# Resources

*Next Generation Resource Assessment and Forecasting for Australian Plantation Forestry*

Project number: VNC519-1920

December 2022

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Forest & Wood Products Australia

# Next Generation Resource Assessment and Forecasting for Australian Plantation Forestry

Prepared for

**Forest & Wood Products Australia**

by

**Philip J. Smethurst, James F. O'Hehir, David Bruce, Braden M. Jenkin, Neil I. Huth, Stephen B. Stewart**

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**IMPORTANT NOTICE**

**This work is supported by funding provided to FWPA by the Department of Agriculture, Fisheries and Forestry (DAFF).**



**ISBN: 978-1-922718-17-4**

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# Executive Summary

Australian plantation forest managers face considerable and increasing challenges to maintain and develop their forest growth and yield planning systems. While increasing precision and detail on the current and future attributes of their plantation resource is required, there is ever increasing opportunity and complexity in using new data sources that are becoming available, especially from sensors (satellite, airborne or ground-based) and process-based modelling. Increased complexity in modern systems development requires specialist skills not usually available in forest companies. Because of these trends, existing industry growth and yield systems are a mix of old technologies and more modern additions, with their functionality constrained by legacy designs and limited capabilities.

This project offered the potential for growers to design and experience elements of a modern system akin to that available to grain growers and other agricultural sectors. This system would for the foreseeable future augment, rather than replace, existing growth and yield forecasting systems by incorporating process-based modelling capabilities and data from sensors. The project also aimed to evaluate cooperative business models that could develop and sustain delivery of these advanced technical services to the forest plantation industry.

Process-based modelling here refers to modelling that includes specific mathematical representation of ecosystem processes that lead to wood production, e.g. the use of light, water and nitrogen for carbon fixation (photosynthesis) and allocation to stems. This type of modelling contrasts with empirical modelling that has long been used by the industry for resource forecasting, which relies on statistical relationships between input and output variables. Empirical modelling loses reliability where forecasts are required into future contexts that have not yet been experienced, e.g. new site-climate-genotype-management scenarios. Literature on process-based modelling suggests that it can be more reliable in such scenarios, as the underlying biophysical processes can account for new conditions in both reality and the modelling. Underlying physiological relationships might remain the same in relation to $CO_2$, temperature and rainfall, but because the actual values of these climate variable change, so too does actual growth and model predictions.

The APSIM modelling framework was chosen as the process-based modelling framework for this project, because it is well-established in the agricultural sector nationally and internationally for research and commercial uses. APSIM simulates plant growth at the plot scale, and prior to this project it had been calibrated for *Eucalyptus grandis* plantations and related tropical and sub-tropical genotypes. During the project, model development added genotypes required for temperate eucalypt plantations in Australia (*E. globulus* and *E. nitens*) and pines in tropical-to-temperate regions (*Pinus radiata*, *P. elliottii*, *P. caribaea*, and hybrids). These models not only use climate variables as inputs, but also management variables of initial stocking, thinning, mortality, weeds, nitrogen fertilisation and irrigation. New genotypes can also be calibrated. These models are available free for public-good use, and licencing for commercial use is also readily available. During the project, several consultants and researchers completed basic training in the use of APSIM for plantation forestry.

The project demonstrated elements of a proposed workflow for merging remotely sensed data with process-based modelling and current inventory and empirical modelling. For a current inventory or growth plot at a specific location, empirical modelling can be used up to a date when new data become available from sensors (e.g. average tree height, stocking or leaf area index from airborne Light Detection and Ranging sensors - LiDAR) or when a user wants to include process-based modelling. Hindcasting can then be conducted from the previous tree measurement date up to the current date. Forecasting can then be used into future climate or management scenarios. In addition, by combining remote sensing and process-based modelling (also called hybrid modelling or model-data fusion), virtual plots can be established anywhere and everywhere on a plantation estate, and hindcasting and forecasting conducted. Even if a virtual plot system was established, ground-truthing and model calibration and testing opportunities would still need to be provided by a selection of growth or inventory plots.

A parallel project (FWPA project VNC516-1920 'Optimising productivity of hardwood plantations: yield gap analysis for *Eucalyptus globulus* plantations in southern Australia') demonstrated how APSIM modelling can be used for yield gap analysis that explores management factors (stocking, weeds and N fertilizer) as well as climate. Process-based modelling would benefit from additional process-based studies in plantations that quantify growth and biomass allocation patterns for particular genotypes in relation to contrasting growing conditions.

Remote sensing options were explored for providing useful sources of data that could complement process-based modelling. Several companies are implementing a program of airborne LiDAR scans of their whole estate every few years. These scans can provide the stand metrics mentioned in the previous paragraph as direct input to the modelling. Examples of doing so were demonstrated at two growth plot locations in south-east Queensland that supported a hybrid of *P. elliottii* and *P. caribaea*. A free satellite product that is also worth exploring further in the future for fusion with the modelling is evapotranspiration (ET), as we found acceptable agreement between it and APSIM-predicted ET at a plot of *E. globulus* near Mount Gambier, South Australia, and these data are available at all Australian locations at a high spatial (30 m) and temporal resolution (monthly). Also, biomass estimates based on satellite data will become available from an orbiting satellite at a spatial resolution of 200 m every three months, which will warrant future evaluation.

Major changes to leaf area in a plantation can be caused by, for example, insect browsing, drought or fire. It would be useful to know when and where this is occurring across a plantation estate without resorting initially to field inspections, and to then incorporate that knowledge into yield forecasting. The project identified useful and free sources of satellite data, and it also developed a tool to interpret those data and alert a manager to a significant change. The tool was developed and tested predominantly in pine plantations in south-east Queensland and the Green Triangle region was found to be useful in detecting monthly to seasonal atypical change within age classes. The symptomatic tool was tested at desktop level, migrated to a cloud computing environment, and it is currently at prototype level.

An example of hybrid modelling using a Kalman filter (particle) approach was provided for a pine plantation in Queensland that demonstrated how tree or site measurements (manual or sensed) could be used to provide an indication of the level of uncertainty of a yield estimate considering future possible climates and other factors, and assist in defining site input parameters that were not known. Pine height was the target variable, which had five observations during the rotation. Each time an observation became available, the filter refined its choice of model, and by the ends of the simulation identified a set of parameters that provided the best overall fit for all observations.

Within-company expertise and consultant services are theoretically options for providing these advanced technical services to the industry. However, a survey indicated that there is overwhelming opinion that individual companies will not have internally the full range of technical expertise required, and that consulting services can be relatively expensive and lack technical flexibility.

The project therefore explored an industry cooperative model that could potentially provide such services with more technical flexibility and at a reasonable cost. Tree Breeding Australia was profiled as an exemplar long-standing model for delivering advanced technical services to the Australian forest plantation sector. The main elements of a similar business model were explored for providing remote sensing and process-based modelling services. These elements include governing documents, mechanisms and governance, membership code of conduct, works undertaken and adoption, member exit mechanisms and strategy, risk management strategy, and a management of intellectual property strategy.

It is strongly recommended that the industry:

1. Further explore the technical aspects of integrating remote sensing and process-based modelling into their workflows for forecasting short- to long-term wood supply, and inputs to natural capital accounting, as these technologies can now be considered for implementation.
2. Rigorously evaluate the developed low-cost forest disturbance prototype tool and compare its cost and information effectiveness with existing paid-for services from higher resolution satellites.
3. Commence a process to develop the details of a collaborative business model for providing these advanced services.

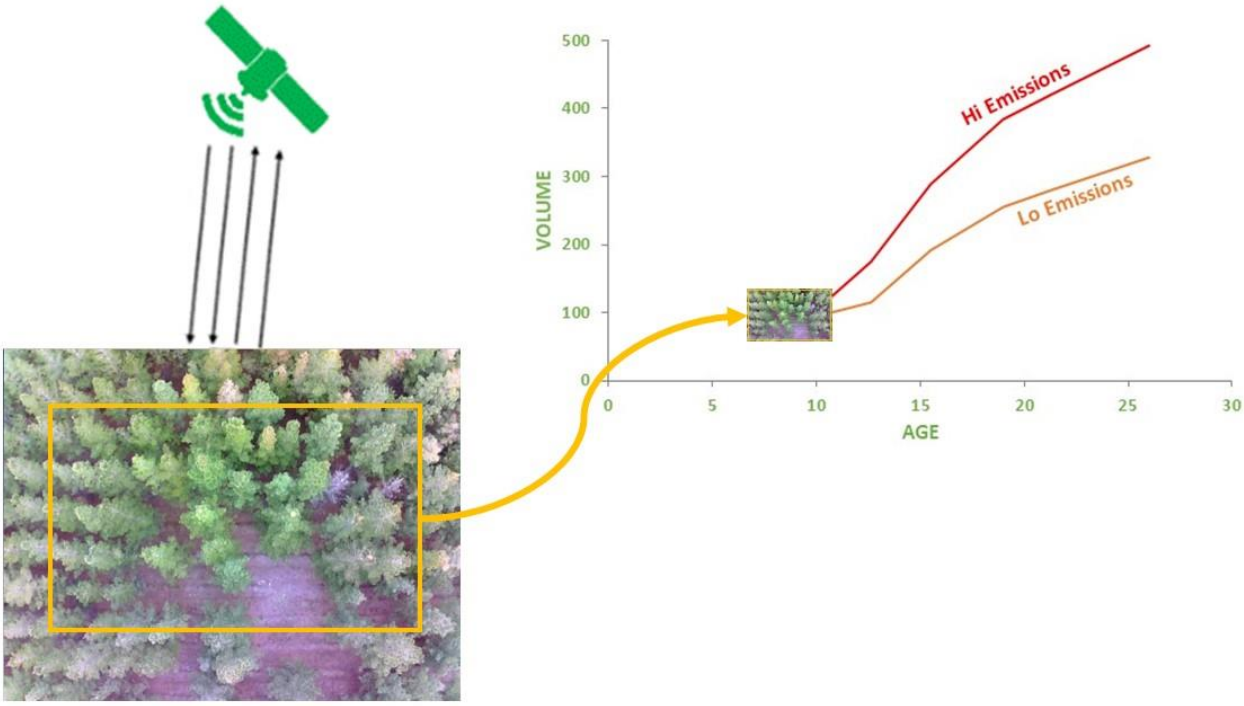
Australia's National
Science Agency

# Next Generation Resource Assessment and Forecasting for Australian Plantation Forestry

## Final Report to Forest and Wood Products Australia for Project Number VNC519-1920

Philip J. Smethurst, Jim F. O'Hehir, David Bruce, Braden M. Jenkin, Neil I. Huth, Stephen B. Stewart

May 2022



## Citation

Smethurst PJ, O'Hehir JF, Bruce D, Jenkin BM, Huth NI, Stewart SB (2022) Next Generation Resource Assessment and Forecasting for Australian Plantation Forestry. Final Report to Forest and Wood Products Australia for Project Number VNC519-1920. Forest and Wood Products Australia.

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## Acknowledgments


We appreciate funding by Forests and Wood Products Australia (FWPA) and its industry partners (Australian Bluegum Plantations, Forest Products Commission, HQPlantations, Midway, and Sustainable Forest Management) for the project VNC519-1920 'Next Generation Resource Assessment and Forecasting for Australian Plantation Forestry', including in-kind contributions. Substantial interactions with HQPlantations and Mt. Gambier Forest Growers Cooperative were much appreciated.

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# Part I Background

# 1 Introduction

Australian plantation forest managers face considerable and increasing challenges to maintain and develop their forest growth and yield planning systems. While increasing precision and detail on the current and future attributes of their plantation resource is required, there is ever increasing opportunity and complexity in using new data sources that are becoming available, especially from sensors (satellite, airborne or ground-based) and process-based modelling. Increased complexity in modern systems development requires specialist skills not usually available in forest companies. Because of these trends, existing industry growth and yield systems are a mix of old technologies and more modern additions, with their functionality constrained by legacy designs and limited capabilities.

In Australia, historically, in-house computerised resource assessment and forecasting systems were developed, used and maintained to support the business needs of forestry enterprises beginning in the late 1960's (Gibson et al. 1969, Gibson 1971, Gibson et al. 1974, Dargavel 1978). Often the systems were essentially computerised versions of those developed for manual calculations. In house biometric and other models were often developed and used to estimate variables of interest (e.g. tree or stand volumes by product) from manual tree measurement on a small sample of the population. Models allowing extrapolation from current to future stand conditions were incorporated to provide future estimates of growth and yield. Usually, experts on resource management and information technology systems were employed to develop and maintain the systems. An exception was the optimisation capability, where relevant, which has been provided by third parties.

A summary of resource management systems undertaken in the 1980s by Research Working Group No.2 - Mensuration and Management, was entitled *'Methods Used in Australian Forest Planning in 1987'* (Anon., 1987). That document provides a useful historical benchmark back to the original computerised systems used by the majority of forest owners in Australia for inventory, planning and yield control for plantation and native forests. This showed that in 1987 resource assessment systems used in Australia were developed and maintained in-house which required in-house technical expertise usually provided by foresters with technical training and computing interests.

In the late 1980s and early 1990s, area and stand record subsystems were progressively migrated to Geographic Information Systems (GIS) as these became more accessible. Data exports from GIS replaced textual area subsystems to supply area data to resource assessment systems. This transition, although seen as revolutionary, in retrospect didn't fundamentally change the core of resource assessment and modelling systems, because often the GIS outputs were simply non-spatial data 'flat' files imported into a resource assessment system. Discussions among resource planners considered potential benefits of resource assessment and modelling systems being embedded in the GIS, but this didn't usually occur, leaving non-integrated spatial and resource systems with an *ad-hoc* interface between them.

In recent years, several forest plantation companies in Australia commenced or are considering acquisition of airborne LiDAR every few years for use in resource assessment. Such data are currently augmenting current systems of inventory and yield forecasting. LiDAR data could also be considered for input to process-based modelling systems, but there were no examples of doing so in

Australia. Although, there were some preliminary examples internationally, the research literature indicated that this approach had a strong likelihood of being useful.

In 2020, the two-year FWPA project VNC519-1920 'Next Generation Resource Assessment and Forecasting for Australian Plantation Forestry' commenced to address these concerns. It's aims were to demonstrate components of a prototype system for resource assessment and forecasting that included process-based modelling and remote sensing. This project offered the potential for growers to design and experience elements of a modern system akin to that available to grains growers and other agricultural sectors. This system would for the foreseeable future augment rather than replace existing growth and yield forecasting systems by incorporating process-based modelling capabilities and data from sensors. The project aimed to provide examples of remote sensing inputs to forest management, and to evaluate cooperative business models that could develop and sustain delivery of these advanced technical services to the forest plantation industry. This report is the final report for this project.

This report is the final report of an FWPA project designed to explore industry needs in this field, and to evaluate and further develop these technologies as prototypes. The 2-year project commenced in July 2020 as VNC519-1920 'Next Generation Resource Assessment and Forecasting for Australian Plantation Forestry'. The report describes industry needs, individual remote sensing and process-based technologies, hybrid modelling, and a business model that can be considered for providing these services to the industry.

# 2 Forest Industry Status Quo and Existing Systems

This and the following section of this report are based on O'Hehir and Jenkin (2021), which a reader is referred to for further details.

Resource assessment and forecasting systems predict current and future quantities and qualities of forest product availability under preferred and potentially alternative management scenarios and other assumptions. During the past 30 years or so, components of resource management systems have been replaced with computerised systems: examples include capture, storage and manipulation of spatial data in GIS; capture of forest inventory primarily with LiDAR sensors; satellite and other platform-based sensors scanning forests for health, extent etc. This was pre-empted by Leech (Leech, 1977). However, for the most part, data derived from these systems are still simplified and used to drive legacy empirical models based on measurements of plantation plots. This was the Phase I that Leech (1977, p.15) referred to as '*To do what was being done before but doing it better*' of the four phases in the development of new technology.

Legacy systems often struggle to support the increasing range of business needs required from plantation resource managers. For example, being based on empirical models for growth and yield estimates, these systems don't provide the functionality required to model carbon sequestration and water usage in an integrated and consistent way. Concurrently, companies have found it hard to recruit appropriately trained specialist staff who understand forest operations. Also, in Australia, forest valuations are based on 'A Standard for Valuing Commercial Forests in Australia' (Leech and Ferguson, 2012), which introduces pressure on companies to use forest valuation systems that are robust, can be understood, and are standardised.

Two technologies that are potentially useful to the industry are remote sensing (measurements from drones, airplanes or satellite) including fixed automatic sensors embedded in trees, soils or the nearby atmosphere, and process-based modelling. Process-based models have largely been developed in Australia and applied overseas, where their potential for applications in resource planning and management have been demonstrated (Landsberg, 1986; Landsberg and Coops, 1999; Tickle et al. 2001; Almeida 2018; Gupta and Sharma 2019). In agriculture, research is now merging these technologies, with an expectation that the combination of the technologies will soon be available operationally for yield forecasting (Zhang et al. 2021). Merging these technologies is a form of hybrid modelling (also called model-data fusion).

# 3 Industry Needs

In 2019, UniSA was contracted by Forest and Wood Products Australia (FWPA) to develop a Resource Modelling and Remote Sensing Investment Plan that identified and prioritised resource modelling (see Figure 1 for a generic system) and remote sensing (see Figure 2 for a generic system) areas of research, development and extension for hardwood and softwood plantations. The plan (Jenkin et al. 2019) was based largely on a survey of people in the industry who conducted or used resource assessment and forecasting. The plan provides a sound basis to consider the status and future industry needs, combined with a targeted discussion with industry partners for this current project to verify any potential changes. A summary of the research findings and priorities are shown in Table 1, which provides an overview of industry investment intentions for future development. Although all aspects of this table are consistent with the current project, and some are specifically addressed by this project (indicated by an asterisk in Table 1), further research and development will be necessary to complete all priorities.

**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* |

Functional components of a generic resource assessment and forecasting system are defined in Table 2. In 1987, most resource assessment system components used by forest managers in Australia were developed in-house. By 2019 most system components (area, inventory and planning) were outsourced, but biometrics were still 100% in-house. Forest biometrics relates to use of mathematical statistics and functions for estimating forest resources (mainly wood). In addition, a natural capital accounting functional component was added arising from the Climate Measurement Standards Initiative (Climate-KIC, 2020; Earth Systems and Climate Change Hub. 2020).

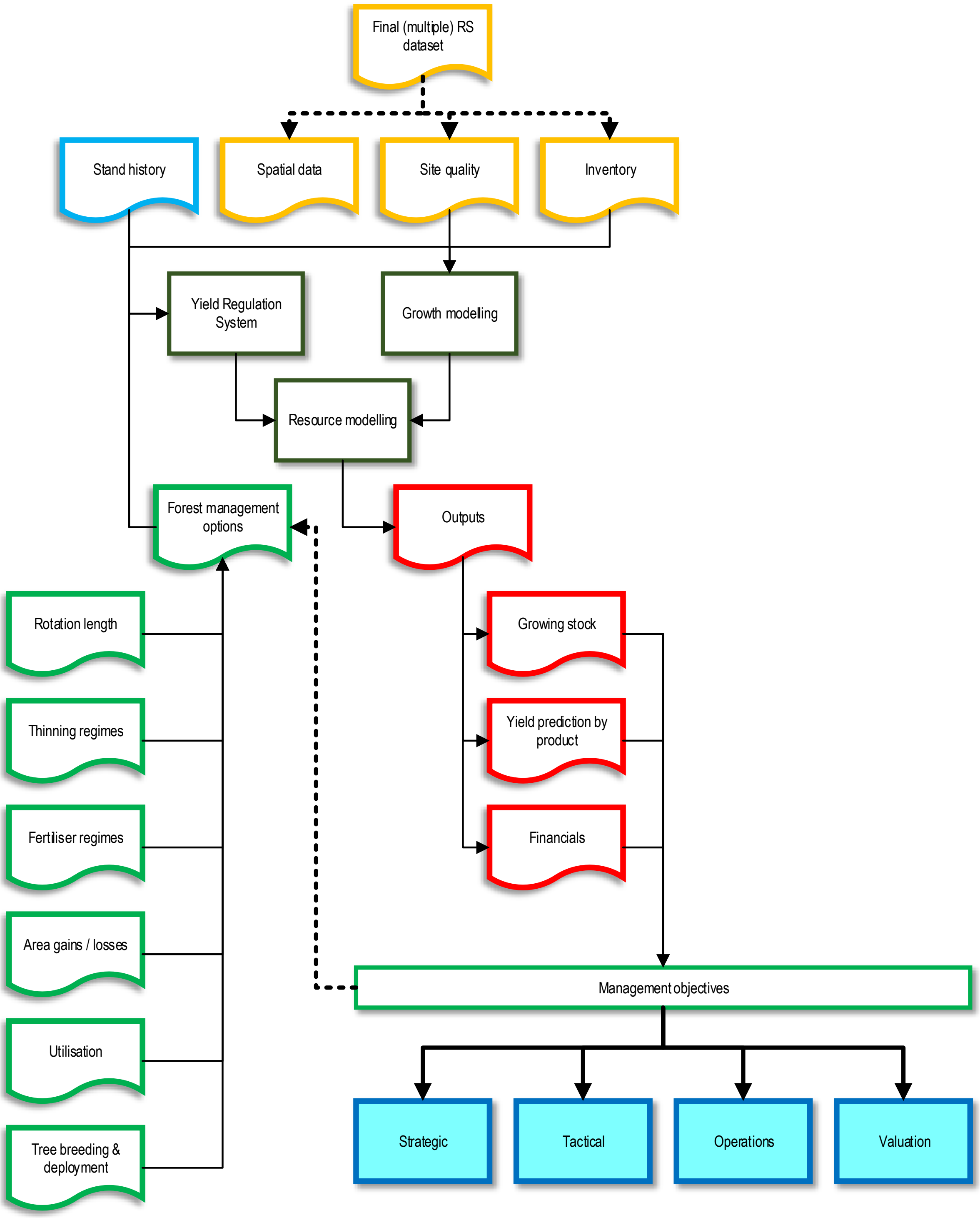


**Figure 1: A schematic of a generic, entity-based resource modelling system (Jenkin et al, 2019, Figure 1).**

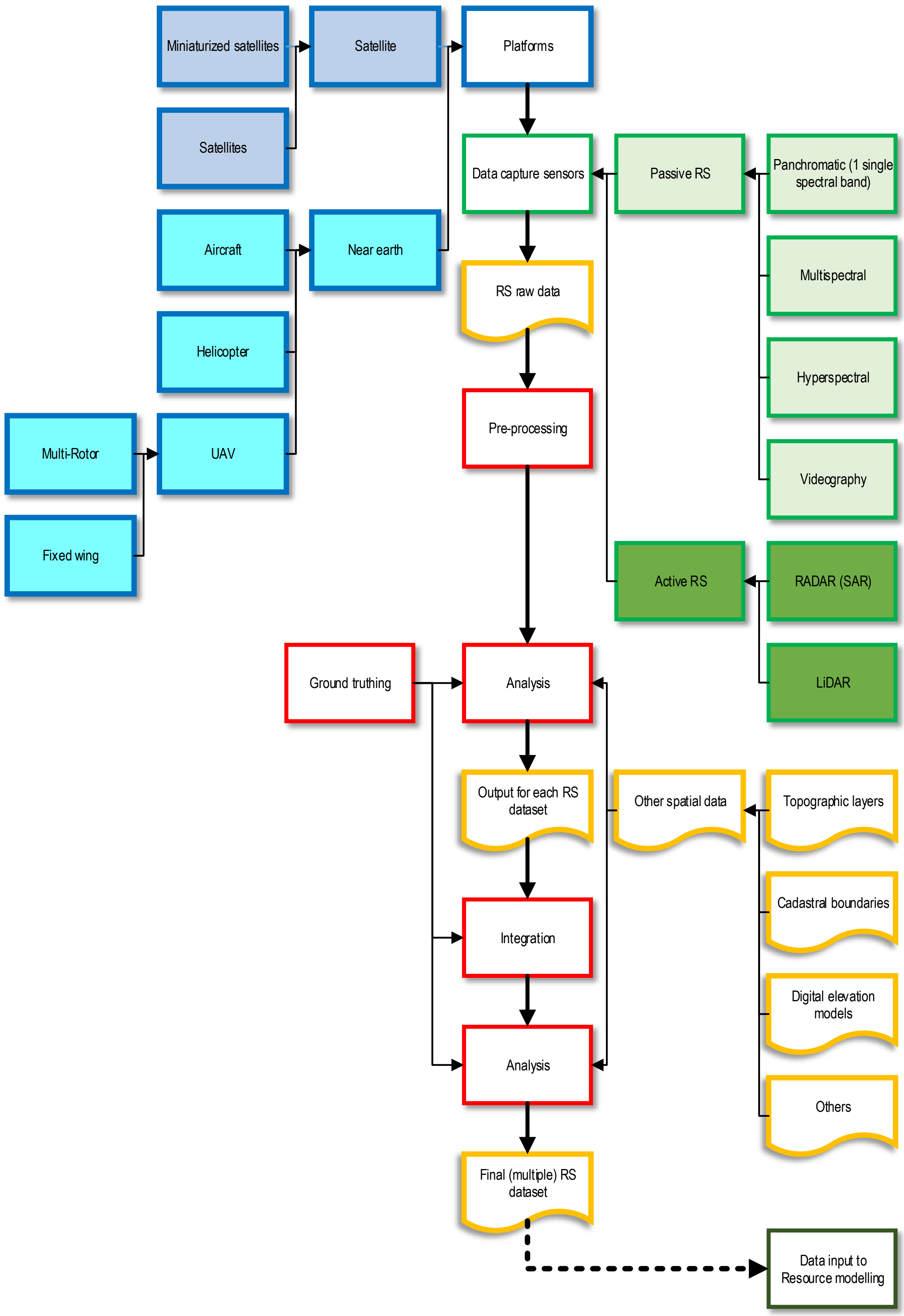


Figure 2: A schematic of a generic, remote sensing system generating input data to a resource modelling system (Jenkin et al, 2019, Figure 2).

