PROCESS-BASED MODELS IN EUCALYPTUS PLANTATION MANAGEMENT: REALITY AND PERSPECTIVES

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Summary

Yield prediction in commercial forestry has been dominated by empirical modelling. Increasingly, however, process-based models are finding application either in support or instead of these traditional models. In this paper we draw the new forestry demands and how these models can answer different kinds of questions such as forest productivity in planted areas and new plantation, water-use, carbon sequestration and effects of climate change on forest production. In this paper we review current performance against management needs, concentrating in particular on the application of the 3-PG (Landsberg and Waring, 1997) and CABALA (Battaglia *et al*., 2004) process-based models. In general we find that process-based models have met many of the expectations of a decade ago. The paper briefly indicates new opportunities of process-based models in the area of wood properties and wood products prediction and in the area of forest health assessment.

Key words: process-based model, forestry demand, forestry productivity, management system, .

Resumen

Modelos basados en procesos para la gestión de plantaciones de *Eucaliptus*: realidad y perspectivas

La predicción de rendimientos en la silvicultura comercial ha estado dominada hasta ahora por el empleo de técnicas de modelización empíricas. Sin embargo, los modelos basados en procesos se están utilizando cada vez más como suplementos o incluso sustitutos de los tradicionales. En este artículo apuntamos nuevas demandas forestales y la forma en que los nuevos modelos pueden dar respuesta a diferentes cuestiones como la productividad forestal tanto en zonas plantadas como en nuevas plantaciones, el uso del agua, el secuestro de carbono y los efectos del cambio climático en la producción forestal. Asimismo, valoramos la eficacia de los modelos frente a las necesidades actuales de gestión, sobre todo en lo relativo a la aplicación de dos modelos basados en procesos: 3-PG (Landsberg y Waring, 1997) y CABALA (Battaglia *et al*., 2004). En general, los modelos de este tipo han colmado muchas de las expectativas que suscitaron hace una década. En este artículo se esbozan nuevas aplicaciones para estos modelos en cuanto a la predicción de propiedades y productos de la madera, así como a la valoración de la salud de los bosques.

Palabras clave: modelo basado en procesos, demandas forestales, productividad forestal, sistema de gestión.

Introduction

Process-based models of forest growth and production have now been around for more than a quarter of a century. Initially seen as research or teaching tools (i.e. the role envisaged for Biomass produced in 1985 and published as McMurtrie *et al.* , they have increasingly become part of the forest management decision making process. That is not to say they have been widely taken up or uniformly applied: some of the leading and more innovative of forest companies have integrated them into their forest growth estimation and management systems (e.g., Aracruz, Brazil; Great Southern Plantations Australia), others use them to support some aspects of their business (e.g. Timbercorp Australia, Arauco, Chile) and the sector as a whole enjoys the benefit of their use to explore problems such as climate change where historical data offers little insight.

In this paper we wish to show that the changing nature of the forestry industry, challenges facing the forestry sector, our increased knowledge of forest function, and the support to managers that the current generation of process-based models can offer, make increased utilization of these tools likely.

Changing forestry

The demands of forest management are changing. In Australia and around the world wood is increasingly being sourced from plantations and less from native forests. Although plantations represent less than 5% of the world's forest resource they supply 35% (624 million m^3) of industrial wood (ABARE-Jaakko-Poyry 1999, FAO 2005). Continuing restrictions on native forest logging meant that future increases in the global supply of wood from plantations expected to provide two-thirds of the world's wood by 2040 (ABARE-Jaakko-Poyry 1999). This growth in supply will require both an increase in the area of plantations and an increase in the productivity of these plantations. Commensurate with this change is a move away from government ownership into private ownership, and increasingly not local ownership but investment and management by global corporations (FAO 2003). Higher capital investment and competition for this establishment capital has increased the demand for a robust assessment of returns on operating capital and an evaluation of the risks associated with the growing of these plantations. The expansion of forestry into new areas where there is little or no historical data is similarly creating difficulties in evaluating investment risk. In Australia, the US and some other parts of the world the entry of trust funds into forest ownership has added further complexity, creating a highly risk adverse, but image conscious (in the sense of wishing to have a positive public profile on behalf of their shareholders) group of owners.

