FRAMES review

Dr Cris Brack
The Fenner School of Environment and Society, Australian National University
Final: Wednesday, 8 March 2017

1 Executive Summary

FRAMES – Forest Resource Assessment and Management Evaluation System – has been used to generate strategic yield regulation information for managing the public commercial forests of NSW for over a decade. The basic modules (Area, Inventory, Growth and Yield and operations Scheduling – see Figure 1 in FC FRAMES review document) – have remained largely consistent over this period and reflect the practice in comparable commercial forest management agencies. However, there have been continuous improvements in the information systems over this time with the incorporation of maturing technology (e.g. LiDAR and GPS) and better integration of multiple sources of data (e.g. the Forest Record and Events Database or FRED). This overarching structure is appropriate for strategic level planning and should be able to continue to adapt to future needs.

Within each module, continuous improvements have allowed for greater precision, reduction in bias, and more potential flexibility:

- The Area module now routinely uses LiDAR to much more reliably identify streams and other spatially identifiable areas that need to be “netted out of production”. The Area system also includes “modifiers” – NHAM, SRM – that further reduce the effective production areas which are essentially sample based (or empirical data from harvested areas) and evolve as licence conditions or other circumstances evolve. Such improvements within the Area system result in estimates that are more “realistic” and applicable in terms of determining harvestable area.
- Although the Inventory data collection has changed little (i.e. still used fixed area plots and basic tree measurements) there has been some improved modelling of harvestable products. But the biggest improvement here is likely to be to more effective use of this data in conjunction with LiDAR and plot imputation methods. Along with improved stratification, also made possible via LiDAR, the precision of the inventory estimates has improved considerably over the life of FRAMES.
- Growth and Yield improvements include recalibration of coefficients in the various models as PGP data become available or major reanalyses are justified by externalities. Recovery experiments have also begun to estimate empirical “correction” ratios that correct the modelled yields down to the realised yields.

The above improvements within each of these module further enhances the efficacy of FRAMES and result in estimates of area, standing stock and yield that are increasingly realistic and achievable.

The improvements in the Area, Inventory and Growth and Yield components of FRAMES however would have relatively minor impacts on the wood flow forecasts. Much greater impacts resulted from tenure changes (loss of areas of mature forest to production) and the imposition of additional constraints (e.g. requiring specific species or product mixes to be produced within each stratum). The imposition of any constraint will result in either (i) no reduction in the objective where the “non-binding” constraint could essentially met anyway or (ii) a reduction in the objective function that could be disproportionately large when the solution is tightly bounded.

Reduction in the harvestable area of mature forest and the introduction of minimum and maximum limits of products had substantial impacts on the overall objective function for Eden. There is also an indication that the regrowth forests of Eden may be growing slower and producing lower quality products than previously modelled, possibly due to the Millennium Drought or because the yield models are being extrapolated to a young stage.

FCNSW has successfully trialled a range of advanced technology including vehicle mounted GPS and airborne LiDAR. The uses include monitoring vehicle movements (especially harvesting machines) to substantively improve the understanding of where wood and yield is located – and integrating this information into FRED to eventually allow reconciliation with forecasts. The LiDAR layers provide much better data for strategic stratification and alongside the plot imputation methods, much better precisions of estimates. Furthermore, the LiDAR can support operational or tactical management as the scale of the data is much more appropriate and estimates can be extrapolated to "those on the ground". As well as improving precision of estimates, the on-ground users should be able to become more confident in the entire mapping and simulation process.

In conclusion then, I believe the FRAMES approach is efficacious for strategic level forecasting and that FCNSW continues to apply and manage this work appropriately.

1.1 Recommendations

a. The increasing coverage of LiDAR across the native forest landscape has allowed substantial improvements in the understanding of forest structure, terrain, harvestability and through plot imputation, spatially explicit stocking estimates. Standards for LiDAR overage should be developed and extended over the entire estate to allow the successful methods to be exploited over entire area.

b. Plan and provide funding for systematic remeasurements of the PGPs. Long term and regular measurements are essential to the ongoing development and monitoring the growth and yield models.

c. Review recruitment and mortality models, especially in Eden where numbers of trees ha^{-1} appear to be lower than expected. Issues need to be identified early to ensure best site occupancy and productivity.

d. Review the strategic inventory system to ensure measurements can be completed (and funded) in a timely manner to support FRAMES. The systematic plot location, while allowing flexibility for future analyses, is relatively expensive and may not produce the maximum information per dollar spent when used in conjunction with LiDAR and plot imputation. Variable probability or regression sampling with LiDAR may provide high precision with lower costs than the current systematic sample.

e. Review individual tree and unmapped area exclusion data to plan for improvements in "operational" modelling of practical / realistically harvestable areas. As more exclusions are identified during operations through GPS identification of individual trees and vehicle pathways, improvements over the simple sample-based averages currently used should be possible.

f. A recovery and correction project to improve the yield modelling at short and long term should be developed and funded. Recovery and conversion / correction ratios for the modelled to realised yields are currently relatively large and variable. Detailed stand structure and topography information from airborne LiDAR may be a useful correlate in modelling the ratios. Detailed individual trees measurements from terrestrial LiDAR or photographs may also prove to be powerful correlates.