**Table 2: Functional components of a generic resource assessment and forecasting system.**

| | | |
|---|---|---|
| Area | Inventory | Harvest Operations Planning, Budgets and Reconciliation |
| Tactical cutting planning and Optimiser | Strategic planning system | Natural Capital Accounting including Carbon/Water/Soil/Biodiversity/Greenhouse gases |
| Permanent Growth/Sample Plot System | Biometrics | Financials/Valuation/Insurance/Loss |

These systems are used to prepare outputs for the following diverse purposes:

- Forest and/or plantation valuation
- Operational planning
- Budgeting – monthly weekly / quarterly / yearly
- Tactical planning, e.g. cutting plans – 1-5 years
- Strategic planning, e.g. long-term wood flow modelling – 1-2 rotations
- Scenario testing for: short term impacts - 1 to 10 years, long term impacts - 10 years plus
- Land and plantation asset management
- Plantation expansion evaluation/land purchase decisions
- Health scenarios assessment
- Natural capital accounting

In relation to harvest planning, approximately 50% of respondents in the survey expressed concern across a range of aspects including accuracy, timeliness, costs, functionality and risks. These concerns are exacerbated by a lack of specialists in the industry who could provide advanced technical services for remote sensing and process-based modelling. Foresters generally don’t have the required skillsets to undertake the required technical developments. Rather, these roles are filled by engineers with various sub-disciplines including communications, electronics and software, GIS and remote sensing experts, virtual reality and so on. It is unrealistic for forest companies to consider that they will be able to access or develop these increasingly required skillsets from their current workforces, or that people with the necessary skill sets are likely to consider direct employment in the forest industry as an attractive career move. There should be a realisation that the best performing people with these highly technical skill sets are those with strong links to industries such as defence, mining and agriculture where they have a history of systems development which can be used to adapt systems for use in forestry. This highlights a need for individuals with specific forestry skills and experience to act as an interface with technical experts and to facilitate adaption and adoption. The issue of needing access to these specialist skillsets will continue to increase over time. It is also pertinent to highlight that because technology is rapidly evolving, to take advantage of developments, it is ongoing engagement with specialists is necessary to take advantage of the latest developments.

# Part II Process-Based Modelling

# 1 Introduction

Process-based modelling is used in agriculture and forestry to simulate ecosystem processes that can include plant biomass growth and yield, soil water and N availability, water and N use by plants, evapotranspiration, light capture and shading in relation to climate, genotype, and management. In agriculture, many models have been produced with various objectives and applicability. Commonly used models for yield prediction of agricultural crops globally are Decision Support System for Agrotechnology Transfer (DSSAT) and Agricultural Production Systems sIMulator Modelling Framework (APSIM). These two models can be considered frameworks of models rather than individual models, as their modular basis enables simulations to be built up using several models that cover the required processes. Individual models cover soils, climate, microclimate, management and crop types. These modelling frameworks have a lot in common in terms of objectives and processes simulated for various conditions, including a range of crops in common.

Australian researchers were pivotal to developing and applying process-based models that included wood yield predictions for plantation forestry. Many forest managers in Australia and internationally see a role for process-based modelling in predicting wood yields (Almeida 2018). These models include 3-PG (Landsberg et al. 2003; Almeida and Sands 2016), Cen-W (Kirschbaum 1999), ProMod (Sands et al. 2000), BIOMASS (McMurtrie et al. 1994), G'Day (Marsden et al. 2013), and CABALA (Battaglia et al. 2004). Concurrently, a *Eucalyptus* model was also included in the APSIM framework (Huth et al. 2001). In contrast to Australia's strong role in research and development in this field, use of these models by the Australian industry was very limited in contrast to the use of 3-PG by plantation companies in South America (e.g. Almeida et al. 2010). Recently, though, interest in process-based modelling for plantations in Australia has increased substantially, as evidenced by several FWPA projects using 3-PG or APSIM. The current project is one of those using APSIM.

In this part of the report, we justify the choice of APSIM in a discussion of modelling options. We then describe the APSIM modelling framework, and specifically present the models in APSIM for plantation forestry, including those developed in this project. We also demonstrate how the APSIM modelling framework can be used to simulate various complexities encountered in Australia: plantations growing over aquifers from which water and nitrate uptake could contribute to growth, and plantation growth in future climate scenarios. Service delivery options for APSIM are also considered in Part II Section 6 and in Parts V and VI. A later part of this report indicates how these models were used in the project to demonstrate hybrid modelling approaches that could include data input from remote sensing. In Parts V and VI of this report we discuss options for on-going service delivery to the industry of advanced technical services that include both remote sensing and hybrid modelling.

A few years ago, a major change to the APSIM platform was implemented, with the new platform being referred to as APSIM Next Generation. The previous platform, which is still maintained, is now referred to as APSIM Classic. All reference to APSIM in this report is in relation to APSIM Next Generation, unless otherwise indicated.

# 2 Model Options

A common question on entry to the field of process-based modelling for plantations is: What are the strengths and limitations of different modelling options, and which one should be used for a particular application? Here we address this question by comparing the attributes of three models: 3-PG, CABALA, and APSIM. These three models were chosen for comparison because they have been used relatively recently in the industry and they remain in active consideration for various applications. A tabulated comparison of many attributes is provided in Table 3, with an emphasis on distinguishing between the models. At a very general level, a potential user has to trade-off technical simplicity (3-PG) versus complexity (APSIM and CABALA), and dedicated forestry models with an unclear pathway for support (3-PG and CABALA) versus one that includes agricultural options and on-going support that is well-established (APSIM). With simplicity also comes a higher need for observations, because simpler models have more reliance on empirical calibration of parameters that define processes and that are summarised in fewer parameters. For example, 3-PG includes a fertility factor, in contrast to the other two models that specifically include nitrogen, and the latter two also have an aspiration to include phosphorus.

The level of empiricism in a model, and data availability for calibration, affects its usefulness for predicting outcomes in future conditions that haven't yet been experienced. Because future climates are trending to be significantly different to the past, it has been argued that process-based models are better placed to predict future forest growth (Korzukhin et al. 1996, Bosela et al. 2022), and there is heavy reliance on process-based modelling for the successful prediction of future climates (Climate Models). However, where detailed processes like those leading to tree mortality are not well-understood, process-based models can be less reliable than empirical models (Adams et al. 2013).

Of relevance is a concurrent FWPA-funded project VNC516-1920 'Optimising productivity of hardwood plantations: yield gap analysis for *Eucalyptus globulus* plantations in southern Australia' led by John McGrath. That project evaluated these three modelling options (and others) for a process-based approach to yield gap analysis for Australian eucalypt plantations, and after several months chose the APSIM model. Industry partners and researchers were particularly drawn to the ability in APSIM to include (i) complex soils (deep, with water, C and N), (ii) silvicultural flexibility (particularly the inclusion of N fertilisation, weeds, and slash management), (iii) science and software engineering credentials, and (iv) links to agricultural models and software support. At that stage, June-October 2020, the available framework included only eucalypt genotypes suitable for tropical and subtropical climates. After the decision to use APSIM was taken, the inclusion of temperate eucalypts was completed, as well as temperate-to-tropical pines, and these models have so far met expectations of the project for analysing yield gaps down to the level of plot-scale management.

As already exists for pine plantations, future use of process-based modelling for eucalypt plantations in Australia will need to take better account of the increasing need for fertiliser as nutrient availability decreases from the higher levels inherited from previously fertilised agricultural and forestry sites. This increasing need for fertiliser is being quantified in a set of new fertiliser experiments across the industry that were established in the FWPA project PNC478-1819 'Optimising nutrition management of hardwood plantations for sustainable productivity and profitability.' Preliminary results indicate statistically significant (and probably economically important) responses are occurring at many sites to N (John McGrath pers. comm.). Biological and economic responses intend to be summarised in the Profert model by Barrie May for use in making fertiliser decisions. The CABALA and APSIM models specifically cater for N using many functions and parameters that define soil N availability, uptake, and use. In contrast, N fertiliser responses in 3-PG are catered for in a single fertility factor. Both approaches can be used, but the heavy empiricism of 3-PG for soil fertility necessitates a greater reliance on calibration with observations, which might also be expected to lead to less transportability of predictions, less confidence in virtual experiments, and a greater need for fertiliser experiments in the field.

All three models have credibility in catering for the main factors involved in plantation yield responses to stocking and climate change (i.e. changes in $CO_2$, temperature, rainfall, and radiation). The simpler approach of 3-PG is quite attractive in this context, i.e. using monthly climate data. The 3-PG model can also be run successfully daily at a catchment scale to predict stream flow (Almeida et al. 2016). Developers have a similar catchment scale hydrology aspiration for CABALA, and although this capability has also been demonstrated in earlier versions of APSIM, it is not yet available in the current version of APSIM that includes the plantation models of interest. Where models have commonality in predicted variables, predictions can sometimes be strengthened by using more than one model in an ensemble approach (Elli et al. 2019).

Predictions of individual tree sizes as well as total volume or biomass yield are important for some uses of forest yield modelling. This capability is available in 3-PG and demonstrated in an earlier version of CABALA, and there are aspirations to include it in APSIM.

Management of weeds is important for plantation forestry. This can be handled generically in 3-PG and CABALA. Weeds as specific herbs, shrubs or trees can be modelled in APSIM plantation simulations. APSIM also includes agroforestry options for the simulation of tree effects on adjacent pasture or crop production. The CABALA and APSIM models simulate C and N cycling through litter and soil, but this option is not available in 3-PG.

As seen here, these three models have several common technical capabilities, but for projects in the near-term the technical differences will probably feature highly in determining the choice of one model over another. A diversity of models at the research level is highly desirable, as it does not constrain model features to the thinking of a small group of researchers, and it therefore allows the testing of new approaches. However, in the long-term, for reasons including (a) efficiency in the use of industry research funds in providing one or more operationally useful process-based models, and (b) importance for auditing and accounting processes of providing a consistent, repeatable and reliable version control system for resource modelling, it might be worthwhile industry considering which of these three models it wishes to support the most for developing a full range of features.

**Table 3: Comparison table of three process-based models currently under active consideration for use in productivity predictions in Australian plantation forestry[1]**

| **Aspect for Comparison** | **3-PG** | **CABALA** | **APSIM** |
| --- | --- | --- | --- |
| Model strengths | Relatively easy to learn and use<br>Simple canopy processes, soils (grow with the root development up to maximum soil depth), and climate (monthly)<br>Many publicly available free versions without legal constraints. Private versions can be created and used, e.g. within a plantation company.<br>Validated for the main planted species in Australia and overseas<br>Climate change effects on plantation growth including increasing $CO_2$<br>Plot, spatial, and catchment scales<br>Widely used around the world and operationally used in several large forestry companies<br>Multiscale<br>Identifies and quantifies growth limiting factors<br>Decision support tool<br>Yield forecasting | Canopy is represented as an array of eclipses<br>LAI response is dynamic and not time dependent<br>Multiple soil horizons for water and N<br>Root system grows to occupy soil<br>Allocation to maximise NPP by balancing supply and demand for the most limiting resource (energy, water, or N)<br>Alternate forest structures are realistically represented<br>Capacity to represent thinned stand as array of eclipses rather than a paler big leaf<br>Co-limitations of climate and nitrogen on productivity<br>Climate change effects on plantation growth including $CO_2$<br>Allows modelling of responses to N fertiliser and pruning<br>Individual tree model gives size class distributions<br>Plans for water balance to include perched water tables<br>Calibrated and parameterised for a few planted species in Australia<br>Applied in several research cases in Australia<br>Decision support tool<br>Yield forecasting | Intermediate complexity for learning and use<br>Simple canopy processes<br>Adequate complexity above- and below-ground<br>Silviculture – weeds, N fertiliser, stocking, coppice<br>Easy-to-use interface<br>Peer science and software review processes<br>Open access with version control<br>Modular<br>Calibrated and parameterised for the main planted species in Australia<br>Climate change effects on plantation growth including $CO_2$<br>Direct links to national soils and climate databases<br>Integrated with Australia's system for agricultural modelling<br>Improvements to agricultural models are easily included in plantation simulations<br>Widely used around the world<br>Decision support tool<br>Yield forecasting |
| Design philosophy | Freely available and let developers define and build the level of complexity required<br>Simplify complex processes that are not feasible to be intensively measured using generalised relationships (e.g. ratio of NPP/GPP) | Services researcher needs by including the complexity required<br>Capture physiological response to changes in the forest - natural and imposed by management<br>Based on a philosophy of representing physiological research on the responses of photosynthesis, | Services researcher and operational needs<br>Includes the minimum level of complexity required to satisfactorily predict yield and other important variables<br>Includes all improvements in the current version, but earlier versions remain available<br>Auto-documentation |

| Aspect for Comparison | 3-PG | CABALA | APSIM |
|---|---|---|---|
| | Provide a practical tool for decision making at a broad scale<br>No version control required, but well documented | respiration, transpiration, and allocation to environment and management | APSIM is widely used around the world in agriculture, with recent international use for eucalypt plantations |
| Key publications and development path | Landsberg and Waring (1997) – original model description<br>Coops et al (1998) – spatial, including satellite data<br>Sands and Landsberg (2002) *E. globulus*<br>Almeida et al (2009) – climate change analysis<br>Almeida and Sands (2016) – improved water balance<br>Almeida et al (2016) - catchment scale<br>Forrester and Tang, 2016 – mixed species<br>There are 127 publications listed on the website | Battaglia et al (2004) – original model description<br>Drew et al (2009) – wood properties modelling<br>Pinkard et al. (2010), Kriticos et al. (2007) – forest health module for weeds and insects<br>Battaglia et al. (2015) - individual tree model<br>Battaglia and Bruce (2017) – climate change impacts on Australian plantations | Keating et al. (2003) – original model description for agricultural crops<br>Paydar et al. (2005) – *Eucalyptus* model<br>Holzworth et al (2018) – new platform<br>Elli et al (2019)– eucalypts in Brazil<br>Smethurst et al (2020) – further description of the *Eucalyptus* model<br>Smethurst et al (2022) – pines and temperate eucalypts added, deep aquifer nitrate, satellite evapotranspiration |
| Comparative reviews:<br>Luedeling et al (2016)<br>Elli et al (2019)<br>Miehle (2009) | <br>Compared<br>Compared<br>Compared | <br>Compared<br>Compared<br>Compared | <br>Compared<br>Compared<br>- |
| Website for access | https://3pgforestryubcca/software/<br>contains model overview, publications, software download, manual, course and developers | None yet, but planning to be available as python/C ++ version later this year | https://www.apsiminfo/ |
| Dimensionality | Typically 1D<br>Spatial version allows link to 2D and 3D water flow at catchment scale | Typically 1D<br>Plan to be linked directly with 2D and 3D distributed flow models | Typically 1D<br>Agroforestry zones (2D)<br>An early case study was spatially interactive for hydrology (3D) |
| Time-step | Typically monthly<br>Daily for detailed water balance and catchment scale | Daily for main model loop<br>Hourly in advanced conductance model<br>Monthly for individual tree module | Daily |
| Scales | Plot (single or multi sites), spatial, catchment, regional, country | Plot (single or multi sites), spatial, catchment, regional, country | Plot (single or multi sites), spatial, catchment, regional, country |

| **Aspect for Comparison** | **3-PG** | **CABALA** | **APSIM** |
|---|---|---|---|
| Platforms supported | Windows | Windows | Windows, LINUX, OSX and clusters |
| *Biophysical Modelling* | | | |
| Forest systems suitability | Even-age, single species plantations<br>Mixed forests | Even-age, single species plantations, agroforestry designs, can model two species in a mixed stand, can model two canopy layers | Even-age, single species plantations<br>Mixed forests<br>Agroforestry |
| Silviculture possible: | | | |
| Stocking | Y | Y | Y |
| Mortality | Y | Y | Y |
| Thinning | Y | Y | Y |
| Pruning | Y | Y | Y |
| N fertilisation | Single fertility factor | N cycle | N cycle |
| Irrigation | Y | Y | Y |
| Weeds | Generic water use | Generic resource use and biomass production | Species or generic full models |
| Slash and litter management | N | Y | Y |
| Modelled Australian plantation species | *P radiata, P elliottii, E globulus,* and *E nitens, E saligna, E grandis, E dunnii, P pinaster, E camaldulensis, Corymbia maculata, E cladocalyx, E pellita, E cloeziana, E pilularis E longirostrata, E tereticornis, Khaya senegalensis, sandalwood, oil mallees* | *P radiata, P elliottii, E globulus, E nitens, E grandis, E kochii, C maculata* | *P radiata, P elliottii, E globulus, E. grandis,* and *E nitens* |
| Can new genotypes be included | Y | Y | Y |
| Can observed data be imported and graphed for comparison | Y | | Y |

| Aspect for Comparison | 3-PG | CABALA | APSIM |
|---|---|---|---|
| Observed vs predicted graphs internally generated | Y | | Y |
| Model skill statistics reported [3] | $R^2$, RSR, ME, MAE, RMSD | | $R^2$, NSE, RSR, ME, MAE, RMSD |
| Photosynthesis representation[2] | Net - using a resource use efficiency factor | Gross- using Farquhar-von Caemmerer-Berry biochemical model<br>Net - accounts for respiration | Net - using a resource use efficiency factor |
| C allocation | Semi-fixed patterns; monthly stresses and growth limiting factors | Dynamic with daily stresses, to maximise NPP | Dynamic - daily limited by highest stress |
| Number of soil horizons | 2 | 3, but planned to be many in new version | 1 to many - user-defined |
| Soil water balance method | Tipping bucket | Tipping bucket, plan for Richards method | Tipping bucket or Richards method (SWIM model) |
| Methane and NO-gases | N | | Some capability |
| Climate effects | Y | Y | Y |
| Soil C | N | Y | Y |
| Nitrogen | Simple fertility limitation factor | Detailed in soil and plant | Detailed in soil and plant |
| Phosphorus | N | N, but planned | N - under development |
| Weeds | Generic calibrations demonstrated | Generic calibrations demonstrated | Multiple species already calibrated can be added |
| Tree size classes | Y | Y | N |
| Mixed forests | Y – several examples | Y | Possible, but not well tested |
| Agricultural crops and pastures | Water use is quantified | N | Y |
| Agroforestry zones for crops (2D) | N | N | Y |
| 1D spatial hydrology (catchment scale) | Y | Y | Past applications |
| Livestock | N | N | Y |
| *Software Engineering* | | | |

| Aspect for Comparison | 3-PG | CABALA | APSIM |
|---|---|---|---|
| Version availability | Versions available in VBA (Excel), C++, Python, and R<br>3-PG (1D) - free<br>3-PG$_{spatial}$ (1D spatially) – free or licensed<br>3-PG hydrology, licensed<br>3-PG_R - free<br>3-PG_Python – free<br>3-PG$_{mix}$ (mixed species) - free | Scion are considering making available a new version that is being developed (D White pers comm) | Current and past versions are available via website |
| Version control | Y – website releases | Plan - via GitHub | Y - GitHub |
| Software and infrastructure maintenance and upgrades | Y – infrequent, voluntary | After June annual update on GitHub | Y- frequent via the APSIM Initiative involving four partners in Australia, one in NZ, and one in USA |
| Support for ongoing maintenance and interface upgrades | Plantation companies for internal versions or via research projects, or by researchers voluntarily | Some support from CSIRO via projects | Provided by the APSIM Initiative |
| Coding in a net language | Y | Y (being recoded in python, C++ for all operating systems (LINUS, UNIX, PC) | Y |
| Open source | Y | Plan is to be made publicly available late in 2022 via a GitHub | Y |
| Development community | Y | Not yet, but encouraged once new version released | Y |
| Highly modular and can benefit from developments for agriculture | N | N | Y |
| Convenient ingestion of gridded soils and climate data, including future climate scenarios | Y | N | Y |
| Convenient batch processing of large numbers of gridded simulations | Y | Y | Y |

| Aspect for Comparison | 3-PG | CABALA | APSIM |
| --- | --- | --- | --- |
| Convenient setup of experiments in the user interface | N | N | Y |
| Convenient set up of sensitivity analyses | Y - sensitivity analysis, NonlinXL optimiser | N | Y - factorial experiment, Sobol, and Morris methods |
| Can non-coders rapidly develop new tree species or cultivars in the model? | Y | N | Y |

[1]Table developed with assistance from Auro Almeida and Don White

[2]Photosynthesis approach as defined by Medlyn et al (2003): radiation use efficiency (RUE), big leaf (BL)

[3] $R^2$= coefficient of determination, NSE = Nash-Sutcliffe efficiency, RSR = mean square error to standard deviation ratio, ME = mean error, MAE = mean absolute error, RMSD = root-mean-square deviation

# 3 The APSIM Modelling Framework

Entry into the APSIM framework is via the website www.apsim.info. The website contains the latest APSIM news, information about the APSIM Initiative that oversees APSIM development and delivery, training, downloading, and support. Public good and commercial licencing options are available during the download process. Once installed, the graphical user interface (GUI) enables access to example simulations, tutorials, individual models, and cloud processing options. Model code can be viewed and downloaded from GitHub, which is also where issues are raised by users.