With this increased globalisation and privatisation of forest ownership, forests have become more tradeable. During the time a tree crop matures it may be sold off one or more times. Valuing forest estates is not simple – the crop of trees on a site reflects the conditions and management during the growing period and not necessarily the longer-term site potential.

Plantation forestry by its nature tends to be high return but also highly demanding of site resources such as nutrients and water. There is often significant investment in deploying improved germplasm to maximise production rates. To ensure that production is sustained or increased through successive rotation a matching of the demands of trees for the essential components of growth and the capacity of sites to provide these needs is critical. Where productivity rates are being raised in successive rotations by improved germplasm, a decline in the site nutrient capital or other requisites for growth may be difficult to detect without well-structured evaluation techniques. As a corollary, the high investment in germplasm, and the production of clonal material with specific site requirements is raising questions about in which situations and with what management inputs will these gains be realized.

Today, when compared with a few decades ago, forestry works in a more demanding and complex social and political environment. The ‘licence to operate’ is now based on a concept of custodianship of environmental and community values. More discerning consumer sentiments are promoting standards of accreditation to demonstrate sustainable and responsible management: access to some markets is now only possible with formal certification. The “off-site” impacts of plantations are subject to increased scrutiny, in Australia, South Africa and parts of South America this is particularly the case for water and stream flows, soils changes and biodiversity impacts. Management and evaluation of these requires a sophisticated analysis of the balance of environmental and economic benefits of forestry along with an assessment of their impact on regional natural resources and the rights of other users.

Increasingly too, forestry is not simply focused on log production but involved also in the delivery of environmental products such as carbon. Within Australia, at least, forestry may in the future be able to receive payment for the provision of ecosystem services such as the provision of habitat for biodiversity and reduce recharge to groundwater systems where rising water tables are contributing to land salinisation. As a result forestry in many places is now in the business of simultaneously providing multiple benefits and assessing the trade-offs and design plantation estates to maximise total benefits is a complex task.

The final change we wish to present is the concept of change itself. No longer can the past be considered a reliable predictor of the future: both biophysically and in the way forests are managed. Climate change may soon devalue the predictive power of years of accumulated inventory data – future changed conditions at a site may make growth data measured under current or past environments a reliable guide to the growth potential and the risks from drought or disease into the future. Furthermore, plantation management is now more dynamic. Germplasm changes are more frequent, the performance of the new material may outstrip that used to develop growth models but positing gains on the basis of genetic gains trials alone is a risky business – the extent to which gains are realised will be dependent on the extent to which site resources may ultimately cap tree production and whether breeding has improved resource use efficiency or the rate of uptake. Management regimes also are changed more frequently, reflecting market dynamics and the more frequent ownership changes, where different owners may target different market sectors or choose more or less intensive management on the basis of differing market analysis. Again in the face of these changes the past may not be overly informative of the future production from plantations. There is also evidence that the world forestry market in pulp is changing and becoming more sophisticated in trading on quality rather than on quantity alone. Traditional empirical systems that predict volumetric outcomes alone may be inadequate and insufficient where the three-way interaction of site, management and climate result in the wood properties that determine the quality of the end product.

Technology changes increase the utility of process-based models

It is probably fair to say (and perhaps often said) that process-based modelling has promised much for a long time with relatively little impact on forestry performance. The contributions until recently have been to act as a framework for knowledge development and a means of establishing knowledge gaps in out understanding of system functioning. The last 10 years has however seen significant changes that make process-based models more appropriate for commercial application. While our understanding of the physiological processes has been good enough to make reasonable predictions of forest growth for some time (see predictions of McMurtrie *et al.* 1990), it has been changes in four other areas that have increased the potential for model application: hardware, software, spatial information availability and attitude (Landsberg).

