates (e.g. volume and stocking data). Remote sensing data could also be integrated into stand records as part of resource modelling systems. Another option is the mechanisms and tools to allow the yield reconciliation between resource modelling systems and the actuals from harvesting. While the forestry sector has known needs, there is a need to promote to forest managers the ever-increasing resolution of remote sensing data, their return frequency, more sophisticated sensors, rapidly decreasing data costs, and the easier access to processed imagery and derived products. There is research required to explore and realise the opportunity to reveal the full potential of the information hidden in (very) dense point clouds and integrate them directly into operational systems. A first step is to understand the current state of remote sensing data with regards to their use in resource modelling and what are the on the horizon advances that could improve the utility of the data for use in resource modelling?

Some areas of consideration include:

- ***Wood properties:*** What is the potential of remotely sensed data to obtain information on individual trees and their physical growing environment? How can the relationships between key wood property traits and LiDAR-derived stand-level variables be developed and deployed? What has been the ability of resource modelling to take account of wood properties in the systems in use?
- ***Use in valuation:*** There is a need to explore and develop mechanisms and tools to make use of remote sensing as a tool to supply data to valuations.
- ***Spatial representation:*** There is a need to explore and develop mechanisms and tools to make use of remote sensing for data exploration and visualisation.

RESEARCH NEED 4: THE BROAD RANGE OF POTENTIAL REMOTE SENSING DATA AND APPLICATIONS IN RESOURCE MODELLING NEED TO BE DETERMINED. THE RESEARCH REQUIRED INCLUDES A REVIEW OF THE CURRENT OPTIONS, DOCUMENTATION OF THE KNOWN NEEDS AND UN-KNOWN OPPORTUNITIES. A SERIES OF OPTIONS AND RECOMMENDATIONS WOULD BE DEVELOPED. THIS WILL ALLOW THE DEVELOPMENT OF POTENTIAL DEVELOPMENT NEEDS.

System interfaces between remote sensing and resource modelling

There is a need to explore and develop user interfaces for remote sensing and resource modelling systems. This includes the development of mechanisms and tools to allow all relevant staff to make use of the outputs of resource modelling: this includes standard use-specific reports, an understanding by all staff and the ability of all staff to access appropriate reports. It is possible that LiDAR data can be incorporated into resource modelling on a close to real-time basis. The challenge is to prepare and transform the data into a useful format. All stakeholders have an interest in the integration of systems and consistency of dataflows, because where these functionalities exist, they facilitate simple and timely execution of tasks; where systems are not integrated and data must be reformatted and manipulated to be merged and checked for consistency this is a time consuming and frustrating task often resulting in difficult or unrepeatable processes and requiring considerable documentation to explain. Where data and information flows incorporate many of these *ad-hoc* stages, key person risk arises. A key step is to understand the current and potential interface options (including add-ons) for remote sensing and resource modelling systems. A seamless input of remote sensing data into resource modelling systems will speed up the application of such data. In preparing data for use, pre-processing of remote sensing data usually includes initial data correction and geo-referencing. Such pre-processed data is not yet ready for input into resource modelling systems as it requires analyses prior to use, which also requires in most cases the use of ground-truthing data. To expedite this process, there is a need to explore and develop mechanisms and tools to pre-process and analyse remote sensing data for input into resource modelling systems, including the remote sensing systems linked to growth models and yield regulation systems. The preparation and analysis could be automated to take account of advances in technology and there is a need to determine the requirements and limitations of current resource modelling systems towards a more complete and seamless integration.

RESEARCH NEED 5: BASED ON THE IDENTIFIED SPECIFIC NEEDS OF RESOURCE MODELLING WHICH COULD BE SATISFIED BY REMOTE SENSING, OPTIONS TO IMPLEMENT SUCH SYSTEMS REQUIRE DEFINITION, SOURCING AND/OR DEVELOPMENT. RESEARCH IS REQUIRED TO DETERMINE OPTIONS FOR DATA INTEGRATION, SYSTEMS COMPONENTS REQUIRED AND OVERALL FUNGIBILITY OF DATA BETWEEN REMOTE SENSING DATA AND RESOURCE MODELLING. THERE IS POTENTIAL TO GAIN VALUABLE INSIGHTS FROM OTHER INDUSTRIES, PARTICULARLY AN INSIGHT INTO CUTTING-EDGE SYSTEMS AND PROTOCOLS AVAILABLE.

A centralised approach

A centralised approach applied to resource modelling

The path to supporting better resource modelling and systems development is surprising simple and has been substantially progressed in an *ad-hoc* manner across industry. Pine growers have largely settled on YTGen as a default system for encompassing growth and yield models as this outsources the responsibility for system maintenance. However, this concentrates the core system to an offshore third party rather than an arrangement like the Southern Tree Breeding Association (STBA) where system development is concentrated in an industry owned and controlled company. Forest management companies are making some investment into improved resource modelling systems but are not obtaining the full benefit they could or covering some of the key risks. If companies desired, it would be possible to concentrate their efforts in a similar way to the STBA, probably at similar cost yet retain control of the development and provide other member services such as regular user meetings and coordination of technical development including statistical modelling. Initially the current provider(s) could be engaged, if willing, or alternatively as separate entity developed (e.g. a not-for-profit limited company limited by guarantee). This would represent an efficient model that could also make applications for co-funding of systems development and modelling via FWPA.

RESEARCH NEED 6: GIVEN THE OPTIONS, OPPORTUNITIES AND NEEDS, THERE IS A REQUIREMENT TO RESEARCH AND DEVELOP COST-EFFECTIVE AND SECURE OPTIONS TO ADDRESS THE RESOURCE MODELLING NEEDS OF COMPANIES. THIS SHOULD INCLUDE CONSIDERATION OF CENTRALISED MANAGEMENT OF DATA AND SOFTWARE COMBINED WITH A SECURE USER INTERFACE BACK INTO THE COMPANIES. ANALYSIS IS REQUIRED OF THE HUMAN RESOURCES REQUIRED UNDER THE DIFFERENT OPTIONS, CURRENT AND ON THE HORIZON OPTIONS.

A centralised approach to remote sensing data capture and supply

Remote sensing can be at a landscape level which is beneficial to the capture, analysis and use of all kinds of data. The desired remote sensing data attributes include high resolution (e.g. spatial, spectral, temporal, and radiometric), timeliness, accuracy, coverage, and low acquisition costs. In considering this option, what are the different options for each of these desired attributes, and is there a role for a centralised approach? For example, the capture, analysis and use of all kinds of remote sensing data that could be automatically fed into individual company systems (e.g. GIS and resource modelling systems). An important consideration is what remote sensing data, systems and roles should be directly under a company's control versus what can be used in a shared environment? There is potential for remote sensing and resource modelling systems be so complex that in-house management becomes non-tenable. This consideration is combined with the new skill sets required to take account of advances in technology and whether such skills should be in-house or outsourced. An important point is that given the rate of change in remote sensing technology it is more likely that current expertise will be found outside of forest companies. There is a need to determine the human resources required to support and realise the potential of remote sensing including the skills required and the training available. It is difficult to see a future where forestry-based training in remote sensing will be enough to provide forestry companies with the level of expertise to operate and develop the required remote sensing tools to the full potential. To feed the future industry requirements, staff would require two degrees to add the missing remote sensing skills or have extensive additional training and experience. There is the potential for automation and systems integration but is it possible or desirable to 100% de-staff considering the ranges of data sources and advances in technology? This again leads to consideration of a need to understand the point at which remote sensing is out-sourced compared to in-house expertise. It is also possible that a single resource modelling and remote sensing system may fail to satisfy the needs of all users. There will be a trigger point making in-house remote sensing and resource modelling systems non-tenable so that an external service provider model needs to be applied. An analysis is required to document and compare a fully or partly centralised service provider model compared to the *status quo* approaches, including the mechanisms of remote sensing data access.