APSIM has strong science and software engineering credentials that are underpinned by a review process for proposed changes. Minor changes (e.g. a spelling correction) can be implemented by the APSIM team without a formal review, but major changes (e.g. inclusion of a new genus, or a significant change to a functional process like phosphorus availability or water-logging effects) prompts a review akin to the review process for a journal paper. Implemented changes create a new version of APSIM that is released immediately when implemented. New versions of APSIM commonly are released daily or weekly, and they can be accessed with the upgrade option in the GUI. Older versions can also be accessed in the GUI.

All APSIM plant models simulate the processes of light capture and conversion to biomass through photosynthesis and C allocation to plant components. Water and N are taken up from soil and, along with climatic variables, if not optimal, lead to a reduction in the capacity for photosynthesis and or higher turnover of foliage, fine roots and other components.

Basic plantation simulations consist of the following:

- clock to indicate start and finish dates of a simulation
- weather file covering that period for that location
- crop model, e.g. *Eucalyptus* or *Pinus*, within which a specific genotype is chosen
- soil model for that location
- management, e.g. transplanting, thinning, mortality, weeds, N-fertiliser, and harvesting
- microclimate model
- surface organic matter model
- soil arbitrator that resolves multiple resource (N and water) demands and supply options
- datastore
- report
- graphs
- summary of the simulation

The time-step is daily, and the biomass of the components of an average plant is the main focus of the process-based modelling part of APSIM models. For plantations, the most relevant output at that stage is stem wood biomass. Although these models simulate processes, there is empiricism at a lower level where parameters of process-based functions are calibrated, which is common amongst all the process-based models for forestry mentioned earlier. In addition, for forest plantations, biomass of stems is empirically related (i.e. calibrated) to provide various outputs of interest in forestry (Figure 3). Outputs of interest for reporting are chosen prior to a simulation. For plantation forestry, these include common stand measures:

Stocking (stems per ha)

- Stem diameter at breast height over bark (DBH, cm)
- Height (m)
- Bark thickness (cm)
- Stem diameter at breast height under bark ($DBH_{ub}$)
- Basal area ($m^2$ $ha^{-1}$)
- Stem Volume per hectare over and under bark ($m^3$ $ha^{-1}$)
- Bark weight (g $m^{-2}$)
- Wood weight (g $m^{-2}$)
- Bark density (kg $m^{-3}$)
- Wood density (kg $m^{-3}$)
- MAI over and under bark ($m^3$ $ha^{-1}$ $year^{-1}$)

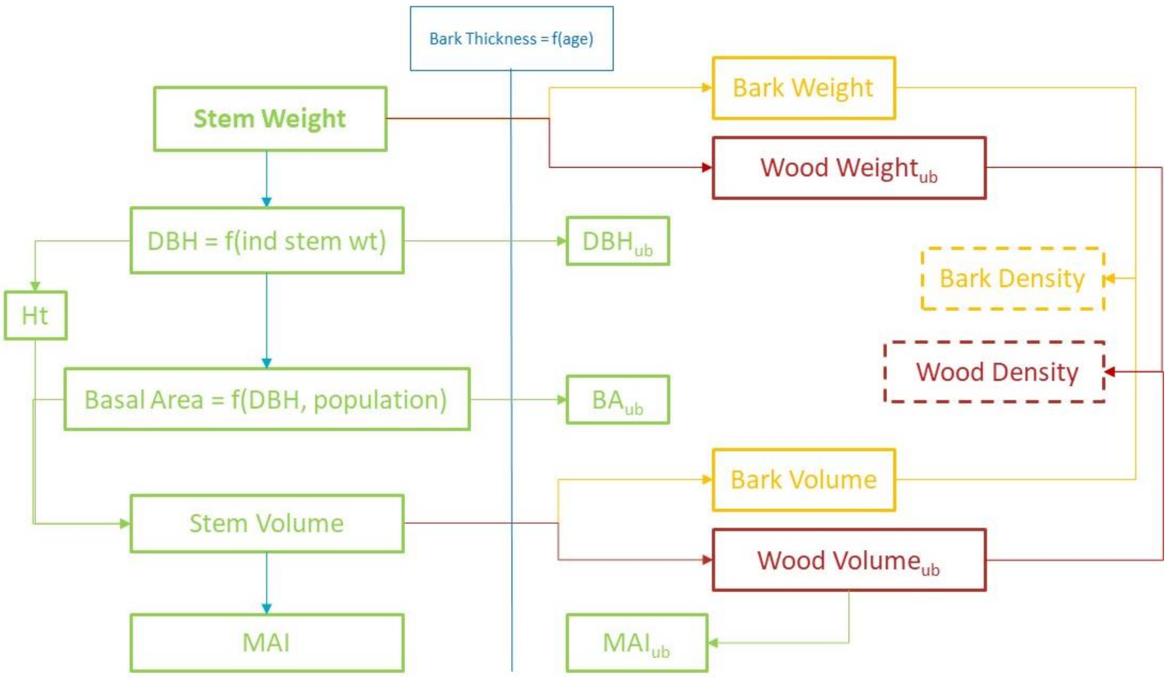


**Figure 3: Schematic of the calculation steps in APSIM for stand metrics. Wood and bark densities are in boxes with broken lines because full calibration of these outputs and bark weight is incomplete.**

Stem size class distributions would be a very useful option, but its inclusion is only at the early planning stage (Figure 4), and a project is needed to implement it. Inclusion of wood quality measures (e.g. from the ResiTool) or predictions are also feasible.

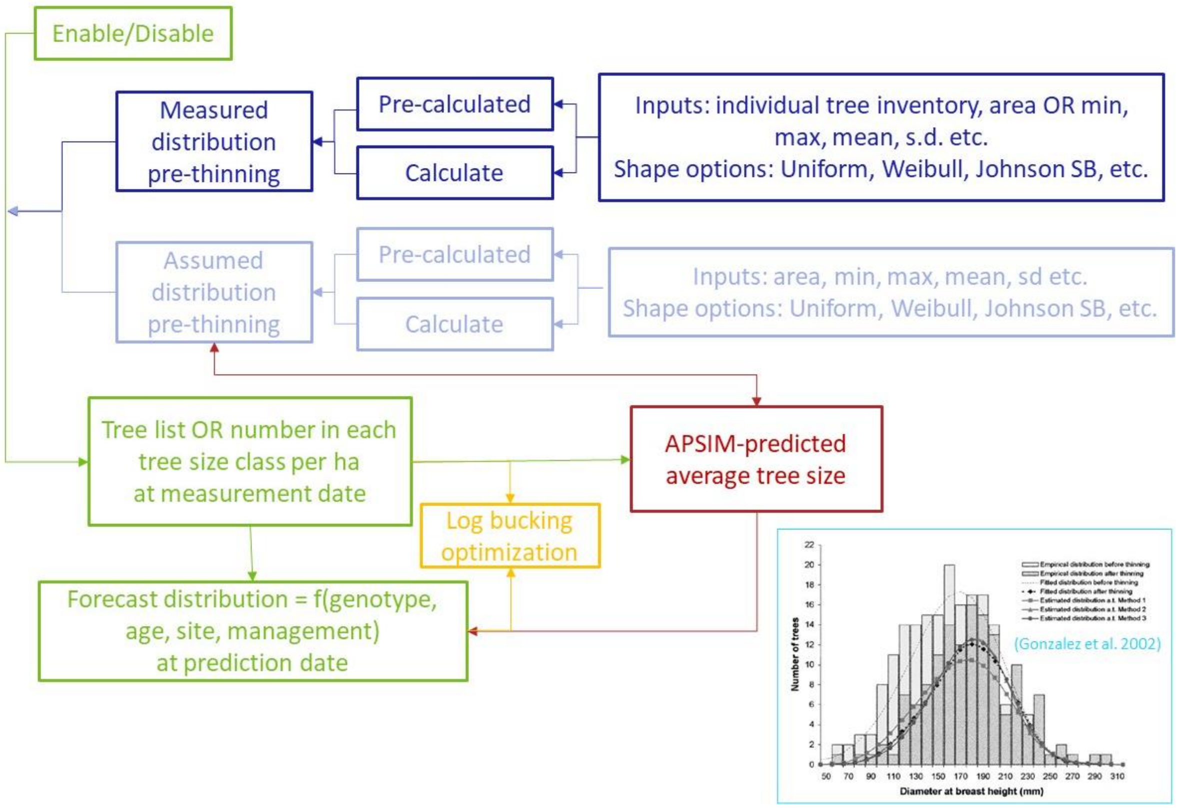


**Figure 4. Design concept for an individual tree tool for APSIM**

Reporting can be on any day or event (e.g. harvesting) in the simulation or summarised across any period. Additional outputs of use can contribute to natural capital accounting:

- Water use and runoff
- Carbon sequestration and N content of biomass and soils
- Nitrous oxide emissions
- Surface organic matter C and N
- Soil erosion

More advanced options for simulations include:

- Map showing simulation locations
- Importing and use of observed data
- Model skill statistics on predicted versus observed graphs
- Auto-documentation
- Download options for soil and weather files for any location in the world
- Export of data as Excel spreadsheets or text files
- Model editing without coding
- Time series and probability statistics

- Climate modifications, and IPCC-based climate change scenarios
- Checkpoint use for starting a new simulation from a time point in a previous simulation.
- Irrigation
- Life cycle modelling, e.g. for insects
- Organic matter management
- Experiments using multiple levels of multiple factors, which can include sites, climate and management options. As well as being used to simulate actual experiments in the field, this option also enables hypothetical (virtual) experimentation, and therefore a basic level of sensitivity analysis.
- Interaction with R code, which is useful for batch runs of large numbers of sites
- Advanced sensitivity analysis using the Morris and Sobol methods.
- Agroforestry options using proxy or modelled trees.
- Livestock management
- Socio-economic analysis.

# 4 APSIM Models for Australian Plantation Forestry

Here we provide an overview of the *Eucalyptus* and *Pinus* models in APSIM as they were at the time of reporting. Both models have the same structure, but function parameters differ at the genus and specific genotype levels in the models. We describe the *Eucalyptus* model, and then note the main differences in the *Pinus* model. Examples are provided.

'Genotype' as referred to here is a specific combination of physiological parameters that define a plant model's behaviour in the APSIM framework, where they are also called 'cultivars'. This is similar to use of the 'genotype' term by tree breeders (G. Dutkowski pers. comm.), i.e. a very specific combination of genes, but the specific set of parameters in APSIM can be arrived at by calibration using observations at any level of taxa such as genus, species, provenance, family, and clone.

## 4.1 *Eucalyptus* Model

Within the genus, genotypes can be specified to represent any level required, e.g. species, provenances, hybrids, or clones. Currently there are genotypes for *Eucalyptus globulus*, *E. nitens*, *E. grandis*, *E. urophylla*, *E. saligna*, and *hybrids*. This project added the temperate genotypes required for plantation forestry in Australia (*E. globulus* and *E. nitens*).

Observed datasets on which calibrations of the temperate eucalypts were based came from research and operational plantations in Western Australia, South Australia, Victoria, Tasmania, and Portugal. These datasets are explained and cited in the validation simulations for *Eucalyptus* and *Pinus* that can be downloaded from GitHub, and in the pdfs available on the APSIM website.

Smethurst et al. (2020) described the development and use of APSIM for tropical and sub-tropical plantations in Australia and Brazil. Elli et al. (2020a, 2020b) earlier used this model to study various aspects of eucalypt plantation forestry in Brazil, with a modification to calculating stem volume compared to Figure 3 where wood density was assumed and therefore volume calculated directly from biomass. The current implementation though, is as shown in Figure 3.

Provided in Figure 5 are examples of graphs of observed versus predicted (OvsP) values for several outputs of the *Eucalyptus* model after calibration: aboveground weight, root:shoot ratio, LAI, height, DBH and leaf weight. Statistics for model skill are provided for each graph. The aim during model development is to have each set of OvsP points follow the 1:1 line, but this very rarely achieved due to model imperfections (structure and parameterisation) and errors in observed data due to measurement error. The model statistics shown indicate good model skill and are comparable to those for most other plant models in APSIM and with other forest process-based models.

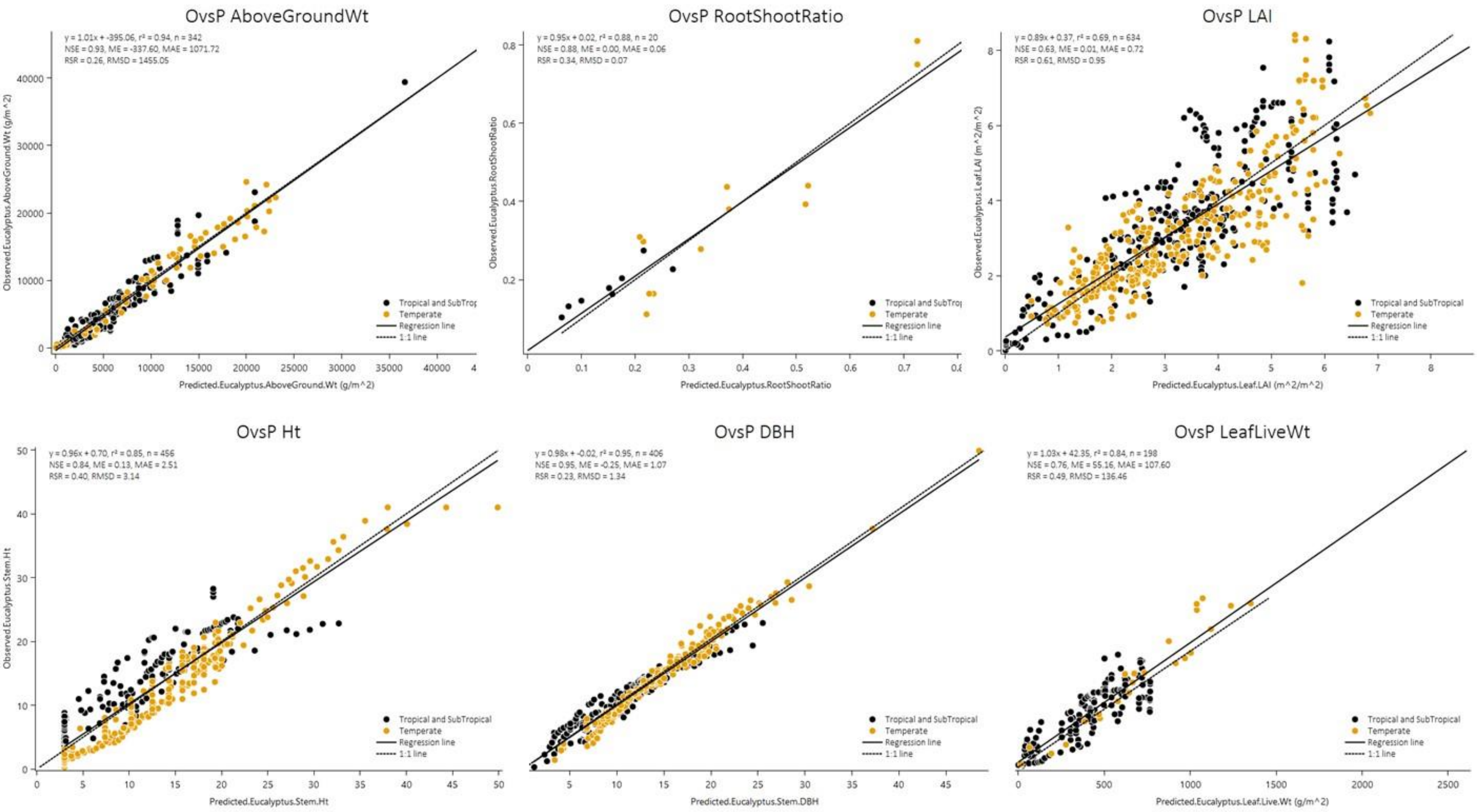


**Figure 5: Model skill graphs and statistics for several outputs of the calibrated *Eucalyptus* model. Observed values are on the y-axis. Predicted values are on the x-axis. Parameter of interest is indicated in the graph title for each sub-graph. Black points are for tropical and sub-tropical genotypes and the yellow points are for temperate genotypes. Multiple points per site were included where available.**

## 4.2 *Pinus* Model

Currently there are genotypes for *Pinus radiata*, *P. taeda*, *P. elliottii*, *P. caribaea*, and hybrids between the latter two species. The entire *Pinus* model was developed during this project. Development of the *Pinus* model started with a renamed copy of the *Eucalyptus* model, and both models have very similar structure. Observed datasets on which calibrations of *Pinus* were based came from research and operational plantations in South Australia, Victoria, Tasmania, Queensland, NZ and USA.

Provided in Figure 6 are examples of OvsP graphs of several outputs of the *Pinus* model after calibration: aboveground weight, aboveground N, cone weight, leaf weight, height, basal area, volume over and under bark, and bark thickness. Statistics for model skill are provided for each graph. The model statistics shown indicate good model skill and are comparable to those for most other plant models in APSIM and with other forest process-based models.

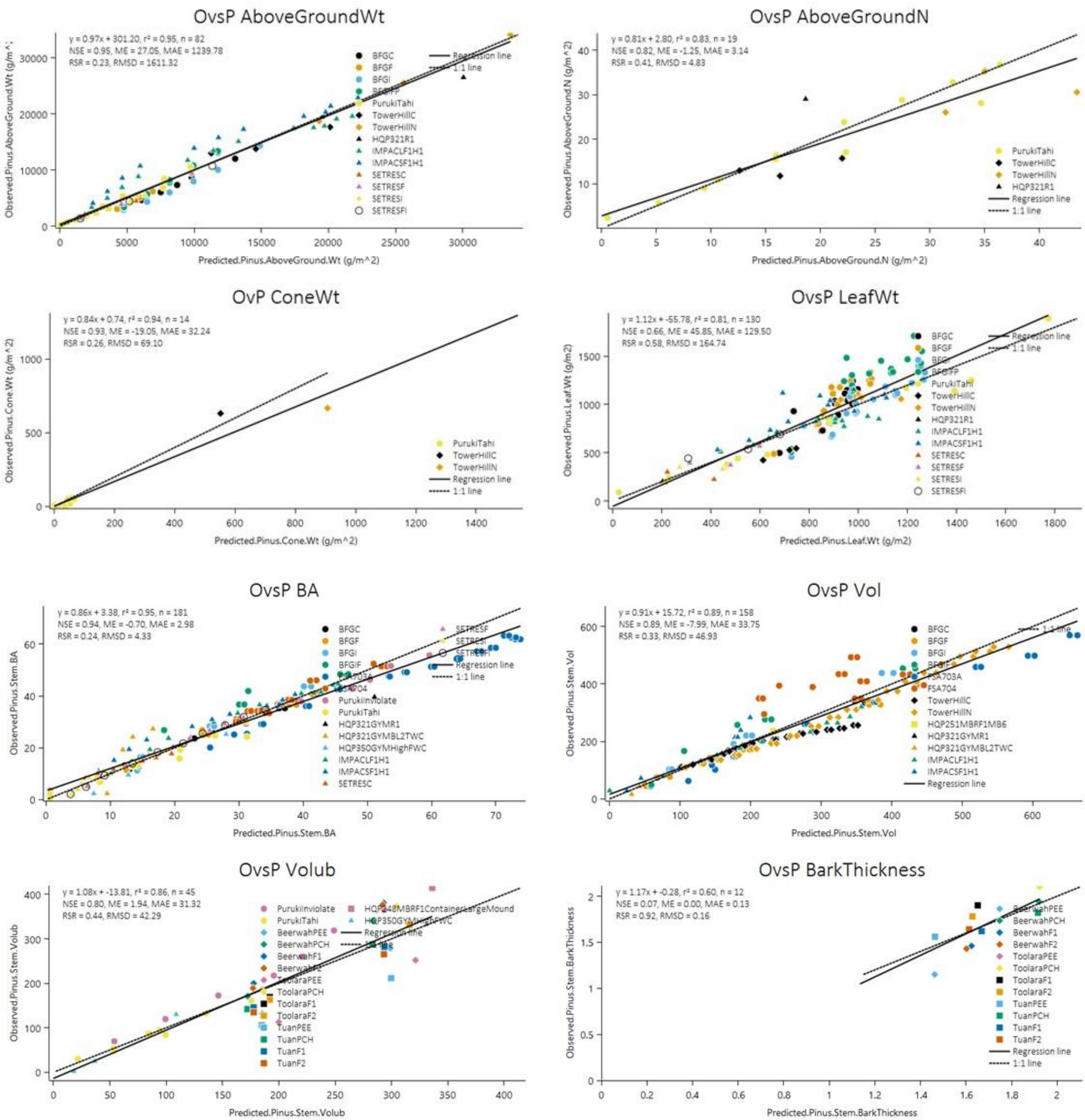


**Figure 6: Model skill graphs and statistics for several outputs of the calibrated *Pinus* model. Observed values are on the y-axis. Predicted values are on the x-axis. Parameter of interest is indicated in the graph title for each sub-graph. Black points are for tropical and sub-tropical genotypes and the yellow points are for temperate genotypes. Multiple points per site were included where available. The legend indicates site names and treatment code.**

Although this development phase of the plantation models in APSIM was completed, several desirable improvements were identified for future projects:

1. Improve specific leaf area and bark thickness specifications.
2. Expand the set of weeds models
3. Add a mortality tool that includes the self-thinning rule and or process-based mortality
4. Improve effects of stocking on C and N biomass allocation patterns
5. Include waterlogging effects
6. Add soil P and K effects
7. Expand wood quality options
8. Geo-locate and interact adjacent plots for run-on, stream flow and groundwater
9. Add tree and log size class distributions
10. Better summarise outputs for environmental accounts (water use, C sequestration, greenhouse gases, biodiversity indexes)

# 5 Examples of Use of the *Eucalyptus* and *Pinus* Models

## 5.1 Aquifer water and nitrate uptake

During the project, the *Eucalyptus* and *Pinus* models were used to explore the hypothesis that nitrate in the unconfined aquifer in the Green Triangle (Mount Gambier) region of South Australia could be taken up and be contributing to high growth rates observed in some locations. A thinned pine plantation over an aquifer at 23 m depth was simulated for 37 years, and an unthinned eucalypt plantation over an aquifer at 4 m depth was simulated for 14 years. This work was published as Smethurst et al. (2022) and it demonstrated that the model could perform well under these complex conditions, i.e. with very deep profiles that contained an aquifer with nitrate to which the roots could grow in or in the capillary fringe and take up water and N. Modelling supported the hypothesis that both water and N uptake could be important for plantation productivity in the region where plantations were growing over water tables that were less than or equal to 6 m depth. Simulated rates of evapotranspiration, an emergent property of the model, were consistent with satellite estimates at the location where both sources of data were available. Other simulated processes or properties were also generally consistent with measurements in the region, i.e. rates of net N-mineralization and N-leaching, concentrations of nitrate-N in the aquifer, and rates of water uptake from the aquifer. Cautions were also provided about using soil values from the Soil and Landscape Grid of Australia. Results were used to identify research priorities needed to prove or disprove the hypothesis.