In the area of hardware, both the processing power and the portability of computers have changed the utility and accessibility of process-based models. Many process-based models are numerically intensive and this is particularly so as models attempt to become more realistic and generally applicable [in the sense of applicable in a wider range of situations] with consideration of heterogenous site, species and weather conditions and inclusive of discontinuous events such as defoliations, frost and waterlogging and shading by neighbouring trees. For routine application, and where many scenarios are to be explore the usefulness of models is greatly reduce if run times are slow. Considerations of a range of site, weather, and silvicultural regime can soon generate large numbers of combinations for simulation. Once models are required to run spatially (say for simulating catchment scale evapo-transpiration), 100,000s of simulations may be required. Computational power and computer data storage now seem to be adequate for these needs, and if not Moore’s Law (the exponential increase over time in compute power) is likely to overrun the problem within a short period of time. The power of laptop computers also means that process-based models are now used by industry staff in the field when assessing site potential (e.g. Great Southern Plantations, Australia), making them a much more immediate part of the decision making process and providing the means of iteratively modelling and measuring for accurate site assessment. Changes in software have been just a profound in their implications as changes in hardware. It is now possible to design high quality graphical user interfaces to models making them more approachable and easier to use. The combination of hardware and software changes puts model development and use within reach of a greatly increased audience. The recent open-source experience with 3-PG (Landsberg and Waring) shows how rapidly and extensively models can now spread. The CSIRO website that freely provides the 3-PGpjs software and documentation (Sands) has had over 600 downloads to different users from more than 40 different countries.

No doubt this represents only a small pool of the total users acting in different applications and fields.

Another change significant to the increased use of process-based models has been the wider availability of the data necessary to parameterise, run and to verify models. As process-based models have become more widely available within the forestry research community, there has been an interchange between experimentalists and modellers such that there is now a rich pool of data for parameterise and testing models. Good examples are the Forest BFG experiments in *Pinus radiata* in Canberra, Australia, the Aracruz Catchment Project (www.aracruz.com.br/microbacia) and BEEP project (www.ipef.br/bepp) in Brazil focussing of *E. grandis x urophylla* and the drought risk project in Western Australia focussing on *E. globulus*. The input data for models is now also more widely available. Good software is now available for developing continuous meteorological coverage from sparse weather station networks (e.g., ANUSPLIN, (http://cres.anu.edu.au/outputs/anusplin.php) or alternatively commercial services offer point-patched daily weather data with good accuracy (e.g., SILO, www.bom.gov.au). Increasingly geospatial modelling techniques are being used to produce spatial coverages of soil properties (e.g. Australian Soil Resource Information System, www.asris.csiro.au). The last, and increasingly available, source of data are remote sensed data layers. Many models will now directly take estimates of Leaf Area Index as inputs. These layers can be calculated from widely available multispectral satellite imagery such as LANDSAT, or from LIDAR data. Other data sources such aerially-sensed radiometrics can be important supplementary information to soil pit data in developing continuous soil property surfaces.

It is now easier to adopt and use existing process-based models. Parameters values for several forest species available and published (or at least available from known sources) during the last years; some examples are presented in Table 1.

Table 1. Relation of available parameters values used in 3-PG and CABALA models for different species

Model	Species	Publications
3-PG	*Eucalyptus globulus*	(Sands and Landsberg)
	Eucalyptus grandis hybrids	(Almeida;Almeida, Landsberg, and Sands;Dye, Jacobs, and Drew;Esprey, Sands, and Smith;Williams *et al.*)
	Pinus radiata	(Coops)
	Pinus patula	(Dye)
	Pinus ponderosa	(Law *et al.*)
	Pseudotsuga menziesii	(Waring and McDowell)
CABALA	*Eucalyptus globulus*	(Battaglia *et al.*)
	Eucalyptus nites	Unpublished
	Eucalyptus polybractea	Unpublished
	Eucalyptus horistes	Unpublished
	Eucalyptus kochii	Unpublished
	Pinus radiata	Unpublished

Not withstanding these technical changes in models and data availability, the most significant factor in the increase perfusion of models into commercial forestry has been a two way change in attitude: modellers have been willing to engage with industry to develop tools of use, and industry (Almeida *et al.*;Sands, Battaglia, and Mummery), because of the new challenges we discussed early, have seen process-based models as a necessary and complementary decision support tool to the empirical models used for company inventory (Landsberg;Landsberg).