RESEARCH NEED 7: COMPANIES MUST MAKE A RANGE OF DECISIONS ON HOW BEST TO ACCESS THE REQUIRED OUTPUTS OF REMOTE SENSING: THIS WILL INCLUDE A RANGE OF TRADE-OFFS (E.G. AUTOMATION VS HUMAN ACTIONS, THE SOPHISTICATION OF THE TECHNOLOGY AND THE COSTS ASSOCIATED). AN ANALYSIS IS REQUIRED OF THE POTENTIAL FOR A CENTRALISED APPROACH TO SUPPLY OF DATA ON A FIT FOR PURPOSE BASIS BY A CENTRALISED SERVICE PROVIDER.

Growth models in resource modelling

Remote sensing replacement of traditional inventory data capture

Updating growth and yield models requires skills and the availability of appropriate data usually from repeatedly measured permanent growth plots, and at least an appreciation of forestry specific mensuration. Where new data are available it needs to be relevant to the new needs of resource management systems and this is often not the case due to the cost and difficulty of collecting this data. For example, three areas of interest rarely included a measurement of growth plot programs are plantation water use, log and wood properties and genetics. A specific use of remote sensing data is for growth and growth model development, and yield estimates including volumes and stocking. Given increasing risk aversion to having staff in the field, the options to capture data on tree growth and performance for use in the resource modelling now and in the future requires consideration. An understanding is required as to at what point and under what conditions could remote sensing further decrease the need for ground measurements and/or potentially fully replace field measurements? There is a need to understand the basis of sampling methods and strategies for data capture (e.g. stocking and survival, volume and forest structure) for use in the resource modelling now and in the future, and the costs involved. The ability to make use of remote sensing data will be in part determined by the need to calibrate and ground-truth remote sensing data for specific applications in forestry. Historically the cost of calibrating and ground-truthing remote sensed data has acted as a barrier to a lack of application. There is a need to determine cost effective mechanisms to address this point. The requirements and mechanisms for calibration and ground truthing associated with remote sensing data needs to be documented and understood. It is possible that there are simple systems to generate and capture the required data, but this requires development.

Research need 8: Remote sensing data has significant potential to replace much of the traditional data captured by traditional inventory. There is a need to research the current and on the horizon options to make use of remote sensing as a replacement and/or complimentary inventory tool. There is also potential that future growth models will include a broader range of input data (e.g. water use) and generate a broader range of outputs (e.g. wood properties). The process and need to calibrate remote sensing systems is an important consideration which must be researched. Consideration is required of the trade-off of cost and precision, the technology needed and the approaches required to be undertaken.

Development of improved growth models

There is a need for better growth and yield model elements in resource modelling systems, including a need for data to build growth models. One consideration is understanding the realistic option to replace tabular yield tables: can we use allometric or other models? There is a need to explore and develop user interface mechanisms and tools to make use of remote sensing outputs in growth models and yield regulation systems. There is also a need to explore and develop mechanisms and tools to make use of close to real-time satellite outputs in growth models and yield regulation systems. This includes a need to explore and develop mechanisms and tools to make use of LiDAR outputs. Time series of UAV-based LiDAR data and/or Airborne laser scanning (ALS) data reveal further hidden information about growth and yield allowing modelling of changes and to predict the future. Research in investigating the potentials of multi-temporal LiDAR is still in its early stages, hence there is a need to consider and further explore this option. In terms of model runs, there would be advantages for systems to remove the need to develop batch data / scripts inputs for runs.

Research need 9: The precision of the outputs of resource modelling is part of a function of the robustness of the underlying growth models. There is a need to understand the potential role of remote sensing in the development and calibration of growth models. Research is required into the range of combinations of remote sensing tools (platforms combined with sensors).

Resolution of forestry

The non-resource modelling needs of forestry in regards to remote sensing

There are opportunities to consult remote sensing experts in agriculture and horticulture to understand the drivers that led to the use of remote sensing in these industries and to consider opportunities for adaptation of those remote sensing solutions to forestry. In both agriculture and horticulture, fixed wing aircraft and drone technology can provide cost effective platforms for various remote sensors deployment across relatively small areas under management. There is a need to determine cost effective mechanisms to realise this potential to forestry, which usually deals with much larger areas and much longer plant-life time monitoring times. A first step is to understand the potential applications of remote sensing technology in forestry operations including consideration of recent changes in the needs of the sector. There are four remote sensing trends: resolution, accuracy, speed and analytics. There is a need to understand the importance of each trend and associated technology to the forestry sector to allow a focus on the development of new / improved processes. A consideration is the cost and benefit of the new types of remote sensing data available for use by the sector - now and in the future. Forestry uses include, among others, the detection of forest types, deforestation and biomass estimation. Moreover, deep learning should be explored further e.g. as an alternative to pixel-based image classification, to detect correlations in time series of huge point clouds.

RESEARCH NEED 10: THERE IS A NEED TO DETERMINE THE DRIVERS AND OPTIONS OF THE USE OF REMOTE SENSING IN OTHER INDUSTRIES WITH SIMILARITIES TO FORESTRY. THIS SHOULD INCLUDE DEVELOPMENT OF AN UNDERSTANDING OF THE NEEDS OF FORESTRY (E.G. THE DIFFERENT APPLICATIONS OF REMOTE SENSING) WITH RESPECT TO RESOLUTION, ACCURACY, SPEED AND ANALYTICS. THE OUTCOME WOULD BE A MATRIX OF 'USES' AND ATTRIBUTES.

Precision requirements: the scope of systems down to the individual tree

With the advent of new technology, is the new paradigm going to be the ability to capture data of every individual tree and to use this data in the resource modelling of the future? There is a need to consider the inputs of broader data into resource modelling systems: what can be managed on a landscape basis compared to an estate, stand or individual tree basis? This identifies a need to explore and develop mechanisms and tools to increase the accuracy of resource modelling systems to generate better results, including volume and taper functions, regional and local growth models, and fertiliser models. There is a need to address the required accuracy of resource modelling outputs linked to the different intended uses. While precision forestry may be possible, what are the potential benefits and value of application of precision forestry, what is the reasonable aspiration level of precision in estimates and what is the weakest link in implementation? A fundamental consideration is the benefit and utility of a swap to resource modelling and data management on an individual tree basis compared to the current approach. For example, is there any benefit to be able to provide individual tree data to the harvester to plan the harvest (thinning) of a stand? There will be a trade-off of the benefit and cost of a small imputation grid size (e.g. 5 x 5 m) compared to individual trees in the capture, management and use of the data and this requires exploration. For example, with the expected point density increase of ALS data, an increase of imputation grid-resolution may negate the need for single tree data. The issues to address with single tree data include the potential for establishing of a tree-life archive: concepts and methods to capture detailed data including spatial position of each tree (from seedlings stage to final product) and further research is required to integrate individual tree-based yield models into operational forestry. An integrated approach is possible. For example, satellite remote sensing tools could be used within the first five years after a tree was planted to capture its spatial position, and then frequently and systematically repeated for updates adding, UAV, airborne, and satellite remote sensing approaches. Satellite technological innovations will allow to detect multi- and hyperspectral imagery of improved spatial, spectral, temporal and radiometric resolution and to include as well as advance radar, LiDAR and SAR measurements from low-orbit as well as geostationary orbits – which provide important (research) datasets to further enhance precision forestry, but how precise does industry wish to be?

RESEARCH NEED 11: WHILE TECHNOLOGY ALLOWS IMPROVEMENT OF DATA RESOLUTION (WITH SOME DIFFICULTIES, DOWN TO THE INDIVIDUAL TREE), THERE IS A NEED TO UNDERSTAND THE UTILITY AND PURPOSE OF SUCH PRECISION OF MANAGEMENT. THIS CONSIDERATION SHOULD INCLUDE THE COST AND TECHNOLOGY REQUIRED. EXPERIENCE FROM OTHER SECTIONS CAN BE INCLUDED IN THE ANALYSIS TO BETTER UNDERSTAND THE OPTIONS. IT IS LIKELY THAT A COMBINATION OF DATA AND DATASETS, INCLUDING TREE DATA LIBRARIES WOULD BE REQUIRED.