## 5.2 Climate change scenarios

A capability is being built for APSIM that will enable relatively easy inclusion in simulations of climate change scenarios consistent with IPCC climate datasets. There is a plan to provide daily climate data by the end of the project for numerous predicted climates at nominated global locations and dates into the future. A user will be able to nominate one or more global circulation models (GCMs), and climate variability will be provided by 30 different yearly sequences of climate based on past variability. A web service has been built to provide this capability for an agricultural project, but encumbrances on the data first need to be checked before making it available for wider use. The type of workflow for a user is shown in Figure 7.

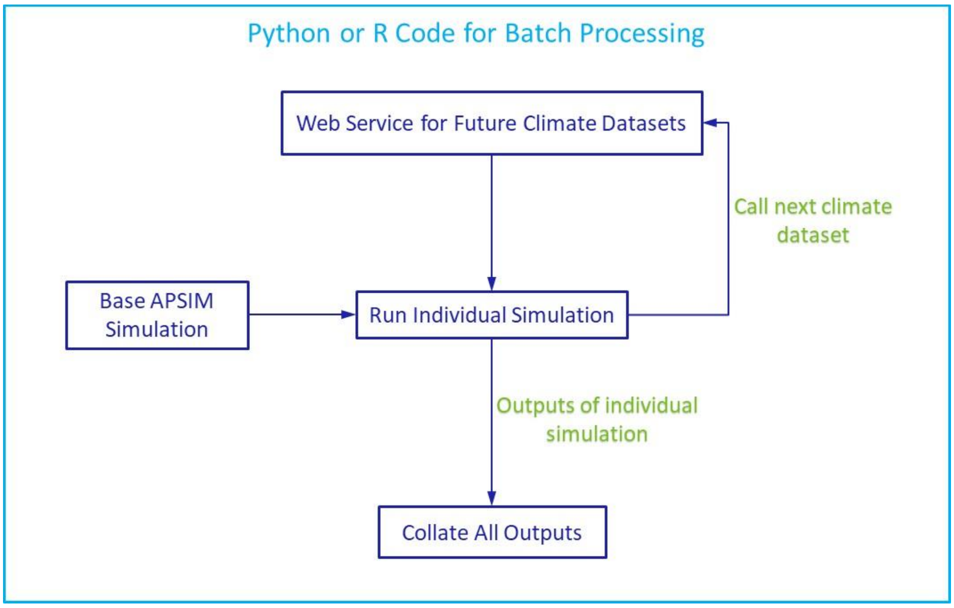


**Figure 7: Workflow for utilising data scenarios of future climates for APSIM simulations**

To illustrate the type of capability that will soon be available in APSIM, examples are presented for two plantations at opposite ends of the country, i.e. *E. globulus* in WA and *P. elliottii-caribaea* in Qld. (Figure 8 and Figure 9). Apart from increasing $CO_2$ concentrations, climate change increased temperature at both sites, and more so for the high emission scenario (HE; $CO_2$ = 541 ppm). Rainfall at the WA site decreased for the HE scenario but was it little affected by the low emission scenario (LE; $CO_2$ = 443 ppm). Rainfall at the Qld site was little affected by both scenarios. Radiation at the WA site decreased for both scenarios and slightly more so for the LE scenario. Radiation at the Qld site was slightly decreased by both scenarios. The processes simulated in APSIM integrate the effects of these climate changes. Effects on simulated wood production will depend on the specific LE and HE scenarios chosen, and the relative potential effects of various climatic and other limitations.

At the eucalypt site in WA, both emissions scenarios were simulated to increase wood yield by 17-19%, but at the pine site in Qld the LE scenario led to a 4% decrease while the HE scenario led to a 8% increase, compared to historic climate. The increase in wood production at the WA site occurred despite a decrease in radiation and small contrasting effects on rain, suggest that increases in $CO_2$ and temperature were the driving influences. These scenarios assumed no weed, mortality, or N-limitation, i.e. rainfed yield potential (Yr). Results will depend on the choice of location, silviculture, genetics, GCM and particular year sequence. For this type of climate change analysis, location has a resolution of 5 km, because this is the spatial resolution of the climate data. A more detailed analysis would take these factors into account and it would involve a large number of simulations for even one location and choice of establishment year. Large numbers of such simulations are often conducted using scripts in R or Python for batch processing of APSIM simulations, and example batch scripts are available (contact P. Smethurst).

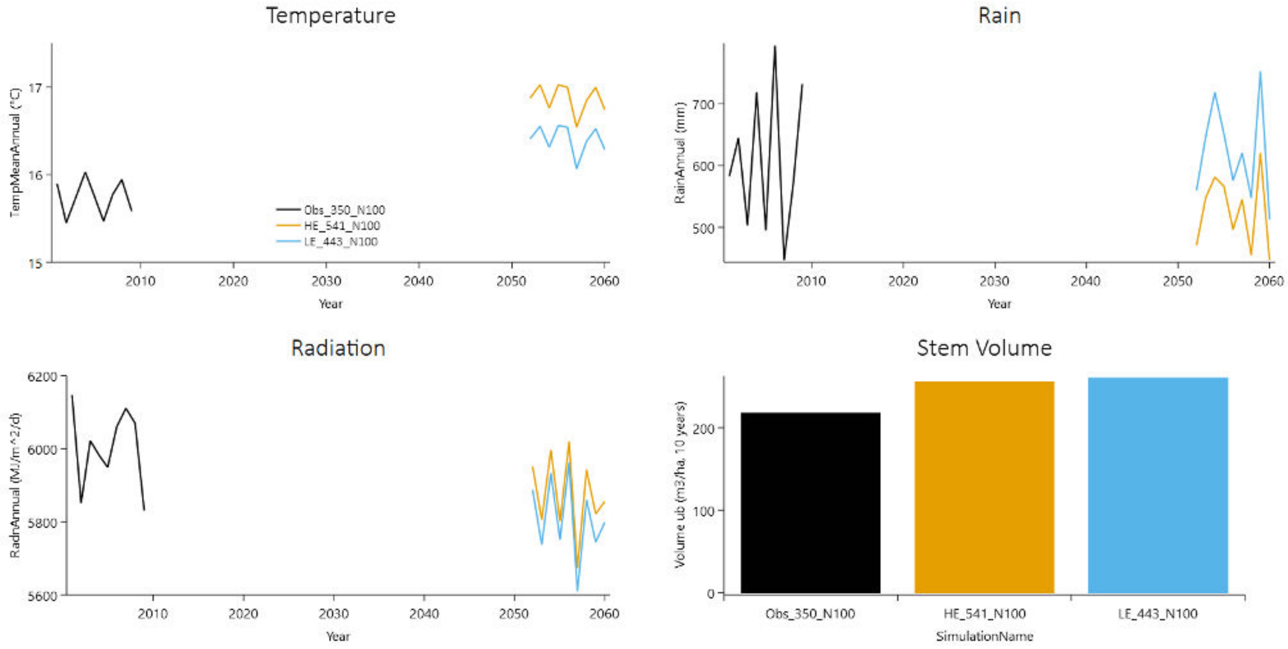


**Figure 8: Simulated results of a 10-year rotation of *E. globulus* at the Springwell site in WA established in 1999 with climates observed (black, 350 ppm $CO_2$) or established in 2050 with one possible climate scenario each resulting from either a high emissions scenario (yellow, 541 ppm $CO_2$) or low emissions scenario (blue, 443 ppm $CO_2$). Shown are annual average of daily mean temperature (top left), mean annual rainfall (top right), annual sum of daily radiation (bottom left), and wood yield (stem volume under bark, bottom right).**

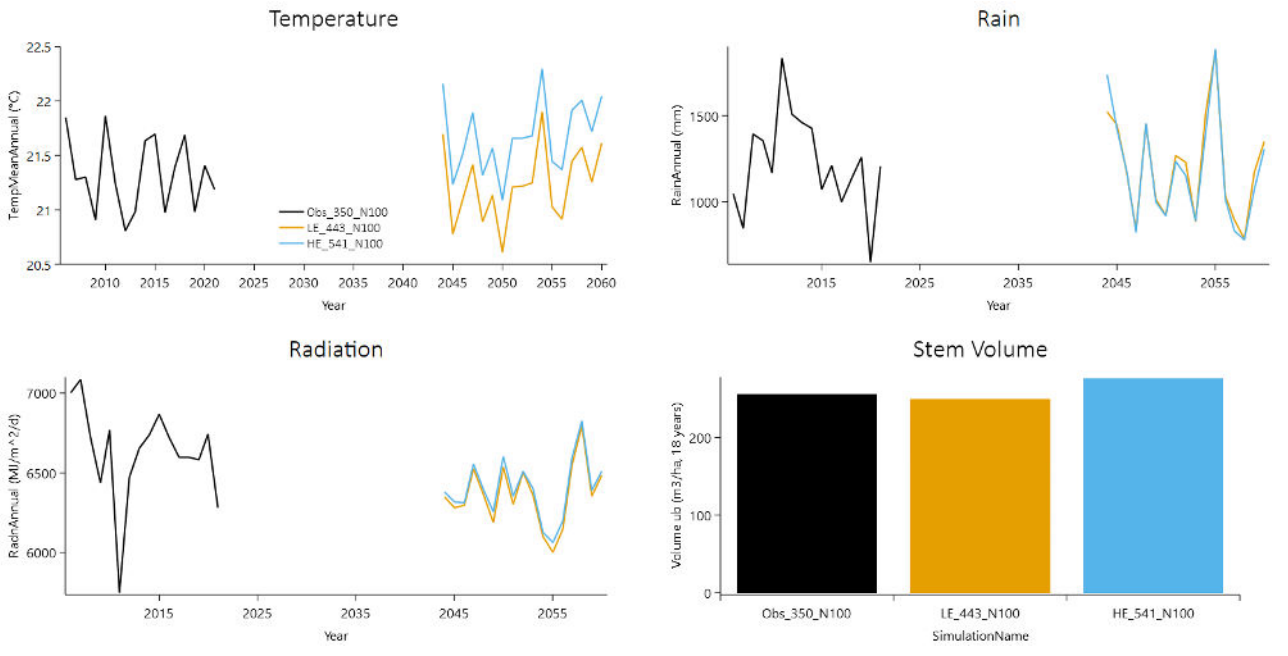


**Figure 9: Simulated results of an 18-year rotation of *P. elliottii-caribaea* at the 159NUTA (plot 2) site in Qld established in 2003 with climates observed (black, 350 ppm $CO_2$) or established in 2042 with one possible climate scenario each resulting from either a high emissions scenario (blue, 541 ppm $CO_2$) or low emissions scenario (yellow, 443 ppm $CO_2$). Shown are annual average of daily mean temperature (top left), mean annual rainfall (top right), annual sum of daily radiation (bottom left), and wood yield (stem volume under bark, bottom right).**

## 5.3 Yield Gap Analysis

We demonstrated how the APSIM model can be used to estimate the magnitude of climatic and management yield gaps, with an indication of the degree of limitation due to sub-optimal mortality, weed control and N-fertilization. These simulations were primarily carried out for the FWPA project VNC516-1920 ‘Optimising productivity of hardwood plantations: yield gap analysis for *Eucalyptus globulus* plantations in southern Australia’ led by John McGrath. The key summary of those simulations is reproduced here as an additional example of the application of APSIM (Figure 10). The 13 plots simulated were drawn from each of the eucalypt growing regions in temperate Australia and were chosen to cover a wide range of productivity. The analysis suggested that all plots would have benefited from additional N-fertilizer, and a few would have benefited also from more weed control and less mortality. Rainfed potential productivity (Yr, i.e. top of the N gap) was in the range 18-57 $m^3$ $ha^{-1}$ $year^{-1}$ for all sites.

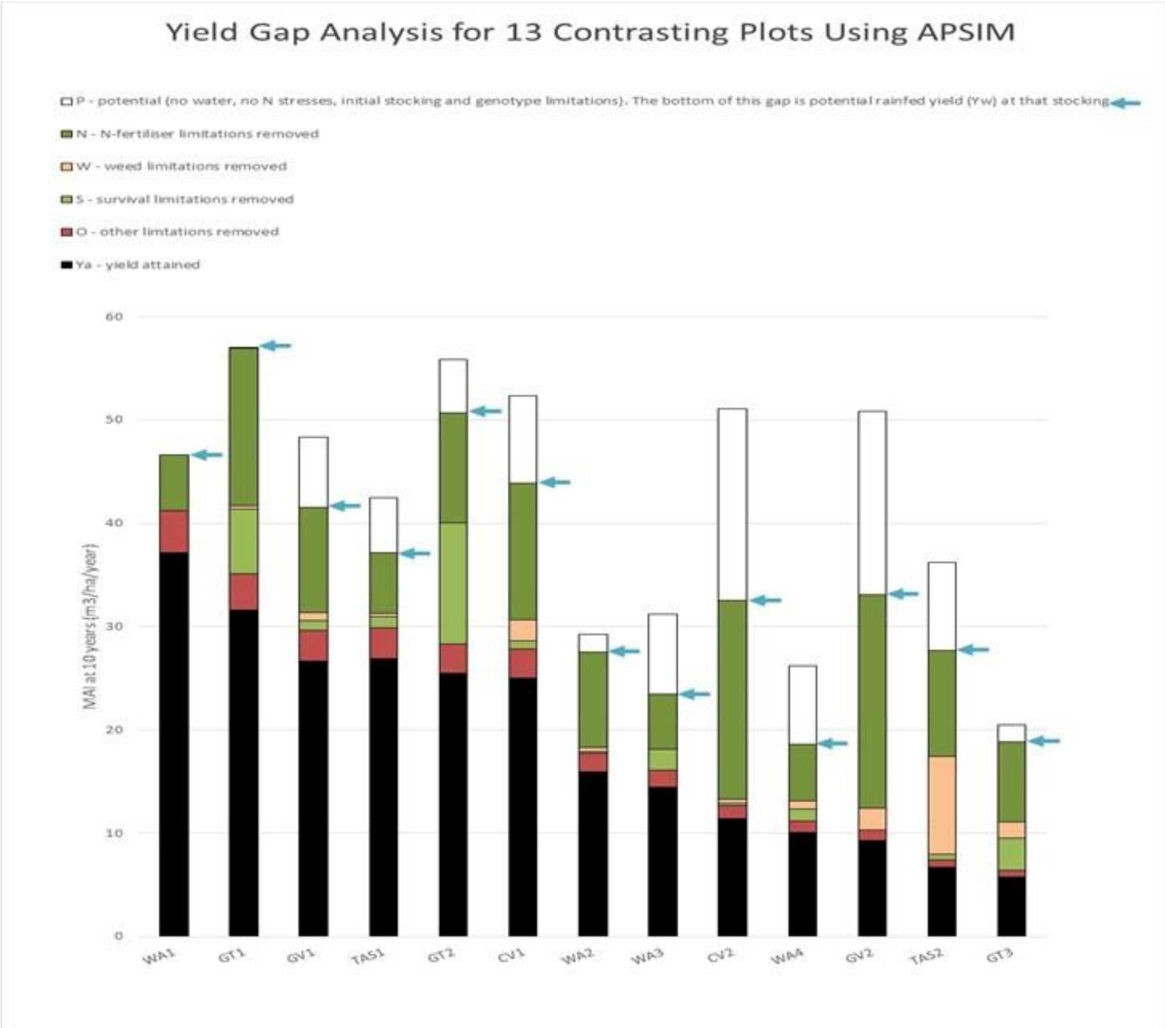


**Figure 10: Simulated yield gaps using the APSIM *Eucalyptus* model for 13 plots across the plantation regions of temperate Australia chosen to cover a wide range of productivities. The top of the dark green bar for N represents water-limited (rainfed) potential yield (Yw). The top of the white bar represents potential yield if all water and N limitations were removed.**

# 6 Delivering APSIM Services for Plantation Forestry

How can APSIM services be provided to the Australian plantation forest industry? The expertise required to well-understand and apply APSIM or other process-based models is generally not found within Australian forest plantation companies, although some company staff are learning to apply 3-PG, the simplest model considered in this report. This situation contrasts with that in several forestry companies internationally that are much larger than any single Australian company. These larger companies have staff with the required expertise. These experts develop and apply custom versions of the 3-PG model.

Basic training in APSIM for plantation forestry was provided to a group during the project. This group consisted of consultants in plantation management and resource assessment and forecasting, company and collaborative staff, and university researchers. However, all participants would best deliver APSIM services in the short-term in conjunction with CSIRO staff who already understand APSIM and plantation forestry (i.e. Neil Huth and Philip Smethurst), or by teaming a forestry expert with APSIM modellers skilled in the use of APSIM in agricultural contexts. Many of these experts are outside CSIRO. Agricultural consultancy services using APSIM are the Birchip Cropping Group and Regrow. Individual farmers, consultants or companies can also subscribe to Yield Prophet for forecasts of grain yield, which uses APSIM. Such a service, via an Application Programming Interface (API), does not yet exist for plantation forestry, but the industry could consider establishing one in conjunction with the APSIM Initiative. Such a service could potentially be used for yield predictions used by log bucking software such as YTGen, or for wood quality prediction using software such as r-Cambium.

Additional skills useful for batch runs of large numbers of APSIM simulations (e.g. all virtual plots across an entire forest estate) are those that assist with the collation of input and output data and their visualisation. These skills are found typically in programmers with R and Python skills, and example codes for batch runs are available. If coding of new tools in APSIM is required, which can be very useful, skills in a Microsoft .NET language are required, e.g. C#.

An option for providing APSIM services to the industry is via a collaborative model, which are explored in Parts V and VI of this report. That model could be designed to deliver APSIM services integrated with remote sensing, inventory and current empirical modelling for the delivery of outputs that are of specific interest to individual forest companies.

# Part III Remote Sensing

# 1 Introduction

Remote sensing of plantation forests has been carried out using mainly passive sensors from aircraft and satellites for a long time (~ 50 -60 yrs). More recently, drones have added the ability for observations with mainly active sensors (e.g., LiDAR) and doing so at significantly higher spatial resolution than from aircraft or space. The trade-offs between platforms are mainly around cost, and spatial and temporal resolutions. Satellites providing up to daily forest observations available at zero cost, but with spatial resolutions typically around 250m, whilst aircraft can provide active or passive observations of forests at typically 5cm resolution, in 3D, but at high cost and thus with low temporal resolution, typically yearly. The current “revolution” in small / micro / cube satellites is changing the data availability for foresters in that high temporal resolution (1-2 days, assuming no cloud) with spatial resolutions between 4m and 30cm are available at cost. This technology will continue to change and at increasing rates. For example, forest biomass will become available (~2023) from the BioMass interferometric P band radar satellite from ESA that is funded and under construction (Banda et al. 2020). The FLuorescence EXplorer satellite FLEX, to be launched in 2025, will provide observations of forest oxygen fluorescence, an early and direct indicator of photosynthetic activity. The currently available experimental satellite LiDAR from GEDI, which provides along-track observations of forest height, will evolve on new satellites to provide potentially useful forest stand metrics from space. Additionally, a suite of remote sensing satellite constellations in design and, or construction will impact forest observations from space in coming years. These include a dual wavelength (S and L band) Radar – NISAR (launch in 2023), EarthDaily Constellation of 5m high spectral optical sensors (launch in 2023), and Landsat Next with much higher spectral resolution than current Landsat 8 /9 (launch in 2029/30). Similarly, at the drone level technology is progressing rapidly, with individual tree metrics re health from hyperspectral sensors and structure from LiDAR current practice. Thus, the forest manager is being required to evaluate new remote sensing technologies on a regular basis and, where prudent, implement often without in-house expertise. This project chose to illustrate an example of a low-cost remote sensing product, the Forest Disturbance Index (FDI), which does not require in-house expertise. The delivery mechanism of such a product is of interest and will be considered in Part V of this report. However, before exploring the FDI, a review of current remote sensing inputs to forest resource modelling is provided.

# 2 Satellite Data for Resource Modelling

General forest (native and plantation) extent mapping is undertaken using both passive and active remote sensing across the globe via applications such as Global Forest Watch, which uses Landsat, Sentinel 2 and Sentinel 1 satellites to provide annual estimates and alerts of forest coverage change since 1997 (Landsat) and 2014 (Landsat plus other satellites). Tools of this type report change in forest extent at a spatial resolution of 30 to 250 m and they do not distinguish between species or cause of change. At lower spatial resolutions, typically 250 m or greater, processing of MODIS satellite imagery provides several global products that are useful for broad scale forest resource assessment. For example, the MOD13, 16-day averages of Normalised Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) are useful for understanding seasonal change. Satellites such as Landsat and Sentinel 2 have been used to correlate spectral observations, often encapsulated in indices such as NDVI, against forest plantation plot metrics such as Leaf Area Index (LAI) and then extrapolated to compartments with similar characteristics (Cohrs et al. 2020; Brede et al. 2020). The capability to regularly access NDVI data using Sentinel 2 imagery was recently provided to participants in the FWPA project 'Optimising nutrition management of hardwood plantations for sustainable productivity and profitability' led by Ian Dumbrell (contact Barrie May for instructions). Tree height and stocking data are currently obtained by airborne LiDAR by some forest companies. This project demonstrated the usefulness of optical imagery; however, forest companies often rely on airborne LiDAR acquisitions to obtain information on vegetation structure such as tree height and stem density. The ongoing development of satellite technology and new sources of remote sensing data are likely to provide effective and low-cost options for characterising vegetation structure across plantation compartments at scale.

The Global Ecosystem Dynamics Investigation (GEDI) instrument flown on the very low orbiting International Space Station, uses Laser pulses that provide 25 m spot observations of forest canopy height separated by 60 m and 600 m, along- and across-track respectively, for 8 tracks per orbit. These non-continuous measurements provide canopy height errors in the order of 2-5 m (Adam et al, (2020); Dorado-Roda (2021) and are thus useful for general estimates of above ground forest biomass, but not immediately useful in accurate resource modelling measurements and predictions.