Current applications and performance

Earlier in this manuscript we introduced a number of areas where forest managers are confronting new challenges. In this section we want to highlight the contribution and the performance of process-based models in supporting management some of these areas and answering, in an integrated way, a wide range of questions that are currently part of the reality of forest sector. Many of these areas were reviewed by Battaglia and Sands (1998a) at the start of the period when process-based models were making an impact in commercial and environmental forestry. It is appropriate to now consider to what extent process-based models have successfully met these needs.

Models predicting plantation growth in new situations

Process-based models have been most used in commercial forestry for predicting the potential productivity in new areas where no inventory data exists or to establish forest productivity classification (Almeida *et al.*). They are now also being applied to guide environmental forest plantings. Where there has been no previous crop to bioassay sites, potential productivity must be predicted from site factors and climatic data (see Battaglia and Sands 1998a for fuller treatment of this topic). Experience has shown that process-based models, applied appropriately can meet this need, but that success can be dependent on input data quality (see Mummery and Battaglia 2002). Where data is adequate the current generation of models typically return correlation co-efficients when observed and predicted data are compared in properly controlled verification exercises (modeller presented only with input data and comparison with observed made by third party) of 0.7 or higher (Fig. 1) and this appears to be sufficient for forestry developments. It is clear that models can identify the best from the average from the poorest of sites. However there are often sites where unexpected site factors result in very large prediction errors (Fig. 1), often associated with soil factors that models do not consider. More accurate assessments are possible where models are tested against highly controlled experimental data, where models are ‘tuned’ to particular site data (as is often the case when models are published) or where conditions are very uniform.

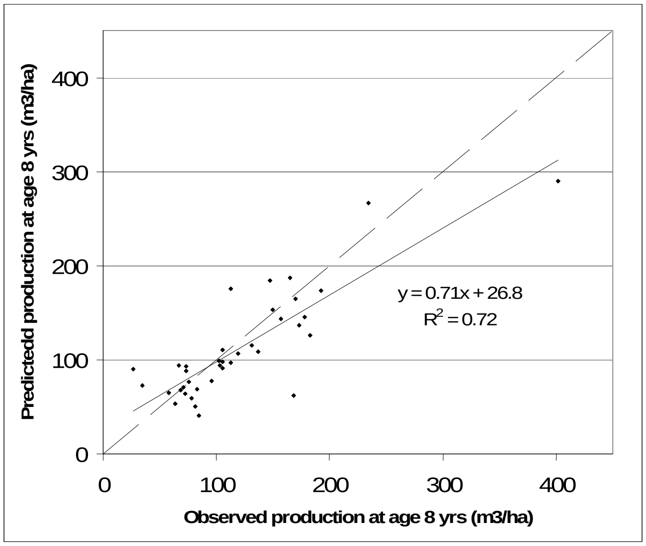

Figure 1. Performance of the process-based model CABALA (Battaglia *et al.* 2004) in predicting growth of *Eucalyptus globulus* plantations in a validation exercise using data collected as part of commercial forestry project assessment (*pers. comm.*. Peter Miele, University of Melbourne).

Models for inventory and risk assessment

Process-based (or hybrid) models offer the potential to move away from invariant growth trajectories determined by site-index alone (Battaglia and Sands 1998a; (Almeida *et al.*). With the development of very large high through-put processing facilities in areas where rotations are short, accurate yield forecasting and early alert of yield fluctuations has become imperative (Almeida *et al.* 2004c). The application of 3-PG within the Aracruz Celulose forest management system provides one example of a process-based model being used to improve yield forecasts (Figure 2). In this example the pronounce effect of a severe drought are predicted and the consequent estate wide yield variation anticipated. This integration of 3-PG model into the management systems of Aracruz Celulose company in Brazil is the most complete example of process-based models being adopted for commercial forestry. The company generates monthly climate surfaces derived from 27 automatic weather stations, covering more than 250,000 ha, combines this data with very detailed soil and forest stands information (age and management practices) and applies specific parameters sets for the most planted genotypes produce estimates of forest growth and the factors that are influencing and limiting production (Almeida;Almeida *et al.*;Almeida, Landsberg, and Sands).