An evaluation of remote sensing options and opportunities

Remote sensing options for use in forestry

The development of forestry specific remote sensing is possible, but a range of options are already in place. There are a wide range of remote sensing data including sources of free data and the costs and robustness of the different remote sensing technologies requires assessment. For example, there is a need to explore and understand the potential of the Sentinel-2 Near-Real-Time Surface Reflectance data provided via NationalMap – an interactive online exploration tool which allows users to query between imageries by pre-defined spectral indices, selected dates and time-series, and compare imageries using a swipe-tool. Such online explorative tools could be further devolved towards customised forestry applications based on (free) satellite imagery allowing investigation of specific forest features (e.g. deforestation, health indices, yield estimates) and change over time, and ultimately support decision-making. Specific questions to address include:

- What is the potential for improved spectral quality outcomes from hyperspectral satellite imagery data applications for forestry?
- There is a need to understand the potential of advanced sensors from satellite data.
- There is a need to understand the potential advantages of SAR has to optical remote sensing for use in forestry applications particularly in forest monitoring.
- There is a need to explore and understand the potential of even higher spatial resolution satellite imagery (≤ 0.31 m), investigate tri-stereo satellite imagery to increase SCD density, and further enhance inventory assessment, and to make further use of the spectral information (e.g. IR for tree health monitoring).
- What is the potential for a wide range of applications including satellite image-based tree detection/classification, deforestation monitoring, and other promising applications for forestry using very high-resolution satellite imagery over time and in spot applications?

An important consideration is to use of combinations of technologies and systems. For example, there is potential to develop advanced individual tree detection (ITD) approaches using and integrating multi-temporal ALS / UAV-LiDAR data (of different resolution), aerial imagery, high-resolution satellite imagery data (e.g. WorldView-4 with 0.31 m panchromatic resolution), and novel ground-based plot inventory data (e.g. terrestrial / mobile scanner data). Another example is the use of airborne captured LiDAR data, and machine learning approaches. Such approaches (e.g. random forest or kNN based imputations of LiDAR derived metrics) are already integrated in operational forestry, but will need to be adapted when modelling growth and yield based on multi-temporal LiDAR data, or when looking at time-series of satellite or aerial imagery for changes in tree health etc.

RESEARCH NEED 12: THE FULL POTENTIAL OF REMOTE SENSING SYSTEMS AND THE RESULTING DATA FOR APPLICATION IN FORESTRY (BEYOND RESOURCE MODELLING) REQUIRES DETERMINATION AND DOCUMENTATION. THE TOOLS, TECHNOLOGY AND SKILLS REQUIRED TO MAKE USE OF EACH OPTION NEEDS TO BE DOCUMENTED TO ALLOW AN INFORMED DECISIONS OF A) WHICH TO USE AND WHEN; B) THE MECHANISMS TO ACCESS SUCH TECHNOLOGY. IT IS POSSIBLE THAT THE TECHNOLOGY CAN GENERATE ANSWERS TO QUESTIONS AS YET NOT CONSIDERED BY THE FORESTRY SECTOR AND INSIGHTS CAN BE GAINED FROM OTHER INDUSTRIES.

Platforms and integrated approach with combined sensors

A range of platforms to transport sensors are available and there is a need to develop a matrix checklist of the fit for purpose status of UAVs compared to satellite data based on a range of attributes including cost, flexibility etc. The platforms are evolving and there is a need to understand the evolution and availability of satellite (including the role of miniaturised satellites) sourced information: a mechanism is required to distil this formation for use by forest managers as noted previously. There is a need to:

- Understand the role of miniaturised satellites with potential for forest managers to operate their own.
- To explore and understand the options and benefits for combing different sensors in a single aerial remote sensing platform for forestry applications. For example, what is the potential and what are the requirements to use remote sensing data from combined sensors to provide operational solutions? A subsequent research question is a practical consideration of the potential for integration of the different sensors (e.g. hyperspectral sensors; LiDAR etc.) in one aircraft or one UAV-based platform.
- There is a need to understand the barriers to the use of very high-resolution satellite imagery over time and in spot applications. This should include a comparison to the status quo approaches.
- Determine the cost effectiveness of use of remote sensing systems to generate data is a consideration which requires determination. For example, what is the cost of development of advanced ITD approaches using and integrating multi-temporal ALS/UAV LiDAR data (of different resolution), aerial imagery, very high-resolution satellite imagery data (e.g. WorldView-4 with 0.31 m panchromatic resolution), and novel ground-based plot inventory data (e.g. terrestrial/mobile scanner data)?

RESEARCH NEED 13: ON A FIT FOR PURPOSE BASIS, THERE IS A NEED TO DEVELOP A GUIDE TO COMBINATIONS OF REMOTE SENSING PLATFORMS AND SENSOR OPTIONS. EACH OPTION WILL HAVE A COST PROFILE, RESOLUTION, COVERAGE AND TEMPORAL PROFILE WHICH SHOULD BE CONSIDERED. THIS WOULD ASSIST COMPANIES TO BETTER UNDERSTAND THE OPTIONS AND WHEN TO MAKE USE OF EACH.

On the horizon options and systems

Mechanisms are required keep abreast of technological developments such as 'on the horizon' airborne sensor technology which will become available in the future and the potential roles and applications. This should include the redefining of the role of remote sensing in forest monitoring. The sensor revolution is going to continue, and specific opportunities include:

- The potential advantages of the current and future (free) SAR data in comparison with optical remote sensing for use in forestry applications particularly in forest monitoring.
- Novel technologies, such as multispectral LiDAR, or single-photon-LiDAR.
- The potential for Virtual and Augmented Reality used for analytics and decision making in forestry management.

- The potential for development of advanced ITD approaches using and integrating multi-temporal ALS/UAV LiDAR data (of different resolution), aerial imagery, high-resolution satellite imagery data (e.g. WorldView-4 with 0.31 m panchromatic resolution), and novel ground-based plot inventory data (e.g. terrestrial/mobile scanner data)?
- The potential for cost-efficient updating of growth and yield models using very high-resolution satellite imagery data and / or inventory-plot based UAV-LiDAR data.

RESEARCH NEED 14: A FRAMEWORK IS REQUIRED TO DOCUMENT ON THE HORIZON TECHNOLOGY DEVELOPMENTS. IT IS MOST LIKELY THAT ADVANCES WILL ORIGINATE FROM OUTSIDE OF THE FORESTRY SECTOR (E.G. DEFENCE), HENCE A WATCHING BRIEF PROCESS IS REQUIRED.

The use of remote sensing in forest monitoring

There is a broad range of remote sensing applications focusing on forest monitoring (e.g. nutrient status; water use; wood volume and biomass; health; biodiversity, fire risk; stand structure monitoring). Time series of forest or tree features documented include leaf area index (LAI), stocking, and crown attributes. There is potential to make use of remote sensing data and data analysis in monitoring of forests at a broad (stand/compartment) scale (e.g. area-based analysis – ABA), or at individual tree scale. The utilisation of satellite remote sensing data provides a cost-effective and flexible tool. To better realise this potential, there is a need to understand the potential advantages of the current and future (free) SAR data compared to optical remote sensing. This can be informed by the documentation of the current and future (free) SAR remote sensing options for use in forestry applications. Another option to be explored is the usage of imagery cloud processing tools as well as the option to combine and fuse (free) imagery datasets, offers high potential to improve forest monitoring towards near real-time.