2 Introduction / Context

Following completion of the *Indufor* review of resource modelling systems and processes pertaining to the Forestry Corporation NSW (FCNSW) softwood plantation estate, the Board Audit and Risk Committee for FCNSW requested an internal audit of HFD resource modelling processes.

The RFA 10-year and 15-year reporting and review processes also includes a requirement to report on *inter alia* FRAMES description, improvements and reviews.

FC therefore proposed that a single review process cover both these requirements, and two documents were consequently prepared to support this process:

a. An update of the 2013 FRAMES development and implementation report (prepared by Sally Bayley).

b. A summary of wood flow model outputs for coastal forests covering RFA, Audit Office Performance Audit reporting and current modelling (prepared internally by Tim Parkes).

This consultancy is the outcome of the review request.

2.1 Terms of Reference

1. Using the FRAMES development and implementation report as a reference, review and comment on the efficacy of the FRAMES modelling system, information base, processes and assumptions including:
   a. Forest area data including forest description, LiDAR metrics and logging history data
   b. Forest inventory
   c. Growth and yield modelling.

2. Review and comment on wood flow forecasts as reported by FCNSW, with particular reference to Eden and Southern RFAs, and improvements that have occurred since modelling undertaken for the RFAs.

3. Comment on current and proposed uses of new technology (especially LiDAR) to improve area definition, inventory, planning and modelling processes.

2.2 General Approach

In conducting this Review, I have drawn heavily from presentations and interviews with officers of FCNSW during 5 – 9 September 2016, and internal reports provided by them (see section 8.1). I also draw on my prior experience with the inventory and planning systems of FCNSW, including those related to River Red Gum (2009) and Cypress Pine (2016). An earlier version of FRAMES had been provided to the ANU for use in teaching and research and my students and I have examined the system and its implicit assumptions during coursework for a number of years. I have also generally kept up with the advances made with FRAMES and inventory in NSW. There was no expectation or provision for field visits or collection of primary data as part of this review. There was also no expectation or capacity for running model simulations or other analytical exercises.

The 2016 FRAMES documentation provided by FCNSW is a comprehensive document and will not be summarised or replicated as part of this Review. That document successfully describes the overall structure and approach used in FRAMES documents the major developments over time. I have reviewed and offered separate comment on that document. The next 4 sections will review some of the issues or aspects of technological and other developments which may impact on the efficacy of the major components of FRAMES. Where appropriate, specific examples will be drawn for some Regions to illustrate these issues. Finally, I discuss changes in the strategic yield models since the previous RFA and suggest some strategic directions for improving the FCNSW inventory and modelling support system.

3 Area / Geographic Information System (GIS)

The GIS is used to determine the Net Mapped Area (NMA) used in FRAMES. Layers of spatial information are used to initially define gross (total) area, then reduce this to NMA by subtracting exclusions due to legal, practical or commercial reasons. The maps of the NMA can be displayed, but this area may be further reduced to account for "non-mappable" aspects (too small to be mapped or not found until operations begin). These non-mappable exclusions include Net Harvest Area Modifiers (NHAM) relating to previously unmapped legal or practical exclusions; and Strike Rate Modifiers (SRM) which account for previously unmapped localities that are found during pre-harvest surveys to contain trees or habitat that must be protected as part of the Threatened Species Licence conditions.

The purpose of the NHAM is to quantify contractor behaviours in the vicinity of "hard" boundaries, over which trees cannot be felled. This issue was more important when harvesting was dominated by manual operations. With the shift to mechanised harvesting, the size of NHAM may be substantially reduced as technology, especially high point density or full wavelength LiDAR, improves the ability to map fine scale topography under forest canopies (i.e allow accurate removal of unharvestable areas from the gross area in the initial phase). Similarly, improvements in GPS locational accuracy and realtime monitoring may reduce the need for "arbitrary" boundaries outside legal limitation that are currently implemented to avoid risks of litigation. Although not strictly required, according to Vanclay (2002) these arbitrary boundaries are "real" and can potentially reduce the NHA a further 20 – 25% depending on configuration. Even if reduced, NHAM factors will remain important due to variations in machinery used, residual GPS error especially under heavy canopy, and operator performance.