Geoscience Australia has for some time provided national estimates of fractional vegetation cover through DEA Fractional Cover. Using Landsat data from 1987, and more recently Sentinel 2 data, the percentage of each 30 m pixel for photosynthetic (green vegetation), non-photosynthetic (brown woody matter including litter) and bare soil is determined using end-member analysis. This product is potentially useful in non-closed canopy forests.

The Terrestrial Ecosystem Resource Network (TERN) in conjunction with CSIRO have developed national products useful for the forest industry. The Actual Evapotranspiration (AET or ETa) is a product derived from monthly cloud free Landsat and Sentinel 2 imagery, daily MODIS and VIIRS data combined with Bureau of Meteorology data using the CMRSET (CSIRO MODIS Reflectance-based Scaling EvapoTranspiration) model (Guerschman et al., 2022). The data, supplied at 30 m resolution, provides a monthly estimate of actual ET. When compared with maximum ET, these data are a good indicator of vegetation stress. The product has application in forest resource modelling. The current product ceased in Feb 2021, but communications with CSIRO suggest it will be extended. TERN produced a 10 year version to 2013 of the Ecosystem Disturbance Index, which utilised land surface temperature and the enhanced vegetation index information from MODIS data at 500 m resolution to detect extreme ecosystem change (floods, fire, etc.).

In an attempt to predict vegetation height and biomass across many regions in Australia, Liao et al. (2020) combined multiple satellite information from Landsat reflectance geomedians, ALOS-Palsar (L Band polarimetric SAR), Laser altimetry derived vegetation structure from IceSat / GLAS and climate data. Focusing on woody vegetation, the research produced estimates at 25 m resolution with errors derived from airborne LiDAR of 3.4 m in height, and 80 t dry matter $ha^{-1}$ in biomass, and a proposal to utilise GEDI data in future work. This kind of research, whilst not specifically directed at plantation forests, illustrates one direction of satellite-based remote sensing, i.e. to combine or fuse data from multiple satellites, which, in this context, is similar to the data fusion illustrated in ETa product from TERN. However, the oft-stated objectives of foresters to look at specific trees is difficult to achieve with sensor spatial resolutions of current low-cost, or free satellites. Much higher spatial resolution is, of course, achievable from space through satellite sensors such as Pleaides-Neo, SkySat and WorldView 3/4. For example, WorldView 3 provides 16 multi-spectral bands at resolutions of 1.24 m and 3.7 m for visible and near infrared, and shortwave infrared respectively, together with an ability to use panchromatic imagery at 30 cm resolution. At these resolutions individual trees are observable. The costs of this data (approx. A$1 per ha – tasked satellite) make regular observation of whole forest estates expensive, but prices will drop as competition in this area increases.

Forests have been digitally observed with satellites since the launch of Landsat 1 in the early 1970s. As the resolution of satellite sensors has improved, so too have the opportunities to observe forest characteristics. Here, resolution refers to not only the spatial resolution (often equated to the pixel size; for example, 30 m for Landsat 9), but also to the spectral and temporal resolutions of the sensor system. Being able to observe not only the visible, but other sections of the electromagnetic spectrum enables foresters to view features such as leaf moisture content in the short-wave infrared (1450 nm, 1940 nm and 2500 nm; Ceccatoa et al. 2001), oxygen emission (690 nm and 760 nm) and chlorophyl content in the near infra-red (760 nm – 88 nm). Satellites, or satellite constellations, with high temporal resolution enable forests to be observed more frequently and whilst forest observations are not required very often, the existence of cloud reduces the capacity of optical sensors to collect data clearly representing forests. For example, the dual Sentinel 2 satellites from ESA provide a repeat observation of a point on Earth approximately every 5 days, cloud permitting. Having this kind of temporal resolution means that cloudy images can be discarded and pixels with thin cloud can be avoided using statistical techniques leading to “clear sky” monthly observations of forests in most places in Australia and seasonal observations in domains which experience greater amounts of cloud. Such data types can be used to develop indexes of vegetation condition, including disturbance.

# 3 Forest Disturbance Index

## 3.1 Data Sources and Calculation of FDI

Vegetation condition on Earth has frequently been assessed from space using the Normalised Difference Vegetation Index (NDVI). This index uses two spectral bands; visible red and near infrared which in healthy plants are absorbed and reflected respectively. Thus, the normalised difference between these spectral samples provides an indicator of plant condition, especially in relation to photosynthetic activity, and difference in this index through time shows change in plant condition. The index is used, for example, by the SkyLab company who use Planet Scope imagery in their delivery, at cost, of their forest change monitor. However, NDVI only utilises two samples of the electromagnetic spectrum. An alternative vegetation condition estimate comes from the Tasselled Cap Transform (TCT), originally developed for crop assessment by Kauth and Thomas (1976) and then modified by Crist & Cicone (1984) for general vegetation and a different satellite sensor. Rather than using only two spectral samples, as in NDVI, TCT uses six spectral samples from Landsat imagery, and potentially more samples in Sentinel 2 satellite imagery, which has 12 spectral bands. Globally useful TCT coefficients for these 12 spectral bands are yet to be created for the Sentinel 2 sensor for ground reflectance data, which is atmospherically corrected. The TCT is a linear combination of weighted spectral bands with the weights, or coefficients, being derived from a statistical optimisation based on input spectra related to vegetation. TCT output axes are orthogonal to one another, with the first three corresponding to Brightness (B), Greenness (G) and Wetness (W). Healey et al (2005) utilised these three axes to detect forest disturbance in Landsat TM imagery, which share very similar spectral bands to Sentinel 2. Over time, G and W reduce with forest health loss compared with B, which tends to increase. Thus: FDI = B – (G + W).

Masek et al (2008) showed that FDI was successful in detecting forest disturbance for homogeneous forest stands, especially when the canopy was continuous and dense. However, for forests containing less continuous canopy, inclusion of soil background and understory vegetation introduces issues that require modification.

FDI is computed at the pixel level, which in the case of Sentinel 2 satellite imagery, is at 10 m resolution. At this resolution most forest pixels will contain reflectance from a mixture of tree canopy, shadow and possibly soil or understorey, dependant on the maturity of the forest, thinning, etc. Statistics can be generated for forest management units (plots, patches, compartments, etc) for a single time pair or "continuously" through time from a commencement point, which could be planting or first thinning, for example.

## 3.2 Implementation of FDI

In this project initial investigation occurred at the desktop level, with relevant satellite images being downloaded and processed to create FDI. To semi-automate the process, Stephen Stewart (CSIRO) implemented the FDI in Google Earth Engine (GEE) using the Python API and vector layers of plantation compartment extents. GEE includes Landsat and Sentinel products, amongst other satellite imagery. This workflow was applied across parcels managed by HQPlantations (HQP) in South-East Queensland and demonstrated early success at two disturbed *P. elliottii x caribaea* hybrid pine compartments within HQP's Elliott River plantation. The first of these sites (Figure 11 to Figure 13) showed disturbance caused by drought followed by clear fell-harvest, followed by wildfire.

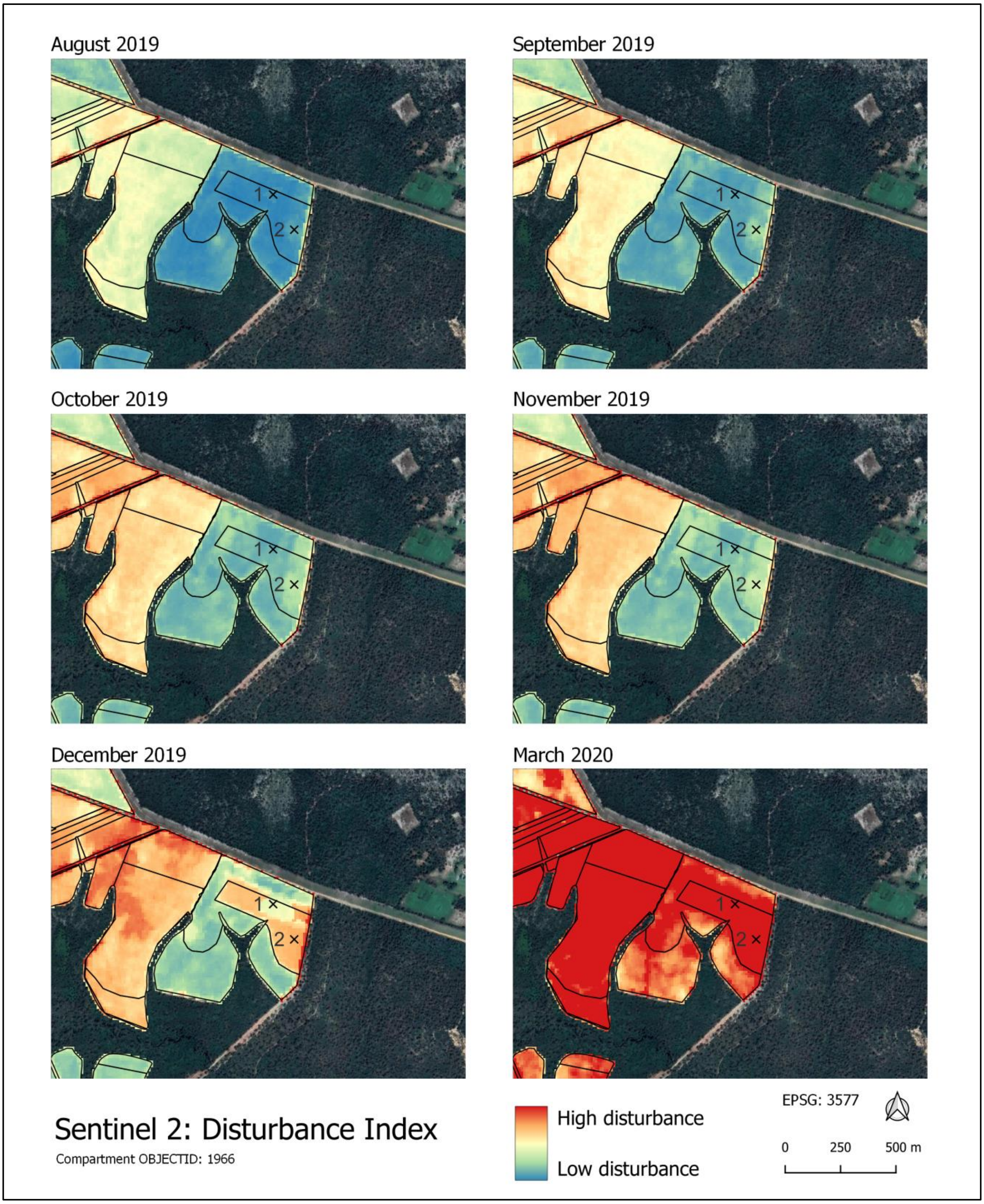


**Figure 11: Sequence of disturbance maps derived from the Sentinel 2 satellite from Aug 2019 to April 2020. Detection by HQP of the disturbance occurred in late November through human observation of high spatial resolution SkySat images. Clear felling occurred in Dec. 2019 / Jan 2020. Points 1 and 2 (crosses) were used to further explore the available time series of images.**

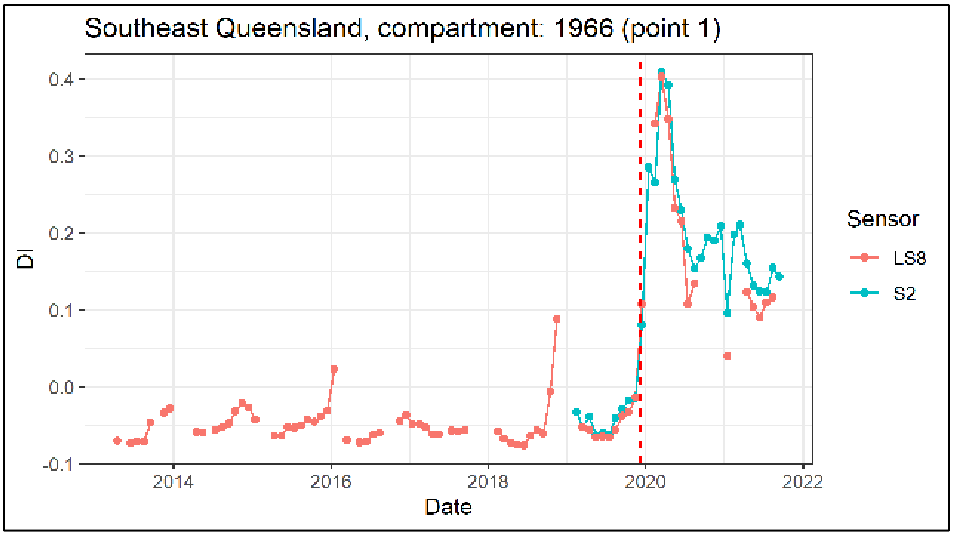


**Figure 12: Long term plot of disturbance at a single and less disturbed pixel (point 1) with the compartment shown in Figure 11, using both Landsat 8 and Sentinel 2 imagery. The annual climate cycle is evident from 2014 through 2018. However, overall disturbance values increase in 2019 with atypical values for most of the year and particularly in the second half of the year.**

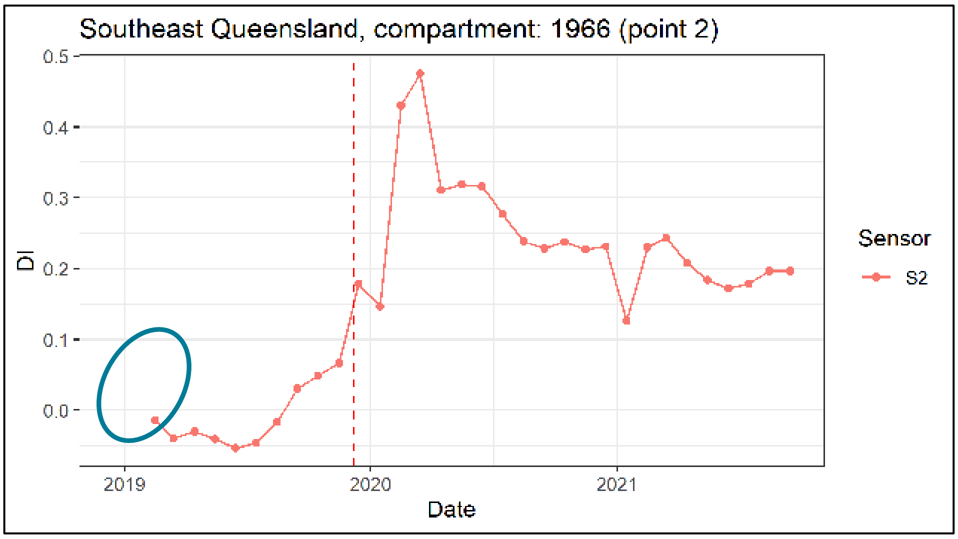


**Figure 13. Shorter term plot of increased disturbance at a single pixel (point 2) with the compartment shown in Figure 11 using Sentinel 2 imagery. Disturbance values increased significantly post July 2019 (blue ellipse) prior to massive disturbance due to harvest / clear fell in December and January.**

The second detected disturbance was caused by excessive scorching from controlled burns (HQP) (Figure 14 to Figure 16).

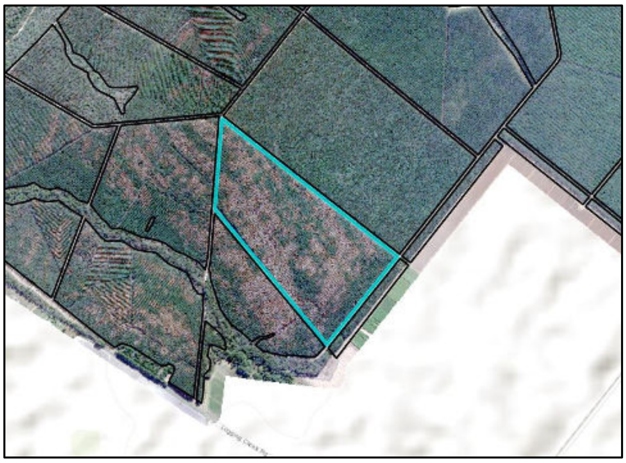

**Figure 14: HQP compartment 418 – enlargement with SkySat imagery after scorching from controlled burn.**

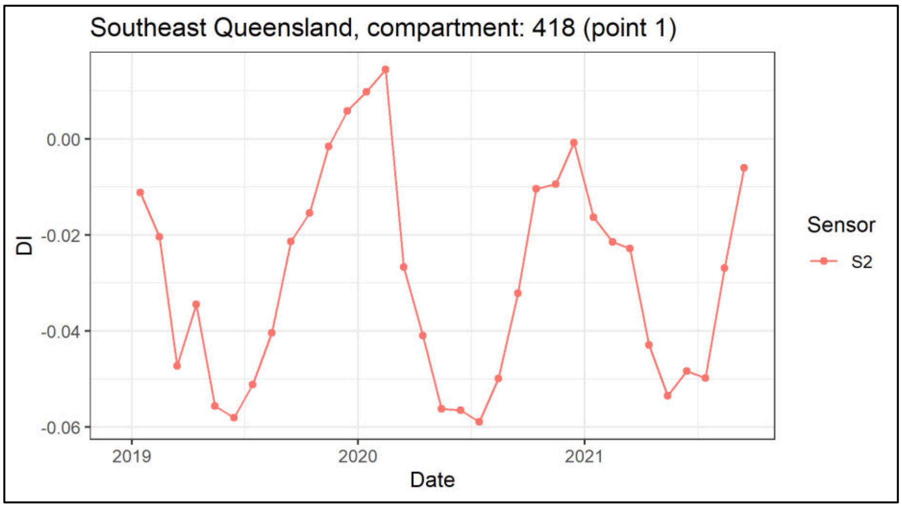


**Figure 15: Shorter term plot of disturbance at a single relatively "healthy" pixel (point 1) with the compartment shown in Figure 14 using Sentinel 2 imagery. Disturbance values show a typical cycle associated with climate.**

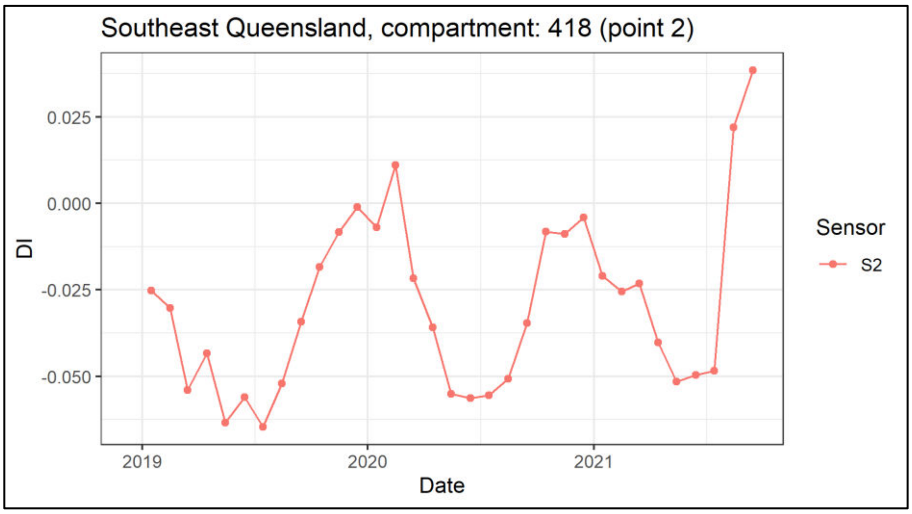


**Figure 16: Shorter term plot of increased disturbance at a single pixel (point 2) with the compartment shown in Figure 14 using Sentinel 2 imagery. Disturbance values for this "scorched" pixel are much larger increase in DI in August and Sept 2021 than for Point 1 where the change in DI is larger than typical seasonal variability.**

## 3.3 Migration of FDI from GEE to DEA

Whilst GEE provides a fast and accessible cloud computing environment, it can be lacking in flexibility. For example, users are generally restricted by the implemented functionality and exporting large images and datasets can be challenging where additional post processing is required. Resource bottlenecks can also arise during more complex workflows. Thus, after demonstrating the utility of the FDI in GEE, an opportunity to use the cloud compute environment at Digital Earth Australia (DEA) was explored. DEA is a platform developed in partnership with Geoscience Australia (GA), CSIRO and the National Computational Infrastructure (NCI). It is powered by the Open Data Cube (ODC), an open-source library for management and processing of Earth Observation (EO) satellite data and is designed to allow scalable processing of EO imagery. Freely accessible satellite data from ESA and NASA are indexed and available via the python-based API, allowing users to experiment and design EO applications across Australia.

The DEA sandbox is a freely accessible learning and analysis environment built within the DEA platform. It is designed for exploration, testing of EO analysis methods and as a service for the development of proof-of-concept applications. It is a prototype for the full DEA platform, providing a managed environment for small scale developments.

DEA and cloud-based services such as GEE reduce the processing barrier of dense time series analyses and facilitates the development of semi-automatic and objective change detection algorithms over a large scale.

Python code was migrated from GEE to DEA sandbox and optimised for the different datasets available within DEA. The FDI was calculated for Sentinel 2 images for its entire collection (2015-present) on test areas of *P. radiata* in the Green Triangle. The location and spatial extent of forestry plantations, provided as a vector GIS layer, was used to focus the time series analysis to known forestry compartments or plots of plantations representing discrete areas of continuous plantations composed of forest pixels (that is, removal of tracks/roads and non-forest pixels).

Records of planting date were sourced from the vector GIS layer and used to group compartments into age classes of individual species, shown below in Table 4. These age class ranges will be subject to change, based on guidance of forest type and region and will be expected to be updated as time progresses.

**Table 4: Initial age classes used in the Green Triangle**

| Class | Age Range (years) |
|---|---|
| 0 | 0 - 2 |
| 1 | 3 - 8 |
| 2 | 9 - 16 |
| 3 | 17 - 30 |
| 4 | >30 |

The location of known disturbances within plantations was sourced from GT forest collaborators and used to test the detection of disturbances in the EO image record. Figure 17 illustrates one such location.