RESEARCH NEED 15: THE OPTIONS AND STRATEGIES TO MAKE USE OF TIME SERIES REMOTE SENSING DATA FOR FOREST MONITORING NEEDS TO BE DETERMINED. THE REQUIREMENTS FOR EFFECTIVE IMPLEMENTATION WOULD INCLUDE DEVELOPMENT OF LIBRARIES OF FOREST CONDITIONS DATA (E.G. THE SPECTRAL IMAGERY THAT CAPTURES SPECIES SPECIFIC NUTRIENT DEFICIENCIES IN A REGION). THE APPROACH TAKEN WOULD ALSO REQUIRE CONSIDERATION: IS IT TO BE AN IN-HOUSE TOOL OR ON A COOPERATIVE BASIS. A PARALLEL CONSIDERATION IS WHAT WOULD BE THE RESPONSES TO IDENTIFIED ISSUES (THIS IS BEYOND THE SCOPE OF THIS INVESTMENT PLAN).

Data

Data sources and management

There is a need to explore and develop mechanisms and tools to better manage the underlying data in remote sensing and resource modelling systems. A potential exists to design a system of data capture and management, in the absence of trying to digitise a paper-based system. A first step is to document the new types of data available for use in resource modelling now and in the future. For example, with the advent of new technology, data will be acquired from multiple sources and platforms (e.g. harvester heads, UAV, aircrafts, satellites) and require effective and efficient management for integration into resource modelling systems currently in use or of potentially in use in the future. The potential of remote sensing is recognised, but the cost of the data needs to be addressed. There is a need to understand and develop cost effective mechanisms for data access and use. For example, there are a wide range of remote sensing data and the forestry sector appears not to have investigated the full potential of these sources, including the free Sentinel satellite data. This should be addressed and include a comparison and contrast the freely available satellite imagery compared to fee-for-service satellite imagery, looking at time series in spot applications etc.

Data management is a priority because even existing data sets are very large and complex, and company due diligence will require archiving of data to ensure auditability. Repeatability of data derived from these datasets is necessary to satisfy appraiser audits as part of forest valuation and potentially estate sales. Derived and source data will need to be kept for long periods especially for long rotation pine crops where the data relate to a past stage of plantation development yet is an input to growth and yield modelling potentially for the remainder of the rotation (up to 30 + years).

Remote sensing generates a large volume of data ('big data') and systems are required to effectively manage this data. Issues to consider include data cost, the cost of management and storage, data input, data access, data processing and analysis, and the speed of the systems. Options include the potential of cloud processing to reduce and potentially replace existing resources and infrastructure involved. The change or establishment of new operational systems (hardware and software included) creates an opportunity for new appropriate metrics and these need to be investigated and identified for dense point cloud data. There is a need to explore and understand the potential a voxel-based data integration.

RESEARCH NEED 16: DATA ONCE SOURCED, MUST BE MANAGED IN A COST EFFECTIVE AND ROBUST (SECURE) MANNER OFTEN DRIVEN BY LEGAL AND COMPLIANCE OBLIGATIONS. THERE IS A NEED TO UNDERSTAND AND DOCUMENT (METHODS, TECHNOLOGY, COSTS ETC) THE OPTIONS OF DATA MANAGEMENT TO ALLOW COMPANIES TO BEST DETERMINE THE OPTION(S) THAT BEST MEET THEIR REQUIREMENTS.

Analytical capacity and the speed of data analysis and timeliness

The desired attributes of remote sensing data (including: high resolution; timeliness of data capture; accuracy; coverage; low cost; access, speed of analysis and use) all which should be documented and understood. The utility and benefits of resource modelling and remote sensing is increased by the speed of data analysis resulting in timely results to forest managers. The evolution of and availability of satellite sourced information requires the ability to distil this formation for use by forest managers. There is a need to understand the potential for improved processing speeds of remote sensed data. Innovative new technologies, such as on-board/orbit quantum and biological computing (in particular to process high-resolution hyperspectral imagery data), will likely be realised in the near future and significantly improve data processing, analysis and distribution. Cloud processing tools as well as the option to combine and fuse free imagery datasets, offers high potential to improve forest monitoring towards near real-time, and these should be explored. These include customised services of cloud processed satellite imagery information. One specific opportunity is the potential of point cloud data derived from high-resolution stereo satellite imagery used to provide large-scale forest inventory assessment. A fundamental requirement is to explore and develop mechanisms and tools to increase the speed of data analysis in resource modelling systems to generate such timely results. For example, there is a need to explore and develop mechanisms and tools to make use of close to real-time satellite outputs in growth models and yield regulation systems.

RESEARCH NEED 17: THE USE AND ASSOCIATED BENEFITS OF ACCESS TO REMOTE SENSING DATA EITHER FOR USE IN RESOURCE MODELLING OR STAND-ALONE WILL BE ENHANCED BY THE SPEED OF DELIVERY OF RESULTS. THERE

IS A NEED TO DOCUMENT THE OPTIONS FOR DATA ANALYSIS AND THE ASSOCIATED COSTS AND TIME REQUIRED. THIS SHOULD BE COMPARED TO THE REQUIRED TIMELINESS OF DATA FOR USE IN DIFFERENT APPLICATIONS.

Appendix 4: Literature review resource modelling and remote sensing

Historic Resource Modelling and Systems (1700s-1980s)

Resource modelling is a forest management activity arising out of the need of forest resource managers to estimate the volume of standing timber available for scheduling harvest planning. This activity also involves projection of volumes into the future to schedule the level of harvesting activity and often with sustainable harvest wood flows as a management objective. The information derived from resource modelling has been the basis of management decision making, forest valuation, silvicultural evaluation and resource allocation.

Historically resource modelling is based on the measurement of trees in plots that are extrapolated to the whole estate as practically not all trees could be measured. This provides the forest manager with a representation of the forest estate about its: location, area by forest type and the volumes and attributes of the standing timber. Typically, summary information is presented as maps and tables of timber volumes both currently standing and projected into the future to account for forest growth and change such as management activity including harvesting, tree deaths and natural disturbance events such as fire, pests and diseases.

Sampling methods included stratification of the estate based on broad scale assessments to improve the efficiency and precision of forest inventory. Long term growth and yield plots were usually necessary to obtain data for developing yield tables that could project stand growth over time. Assessments and surveys require trained personnel and considerable costs. Development of yield tables required access to foresters and biometricians with specialised skills and a strong understanding of the biology of the tree species of interest. All measurements required trained people in the forest at least measuring trees physically with tape measurements for diameter and tree heights using hypsometers. Where appropriate, angle count sampling and tools such as the Spiegel Relaskop (Bitterlich 1990) improved the efficiency of inventories. Land and effective forest area surveys were estimated using survey gear and also required trained operators taking physical measurements.

Paper based book-keeping style systems were developed for calculations with some use of mechanical calculators for efficiency. In general, the equipment and methods used were adapted from other industries including agricultural. Because of its extensive nature the forest industry has been an adaptor of technology and systems rather than developing these from scratch. The development of computing technology in the 1960s provided access to tools that could more efficiently make calculations and allowed data entry in the field as computers became portable (O'Hehir 1995). But for the most part represented automation of the previous manual systems rather than wholescale technological and systematic changes.

Use of aerial photography that had been extensive in World War I for military intelligence provided for forest management a remote method of forest classification by trained photo interpreters. This also provided a lower precision but estimate of forest areas than ground survey methods could provide. The limitations of historical systems have been a heavy reliance of trained personnel and infield work in often difficult terrain and climate. The extent of the forest estates meant that plot-based sampling, stratification, extrapolation are all essential steps in the preparation of resource estimates.

A major advance was access to CAD (computer assisted drawing) style geographic information systems which improved data handling, analysis and visualisation of spatial data and information. These replaced the previous textual electronic database systems. Usually, the data had to be summarised to allow incorporation into the legacy resource modelling systems that were still constrained by the requirement of manually collected data. In the context of forest management, remote sensing involves taking measurements without touching trees. The availability of Landsat images since 1972 gave broad scale estimates of forest cover. Landsat imagery has been improved since in spatial and spectral resolution but are still of little use in intensively managed plantations where higher precision is required. Terrain modelling sensors such as LiDAR have replaced hypsometers for extensive forest measurement. These provide total coverage of forest estates and a metric that can be used in combination with calibration with physically measured plots to extrapolate estimates. However, despite these advances the projection of forest growth and attributes in time is reliant on legacy methods including the continuing existence of tabular yield tables many years after mathematical methods and models have become available.