SRM are usually estimated as an "equivalent" reduction in NHA, expressed as a percentage. The percentage is estimated from monitoring completed operations (i.e. the reduction experienced under application of the Licences), although there is some external opinion that a fixed percentage amount to be additionally reserved is set by those Licences. Vanclay (2002) also noted that some, otherwise merchantable, trees have been left "for no apparent reason" and good supervision and training is required to minimise these unnecessary deductions to commercial outcomes. Both NHAM and SRM are designed to avoid incorporating economic write-downs or exclusion for "no apparent reason". However, exclusions for defined reasons would be best dealt with through silvicultural modelling when inventory data is sufficiently detailed. In the recent Cypress Pine analysis, I noted that reservation of individual trees may also include an exclusion area around those trees, but that exclusion area may not simply denote an “average” landscape – large trees may easily be large because the site is above average quality and therefore above average volumes may be in the exclusion zones.

However, the NMA, even when reduced by NHAM and SRM, may still overestimate the area practically or commercially available at a coupe level if the residual harvestable area is too scattered or contained within a “ring” of excluded areas. Human intervention is required at this point and a GIS analyst would need to make a “tactical / operational” decision on whether to withdraw the entire compartment or coupe from the harvestable area. Such withdrawals may easily exceed the percentage reduction assumed by SRM and will become greater as more Licence conditions are added. Such changes will have an impact on the Strategic levels of yield planning. For example, North Coast modelling of NMA undertaken for the 2012 analysis did include an analysis of “small and isolated polygons”. This analysis identified between 0.5-1% of NMA was affected, depending on terrain and reserve boundaries. This factor was applied at the Price Zone level.

The GIS is also the major repository of silviculture and fire history data. Since 2011, this type of spatial data has been collected in the Forest Record and Events Database (FRED), with historical data progressively being added as practical. Spatial precision varies from blanket “100% of the compartment was treated/affected” through to increasing use of remote sensing and GPS tracking of major harvesting machinery for spatial attribution of harvesting extent.

Although a GIS is, by definition, a spatially referenced system with position and distance between objects explicitly recorded and available for calculation and manipulation, NHA as used in FRAMES is aspatial. Essentially, FRAMES works with the net quantum of hectares available for harvest without considering where those hectares are (contiguous, dispersed, closeness to boundaries, average size of patches, etc.). To gain some spatial reference within FRAMES, areas can be classified or stratified by some geographic metric (e.g. distance to a specified point) so that the NHA within each specified spatial condition can be determined. FCNSW uses Price Zones (geographic areas around industry centres) as a broad spatial stratification. Such Price Zone stratification may be useful for ensuring yields and management operations are spread in a pre-defined manner across the entire estate (for commercial, practical or political reasons). Price Zone stratification should not be expected to have any impact on improving the sampling precision (see Section 4) as it is largely just a reflection of location rather than homogeneity of the forest. However, additional stratification programs (e.g Forest Types) can be applied within the GIS which can be used to improve inventory precision. The limitation on the number of strata created (for both geographic and homogeneity reasons) is usually the number of inventory plots needed within each individual stratum – under normal stratified random sampling with fixed area plots, there is a theoretical minimum of two plots per stratum, but a practical requirement of 5 – 25 plots. More recent developments with LiDAR and other advances (see Section 4) have the potential to significantly mitigate this limit on the number of stratum that can be used in FRAMES.

The current stratification used for North Coast modelling includes both forest types (identifying highly productive forest types such as Blackbutt and Moist Coast Eucalypts) and LiDAR-based volume-equivalent stratification. Likewise, Eden area mapping incorporates LiDAR-derived volume stratification.

3.1 Efficacy

Overall, it is my opinion that due care has continued to be taken in all aspects of the area / GIS and the outputs from this system continue to useful and reliable for their purpose of strategic level yield modelling.

The increased use of LiDAR to improve mapping; development of FRED and linking FRED to the sales systems will improve the reliability and currency of the Area system data.

The ability to define an increased number of stratum has improved the potential to include some geographic constraints in the yield optimising, although the aspatial nature of FRAMES reduces the ability to incorporate restrictions or constraints based on spatial relationships like adjacency or maximum area of treatment. Such spatial constraints can currently only be implemented at operational/tactical levels, although here the GIS will be extremely useful / critical.

4 Forest Inventory

The current FRAMES inventory system is based on systematically placed, fixed area plots. The intensity of these plots varies across the State depending on history, heterogeneity and value of the products. However, in general, the number of plots is set so that the strategic level "snapshot" of High Quality (HQ) volume has a confidence range for mean volume of +/- 30% (p=0.05) per stratum.

Although the sampling intensity is designed to provide a minimum level confidence range around the mean, FRAMES uses each individual plot in its simulation (see Section 5) and does not use the inventory mean values *per se*. This is most appropriate for the FRAMES-based simulation approach.

The systematic placement (using a grid with a random start point) provides an equal probability sample across the NHA. No plots are established in areas identified in the GIS as being unavailable for harvest. Consequently, the strategic inventory system cannot provide any details on stand structures or habitat values in these areas. This may be a disadvantage when habitats or distance to habitat structures are important in strategic decision making.