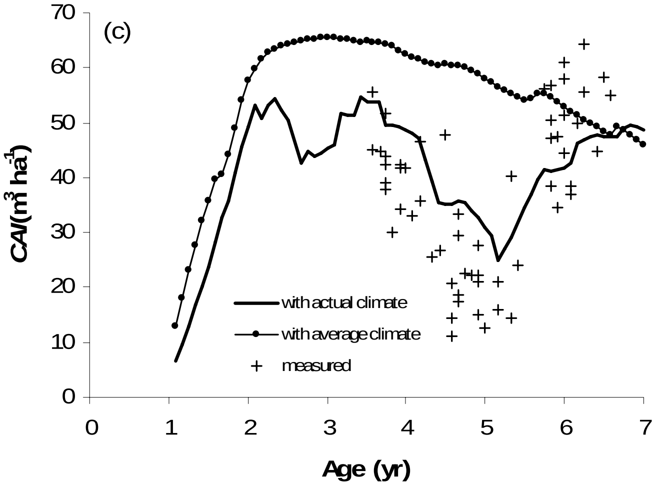

Figure 2. Predicted and observed current annual increments (CAI) of stem wood for the Microbacia region of Aracruz Celulose's estate in Brazil based on average climate data and the observed weather data for the period with the CAI from measurements made in permanent sample plots within the region superimposed**.** Modified from Almeida et al 2004c.

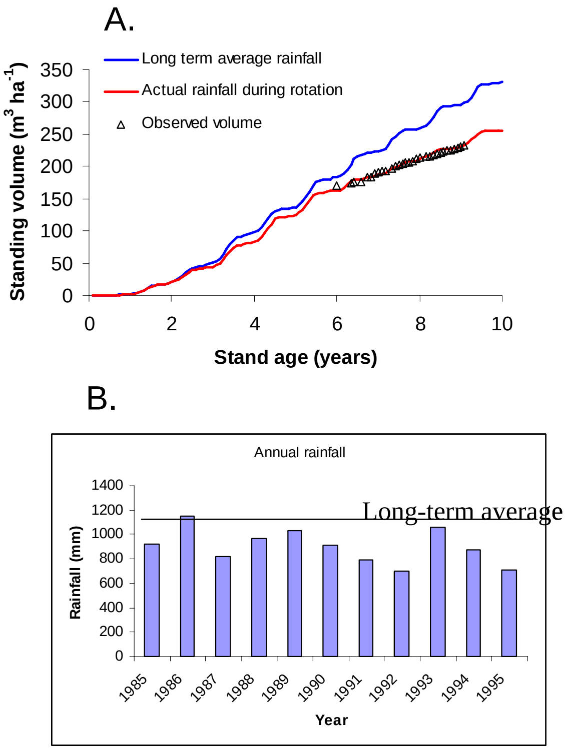

Figure 3. An example of the use of CABALA to account for the effects of long term weather patterns (B) of yield compared to the growth potential that might be expected under average climate condition for a plantation near Manjimup, Western Australia, Australia (A).

Another excellent example is shown by the use of ProMod (Battaglia and Sands 1997) to calculate forest land value in Australia (Sands *et al.* 2000). In this case a protracted period of drought was demonstrated to have resulted in the standing production on an estate being valued for sale as not fully expressing the site potential if it was assumed that future weather was similar to the long term average weather. The impact of this can be seen for one of these sites where CABALA has been run with real and average climate data for the 10 year rotation (Figure 3).