Next Generation Forestry Systems - focus on Remote Sensing

Remote sensing technologies have replaced many aspects of manual forest measurement in the last 10-15 years, reshaped the forestry sector and will continue to reform this industry towards high precision forestry in the future. The term 'precision forestry' refers to the usage of technologically advanced sensors and analytical toolsets, to measure and generate detailed, accurate and timely forest information, and to support site-specific forest management (McRoberts, Cohen et al. 2010, Dash, Pont et al. 2016). Relevant remote sensing instruments are mounted on unmanned aerial vehicles (UAVs), helicopters, aircrafts, or satellites. These remote sensors can be divided in active (e.g. LiDAR, radar/SAR) and passive (e.g. spectrometer, radiometer: imaging/ multispectral/ hyperspectral) sensors. In the following we will shed some light on current and future remote sensing technology trends and how these can further advance inventory forestry, forest resource modelling and forest monitoring and forecasting.

Individual tree and area-based approaches

Medium and highly dense point clouds derived from ALS or UAV-LiDAR scans contain the necessary information to model and analyse forests at individual tree level. Existing operational systems use – if at all – low-density airborne laser scanning (ALS) data, area-based models and thus aggregated yield estimates. Promising individual tree detection (ITD) methods based on denser LiDAR point clouds were developed during the last few years (Kathuria, Turner et al. 2016, Bryson 2017, Bryson and Gordon 2018, Windrim and Bryson 2018). However, to implement individual tree-based approaches into operational workflows, there are still a couple of challenges for which further research is required: Algorithms for medium dense point clouds (Kathuria, Turner et al. 2016) require training data consisting of horizontal positions (of at least sub-meter accuracy) of all trees inside reference plots. Thereby the challenge is to acquire such position accuracy for these reference trees. RTK/GNSS under dense canopy lead to unacceptable position inaccuracies (Dash, Pont et al. 2016), thus further research is required. There is also a strong business need arising to manage harvesting operations more precisely, to a sub operational and even a tree level. Novel integrated RTK/GNSS positioning systems on harvesting machines promise tree positioning of <1 m (Hauglin, Hansen et al. 2017). However, solutions for forest-wide sub-meter tree positions are not available prior to harvesting, but such solutions would not only significantly improve harvest planning, open but also enable LiDAR-based forest modelling (incl. wood volume) on individual

tree level and improve the georeferencing of other remote sensed forest data.
Future research on ITD and sub-meter tree positioning (prior to harvesting) for operational forestry could include:

- Establishing a tree-life archive: concepts and methods to capture detailed data including spatial position of each tree (from seedlings stage to final product). Satellite remote sensing tools could be used within the first five years after a tree was planted to capture its spatial position, and then frequently systematically repeated for updates adding UAV and airborne remote sensing approaches.
- Development of advanced ITD approaches using and integrating multi-temporal ALS/UAV LiDAR data (of different resolution), aerial imagery, high-resolution satellite imagery data (e.g. WorldView-4 with 0.31 m panchromatic resolution), and novel ground-based plot inventory data (e.g. terrestrial/mobile scanner data).

Utilising denser point clouds, increased imputation grid-resolution – as an alternative to tree level approaches – will also open room for future research. Interpine (Herries 2016) recently demonstrated that using LiDAR imputation using a 5 m dynamic analysis frame, instead of a 25 m yield pixel resolution, will create higher spatial resolution of forest yield estimates. This not only offers managers a more transparent visual representation of forest yield, but also improves estimates of volume and product yield for smaller areas. With the expected point density increase of ALS data, it is worth further exploring an increase of imputation grid-resolution. Another likely future research direction is the utilisation of satellite remote sensing data for area-based analysis (ABA) of forest stands, which provide a cost-effective and flexible resource for many forestry monitoring tasks (e.g. wood volume, biomass, LAI, biodiversity, fire risk). Remote sensing research solutions in the area of forestry need to be integrated with assays for wood properties, environmental physiology and genetics in order to quantify the drivers of growth and wood quality. This has allowed the development of a forest phenotyping platform. As part of the "Growing confidence in forestry's future" program (SCION 2014) forestry researchers are currently working on such goals while they investigate remotely sensed data to obtain information on individual trees and their physical growing environment and quantify relationships between key wood property traits and LiDAR-derived stand-level variables.

Multi-temporal LiDAR data

Yield estimates based on ALS (or UAV-LiDAR) data and grid-based imputation models have brought great benefits to forestry industry. Further research is still needed to integrate individual tree-based yield models into operational forestry. ALS are used to model and estimate yield as a snapshot of wood volume in time, which is then used for harvest planning for the medium term, say 1 to 5 years. Usually after three years the next ALS flight is scheduled to update the model. This data is a big cost factor. Time series of ALS scans reveal further hidden information about yield growth to model changes and predict the future. Multi-temporal LiDAR data haven't been investigated much yet. Referring to McRoberts et.al (McRoberts, Chen et al. 2018), the shelf-life of airborne laser scanning data when used with model-assisted estimators is at least 10 years. Thus, two or more ALS time series scans could be used to predict the future for the next 5+ years, and the model could be updated and improved with each new ALS dataset. For such updates, UAV-LiDAR scans of selected areas/plots could be used instead - to much lower acquisition costs. Such combination of existing data as well as combination of different LiDAR platforms is ongoing and future research and potentially lead to new operational solutions (Peters 2018).

Open Satellite data

Among the freely available satellite data, Landsat-8 (L8) imagery used to provide, with 30 m, the highest spatial resolution for R, G, B, NIR, and SWIR bands at a revisit time of 16 days (or 8 days combining L7 and L8). With nearly identical spectral bands, ESA's Sentinel-2 (S-2) sensors, available since 2016 (S-2A) respectively 2018 (S-2B), provide free imagery data with 10 m spatial resolution for R, G, B, and NIR bands or 20 m for SWIR, and a revisit time of 10 days (or approximately 5 days combining S-2A and S-2B under cloud-free conditions). Further free Sentinel data include (a) a synthetic aperture radar (SAR) imagery available through S-1A and S-1B, and (b) Sea and Land Surface Temperature Radiometer (SLSTR) data through S-3A launched 2016 and S-3B launched 2018 – which offers an improved alternative to MODIS data providing nearly the same spectral information at about the same spatial resolution. The Sentinel series is planned to be further extended to C and D in the coming years. The forestry sector appears not to have investigated the full potential of these free Sentinel satellite data sources. In addition, the usage of cloud processing tools as well as the option to combine and fuse free imagery datasets, offers high potential to improve forest monitoring towards near real time. Moreover, the fact that (inter)governmental organisations such as ESA set up satellite missions and provide easy and free access to multispectral satellite imagery data (Sentinel) with medium resolution (10 m), is forcing commercial satellite data vendors to respond with decreasing costs and/or improving the quality of their products.

Very high-resolution satellite imagery

The use of very high-resolution satellite imagery data with spatial resolution <0.5 m and spectral range from visible to NIR has large potential for forest management. These imagery data sets can reveal information about forest health, and to some extent tree positions and crowns (depending on tree structure and distance between trees). Furthermore, monitoring systems using very high-resolution satellite data can investigate forest degradations, and changes of forest health, and other changes in time (e.g. harvested or damaged trees). The main reasons forestry industries are not fully using such datasets in their operational workflows are the limitations of looking through the canopy, the high acquisition costs, as well as complex image processing and analysis procedures. This gap will be filled in the future by the before-mentioned services offered from commercial satellite imagery vendors, as for example MAPIZY – a company which offers grid-based (e.g. 50x50 m) forest inventory created from very high-resolution Satellite imagery (e.g. WorldView-4, GeoEye-2) using deep learning approaches (Mapizy 2018, Ravanbakhsh and Ramzi 2018).