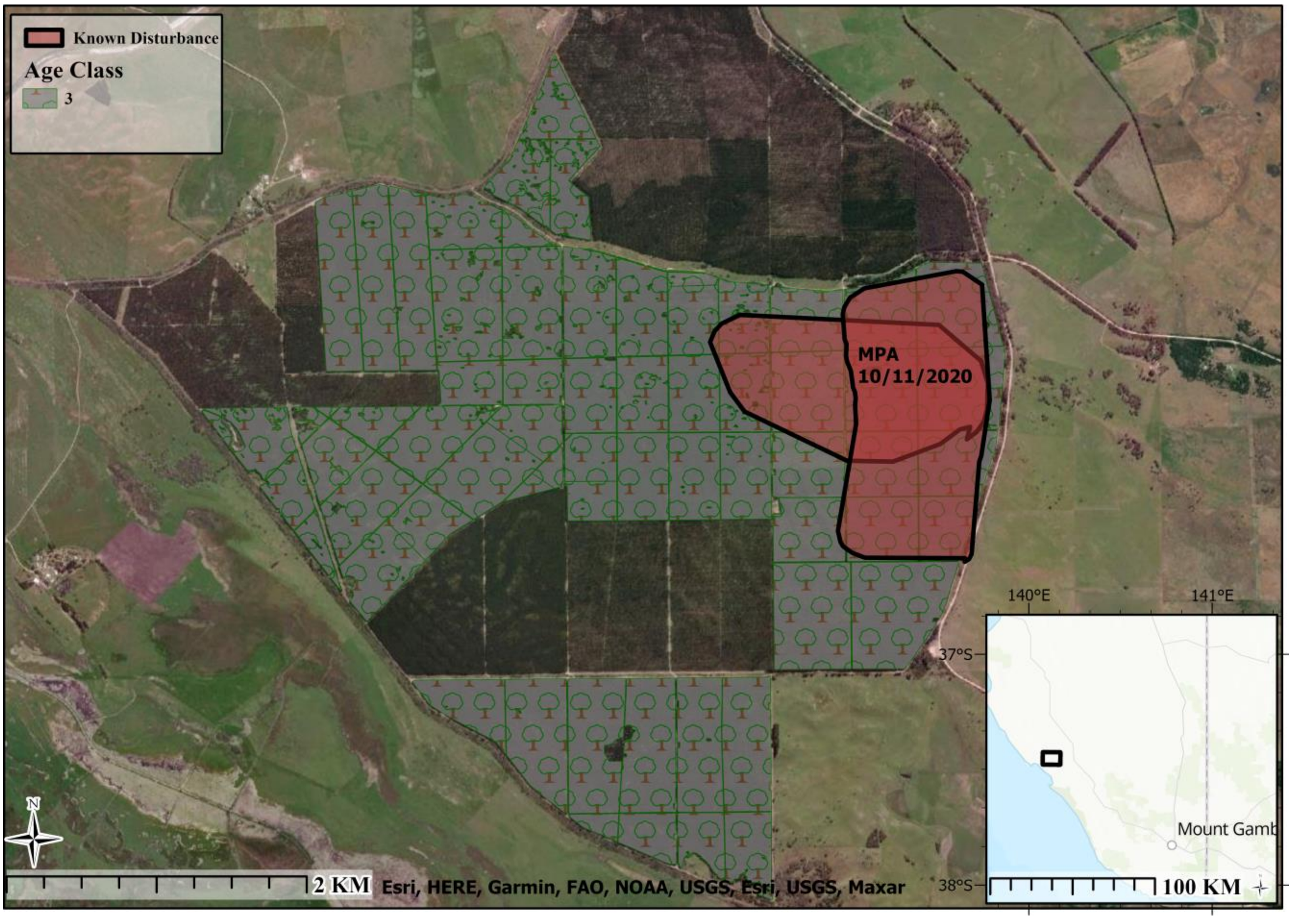


**Figure 17: Compartments of pine forests in SE South Australia in Age Class 3. Overlain is a vector GIS layer of known disturbances as provided by GT foresters. Detected in aerial surveys on 10/11/2020, classified as Pine Aphid (MPA).**

As is true of all optical satellite sensors, atmospheric conditions (cloud cover, smoke, haze) can affect the quality of images and integrity of spectral based observations. The cloud-masking done by ESA on Sentinel 2 images generally can reduce and target most dense clouds, but thin wispy clouds, or smoke haze often go undetected and unmasked with the algorithms used in the analysis ready datasets (ARD). To reduce or remove the impact of these types of atmospheric issues, image data over a nominated time period (month or season – 3 months) was used to compute geometric median composite images (geomedians). Geomedians are spectral composites from a temporal stack of imagery, where the pixel value represents the optimised median values for all spectral layers in the nominated time period, whilst still maintaining correct relationships across differing spectral bands. These images function as the baseline dataset representing the healthy forest for the specific age class and species.

To investigate the use of FDI, geomedians were calculated for compartments shown in Figure 17 for available Sentinel 2 imagery. In total, 83 images ranging from 2015 to 2020 were used to create geomedians for the 4 respective seasons as shown in RGB in Figure 18.

Using the datasets delivered by GT Foresters, shown in Figure 17, the satellite image record was queried to detect when the likely disturbance occurred. Clear defoliation and degradation are shown in the RGB image of Figure 19, dating from June 2020.

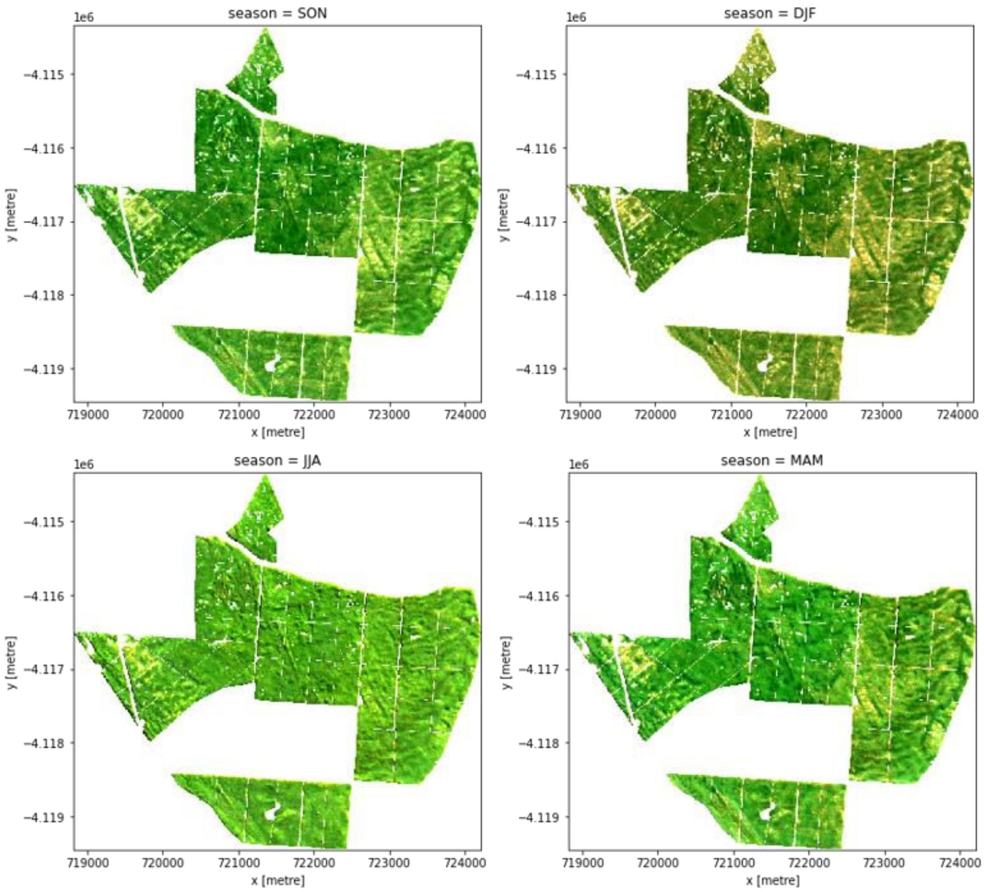


**Figure 18: Example RGB plots of geomedians for seasons, spring (SON), summer (DJF), winter (JJA) and autumn (MAM) from grouped imagery from the available Sentinel 2 record (83 images), ranging from 2015 to 2020. Coordinates are in Australian Albers, GDA94 (EPSG3577).**

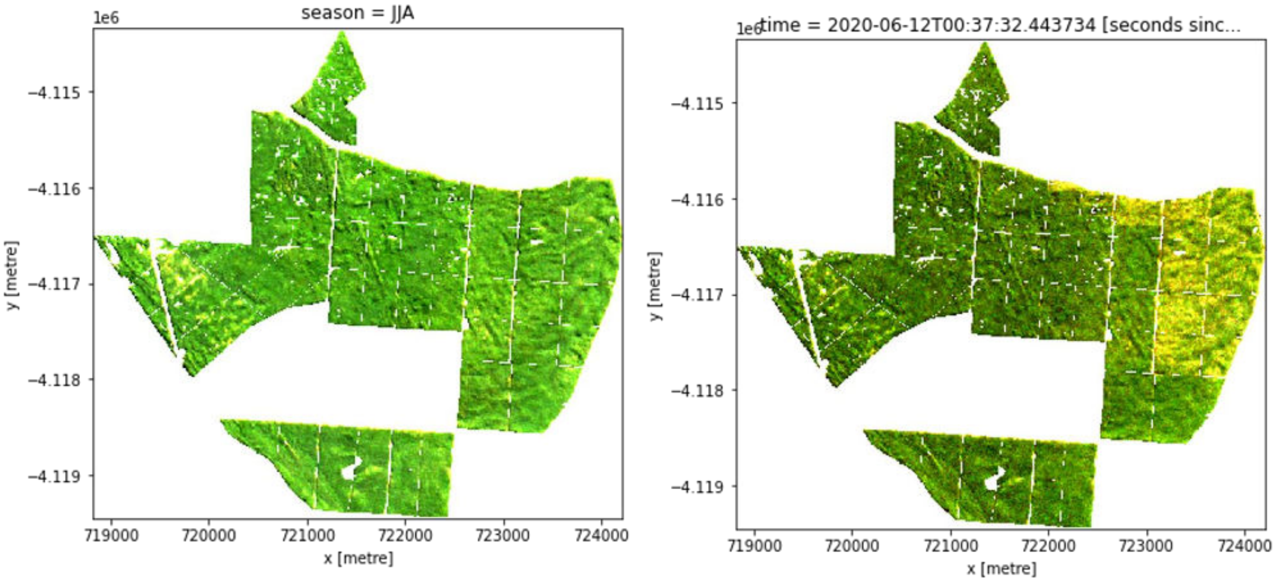


**Figure 19: RGB plots of geomedians for compartment from winter months and a single image from 12/06/2020 showing the apparent extent of the disturbance from Figure 16. Coordinates are in Australian Albers, GDA94 (EPSG3577).**

FDI values were tested against the calculated geomedians for the relevant season. Areas detected in October of 2020 in aerial surveys show indications of disturbance starting in early to mid 2020. Significance was tested with a Welch's t-test, shown in Figure 20.

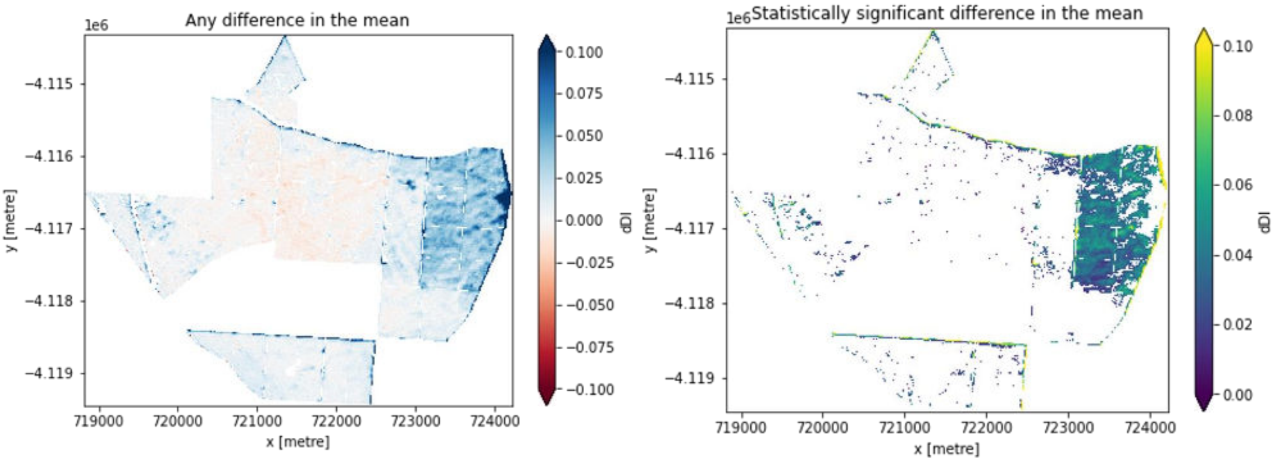


**Figure 20: FDI values tested against the mean value of respective geomedians. Differences in mean are interpreted as the disturbance detected in October 2020 as the canopy loss. Coordinates are in Australian Albers, GDA94 (EPSG3577).**

## 3.4 Limitations and Opportunities

Calculating geomedians is a computationally intensive process, requiring significant memory and processing time for the robust calculations. The DEA sandbox environment can be used for relatively small-scale computations and analyses as shown above, with parallel processing greatly increasing the environment's capabilities. To increase the spatial coverage to a continental scale and to reliably process data as new imagery becomes available, an extended cloud processing platform will need to be considered.

GA offers DEA processing and access through the NCI for sponsored projects. This avenue would support the significant scaling up to continental processing of datasets and potentially could be delivered as a service through GA. Alternatively, Flinders University is currently undergoing an exploratory process to match the imagery accessibility and processing capability of the NCI through their Deep Thought, High Performance Computer.

Either of these computing environments will enable not only the computation of geomedians across large spatial extents, but also the analysis of forest disturbance at specific locations through multiple seasons and years, thus enabling a genuinely spatio-temporal forest disturbance early warning tool. The tool is symptomatic, not diagnosing cause. In addition, the spatial resolution of Sentinel 2 will lead to some detection which is resultant of mixed reflectance, rather than forest canopy disturbance. Of course, this issue could be resolved with higher spatial resolution satellite imagery, but at increased cost.

# Part IV Hybrid Modelling

# 1 Introduction

Hybrid modelling, also referred to as model-data fusion, is where model behaviour accounts for new data from outside sources (measured or modelled separately). In our context, we learnt here how APSIM modelling could account for data inputs from LiDAR or other remote sensing methods, and traditional forest inventory and empirical growth modelling. Even simulations set up initially with the best range of inputs (soils, weather, genotype and management) usually fail to exactly predict tree growth at a given site. We can only know this at a given site if we have a plot of tree measurements. Tree measurements can come from traditional inventory or remote sensing (e.g. Part III). For example, from LiDAR remaining stocking after mortality and average tree height can be estimated. Other input data or simulated variables might also be different to what has eventuated, e.g. weather, and evapotranspiration and biomass data can from satellites. In these cases, process-based modelling can be recalibrated to better reflect observations and thereby increase confidence in yield forecasts.

Here we present examples of hybrid modelling of *Pinus* plantations, firstly by a recalibration process, then by elimination of multiple potential growth trajectories (derived from a large range of variation that can be expected in input variables) to leave a set of possible trajectories. This latter approach in our case was called the Ensemble Kalman Filter method, which is one type of a particle filter approach.

# 2 Example Workflow for a LiDAR Virtual Plot

Several Australian companies have or are considering obtaining LiDAR data for their whole estate every few years. If these data were divided into virtual plots (LiDAR plots) they could theoretically cover the whole estate, or at least be at a spatial intensity that is much higher than the current intensity of growth (i.e. permanent sample plots or PSPs with periodic measurements) and inventory plots (no intention of remeasurement). Similarly, a LiDAR plot could be established at each PSP location. Here we describe a workflow for implementing a virtual plot system (Figure 21). Using knowledge of plot location, soil, climate, genetics, and management, one or more similar growth plots are identified in the growth plot database, and the generalised APSIM model calibrated to achieve a suitable model skill. Data from LiDAR on stocking and tree height at time 1 (T1) can then be used to further calibrate the model for that specific plot location. In addition, or alternatively, other remotely sensed data can be used, e.g. evapotranspiration (ET data from TERN) and biomass. This process results in an APSIM growth model calibrated specifically for that plantation up to the time T1. Intervening climate data can then be used to project growth up to the present (i.e. hindcasting). Likewise, future climate scenarios can be simulated to project growth to a future date (T2) (i.e. forecasting). Outputs at any stage are possible for use outside APSIM. This process is demonstrated here as an example for a LiDAR plot in a pine plantation in Queensland that was also a growth plot (Figure 22). In this example, heights observed earlier than the most recent one (that was the target for calibration) aligned very well with simulated values. Further demonstrations were shown in the project for another pine location in south-east Queensland, one pine plantation in South Australia, one eucalypt plantation in South Australia, and one eucalypt plantation in Western Australia. In some cases, the alignment of earlier points not targeted by calibration were not as well aligned as shown in Figure 22. Two examples were published in Smethurst et al. (2022).

As an alternative to plot-by-plot calibration as demonstrated here, which would be possible to implement with a high degree of automation, an Ensemble Kalman Filter approach offers several advantages, as explained in the next section of this report.

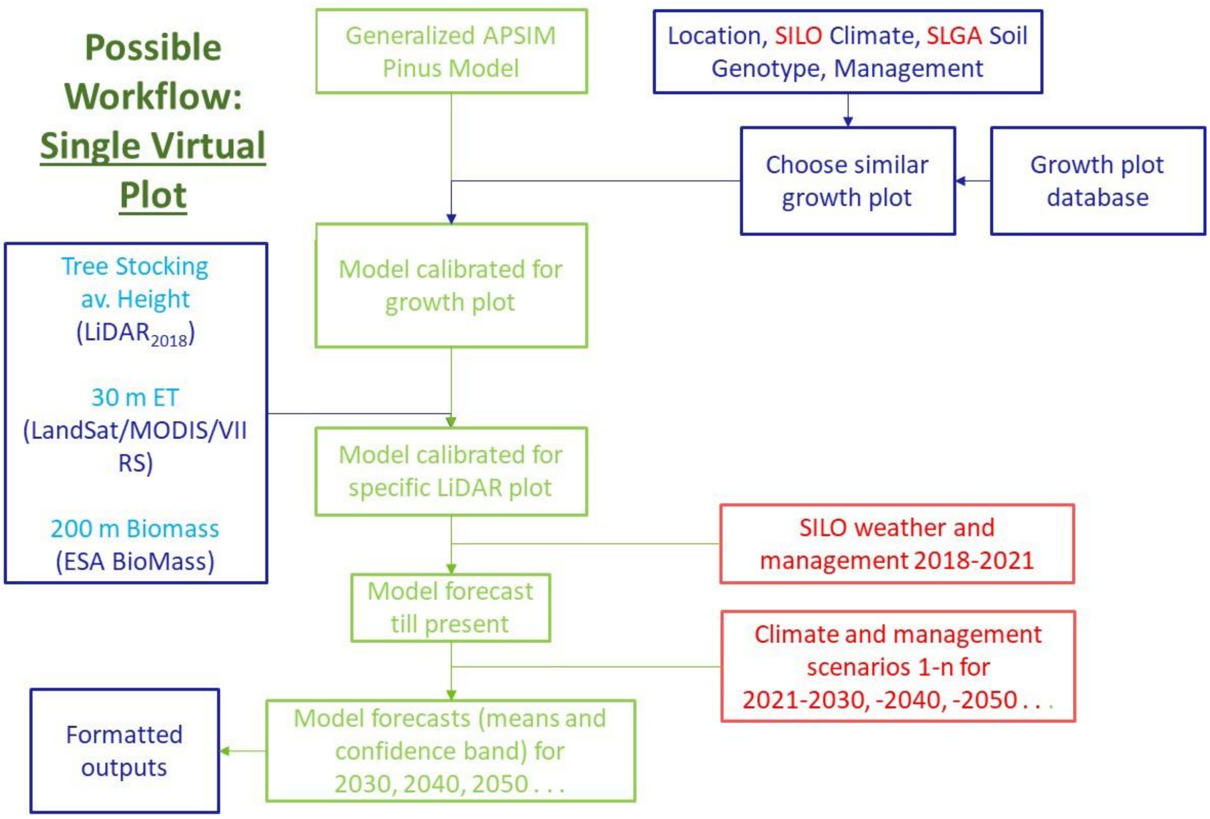


**Figure 21: Schematic of a possible workflow for simulating the growth of a virtual plot of pines established from LiDAR data.**

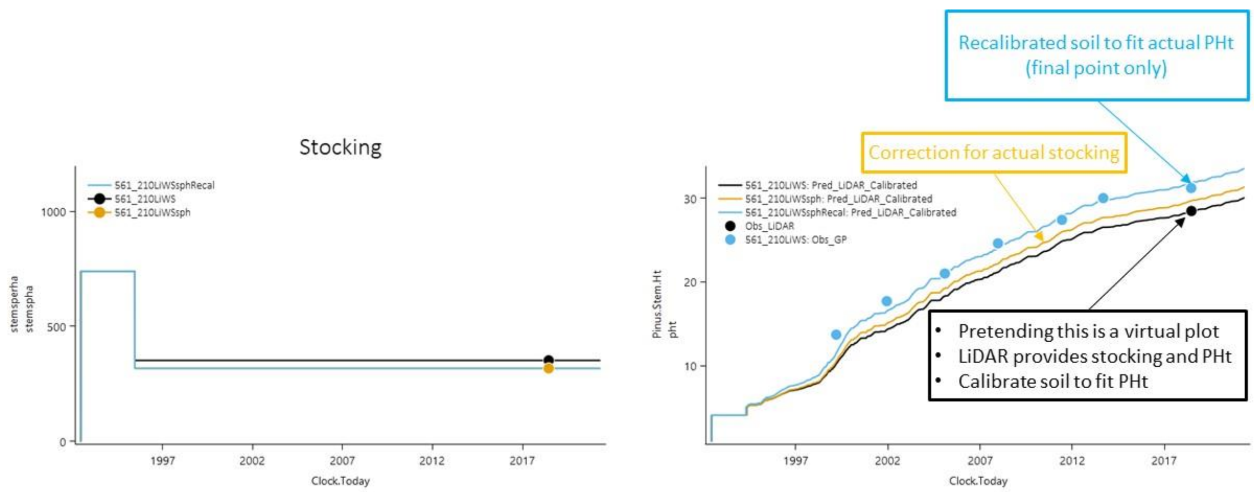


**Figure 22: Example of calibration of a LiDAR virtual plot (black) that was also a growth plot (blue). Points are observations and lines are simulated values. The black points were provided by LiDAR and a simulation conducted (black line). Then stocking was changed in the simulation to reflect actuality (amber line), and then a further correction for known average stem height most recently measured (blue final point and line).**

# 3 Ensemble Kalman Filter Example

In the Ensemble Kalman Filter approach, a large set of possible growth trajectories are simulated for an estate considering the full (or most important) range of errors in model inputs and observations. When an observation becomes available from inventory or remote sensing, the method eliminates those trajectories that do not fall within the range of possibilities set by the observation and measurement error. This leaves a predicted mean and error for a forecast date. Each time an observation becomes available, the number of future growth trajectories is reduced, and a new mean and error calculated for the forecast value, generally reducing the error. Thereby the estimated accuracy of prediction improves as the forecast date approaches.

This method was advocated by Tompalski et al. (2021) for hybrid modelling in forestry, and examples are available for agriculture (Pandya et al. 2022, Dhakar et al 2022, Ziliani et al 2022).

There are several likely advantages of this approach:

1. Production of the database of simulations needs to be updated infrequently.
2. Interrogation of that database can be by company staff using a suitable user interface.
3. Future model outputs are forecast with errors estimated by a documented method.
4. Templates for this approach are becoming available to the APSIM community.