Another, and similar, use of process-based models for inventory has been for risk assessment where models have been used predict the variation in yield from rotation to rotation. In assessing the potential of a location in Australia for plantation development Battaglia (2005) applied CABALA with weather selected from different time periods to identify the likelihood of plantations meeting economic return requirements (in this case a yield of 150 m^3 at harvest).

An emerging application of process-based models is to assess the impacts of climate change on risk and yield from existing plantations (Kirschbaum 1999; Bergh et al. 2003; Magnani *et al.* 2004). These studies have suggested that the effects on productivity could be profound but that such effects may be very site (particularly nutrition) and climate specific with the range of effects reported in these studies ranging between 0-75%.

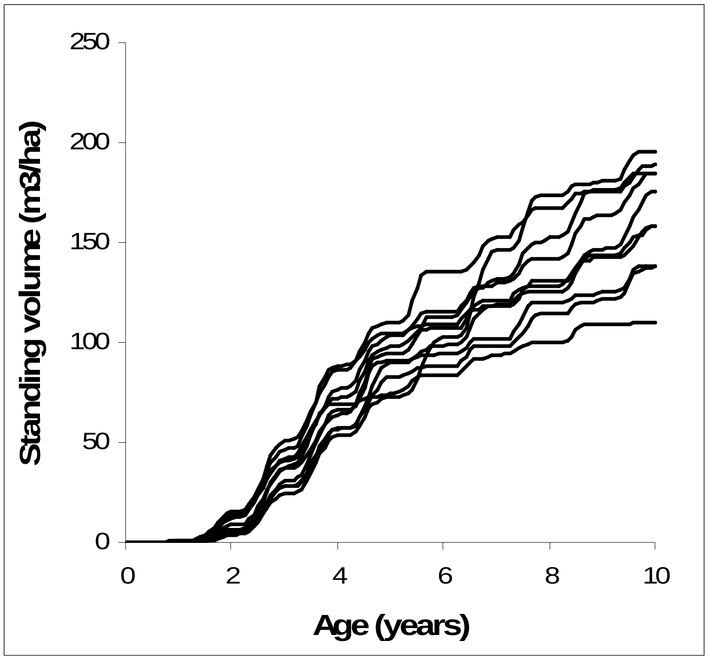

Figure 4. CABALA predicted growth curves for plantations established near Richmond, Tasmania, Australia from 10 different planting dates with identical site conditions but the actual weather that prevailed.

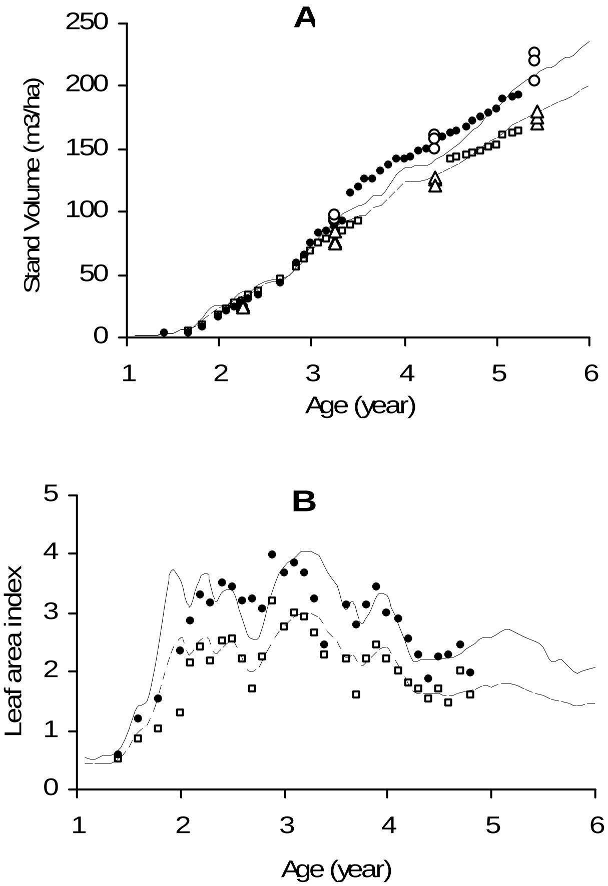

Figure 5. Example of 3-PG predictions (lines) plotted along with observed stand volume and leaf area index data for two differing clones of *E. grandis x urophylla* planted in adjacent plots in Espirito Santo state, Brazil. In figure A the small symbols are monthly inventory data and the larger symbols are data from annual destructive samples.