Looking at the current generation of commercial satellites providing very high-resolution imagery, WorldView-4 and GeoEye-2 are leading with 31 cm GSD. Looking ahead, the Indian Space Research Organisation (ISRO) plans to launch the Cartosat-3 satellite in 2019, capable of taking images of the earth with a resolution of 25 cm. This will improve the potential for a wide range of applications including satellite image-based tree detection/classification, deforestation monitoring, and other promising applications for forestry. However, commercial (very) high resolution imagery are still (very) expensive to acquire, but as mentioned earlier there are signs that this situation is changing.

From multi- towards hyperspectral satellite imagery

Hyperspectral satellite imagery data is not yet used in operational forestry. Asner et. al (2015) discussed the value of hyperspectral satellite data for the identification of forest biophysical and biochemical properties. One of the most relevant currently available data sources is Proba-1, a satellite launched in 2001 providing up to 62 spectral channels/bands (1.25 nm at 400 nm and 11 nm at 1050 nm) in the visible and NIR spectrum at 20-30 m ground resolution. Another example of such innovation is the hyperspectral data being acquired from the decommissioned Nasa EO-1 Hyperion satellite sensor. With a similar spectral and spatial resolution Hyperion provided more than 200 wavelengths/bands ranging from 400 to 2500 nm. These two missions have proven the feasibility and usage of hyperspectral satellite data for many applications. In the upcoming five years several new hyperspectral satellite missions are planned: EnMap, HyspIRI, HypXIM, Shalom, HISUI, and Prisma, which will reshape this potential with advanced sensors and improved spectral qualities. This will open new potential for forestry research and applications including forest classification, forest water resource estimation, forest health assessment (e.g. chlorophyll content) and mapping, and many others.

SAR

Satellite SAR imagery convey great potential for future forestry research. SAR, a form of radar, is an active remote sensing method and thus not relying on the sun. Consequently, SAR has many advantages to optical remote sensing: all weather capability; day and night operation; no effects of atmospheric constituents; subsurface penetration; and sensitivity to dielectric properties, surface roughness, man-made objects as well as target structure. These benefits of SAR data surely offer various future research areas for forest monitoring.

Many SAR satellites are currently in orbit, including Radarsat-2, Risat-2, SAOCOM-1A, PAZ, Cosmo-SkyMed (SG), ALOS-2/ PALSAR-2, INTA/Indesat, SAOCOM-1A, KOMPSAT-5, ICEYE-X1, NovaSAR-1, TerraSAR-X, and Sentinel-1. In particular, the latter SAR satellite sensors are relevant for forestry applications. The freely available Sentinel SAR data (S-1A launched 2014 and S-1B launched 2016) provide a spatial resolution of 20x22 m (at 10x10 m pixel size). NovaSAR-1 offers a spatial resolution up to 6 m and uses C- and X-band radars and can therefore deliver a better measure of standing timber. TerraSAR-X uses the X– band and offers a spatial resolution of up to 1 m, consequently even individual trees are discernible.

The main advantages of using SAR sensor data for forestry include:

- Ability to penetrate through clouds (weather independent)
- Imaging capability at any time of day or night
- New image products by coherent combination of radar images
- High-resolution (1-5 m already available, better resolution expected in future missions)
- Frequent revisits (soon to be daily)
- Wide swath coverage
- Complementary to optical systems
- Ability to see timber through the canopy (S- and L-band)
- High resolution capability (independent of flight altitude)
- Easy access to the data
- A prospering Earth observation (EO) field with dozens of commercial SAR satellites to be launched soon

Potential future forestry applications of Satellite SAR (and also airborne RADAR sensor) include:

- Soil moisture estimation
- Estimation of forest height, and biomass
- Deforestation monitoring
- Wetland classification and monitoring
- Fire detection
- Topography (DEM generation with interferometry)

Airborne and UAV-based sensors

The deployment of UAVs in agriculture is well advanced compared to forestry. Drones are successfully used for the detection of weed infestations, crop condition and yield monitoring (Dash, Pont et al. 2016). Developments in forestry have been to some extent slower due to the large areas to cover and more difficult terrain. However, recently UAVs have been gaining more acceptance in operational forestry. Current research projects focus on the use of infrared sensors for tree stem or wildlife detection, the use of hyperspectral sensors for forest health monitoring or the usage of LiDAR to capture very dense point clouds. The integration of these different sensors in one UAV-based platform remains challenging.

Comparing UAV-based approaches with spaceborne sensors, UAV certainly offer much higher spatial resolution and provide higher flexibility in terms of which sensors to use, where and when to operate, and when to repeat data acquisition. In the future UAV-sensors will further advance and drones will become stronger (increased payload, longer battery duration) and smarter (integrated multiple sensors). Although spaceborne imagery prices are expected to decrease in the future, at the moment UAV-based hyperspectral imagery is still more affordable than the one from satellite-based sensors (Farmmanagement 2016).

Further development of airborne sensors, in particular laser scanners, is expected. Technological sensor advances will continue to decrease the size of sensor electronics and likely drive further increase of processing speed as well as on-board recording- and storage capacities. This will significantly decrease the payload of UAV-based remote sensing systems and allow for longer flight times and simultaneously usage of multiple integrated sensors (e.g. LiDAR, radar, IR, optical). Furthermore, drones can be also used as transportation tools, for instance for tree seedling deliveries (InterpineGroup 2018) or even seeds.

Remote sensing data integration

Combing different sensor data is not yet explored much but has great potential for forestry applications. Dash et.al (Dash, Pearse et al. 2018) compared UAV-based and Satellite-based monitoring of forest health using multispectral imagery. Both approaches have significant capabilities to detect plant stress, and even more when combing these data sets. The authors suggest further studies to investigate the fusion of both data sources.

As mentioned earlier, UAV-LiDAR of selected forest plots could be combined with ALS datasets to update yield estimates. Pearse et al (Pearse, Dash et al. 2018) pointed out the potential of point cloud data derived from stereo satellite imagery used to provide large-scale forest inventory assessment. The authors used Pléiades-HR 1A & 1B satellite imageries (panchromatic spatial resolution of 0.5 m), which resulted in a final satellite point cloud data (SPCD) density of 1.9 points per square meter. Results also clearly show the usefulness of such SPCD for the prediction of forest inventory attributes in intensively managed forests on steeper terrain. Future work could use even higher resolution imagery (≤ 0.31 m), investigate tri-stereo satellite imagery to increase SCD density, and further enhance inventory assessment, and to make further use of the spectral information (e.g. IR for tree health monitoring).

Another example is the work of Zieher, who suggested a voxel-based data integration of UAV point clouds, terrestrial laser scanning (TLS), and terrestrial photogrammetry data (Zieher, Toschi et al. 2018). Such voxel-based data integration approach could be also applied to integrate (multitemporal) UAV-, airborne- and Satellite data for various applications in forestry.

Cloud processing

Cloud processing of Satellite imagery with the option to integrate aerial/UAV imagery and point clouds, plot inventory data and other geospatial data, will reduce and potentially replace existing resources and infrastructure involved (e.g. data storage, GIS/RS software licenses, associated personnel skills and expenses). Open-source libraries for cloud-based satellite image processing are already available, such as Google Earth Engine, DigitalGlobe's GBDX, or Digital Earth Australia's Jupyter Notebook. At the same time commercial vendors of (very) high-resolution space imagery will increasingly offer customised services of cloud processed satellite imagery information. Companies as SwiftGeospatial (SwiftGeospatial 2018) already cloud-process high and medium resolution satellite imageries to provide near-real-time services such as tree health, harvesting and fire break analysis using deep learning algorithms. Current challenges of such services include cloud and shadow handling, exact plantation positioning, sensor consistency, and reliable detection of thinning areas (Breetzke 2018). Temporal resolution of high-resolution satellite imagery has already progressed to daily revisits, and when combining multiple sources, areas of interest can be monitored several times a day. Since September 2018, Geoscience Australia in corporation with CSIRO-Data61 and other government agencies provide Sentinel-2 Near Real-Time Surface Reflectance data, available through NationalMap – an interactive online exploration tool which allows user to query between pre-defined spectral indices, select dates and time-series, and compare 2+ imageries using a swipe-tool (Cannings 2018). Such online explorative tools could be further devolved towards customised forestry applications based on (free) satellite imagery – to investigate specific forest features (e.g. deforestation, health indices, yield estimates) and their changing in time, and ultimately support decision-making.