Data collected on each plot includes traditional tree-level parameters for trees greater that 10 cm DBHOB (Species, DBHOB, height (on a sub-set)); product quality features; habitat features and accessibility. The product quality features are based on a commercial inventory system – YTGen – which has been calibrated to predict product by quality class outturn based on classifications of the stem conditions and a user-specified cutting strategy. Inventory files from previous systems (MARVL and Atlas Cruiser) have been converted to the newer YTGen system.

As airborne LiDAR is becoming increasingly available, it is being used in conjunction with the strategic "ground" inventory plots to support a Plot Imputation approach to forest inventory. Plot imputation utilises a relatively mature sampling approach – Nearest Neighbours – to allow spatial predictions of inventory parameters from LiDAR data. These predictions have a number of advantages over traditional inventory systems (plot means) and allow for a realistic variance or heterogeneity across the landscape. Although such a powerful plot imputation system may confer significant advantages for operational / tactical planning (e.g. estimates of volume at sub-ha levels across entire compartments or coupes), the original FRAMES simulation system was not designed for such spatial precision or detail.

However, the increased precision of the Plot Imputation method (along with the improved forest structure information provided by LiDAR) means that more stratum can be reliably defined and more precise estimates made on these stratum for the given number of fixed area plots.

Other technological and processing advances are also becoming increasingly available to improve forest inventory. Ground-based scanning lasers, multi-spectral scanners, high resolution digital cameras and drones are increasingly available as consumer-level goods. Given that the biggest expense in forest inventory is usually the “cost of putting boots on the ground” then it may be appropriate to gather as much detail as possible during each field visit. Technology can allow the capture of 3 dimensional images (laser point clouds as well as visual and non-visual images) of every tree in the plot (as well as conceptually every tree encountered on the way to the plot). Such data could provide much more objective and repeatable data on products and product quality (than YTGen); reduce reliance on tree taper or DBH:Height models; provide more details about tree canopy and habitat; and allow improved detail about tree health and growth condition. Forestry Tasmania, for example, record observations as crews walk into their inventory plots then use this information to improve mapping of vegetation and their understanding of the heterogeneity of the forests.

Laser-based or multi-point digital photographs also allows the automatic derivation of stem maps. Such stem maps potentially allow distance-dependent growth and yield models to be utilised. Distance-dependent growth models are usually more reliable (unbiased and precise) than distance-independent models (as currently used in FRAMES) but have until now been impractical due to the previous high cost of surveying required to collect the stem map data.

4.1 Efficacy

Overall, it is my opinion that the current strategic inventory procedure with fixed-area plots systematically located, although not “cutting edge”, is adequate for the provision of strategic level data into FRAMES. The process should continue to provide useful and reliable data for this purpose.

Establishment and measurement of the Native Forest Strategic Inventory (NFSI) plots is a major undertaking for FCNSW. Ideally, resources should be available to ensure a systematic approach is funded for these inventories so that the “snap shots” do not become too dated (FCNSW documents suggest within 10 years). However, I understand that the current inventory schedule may not be meeting this target. Improvements with related systems (e.g. FRED) may reduce the need for remeasurement, but ultimately evidence of wide-spread accuracy of the simulations or new “snap shots” will be required.

FCNSW has demonstrated the success of using strategic plots in conjunction with LiDAR and plot imputation to substantially improve operational / tactical level inventory data. These improvements can be brought into FRAMES through an increase in the number of stratum that can be created with acceptable precision, which can significantly improve the spatial aspects of the model. The use of LiDAR and plot imputation approaches should be continued and expanded.

The opportunity also exists to exploit currently available technology to gain substantially better *in situ* data during travel to the plot as well as when at the plot with little additional effort. These additional data could easily improve the precision of product estimates and provide input into significantly improved growth and yield models.

5 Growth and Yield Modelling / simulation

FRAMES "virtually" visits each strategic plot and simulates the overall plot growth, then individual trees within the plot are grown annually to the next (5-year) period. Trees are simulated as dying (mortality) with a probability related to their size and plot-level competition while 10 cm+ DBH trees may also be simulated as entering into a plot or being recruited as small trees growing large enough to cross the size threshold. If the plot meets silvicultural prescription thresholds (basal area limits, time since previous harvest or "delay" criteria) individual trees are virtually harvested – starting with the first in an ordered list and continuing until stop thresholds (basal area reductions, volumes) are met. To meet licence requirements for habitat, seed and similar trees that need to be retained, the tree list is reordered and appropriate trees from the lesser commercially valuable stems are selected for retention. The volume and taper of trees selected for harvest are simulated and (using the YTGen classifications) divided into logs grades. Plot/compartment volumes and grades may be downgraded or modified to account for practical outcomes (calibration). This process proceeds for all periods in the planning horizon and results in a Yield Table of products and stand characteristics per hectare for each period. This process is repeated for each plot.