Models for efficient deployment of germplasm and capturing GxE

In process-based models, different genotypes or clones of a species are treated the same as a different species – that is they have their own parameter sets. Where the phenotypic differences between clones has been established (Almeida) models have been used to include genotypic differences in estimates . This is an emerging field of application – the extent to which individual clones or genotypes are parameterised, or to which it is economically justifiable to do so, will depend on the strength of the genotype by environment interaction, the degree to which the physiological basis of this interaction can be identified, and how well model parameters map to these physiological or morphological traits. Almeida (2003) identifies biomass partitioning and the sensitivity of light use efficiency to vapour pressure deficit as factors key in the differentiation of clones of *Eucalyptus grandis x urophylla* (Figure 5). To make models parmaterised for individual clone a useful operationally requires one further step – that is a means of readily, rapidly and cheaply screening material in the glasshouse or nursery for trait characteristic and linking these differences to parameter values in models. Without this operational step the cost and time in parameterising models will mean that only a subset of material being deploy can be characterised and with some time elapsed from the selection of the elite material. Nevertheless, in principal this use of process-based models has been demonstrated.

Even where it is not intended to parameterise individual germplasm lines, sensitivity analyses of model parameters can be used to identify the extent to which changes in traits through breeding or selection may lead to productivity benefits (e.g. Battaglia and Sands 1998b). For example, CABALA was used to evaluate the sensitivity of productivity and the risk of drought death to the range of differences between germplasm lines in instantaneous water-use efficiency (mol C fixed per unit time / mol of water transpired per unit time) often observed (e.g Le Roux *et al* 1996, Osario *et al.* 1998). This analysis was made under conditions of resource limitation or seasonal changes in vapour pressure deficit and water supply and cane to the conclusion that provided the risk of drought death was acceptable, productivity was inversely correlated with instantaneous water use efficiency (Almeida *et al*, 2006) – that is a conservative water use pattern resulted in less wood production (*pers. comm.* Don White, Ensis).

Precision silviculture and efficient production

Process-based models offer the potential to fine tune or optimise management for site conditions. For combinations of site climate and soil conditions the risk and returns from investment in management inputs can be assessed. One good example of this was the drought risk project in Australia, in which CABALA was used to investigate the relationship between site rainfall, production, the risk of drought death and initial planting stock (Mendham *et al.* 2005). This industry funded project was a response to drought-death in a small proportion of the extensive blue-gum estate of Western Australia and a realisation that management of soil water stores was critical for maximising production and reducing mortality risk. Through a combination of modelling and field experimentation appropriate planting densities were identified for different regions (Figure 6). In producing these scenarios the historical rainfall records were used to generate the variance around these mean estimates.