New Sensors and new sensor technologies

In the future, additional or improved sensors are very likely to contribute to forestry research and provide added values to the complexity, quantity and quality of forest tree data. With ever increasing resolution, return frequency, more sophisticated sensors, rapidly decreasing data costs, easier access to processed imagery and derived products, remote-sensing approaches will provide a wealth of research and effective management data for the forestry sector.

In the last decades satellite remote sensing technologies have transformed the geospatial industry. This transformation can be captured in four remote sensing trends: resolution, accuracy, speed and analytics

(DigitalGlobe 2015). Resolution refers to the ever evolving spatial, spectral and radiometric resolution of Satellite imagery products. Accuracy relates to the position accuracy and precision of satellite imagery data – in other words that the images match with what is actually on the ground. Imagery's positional accuracy has been steadily improving with errors around 20 m in the early 2000s to 3 m today (Navulu, Pacifici et al. 2014). Speed refers to the constantly decreasing time to collect, process and distribute remote sensing products. Analytics stands for sophisticated information extraction techniques, including deep learning algorithms to explore large time series data, but also refers to the use of crowdsourcing tools to address the need for information suited for "actionable intelligence" and decision making.

In the coming decades innovation in satellite construction and operation are expected. These may include larger antenna and mirror structures, innovative approaches to refractive and reflective optics, the use of compact spectrometers to allow for the reductions in overall size and mass of optical instruments, more efficient cooling systems that will allow the extensions of these size benefits far into the infrared region of the electromagnetic spectrum, and the development of solar power and solid-state radio frequency amplifiers (Paganoa and Kampeb 2001, Khorram, Van der Wiele et al. 2016). These technological innovations will allow detection of multi- and hyperspectral imagery of improved spatial, spectral, temporal and radiometric resolution from low-Earth orbit and include LiDAR and SAR measurements from geostationary orbits which will provide important datasets to further enhance precision forestry. They may also allow adjustable imaging systems where wavelengths can be selected based on customers' needs.

Two of the key larger Earth observation (EO) satellites put into orbit in 2018 and relevant for future remote sensing research in forestry include: ESA's Sentinel-3B (as described earlier), and Japan's ASNARO-2 - a X-band SAR radar satellite with a 1 m ground resolution. Another new radar sensor "NISAR" (NASA) is scheduled to be launched in 2020. Moreover, in 2019 a new NASA laser instrument will be launched on board of the ISS: The Global Ecosystems Dynamics Investigation LiDAR (GEDI) – a full-waveform LiDAR with the highest resolution and densest sampling of any lidar ever put in orbit. This will provide global 3D canopy data. The GEDI sensor addresses the following core questions relevant to forestry research: (a) quantify the spatial and temporal distribution of forest structure and its relationship to habitat quality and biodiversity; (b) quantify the distribution of above-ground carbon at fine spatial resolution; (c) quantify the sequestration potential of forests through time under changing land use and climate; (d) quantify changes in carbon resulting from disturbance and subsequent recovery (NASA 2018). Moreover, the World Meteorological Organization (WMO) currently lists 299 EO satellites to be launched in the future; and 114 of the in the next 5 years (WMO 2018).

Beyond innovations in satellite technology, a range of new satellite platforms are being developed. These platforms include a group of miniaturised satellites which simultaneously gather scientific data. Such miniaturized satellites of lower mass and size can be grouped into "Smallsats" (100-500 kg), Microsatellites (10-100 kg), Nanosatellites or "CubeSats" (1-10 kg), Picosatellites (0.1-1 kg), and Femtosatellites (10-100 g). The latter two require a larger "mother satellite" for communication with ground controllers. The relatively simple, less risk-taking and associated low-cost architecture of such minisatellites, are enabling easy access to the space industry, and usually multiple minisatellites are orbiting simultaneously around the globe. This allows cheaper and more frequent access to satellite data and will establish new business models. Minisatellites can be developed in a few months (or years) compared to the 10+ years development cycle of current systems – from conception to launch. According to the Euroconsult report 2018 (Werner 2018), it is anticipated that 3300 satellites with a mass over 50 kg as well as 6200 minisatellites will be launched between 2018 and 2027. 15 to 20% of these are expected to be Earth-observation satellites. Minisatellites companies, such as Spaceflight, intend to offer people the ability to order a high-resolution image of any spot on the planet delivered to their smartphones in less than 90 minutes for under 100 US$ (Werner 2018). Developments in sensor technologies are continuously redefining the role of remote sensing in forest monitoring. Consequently, precision forestry is fast becoming an achievable reality. The sensor revolution is going to continue. Remote sensing will further decrease the need for ground measurements and potentially fully replace them.

Other novel technologies

Future forestry research will certainly be affected by improved versions of currently used sensors mounted on drones or aircrafts. Nevertheless, the forestry industry should also be advised to look at novel technologies, such as multispectral LiDAR (Hopkinson, Chasmer et al. 2016); single-photon-LiDAR (Higgins 2016); or acoustic tomography sensors which allow to reveal tree distribution and tree density; or novel techniques to enhance the quality of captured imagery (e.g. High Dynamic Range Bio-Vision). In regard to the processing speed of remote sensed data, innovative new technologies, such as on-board/orbit quantum and biological computing (in particular to process high-resolution hyperspectral imagery data) will likely be realised in the near future and significantly improve data processing, analysis and distribution – also relevant for future forestry research. The ultimate solution will be unlimited computing and power on orbit (Khorram, Van der Wiele et al. 2016).

Smart forest data system, VR, and AR

Future forestry systems will likely head towards "Smart forest data systems" – single (customised) cloud-based system which integrates all spatial and non-spatial forest data of interest (e.g. multi-temporal LiDAR point clouds, aerial and satellite image series), all data processing and analysis tools as well as all derived results (e.g. wood volume, biomass, yield growth, changes in tree health) and which provides specific planning and analysis tools for decision makers and automatically updates forest data (spatio-temporal tree/stand characteristics), forest maps, and tree/forest statistics. Such smart systems will also likely integrate sensor data from different platforms (UAV, aircraft, satellites). Furthermore, the more detailed a forest is remotely scanned, the better the resulting (smart) photo-textured 3D models. Accordingly, new possibilities and research question arise in the area of Virtual-and Augmented Reality used for analytics and decision making in forest management.

Big Data and Machine Learning

With evolving LiDAR and imaging sensor technology, there has been an immense increase of captured data quantity. To reveal the full potential of the information hidden in these (very) dense point clouds and integrate them directly into operational systems, further research is needed. Recent approaches have already identified the benefits of additional metrics such as voxel metrics (Pearse, Watt et al. 2018). First results are promising, and further research in the upcoming years will surely improve imputation models. With the change or establishment of new operational systems (hardware and software included), new appropriate metrics need to be investigated and identified. Using airborne captured LiDAR data, machine learning approaches such as random forest or kNN are already integrated in operational forestry. However, such approaches will need to be adapted when modelling yield growth based on multi-temporal LiDAR data, or when looking at time-series of satellite or aerial imagery for changes in tree health etc. Regarding the detection of forest types, deforestation and biomass estimation, deep learning should be also explored further as an alternative to pixel-based image classification.