Major disadvantages of this method are:

1. Plantation companies are unlikely to have the skills required to set up, run and collate the numerous simulations required. This therefore periodically becomes a task for a consultant.

Here we provide an example for tree height of a pine plantation in south-east Queensland. Tree heights were measured on 5 occasions during the 15 years of the rotation with an assumed error of 5%. A simulation was set up with a range of uncertainty for five factors (Figure 23left, part of a screenshot of the APSIM interface): plant available water content of the soil (PAWC), soil organic matter (SOM) concentration, C:N ratio of the SOM (CN), amount of residue at establishment (Residue), and survival of the crop (Survival). This range of combinations of factors led to the simulation of a multitude of possible growth trajectories of the crop are also shown in Figure 23 for height (top right) and Lai (bottom right). Each time an observation became available it enabled elimination of a number of these trajectories (Figure 24 top), there was a tendency for over-prediction, which indicates a need to improve the height calibration for that genotype. The final combination of inputs provided the best fit of simulated values compared to observations (Figure 24 bottom).

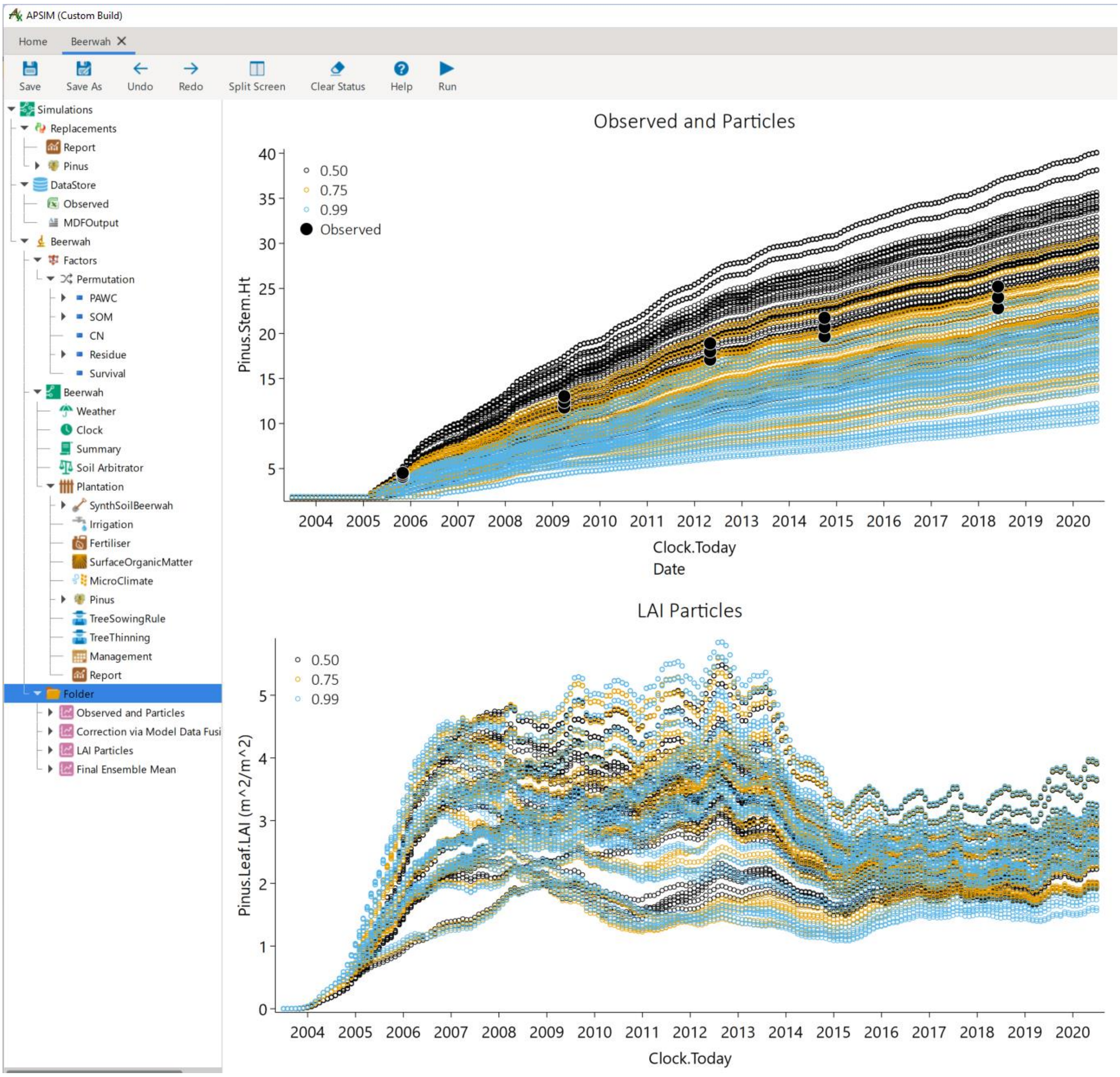


**Figure 23: Screenshot of the APSIM interface showing the simulation setup (left) and resultant trajectories (particles) of the Kalman Filter approach for height (top right) and LAI (bottom right), as well as observed heights.**

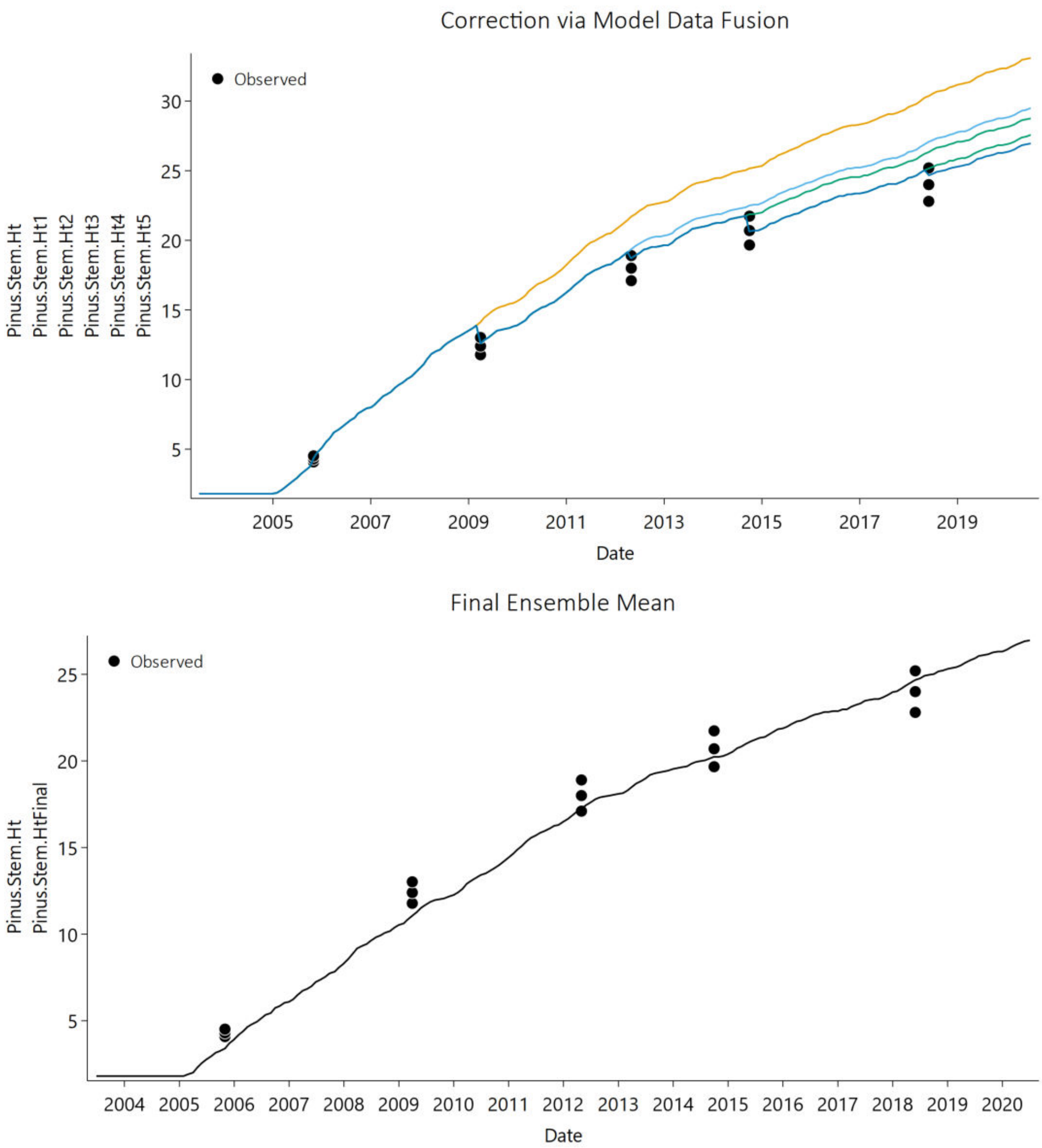


**Figure 24: Screenshot of the APSIM interface showing the simulation setup (left) and resultant trajectories (particles) of the Kalman Filter approach for height after identification of the most useful combination of input parameters on each occasion of a height measurement (top) and the final combination (ensemble mean) that provides the best overall model (bottom).**

# Part V Service Delivery

# 1 Introduction

This part of the report is based on Jenkin and O'Hehir (2021a, 2021b), which a reader is referred to for further details.

Forestry as a business relies on the supply of current and future log resources. A fundamental requirement is to estimate, with confidence, the quantum and attributes of logs available currently and to predict future availability. This requires a set of base data, a series of predictive models, and a planning system. Currently such systems are largely business specific, composed of a mix of bespoke and off-the-shelf components. With business evolution and increased complexity, individual companies seek solutions; do they continue to manage in-house or seek an external service provider?

Earlier in this report we presented a proof of concept of the technical components of the project, i.e. the development and application of hybrid modelling that integrates the APSIM modelling framework with remotely sensed data. Here we consider the concept, foundation principles, potential segmentation and future options for services using these technologies. Different service-provider models are considered based on industry experience, focusing on a case study of a long-standing example and successful collaborative service provider drawn from the Australian forest plantation industry, i.e. Tree Breeding Australia (TBA). We finalise this part of the report with a set of guidelines for setting up a cooperative model.

# 2 Technical Services Needing Integration

The technical proof of concept that integrates inventory (including empirical modelling), process-based growth modelling (e.g. APSIM, Part II), and remotely sensed (Part III) and existing system data is summarised schematically in Figure 25. Both empirical and process-based models project forward from a point in time with specific tree or stand attributes to conditions at a future time. Traditionally, systems have relied on inventory data ($T_{INVENTORY}$) on a sample of the plantation to project forward via empirical models to the present ($T_{CURRENT}$), from which models predict future yield ($T_{FUTURE}$). The accuracy of this approach has high statistical reliance on future growing conditions being similar to past conditions, which is coming increasingly into question with increased climate variability and change.

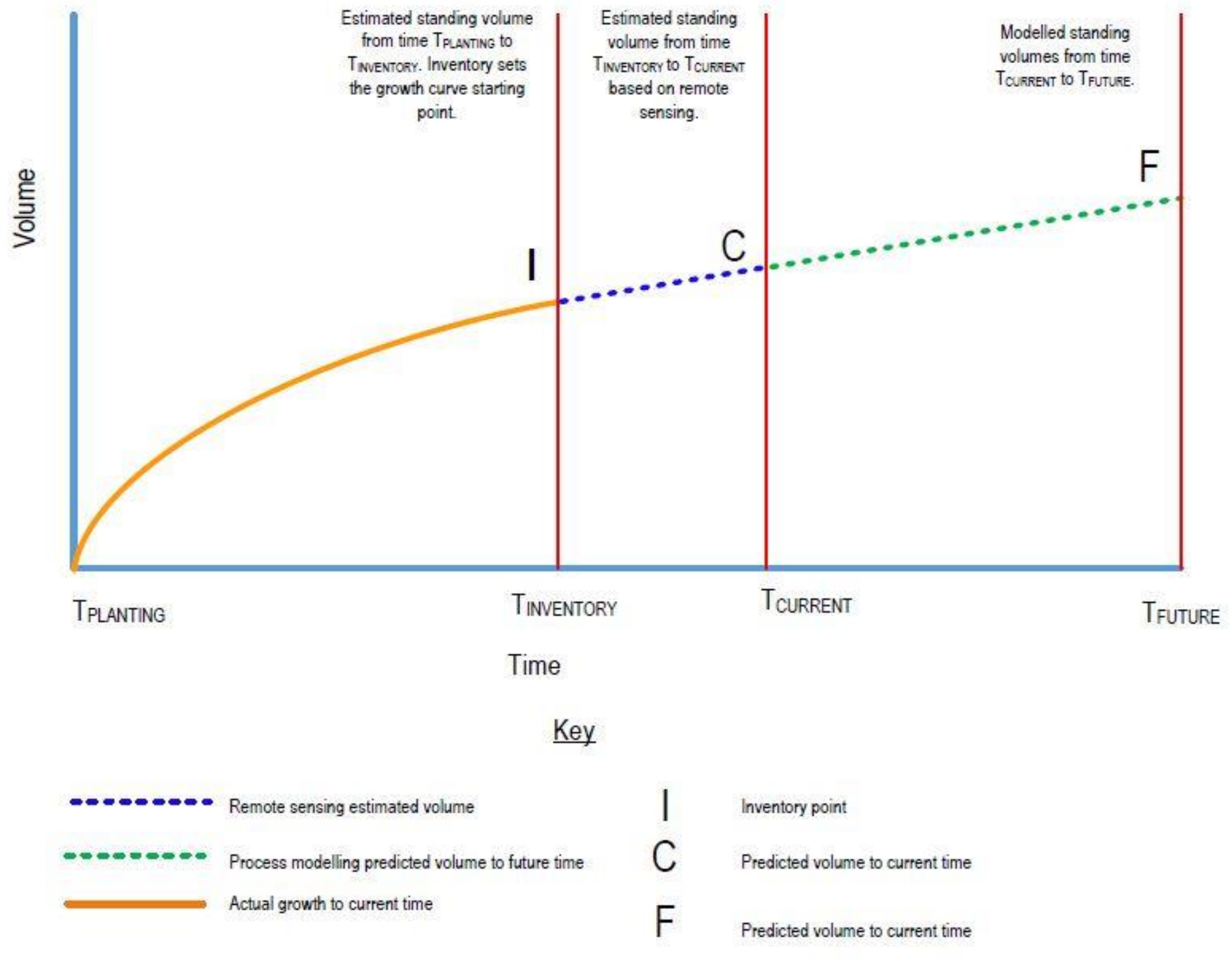


**Figure 25: Schematic of one potential integration of inventory, empirical modelling, remote sensing and process-based modelling.**

The proposed system makes use of current or earlier time ($T_{CURRENT}$) inventory, empirical modelling, and remote sensing data ($T_{INVENTORY}$) to estimate stand condition at current time. These process-based estimates are based on, for example, height and stocking estimates from remote sensing, and standard inputs needed for the simulations, i.e. soils, management, genetics, and past climate or future climate projections. (Part II) The APSIM process-based models for plantations mainly aim to predict the biomass of tree components (reproductive organs, foliage, branches, stems, coarse roots, and fine roots), while also predicting other salient ecosystem processes (e.g. soil water and nitrogen availability and use, light use, litter production, soil carbon, nitrous oxide gas production). Stem biomass is converted to wood volume using allometrics that are embedded in current empirical models and included in the process-based models. Process-based modelling enables inclusion of management inputs such as thinning or fertiliser application, damage events (e.g. pests, diseases, and drought) that reduce stocking or leaf area, and intervening climate via process effects rather than relying solely on direct statistical relationships. Use of remotely sensed data (Part III) can also enable stand modelling where there have been no on-ground measurements, i.e. virtual plots. The system has the potential to increase confidence in standing and future yield estimates, reduce error, and reduce the need to undertake on-ground inventory.

The process-based model predicts mean tree attributes for a unit of plantation (a minimum area of management and modelling) represented by one or more virtual, inventory or research plots. A tree size distribution could be added to aid harvest planning.

Using uncertainty ranges of inputs for process-based modelling at a specific location, a range of potential growth curves can be estimated from which many can be eliminated each time inventory or remotely sensed data become available. The outcome is a distribution of possible outcomes with a forecast mean and uncertainty. This is the Ensemble Kalman Filter method described earlier in the report (Part IV).

Process-based models require the calibration of coefficients that help define the simulated processes. By doing so, the effects of management, genetics, soils and climate can be adequately simulated. Using APSIM, calibration was previously provided for tropical and sub-tropical eucalypts – mainly *E. grandis* and related hybrids (Smethurst et al. 2020). During this project, APSIM was also calibrated for temperate eucalypts and temperate-to-tropical pines (Smethurst et al. 2022). A specific genotype definition within APSIM can be calibrated at various levels of taxa such as species, provenance, family, hybrid or clone levels. Smethurst et al. (2022) also demonstrated the ability for APSIM to simulate other complexities of the growing conditions encountered in Australian plantation forestry, which in this example were deep soils with aquifers that can potentially supplement water and nitrogen availability that the model usually assumes is limited to rainfall and surface soil nitrogen, respectively.

The technical services that need to be integrated to provide for hybrid modelling can be summarised as follows.

1. Provision of input data layers of soils, climate, genetics, and management for each rotation of a plantation.
2. Provision of remotely sensed data, summarised to provide inputs to APSIM modelling, and updated to take advantage of improvements in the technology.
3. Tailoring of modelling capabilities to provide the outputs required for specific uses, e.g. calibration for specific genetic-management combinations, hybridisation of new remote sensing data products, log sizes, greenhouse gases, litter turnover and soil carbon, natural capital accounting, and impacts of extreme events on wood supply.

The technical skills required to provide these technical services can be summarised as follows.

1. General understanding of plantation forestry in Australia, e.g. technical details, operations and business environment.
2. Remote sensing data management skills across several platforms, e.g. LiDAR, drones, satellites, and Cloud.
3. Specific remote sensing data management skills, e.g. Lascanopy, LasTools, ARC-GIS, sensor selection, image calibration, multi and hyper spectral image processing, access to and processing in cloud computing environments.
4. General process-based modelling skills – understanding of the processes that underpin tree growth, model structure, model modifications, set-up of simulations, tailoring outputs.
5. Specific modelling and data management skills, e.g. Microsoft Office, .net programming, R, Python, SourceTree, data visualisation, and GitHub.
6. IT skills related to web-based data storage and delivery of information to users

# 3 Business Model Experiences

Managers regularly evaluate the cost-effectiveness of various options for providing technical services to the industry, particularly in-house and consultancy services. A large proportion of industry managers also thought it worthwhile exploring cooperative models, as, in some cases, that option can provide more flexible and cost-effective services. The latter option was the focus for this project.

Here we provide a summary of several cooperative services to forestry or agriculture, and then focus on Tree Breeding Australia (TBA).

## 3.1 Agricultural Examples

Southern Farming Systems Limited (SFS) is an Australian public company with deductible gift recipient status. The SFS website describes the entity as a *'farm driven, non-profit organisation assisting higher rainfall farmers with practical research and information that produces sustainable results'*. The entity was initiated in 1995 by six founding members seeking to work collaboratively to increase farming profitability in higher rainfall zones noting that the *'issues were often different from those faced by farmers in other areas and different solutions would be required.'* It conducts jointly funded trials and projects, independent trials for members and contracted research for industry. Areas of interest include grazing, agronomy, crop nutrition, and variety trials. Trial results are segmented into member's only and public reports. The group has expanded to 600 members in five branches across two states (Victoria and Tasmania) in higher rainfall zones. Southern Farming Systems provides a network for members to share ideas and experiences, and to undertake practical research designed to produce long-term solutions. Partnerships have been established with research and extension agencies, and agribusiness, including linkages with international parties. Partners provide financial resources towards research and extension programs, and knowledge and technical expertise. A hierarchy of partners has been developed; Premier, Signature and Patron partners. Southern Farming Systems remains an independent provider of information while recognising the beneficial nature of such partnerships. Membership packages are flexible and include regular newsletters and updates of current research projects, trial results, free entry to all SFS field days, local crop walks and workshops, as well as exclusive access to the 'SFS Members Only' area of the website. The SFS does not seem to provide yield forecasting services of the type being considered in this report.

The Birchip Cropping Group Inc. (BCG) is an 'Other Incorporated Entity' registered as a Deductible Gift Recipient. The group describes itself as '*a not-for-profit agricultural research and extension organisation led by farmers from the Wimmera and Mallee regions of Victoria. Aiming to improve the prosperity of farmers and agricultural communities through farmer-driven innovation, research and extension.'* A group of Birchip and district farmers established the Birchip Cropping Demonstration Sites in 1992 focused on grain varieties, pulse crops and agricultural products performance in local soils and conditions, and sharing information '*for the betterment of grain growers in the region*'. The group conducts research in agronomy, farming systems, climate, plant nutrition, crop disease, weed and pest management, precision agriculture, agriculture technology and on-farm connectivity. The BCG provides help to conduct research across sites in three regions of Victoria. It has 20 staff, over 400 members and a reputation for exceptional field research and professional extension activities. Activities have resulted in adoption of new agronomic technologies and farming practices; specifically assisting farmers to '*make decisions, develop risk management strategies, increase profits and operate sustainable farming operations'*. Members can access information such as a technical bulletin and BCG season research results, and receive free entry to flagship events. Activities are overseen by a Board structure supported by staff, an Advisory Committee, a Research Committee, and partners.

On a subscription basis, the BCG provides services that use APSIM for crop yield predictions and are based on the 'Yield Prophet' software that was developed in conjunction with CSIRO.

For both SFS and BCG there is a cycle of need, motivation and intent underpinned by a process of self-help. The entities were developed in geographic zones to address local issues. SFS would appear to be more self-contained, whereas BCG is assisted by primary research agencies. Independence is a stated attribute, with reference to partners (BCG) and sponsors (SFS). Members in SFS and BCG receive access to information and research outcomes. Membership of BCG are provided with discounts on paddock specific runs of a yield forecast system.

## 3.2 Forestry Examples

As for other technical services in forestry and other sectors, there are three models to undertake tree breeding activities: in-house, outsourced (e.g. to a consultancy or cooperative), or a hybrid of the two. The collaborative approach to tree breeding was established back in the 1950s-1960s. For example, the Cooperative Forest Genetics Research Program, the North Carolina Forest Productivity Cooperative, and the North Carolina State University Co-operative Tree Improvement Programme (NCSUCTP). These cooperatives provide technical assistance, research and educational resources to support sound genetic and silvicultural decisions for managing the forest resources of their members. Return on investment for members is driven by increased productivity and greater disease resistance of improved varieties of *P. elliottii* and *P. taeda*, for example, which can yield 40-55% more usable wood at harvest compared to unimproved varieties. Noted by NCSUCTP in 2020, '*at age 64 years, the Co-operative Tree Improvement Program continues to provide value to the members, to NC State University, to the forestry and scientific communities, and to the landowners and citizens of the region*'. Hence, these programs show that it is cost effective for plantation managers to collaborate and share the operational costs of breeding with other companies. A summary of the attractions of a cooperative model are provided in Table 5.