Each strategic inventory plot therefore is used to create a number of "yield tables" – volumes (by product) or other stand parameters for each period – for each proposed silviculture and "delay" period. The plot can "represent" a certain number of hectares in the appropriate strum or potentially be averaged with other plots under alternative stratification process that minimises variance between plots (i.e. a more traditional inventory based stratification approach designed to minimise sampling error).

However, more recent versions of the FRAMES simulator allow two different modes of modelling. In addition to the conventional yield tables described above, where silviculture and future management options are embedded by the Simulator, a second mode now allows plot level "Type II" yield tables to be generated. Type II yield tables provide the opportunity to harvest over a range of time periods and silviculture options. When a harvest event is scheduled in a particular period, the model then transitions to a yield table associated with the post-harvest state. This Type II mode was used for the Eden imputation-derived analysis in 2016.

There are numerous equations or models required for the simulation component of FRAMES: Stand basal area growth; tree basal area allocation or DBH growth; height from DBH; mortality and damage (natural and induced by human activity); recruitment; tree volume; tree taper/shape; product volume and calibrations. There may be species group and/or regional specific models developed. Stand and tree basal area / DBH and height models are developed from data provided by Permanent Growth Plot (PGP) system; while taper, mortality and recruitment models are developed from a range of data sources from routine inventories to specified research plots. Calibration models were developed from FRAMES-specific inventory projects over “appropriate” scales of harvesting to account for internal/hidden defect, harvest damage and other practical issues.

Most of the biometric (growth) models were developed in 2000 – 2003 under various projects (partially) funded by the RFA process. The most recent model development is for the native forest species plantations by Goodwin (2012), where some major changes to the model structures and modelling logic was proposed to improve precision and accuracy. Goodwin (2015) also reviewed the Eden growth model.

Predominately, the mathematical forms used for the various models are all examples of common forms used in the forestry growth and yield literature. They are generally robust and as parametric statistics their fitting procedures are relatively transparent. However, there are a large number of corrections, write-down, leakage and calibration factors which may interact in various ways and cause some confusion. A flow diagram of these various factors and their conditional implementation would be useful. Publication in a technical or professional journal could add further confidence in the biometric models.

The exception to the model form comments above appears to be the pre-1994 hardwood plantations which did not use the Goodwin (2012) models. The grown forward growing stock of pre-1994 plantations have been calibrated by a comprehensive inventory undertaken in 2015-16, and areas which were classified as unlikely to be commercial were excluded. Projections for the remaining pre-1994 blocks were found to match the inventory results so the current yield tables were not changed. FCNSW is planning to use the Goodwin models to rebuild yield tables at a more tactical level for future reviews.

Ideally the Permanent Growth Plots (PGPs), which provide the bulk of the growth data, are measured every 5 years and cover the full range of site and species present. Unfortunately, regular establishment and remeasure of the PGPs is not keeping this ideal. Recent reports (Cypress Pine and River Red Gum) have specifically criticised the length of delay between measurements, although noting that in slower growing species this may not be a major issue and the return measurement time can easily extend beyond 10 years. Long periods between measurements however may reduce the potential to determine the effects of climate change, drought or other large scale environmental change. However even the fastest growing trees (the native species plantations) are not being remeasured within the preferred period (Goodwin, 2012) and re-measurements are becoming urgent to maintain credibility of the models.

The Eden region essentially only has one set of growth data available from its PGP (establishment then 1 re-measure) and this series largely incorporates just the period of the Millennium Drought so it may not be representative.

Substantial discussions were had during September on regeneration and recruitment. Inventory data for the Eden Region in particular suggested that the number of trees in the smallest DBH classes (10 – 20 cm) were lower than expected in earlier modelling work. This stand cohort may also have been impacted by the Millennium Drought, and further investigations of the issue are warranted. In other regions, regeneration and recruitment had been seen as an issue, especially where Australian Group Selection (AGS) was being practiced. It was inferred that the gap size was too small for light demanding eucalypt species like Blackbutt to adequately repopulate the site. In these Regions, AGS was being replaced by a new silviculture option – Single Tree Selection for Regeneration (STS-R). This option is similar to the more traditional

Seed Tree silviculture with the exception that the seed trees are not necessarily harvested in a subsequent visit, and the retained trees essentially include seed and habitat trees. To ensure average retained basal area is consistent with the requirements of the Integrated Forestry Operations Approval (IFOA), STS-R is modelled in FRAMES by reducing the minimum basal area threshold required after harvest and disabling the percentage basal area proportion limitation in some areas while other areas in the coupe retain a higher residual basal area to maintain the overall "minimum" basal area conditions of the harvesting licences.

Regeneration data provided by the FCNSW inventory system suggests that STS-R is much more likely to produce successful regeneration than AGS. It has also been reported that AGS, on the North Coast at least, commonly results in lantana or other weed infestations instead of Blackbutt regeneration. However, AGS was not applied in the Eden Region and the reasons behind the lower recruitment levels in the 10 cm DBH class remains a concern.