Moreover, research is needed to provide adequate solutions for the storage, processing and management of remote sensed "big data". Factors contributing to the massive growth of data include improved sensor technologies; open access to satellite imagery; and open access to DEMs, to field-based data collected by researchers or government agencies, and to vast and frequently collected meteorological data (Khorram, Van der Wiele et al. 2016). The Australian Geoscience Data Cube (AGDC) is an excellent recent example for how (Landsat) satellite data can be stored, processed, analysed and distributed (Lewis, Oliver et al. 2017). Datasets already piloted for AGDC include Sentinel-2, MODIS, SRTM, and others. AGDC is an open access software that facilitates the use of EO data and demonstrates how desirable it is now to get free and open access to such satellite data analysis tools. The Committee on Earth Observation Satellites (CEOS) currently studies the issues around next-generation EO data system architectures, and the opportunities offered by approaches such as the Data Cube and commercial cloud storage as well as processing solutions (UN 2017). The illustration in Figure 9 below illustrates the future global data flow options for national forest monitoring systems prepared by the CEOS Space data coordinator group for GFOI (Global Forest Observations Initiative) and indicates future remote sensing- and data cube services providing selective data download options (top-of-atmosphere corrected reflectance) as well as low data volume downloads such as forest maps.

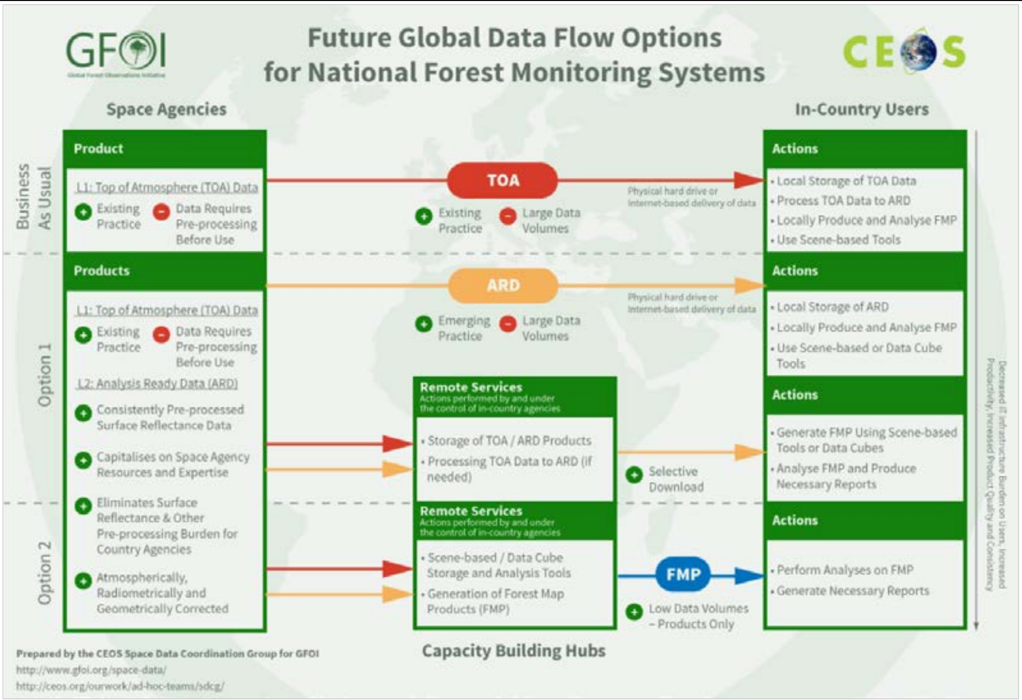

FIGURE 9: FUTURE GLOBAL DATA FLOW OPTIONS FOR NATIONAL FOREST MONITORING SYSTEMS

RS Research in other areas

The illustration below describes the market research and forecast for the US industry with drone technology. It is evident that the vast majority of drones continue to be applied in the agriculture sector.

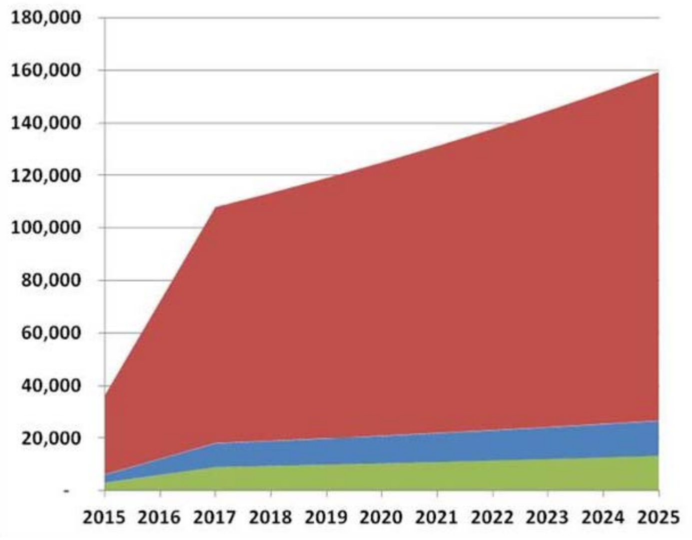

FIGURE 10: ANNUAL UAV SALES FOR AGRICULTURE, PUBLIC SAFETY AND OTHER MARKETS, SOURCE: (AUVSI 2013)

Nutrition and health applications as in agriculture and horticulture

Remote sensing has not generally found application in nutrition and health applications in Australian forestry compared with the rate of adoption in agriculture and horticulture for these purposes. There are opportunities to consult remote sensing experts in agriculture and horticulture to understand the drivers that led to the use of remote sensing in these industries and to consider opportunities for adaptation of some of this remote sensing to forestry. To date a clear barrier to forestry applications of remote sensing for nutrition and health assessment has been the extensive scale of forestry activities compared with agriculture and horticulture, and the lack of precision of the available remote sensing data from satellites. The cost of calibrating remote sensed data with on ground measurements has contributed to a lack of application. In both agriculture and horticulture fixed wing aircraft and drone technology can provide cost effective platforms for various remote sensor deployment across the relatively small areas under management.

Training in forestry-RS

Relevant and advanced skills required to apply remote sensing (and GIS) technologies for forestry applications are significant. The forest industry will require graduates with skills in forestry (science ecology, management) and Remote Sensing. Current forestry education and training in Australia, published by the Institute of Foresters of Australia (IFA), is listed in Table 7.

TABLE 7: A SUMMARY CURRENT FORESTRY EDUCATION SUPPLIERS.

University	Program	Major/Minor
Undergraduate study		
Australian National University, Canberra	Bachelor of Sustainability and Environment	Forest Science and Policy / Sustainability Studies / Environmental Science / Resource and Environmental Management
Southern Cross University, Lismore NSW and Mt Gambier SA	Bachelor of Forest Science and Management	
University of Melbourne, Victoria NSW	Bachelor of Science	Forest Ecosystem / Ecosystem Science
Postgraduate study		
Southern Cross University, Lismore NSW and at Mt Gambier SA	Master of Forest Science and Management	
Australian National University, Canberra	Master of Forestry	Forest Policy and Management / Forest Science and Methods
	Master of Environment	Natural Resource Management / Biodiversity Conservation and Management / Sustainability Science / Water Science and Management
	Master of Environmental Science	Ecological Science
University of Melbourne - School of Ecosystem and Forest Sciences	Master of Ecosystem Management and Conservation (new degree in 2019)	
	Master of Science (Ecosystem Science)	Ecosystem science / Forestry and Forest Sciences

In all the listed university programs, only the basic principles of remote sensing and its applications for forestry are taught as part of one 'spatial tools for forestry' course. To feed the future industry requirements, one would need to have two degrees to add the missing remote sensing skills or have extensive additional training and practice.

It is hard to see a future where forestry-based training in remote sensing will be sufficient alone to provide forestry companies with the level of expertise to operate and develop to the full potential the remote sensing tools they require. This means the role of the forester will be to liaise with people who have those skill-sets and they'll need an appreciation of remote sensing rather than expertise. It will be up to organisations if they will employ remote sensing experts or engage consultants. Given the rate of change in remote sensing technology it is more likely that current expertise will be found outside of forest companies.

Forest & Wood Products Australia

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