**Table 5: The benefits of a collective structure for tree improvement.**

| Consideration | Narrative |
|---|---|
| Skills | A single entity based tree improvement program may not be able to hold the required highly specialised technical skills and maintain a position on the cutting edge of technology (Borough & Boomsma, 1991, p.1). |
| Analysis | More complete modelling of genetic components is possible as developed by TBA. |
| Efficient use of data | Inefficient use of data and information is undesirable for large national breeding programs. |
| Cost efficiencies | A collaboration model provides cost efficiencies (Borough & Boomsma, 1991, p.1; McRae, 2014, p.3) with 'users' sharing cost of maintenance and development across species and breeding programs (McRae, 2014, p.7). Provision of support is critical (e.g. training, maintenance and enhancements) (McRae, 2014, p.7). |
| Security | A model provides enhanced security of resources (e.g. genetic material, data and specialists) (McRae, 2014, p.3). |
| A single breeding population | A single combined approach has resulted in a breeding population with a national breeding objective(s) and common goal (McRae, 2013, p.1; McRae, 2014, p.XX). The programs are global but have a local focus in deployment to manage genotype by environment interactions and variations in company objectives. This has been achieved by consolidation of private, state and federal programs into a national (industry wide) program (McRae, 2014, p.3). At the time of commencement of STBA, there were six tree breeding programs in place and anyone could have satisfied most of Australia's needs (Borough & Boomsma, 1991, p.1); there was duplication. |
| Risks spreading | A collective approach allows undertaking of higher risk research due to a dilution across a broader base (Borough & Boomsma, 1991, p.1). |

## 3.3 Tree Breeding Australia

The TBA was established in 2019 when it took over the role of the Southern Tree Breeding Association (STBA), which had been incorporated in 1980 under the *Associations Act of South Australia 1985*. A limitation of the association structure was that it was governed by state legislation whereas TBA is a company governed by Federal legislation under the *Corporations Act 2001*. The primary role of TBA is to generate (1) improved genetic materials for priority tree species, and (2) associated IP (intellectual property such as databases, software, and genetic material). The TBA is formalised in several documents that cover the board, technical advisory committee, membership, operations, and sunset mechanisms. The documents also specify what the organisation does not do. Specifically, TBA does not produce improved seed for deployment; this is undertaken by specific classes of members and third parties under license. Genetic materials and objective data to support decisions is provided to members and licensees engaged in seed production, plant propagation and plantation forestry.

The evolution of this collaborative model from an association to a company represents 42 years of experience in providing this type of advanced technical service, and the legal, financial and technical facets of collaboration that needed to be considered. We rate this as the strongest example to follow that we are aware of if the industry needs to set up a collaboration to provide a new range of advanced technical services.

# 4 Collaborative Business Model for Providing Advanced Technical Services

Here we provide insights into the requirements of a service provider model that could potentially augment or replace current internal resource assessment and yield forecasting processes. A service provider model must instil confidence to encourage and retain membership. This confidence will be tested by due diligence, and a service provider must be able to demonstrate durable benefits. To ensure this, a robust, functional, and enduring structure is required, i.e. financial viability and governance.

To ensure precision of language, which has legal implications, confusion around cooperatives, collaboratives, and consortiums is addressed. A collaborative model includes parties contributing and aligned towards a collective goal, but it is important to recognise that inputs of collaborators may not all be equal. Neither a consortium nor a co-operative are legal entities in their own right unless incorporated, hence the interest of individual parties and the arrangement are not separated. This creates liability issues and concerns regarding the protection of individual party IP, and the IP created by the activities undertaken. Hence, with neither a consortium nor a co-operative, are the works to be undertaken within a separate entity. If incorporated as a company, legal structures service a key intent to quarantine members from entity ownership (and therefore influence) and liability. This allows development of a membership structure which can silo interests (e.g. species by geographic zones). Technical skills, data and IP management are critical. A service provider model allows access to cutting edge skills, development of bespoke systems, and security of data. Member interfaces allow member access to analytical systems which leverage off collective data, while generating member specific reports, information, and outcomes. As a guide for use if such a business model collaboration were to be set up, we outline here the requirements of a robust service provider in the field of resource assessment and forecasting in Australian plantation forestry.

## 4.1 Operation of a collaborative enterprise model

The following aspects are salient to the operation of a collaborative enterprise model.

### 4.1.1 Governing documents

Efficient operation of a service provider model requires a comprehensive set of ‘rules’ documented in a constitution and supporting bylaws. For expediency, bylaws contain greater detail requiring updates at the discretion of the Board (but with a mechanism for member intervention). Governing rules must define roles and responsibilities of all parties and address issues such as defining and controlling member behaviour including interactions between members and with non-members.

### 4.1.2 Mechanisms and governance

There are three cohorts of management: a board of directors, member working committees, and employees. Board structure and composition must be designed to protect member’s interests and specific bylaw clauses are required. Directors focus on governance and the business, while representing the business. Technical and operational matters are best done by member working groups and committees which separate resourcing and decision making to prevent conflict and conflicts of interest influencing resourcing decisions. Member representatives (represent the interests of individual members and resourcing) and a technical advisory committee (focusing on technical aspects) requires different skills at the different levels of management to minimise conflicts of interest. In the TBA model, the technical advisory committee can include stakeholders other than members, and even competitors. This approach strengthens the scrutiny of the technical developments. Day-to-day operations are managed by employees (management, technical and scientific).

### 4.1.3 Membership code of conduct

Interactions between members and non-members requires codification to ensure consistency and clarity as to obligations, limitations, and responsibilities. While a mechanism to protect IP, it is also a mechanism to help protect entity reputation. This can be a specific issue where a member service provider also performs external contract works.

### 4.1.4 Works undertaken and adoption

To best service members, a process of development of works to be undertaken is required (e.g. a strategy, five-year and annual programmes). Where membership is structured in special interest silos, this can involve multiple programmes with or without overlaps. This is to allow focus on short-term membership needs and longer-term objectives. A budget is then formulated in support and used as a basis of membership fees on a programme-by-programme basis. As a not-for-profit, any surplus is to be re-invested in entity activities. Systems and functionality must ensure the potential for rapid up-take by members into operational application.

### 4.1.5 Member exit mechanisms and strategy

The Australian forestry industry is relatively small, and reputation is important. Hence, serious disputes are unlikely to arise, and issues will be resolved amicably. Regardless, a membership-based structure requires mechanisms for voluntary exit and to enable expulsion of a member (including grounds of expulsion). On exit or expulsion, there is a need for a clear statement of management of IP, ongoing rights, and responsibilities. Where activities include trials or other physical activities on an ex-member's site, there is a need for mechanisms to allow continued access by the membership entity for a reasonable period of time.

### 4.1.6 Risk management strategy

Proactive management of brand and reputation is required as a basis of company value and securing and retaining membership. A first step is to identify potential issues and risks, and to develop strategies and governing rules to eliminate or reduce the risk of adverse outcomes. For example, a separate entity could provide similar services to non-members and members on a fee for service basis. This provides a mechanism to manage conflicts of interest, manage risk, and allow the entity to provide services to other parties without interference and disclosure of client IP.

### 4.1.7 Management of intellectual property strategy

Ownership and treatment of IP must be addressed and clearly documented in bylaws. There are multiple types of IP including but potentially not limited to: initially contributed (background) IP on joining, IP contributed on an ongoing basis, and IP generated (created) by entity activities, which can be because of access to and use of member contribution IP. Given applicability of IP generated by a membership-based entity to non-members, there is a need for boundaries (guidelines in the bylaws) on access and rights of IP use, which can include geographic restrictions (subject to how membership fees are calculated, and the territory declared or covered by the membership). For example, the TBA model is a mechanism to capture, store and protect corporate knowledge (IP) and an outcome of TBA activities is generation of significant IP that TBA owns. Where significant IP is held and generated, there is a need for a robust sunset clause to protect and secure IP post termination or otherwise cessation of entity operations.

## 4.2 Technical aspects of a collaborative model system

The following technical aspects are salient to a collaborative enterprise model that targets a workflow similar to that in Figure 26.

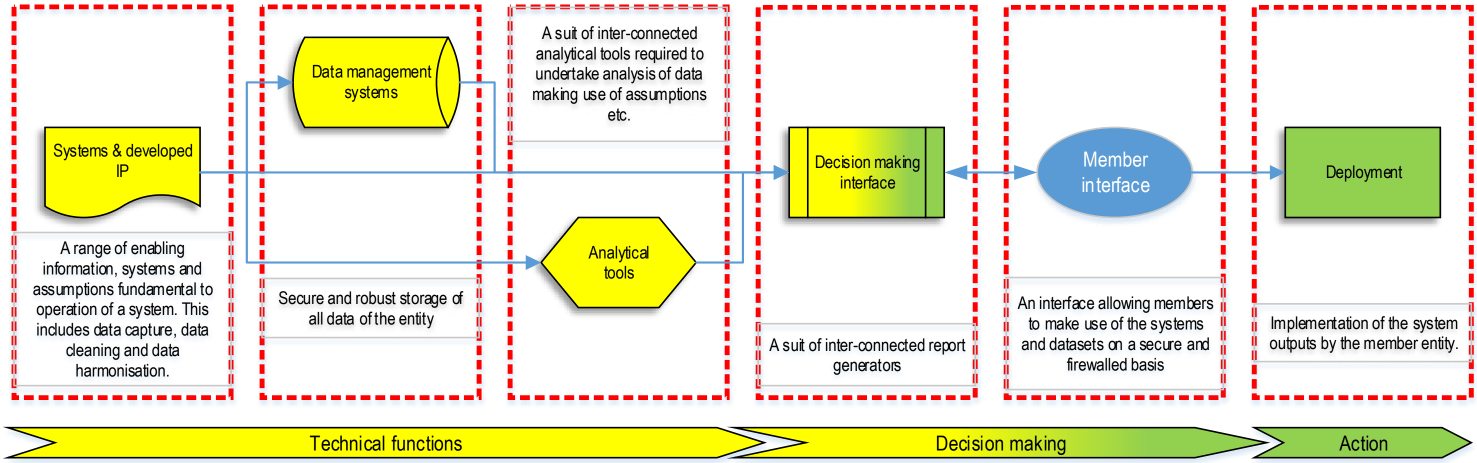


Figure 26: A summary of the technical elements of a service provider model.

### 4.2.1 The system functionality, analysis and member interface

A system must have a high degree of flexibility. A system of how services are provided must consider structure, tools deployed, and outcomes. A system must have an ability to include developed IP and systems, a range of analytical tools, and decision-making capabilities allowing members to interface to the system to interrogate or process their data (Figure 26). To facilitate member use of the developed systems they will need to link with member internal systems; this requires management of fungibility and security (e.g. firewalls). Communication and electronic platforms enable different companies to do things collectively; this has not always been the case due to geographic distance as a barrier to collaboration. To maximise utility, a system should include an ability to address species by geographic zones. Examples of technical functionality and input from this report are the use of APSIM (Part II) for stand metrics and modelling, and remote sensing detection of forest disturbance. Both examples require diverse data collection, input to software (local or cloud), selection of parameters, analysis, and the delivery of results to growers.

Easy access, most likely through web portals, to meaningful results is critical for growers, and most likely will be through web portals.

### 4.2.2 Data and data management

A system must include an ability to capture, store, process and secure all data. Providing a solution to complex data issues allows maximum use of available member data. As a model, the TBA system allows use of a broader range of data than with more conventional systems. It is possible that an entity operating a stand-along programme will face a challenge of the use of imperfect data, which compounds a situation where data availability is limited by the time taken to reach biological outcomes (e.g. trials are established, grow and are assessed in a linear sequence). Membership includes an ability for TBA to access unprocessed data that might not meet requirements for simple internal analysis. Further with multiple member's data, from multiple trials at different stages of development (timing), data generation is continuous allowing a rolling-front approach.

### 4.2.3 Technical tools, skills and outcomes

Inputs to resource modelling have evolved, with changes in technology enabling more efficient measurement (e.g. Resi-tool application) and the inclusion of wood properties. This enhances the value proposition for a collaborative business model. Technical staff are vital. There are few specialist resource modellers. Individual forestry companies will have internal staff in support of resource modelling, but can they retain critical specialists to service these programs? The collection and analysis of remotely sensed data from drones through satellites is another area in which only a few plantation companies have specialist staff. A key point is a challenge to keep specialists gainfully employed by a single company; they need the high-tech working environment and challenge and freedom from operational distractions. A collaborative model has an additional benefit where individuals from normally competing companies 'get in the same room' and synergies expand potentials. A sense of a common purpose can carry over as individuals get to know each other better in such an environment. This is best described as a sense of alignment to a common cause when the model developed has appropriate structure and mechanisms. Addressing resource modelling of multiple species can generate efficiencies with specialists working across multiple programs. A developed system must have the ability to rapidly integrate research outcomes into operational systems on a rolling front basis to minimise time lags until benefits are realised. Consideration is required of linkages to external research agencies (e.g. CSIRO, tertiary institutions and/or international agencies).

# Part VI Synthesis and Recommendations

# 1 Synthesis

Research reported here is the first attempt in Australian plantation forestry to identify and demonstrate how the complex technical components of a modern yield forecasting system (i.e. including remote sensing and process-based modelling) could be integrated to provide wood production and several other natural capital outputs specifically tailored to the needs of individual companies. Individual companies are unlikely to have and hold the internal capabilities to provide such services, which necessitates the reliance on consultancy services or an industry collaborative model. A collaborative business model was identified that could potentially provide these services.

Process-based modelling capabilities were demonstrated using the APSIM modelling framework. Models for the Australian plantation estates of *Pinus* and *Eucalyptus* were developed, and they performed adequately across a range of contexts. Three examples of their use were provided:

1. *Pinus* and *Eucalyptus* plantations growing over an aquifer were simulated to take up water where the aquifer was reasonably shallow (4 m depth) but not if much deeper (24 m). Where the aquifer was shallow, these simulations also quantified the hypothesis that nitrate in the aquifer could be taken up, and that both water and nitrate uptake contributed to increased tree growth rates. In addition, simulated rates of evaporation were similar to those estimated by a satellite product.

2. Climate change scenarios were demonstrated for a *Pinus* plot in Queensland and a *Eucalyptus* plot in Western Australia. Increased temperature and $CO_2$ concentrations led to increased tree growth where adequate rainfall and other factors prevailed. The availability of data services behind this capability are being investigated by CSIRO for broader availability.

3. Yield gaps in a range of *Eucalyptus* plantations were quantified in a related project using APSIM. That project refined the method of yield gap analysis beyond previous examples, which had identified gaps due to climatic limitations, to include gaps due to three important management factors: survival, weed control, and nitrogen (N) fertiliser. The analysis suggested that sub-optimum survival and weed control limited growth at several locations, but that there was more significant gap due to a lack of N-fertiliser.

Remote sensing options were demonstrated for two main purposes:

1. Provision of data for use in process-based modelling

   Airborne LiDAR data provided estimates of stocking and tree height that were used to iteratively calibrate simulations and update their estimates of plot-level wood volumes using the APSIM *Pinus* model. These forecasts extended the growth pattern that had earlier been based on traditional inventory. This process was demonstrated for two *Pinus* plots in Queensland.

   In addition, instead of the iterative calibration approach, a Kalman filter approach was demonstrated that produced a multitude of growth trajectories based on a wide range of combinations of input variables, a number of which were rejected because they failed to achieve similar values of observed variables. The remaining growth trajectories provided estimates of mean and uncertainty for forecast variables.

2. Alerts to major disturbances that could affect yields

   Temporal sequences of freely available satellite data were used to detect a change in stand condition that could affect wood availability (yield). The software was tested in Queensland and the Green Triangle.

The collaborative business model used by Tree Breeding Australia was summarised. This model was appropriate, because it has a success track-record of delivering advanced technical services for the provision of improved planting stock for the industry. Aspects to be considered when adapting this model for the advanced technical services of remote sensing and yield forecasting were also summarised.

Project evaluation was conducted amongst participants using the form provided in Appendix 1.

# 2 Recommendations

It is strongly recommended that the industry:

1. Improve remote sensing and process-based modelling skills available to the industry and individual companies in both a collaborative model and ~~or using~~ consultancy services by focusing initially on remote sensing with a view to fully operationalising hybrid modelling within about five years.
2. To fully utilise these services, the industry generally needs to ensure that adequate programming and data manipulation skills are also available, e.g. for Python, R and cloud computing.
3. Further develop, test, and operationalise the disturbance index tool.
4. Remain alert to and evaluate new satellite data services that could be useful to the industry.
5. Improve the APSIM models for forest plantations to better service industry needs, e.g. by including individual tree sizes, wood quality measurements, and biomass development trends of the main genotypes under contrasting conditions.
6. Build for each forest plantation estate, soil data layers that adequately represent soils at the plot scale for use in process-based modelling.
7. Form a working group to fully explore and develop a collaborative business model for evolving and delivering these services.

# Abbreviations

| | |
|---|---|
| API | Application Programming Interface |
| APSIM | Agricultural Production Systems sIMulator Modelling Framework |
| BCG | Birchip Cropping Group |
| CABALA | CArbon BALAnce model |
| DSSAT | Decision Support System for Agrotechnology Transfer |
| GIS | Geographical Information System |
| GUI | Graphic User Interface |
| IP | Intellectual Property |
| LiDAR | Light Detection And Ranging |
| NCSUCTP | North Carolina State University Co-operative Tree Improvement Programme |
| OvsP | Observed Versus Predicted Graph |
| SFS | Southern Farming Systems Limited |
| TBA | Tree Breeding Australia |
| TERN | Terrestrial Ecosystem Research Network |

# URLs

| | |
|---|---|
| BioMass | https://www.esa.int/Applications/Observing_the_Earth/FutureEO/Biomass<br>https://www.sciencedirect.com/science/article/pii/S0034425719301233 |
| Birchip Cropping Group. | https://www.bcg.org.au/ |
| Climate Models | https://skepticalscience.com/climate-models.htm |
| DEA Fractional Cover | https://www.dea.ga.gov.au/products/dea-fractional-cover |
| EarthDaily Constellation | https://earthdaily.com/earthdaily/ |
| Ecosystem Disturbance Index | http://www.auscover.org.au/datasets/ecosystem-disturbance-index/ |
| FLEX | https://earth.esa.int/eogateway/missions/flex |
| GEDI | https://gedi.umd.edu/ |
| Global Forest Watch | https://www.globalforestwatch.org/ |
| Landsat Next | https://landsat.gsfc.nasa.gov/satellites/landsat-next/ |
| MOD13 | https://modis-land.gsfc.nasa.gov/pdf/MOD13_User_Guide_V61.pdf |
| NCI | https://nci.org.au/ |
| NISAR | https://nisar.jpl.nasa.gov/ |
| ODC | https://www.opendatacube.org/ |
| Regrow | https://www.regrow.ag/ |
| SkyLab | https://www.skylabglobal2.com/ |
| TERN | https://www.tern.org.au/news-australia-wide-aet-data/ |
| Yield Prophet | https://www.yieldprophet.com.au/yp/Home.aspx |

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# Appendix 1 Evaluation Form

## FWPA Project 'Next Generation Resource Assessment and Forecasting'

### Project Evaluation May 2022

**<u>Returns</u>**: Please return responses to . . . . . . . . . . . . . . . . . . . . by COB Wednesday 25$^{th}$ May.

**<u>Purpose of evaluation</u>**

The outcomes of this feedback will inform use of project outcomes and help define subsequent research. The purpose of this feedback is to:

- <u>Project management</u>: Understand how well the research project was managed.
- <u>Communications</u>: Understand how well communications were maintained.
- <u>Deliverables</u>: Understand the extent to which the research delivered outputs and met the expectations.
- <u>Adoption</u>: Understand to what extent outputs of the project have been useful already or are expected to be used in the future.
- <u>Value of investing in the project</u>: Understand the extent to which the project was a good investment.
- <u>Project development</u>: Improve on the development of future research proposals by considering expected and actual research implementation and outcomes.
- <u>Project outcomes</u>: Enhance future research outcome utility and implementation by industry.
- <u>Further research ideas</u>: Consider any required next steps or subsequent research required to be undertaken.
- <u>Availability of publications, software, and other outputs</u>: Determine which research outputs should be more formally published or otherwise made available to participants and more broadly.

**<u>Format of Evaluation</u>**

- Short and long forms of evaluation are offered. Participants are requested to do one or both.
- We suggest that participants complete this form electronically in MS Word, which will allow the extension of answers if that is needed.

**<u>Anonymity of Evaluation Data</u>**

- Participation in the survey is not compulsory.
- Respondents can choose not to identify themselves, but they will need to do so if they request a response in relation to specific items.
- Data collected in this survey will be anonymised when results are summarised.

## Evaluation – Short Form

Please indicate how strongly you agree with the following statements by placing a mark in the appropriate box. Comments can be added for clarification.

| Statement | Disagree Strongly | Disagree | Disagree Slightly | Agree Slightly | Agree | Agree Strongly |
|---|---|---|---|---|---|---|
| The project was well managed | | | | | | |
| Good communications were maintained | | | | | | |
| Deliverables were completely delivered | | | | | | |
| The project completely met expectations | | | | | | |
| My expectations of the project were clear from the start | | | | | | |
| The project has already assisted in decision making | | | | | | |
| Learnings from the project will be valuable for future decisions | | | | | | |
| The project was a worthwhile investment in research | | | | | | |

Comment on any aspect: . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .

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## Evaluation – Long Form

**Project Development**

Development of a research project that responds to identified research needs. At project end and reflecting back, were the identified research needs realistic?

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Are there any elements that were not included that should have been?

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Considering the proposed in-kind budget and actual inputs, where expected in-kind requirements realistic?

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**Project implementation**

Communications to project partners was via Project Steering Committee meetings, draft project reports, workshops and updates. Which is/are the most effective?

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Detailed and focussed workshop updates (e.g. 30 minute webinar) are possible. Should these be more used to update research progress and outcomes?

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**Project outcomes**

The stated project objective was to; *'provide a business and technical pathway for the Australian plantation forest industry to cooperatively invest in remote sensing and resource modelling technologies and systems to satisfy current and future needs'.* Was this objective realistic and achieved?

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Development of a research project and securing project partners creates expectations of research outcomes. Did project outcomes meet expectations?

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A range of information resulted from this project. List the most useful pieces of information

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What were unexpected outcomes of this research?

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Have research outcomes stimulated thinking of possibilities for implementation in your organisation?

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How will outputs be applied / implemented in your organisation?

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Of research outcomes, which should be considered for publication for broader distribution of results?

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How have research outcomes contributed to industry capacity development?

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How have research outcomes contributed to capacity development in your company?

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**Subsequent research ideas and other comments**

What would you suggest are subsequent research needs to build on outcomes of this research?

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**Would you be happy to be contacted for clarifications if needed?**

If so, please provide you name and contact details: . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .
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