Vanclay (2000) voiced concern that the harvesting simulation (i.e. selection of trees to remove or retain) was not realistic and could substantially overestimate the merchantable volume. A FRAMES-specific sampling exercise undertaken on the North Coast in 2007 – Recovery Study –was undertaken to moderate volume estimates by quality class to account for internal defect, cutting errors, breakage and grading errors. The corrections reported were quite substantial with 30% of High Quality Large Blackbutt logs (highly desirable) being downgraded. Lesser desirable species could have over 60% of their High Quality Large logs downgraded to small, low quality, pulpwood and even waste. Subsequent correction factors and changes have improved (reduced) the amount of downgrade.

A structured monitoring program has been developed – Actual vs Predicted Harvest Reconciliation – in response to the Auditor General's (2009) recommendation. This program allows detailed and specific data on the application of the simulation components of FRAMES to be compared with sales data. The program is integrated with FRED, Sales and strategic inventory plots to compare "Analysis Group" predictions of growth, yield and silviculture. The most recent analysis (2009-2013) suggests there is no significant difference between the mean HQ volume ha^{-1} predicted and realised. The Analysis Groups appear to be useful aggregations of harvested area by silviculture and species group. However, further parameters of potential interest beyond just HQ sawlog could also be monitored which may help disaggregate the various potential model components and errors. The lack of any significant difference, while welcome, could also be due to the relatively large variance within the Analysis Groups, short projection periods and relatively weak statistical test (e.g. only 2 of the 10 Analysis Groups has a mean Actual HQ greater than Predicted HQ – an unbiased model would expect 5 out of 10). Unusually, the variance (used to estimate PLE in the Report) was greater for the Predicted values than the Actual – parametric models tend towards the mean which results in less variation in the predictions. Improvements in the form of spatial recording of harvest tracks, GPS tagging of log dump volumes and LiDAR-based volume estimates will likely improve future reconciliation processes.

5.1 Efficacy

The Growth and Yield simulator component of FRAMES, especially where regional moderation or Recovery data is available for "calibration", is likely to be useful for short and medium term predictions. The limited Reconciliation studies tend to largely confirm the efficacy of yield predictions in the short term.

The paucity of PGP measurements over the past decade and lack of continuous biometric model development however makes longer term projections less reliable. The often substantial corrections observed in the Recovery Study suggests that the simulations models are not performing completely adequately and some bias exists. Although Recovery study based coefficients allow an empirical correction to this bias, such a correction is unlikely to be constant over time. While Recovery / Calibration Studies are planned for all Regions, a number (e.g. Cypress) have not been fully implemented.

Lower recruitment levels in Eden (compared to modelled values) and the "switch" to STS-R from AGS on the North Coast (justified partially by low realised regeneration in contrast to the simulated recruitment) also suggests the recruitment and/or mortality models are not performing adequately. Mapping or modelling of weed infestation, including Bell Miner impacts as appropriate, may also be needed. Designed experiments or targeted monitoring of regeneration / recruitment over a variety of species groups, sites and silviculture is recommended to improve the efficacy of this component.

6 Optimisation

Optimisation of the wood flow (yield scheduling) is largely performed using the commercially produced product *Woodstock*. Woodstock determines the optimal allocation of net harvestable area (Section 4) to yield tables (Section 5) to maximise an objective subject to constraints. Objectives and constraints can change with each *run*, and over the period of the RFA have indeed changed in general. Originally, the objective was largely to maximise the production of large HQ logs, but increasingly this objective has been modified to simply maximising all HQ logs. Other corporatized entities (e.g. Forestry Tasmania) have an objective of achieving "…a sustainable commercial rate of return…" which may be interpreted as maximising the net present value (in dollar terms) of the yield schedule.

Constraints vary, but largely include minimum or maximum volumes produced or areas treated in different periods, forest types or strata especially to meet Wood Supply Agreement commitments.

Sustainable production, for example, is often modelled as a constraint to produce (approximately) the same, or increasing, volume of desired product in each period. Early implementations of this sustainability constraint could lead to "optimal" solutions where one species or supply zone was targeted in some periods only, which lead to uneven and unacceptable management conditions. Over the past decade, these constraints were "tightened" to require similar yields over the periods by forest type and Supply Zone. The North Coast model, which covers the largest geographical extent of the FCNSW's resource models, now incorporates customer allocation-based constraints that allow the inclusion of economic drivers in the model formulation. The 2012 North Coast model also incorporated an objective function to maximise the NPV of mill door price.

Each time a constraint is added or "tightened", the value of the objective function will be reduced (unless the constraint is non-binding, and in fact, not needed). Thus, over the life of the RFA, the estimated production of Large HQ logs produced over the period will have been reduced as each constraint has been added, over and above reductions resulting from reductions in the areas available for harvesting.

However, the reduction in the objective value may be disproportionately greater (or lesser) than any change made in the constraints (e.g. increase reserve areas or reduce the NHA) or the yield table (e.g. increase the SRM). For example, constraining the amount of mature forest that can be harvested (or reducing the NHA of this forest type) may lead to the early harvesting of regenerating forest to ensure the "even flow" or minimum periodic volume constraints are met. As these regenerating forests may be being harvested earlier than their individually optimal period in order to meet the estate-wide constraint (i.e. before their maximum product Mean Annual Increment (MAI)), the total volume of desired product is reduced by this early harvest as well as the volume (and subsequent growth) in the mature forests that are unavailable. The MAI curve can be quite steep for regenerating forest as it moves up to its maximum, although it may reach a near plateau after that maximum.

Some additional constraints can result in the yield scheduling becoming unfeasible, i.e there is no combination of area and yield table that would allow all the constraints to be met. The imposition of strict equalities (e.g. yield in Period1 = Period2) often creates these infeasible solutions and a common response is to utilise goal targets instead of hard constraints. Thus, it would not be unexpected for the yield schedule produced from Woodstock to initially look quite variable over each period in a planning horizon depending on the goal settings. Some manually "smoothing" can be applied outside the LP model with some yields moving back or forward by 1 or 2 periods. Care is needed in this manual smoothing, especially when the growth consequences due to the non-symmetric MAI curve may mean substantial potential volume is lost when harvesting is advanced to an earlier period, but not gained when delayed to a later one.

Although technically possible, constraints can be added to ensure the yields are "smoothed", and spatial constraints (e.g. minimum return times or times between harvesting adjacent compartments) can be applied, but it is rarely practical in real world problems. Such constraints require individual harvesting units to be individually designated along with a separate constraint for every spatial condition required, which normally leads to a combinatorial "explosion" of constraints. Given the strategic nature of FRAMES, it is usually expected that these spatial and finer levels of temporal constraint are Operational or Tactical issues – to be resolved by on-ground personal once the "big picture" strategies have been identified. However, the special and fine-scale temporal constraints will have an impact on the overall objective and the strategic yield will be reduced. It is difficult to determine *a priori* the level of this reduction, and some spatial constraints may actually make the solution infeasible.

Linear programming systems like Woodstock are inherently limited in the size of the problem that can be solved. Sophisticated advances (like moving from Type I yield table models to Type II, as has been recently achieved by FC NSW) can expand the size of the problem that can be resolved, but rarely can such advances improve the ability to directly implement the solution at an Operational or Tactical level, nor quantify the loss that such implementation will suffer. Similarly, the LP framework is unlikely to ever be able to fully exploit the wealth of spatial data that can be provided by spatially fine-resolution and wall-to-wall inventory (e.g. LiDAR and plot imputation); improved and distance-dependent growth and yield models that can be driven by modern ground-based collection tools; or incorporate optimal distance to mill and other spatial modelling tools.

Linear programming systems are also based on deterministic assumptions, i.e. the inputs are assumed to be known or certain. The optimal solution is thus valid for the initial input data but if any part changes beyond a very restricted range, the solution must be recomputed with the new data set.

Simulation (e.g. simulated annealing) or knowledge-based / expert system approaches provide an alternative to LP. Although technically such alternatives are "satisfying" rather than "optimising" they can produce results that are superior to an LP once tactical / operation constraints are incorporated. Such alternatives could take much more complete advantage of the fine spatial resolution of the LiDAR / plot imputation approaches being developed within FCNSW and the spatially explicit modelling that the more advanced inventory technology allows. An expert system can also "explain" why particular options are selected (at least provide a logic tree and/or weighted hierarchy of decisions), while also being able to "learn" when schedules are over-ridden or changed (Brack and Marshall, 1996).

6.1 Efficacy

I believe that Woodstock, assuming appropriate inputs provided by the Area, Inventory and Simulation components of FRAMES should continue to provide useful and reliable outputs for its strategic purpose. Estimates of the strategic yields and optimal function values are discounted to account for the spatial, temporal and other tactical / operation constraints that cannot be practically incorporated into the Woodstock model. On the recommendation of URS, when reviewing the 2012 North Coast model, a safety margin of is applied to all yield estimates – a 10% factor is applied to native forest yields and 15% for post-1994 plantation yields.

Advances in decision support systems, especially those that can more fully take advantage of the increased precision available to FCNSW as described in Section 3, 4 and 5, should be explored. These systems can still use the Woodstock yield schedules as an initial input but have the potential to substantially improve implementation and overcome the strategic / tactical / operational disjunct.

7 Changes in yield projections over the RFA periods

The overall FRAMES approach has not changed substantively in structure over the past 1 – 2 decades. Improvements in the precision and reliability of the data, especially the Area system (with LiDAR, plot imputation, FRED and GPS) has occurred and has resulted in substantial overall improvement in precision over this time.

Changes in the simulation, especially through the implementation of calibration or recovery factors may have also reduced bias, especially over predictions of large HQ products. Other changes in the simulation includes some modification to the thresholds that trigger a harvesting simulation (e.g minimum volumes increased for area designated as difficult (expensive) to access). The implementation of STS-R may also have provided an opportunity to gain more commercial volumes early in the schedule period while encouraging better regeneration to grow products for the later periods.

However, the greatest impacts on the yield projections have likely resulted from changes in the objectives and constraints modelling in Woodstock, and land-use change decisions made outside FCNSW control. The imposition of constraints that provided a more temporal balance of harvesting of preferred forest types (e.g. Blackbutt in the North Coast and Spotted Gum in the South Coast) meant that these forest types could no longer be scheduled completely in the early periods, although they could return later in the schedule. Given the relative growth rates of these species as compared to the less marketable species, such a scheduling change could cause a substantial drop in the strategic yield. The resulting inclusion of more non-preferred species into the immediate harvesting schedules may also have a significant impact on harvesting contractors and millers. Similarly, additional constraints on minimum thresholds of volume (by species) for each price zone would have also resulted in a substantive reduction in the overall strategic yield and areas are forced away from their individual optimum harvest age to meet the new constraints.

However, while increases in less marketable species can be a side effect of tighter constraints on the delivery of better quality species, FCNSW uses additional constraints to control the delivery of less marketable species so that these cannot artificially “top-up” the commercial yield. Multiple runs of the Optimiser with different constraints may be required to gain a complete picture of all HQ species and product volumes through time when determining the “final FRAMES outcome. Likewise, short-term volume smoothing constraints at localised (Price Zone) levels, act to match supply to known contractor capacity and also ensure projections are consistent with historic trends.

Reductions in the NHA due to political decisions on land use (e.g. reclassification of tenure to National Park) have had a disproportionate effect on the overall yield regulation, especially when the areas transferred to national park contained substantial amounts of currently merchantable timber (and thus allowed regenerating forests more time to grow) and plantations. It is likely that the transfer for four commercial forests into conservation tenure in the Eden region is a significant contributing factor to the requirement to harvest regrowth forests well before their optimal to meet yield flow constraints.

8 Conclusions

FRAMES continues to provide reliable and useful information to support strategic level management and the estimation of long term yield flows. The data underpinning the system has largely undergone an incremental improvement process, particularly in the Area sub-systems, although the simulation sub-system remains reliant on “calibration” or “correction” factors to remove bias.

FRAMES continues to provide best-case estimations of strategic decisions (e.g. impact of changes in NHA due to large scale Licence condition changes or supply zone changes) but in its current implementation is not well suited to support operational and tactical decision making. The quality (precision or fineness of scale) of modern inventory data currently available to FCNSW currently exceeds the capacity for its use in FRAMES in its traditional form. Similarly, substantive improvements in data collection technology and modelling theory are available to FCNSW although the current FRAMES structure limits its optimal use.

It pleasing to see that FCNSW has begun to explore changes to the FRAMES structure (which is largely predicated on strategic yield scheduling using an optimisation of strategic decision variables) to one that can more fully take advantage of the LiDAR, plot imputation and modern inventory technology and theory now available. In addition to improvements in the quality of spatial data, most notably the use of LiDAR and mobile tracking data, FCNSW has continued to improve the functionality of FRAMES. The FRAMES Simulator has evolved and adapted so that it is now able to generate Type II models. This will enable the incorporation of plot imputation (Nearest Neighbour) outputs in FRAMES models. FCNSW has also continued to refine and develop analysis techniques and database management necessary to handle the huge volumes of data associated with plot imputation. Work has commenced on a prototype spatial tactical model that will deliver forecasts at a spatial resolution superior to the current Price Zone approach.

Such alternatives can largely erase the strategic / tactical / operational disjunct that otherwise requires allowances for "headroom", discount or other "flexibility" when making strategic yield estimates.

9 References

9.1 Internal documents sighted

Goodwin, A. (2012) Review and Recalibration of Hardwood Plantation Growth Models Part 1 – Tree Volume and Stand Growth Models.

Description of North Coast timber resources modelling "base case" used for the Natural Resources Commission (NRC) Timber Industry Investigation (2016).

Extracts from 2015 Annual Valuation Report (2015).

Performance Audit Report: Yield Forecasts – Hardwood plantations (2011).

Forest Resource and Management Evaluation System (FRAMES): A report on its development and implementation to 30 June 2016 (2016).

Vanclay (2002) Review

9.2 Other references

Brack, C.L. and P. Marshall (1996) Test of Knowledge-based Forest Operations Scheduling Systems. Canadian Journal of Forest Research 26: 1193 - 1202.