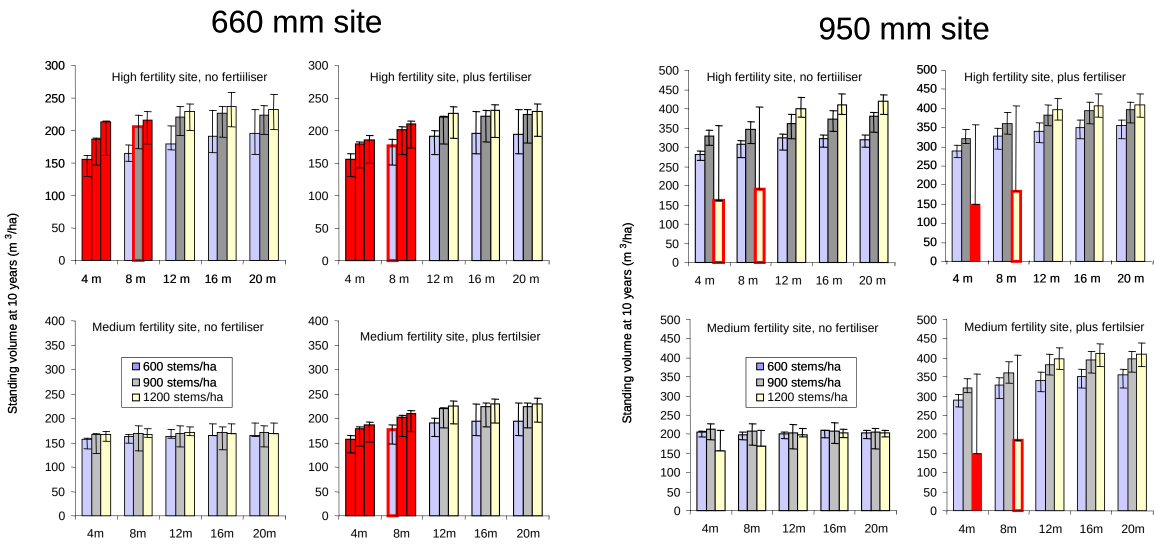

Figure 6. – Examples of CABALA predictions of productivity for a high and medium rainfall site for 600, 900 and 1200 stems/ha stocking rates under a range of scenarios of soil depth, fertility, fertilization and rainfall. Error bars represent the range in productivity predicted for 10th percentile rainfall (923 mm/annum) through to the 90th percentile (1099 mm/annum). Drought risk from age 3-6 is indicated with heavy outline (moderate drought risk) or heavily shaded (severe drought risk).

Predicting multiple benefits

One of the most common demands in forest sector is quantify multiple benefits of forest, mainly planted forests. Process-based models can provide important inputs (productivity surfaces and estimates of water use and carbon sequestration) for land use planning tools. One example of it is the Scenario Planning and Investment Framework (SPIF) tool developed by Ensis (www.ensisjv.com) that is a forestry planning and extension application for targeting where to establish new forests or to assess the commercial and environmental outcomes from project proposals. An important input into this tool are productivity layers for different species (in this case derived from ProMod and 3-PG) that allow the assessment of wood values in assessment of total amenity from different land-use configurations.

Summary of process-based model performance

In general models have met the expectations of a decade ago (Table 2). Performance has most been demonstrated in those areas of most pressing need – over the last decade in the area of new plantation establishment as a result of the substantial global increase in plantation area and secondly in their as surrogates or in support of climate change experiments.

Table 2. Success of process-based models in meeting the opportunities identified a decade ago in Battaglia and Sands (1998a). Number of ticks demonstrates relative uptake or frequency of demonstration.

Opportunity	**Has been demonstrated?**	**Is used commercially**	**Comment**
Yield prediction of established plantations; weather variation	✓✓	✓	Increasing opportunities with climate change
Yield prediction of established plantations; response to management	✓	✓	Used only for volumetric assessment, increasing opportunites for wood properties assessment. General correlation co-efficient between observed and predicted now >0.7 but lower where data poor.
Selection of new plantation sites or of species for particular sites	✓✓	✓✓	Individual clones parameterised
Factors limiting site productivity and refinement of silvicultural prescriptions	✓	✓	Not used as widely as could be to guide investment decisions about potential returns from management inputs.
Risk assessment	✓	**?**	Area of growing interest as interest in partitioning deviation from expected performance among sources of variation. Also increasing interest in risk from climate change and pest disease requiring models to assess impact of change
Models as surrogates for experiments	✓✓	✗✓	Models are now widely used in support of experimental systems and to structure research programs.

Emerging applications

Wood properties and product prediction

Currently process-based models used commercially are focussed on volumetric prediction, usually at the stand level. However, it is clear that management, site characteristics and climate influence not just the size distribution of trees but the wood properties (Aloni 1989). While models exist that incorporate allow prediction of some wood properties (e.g. Fritts et al. 1991; Mäkelä and Mäkinen 2003) these are not suitable for commercial forestry, perhaps being in a similar state of technology transfer to process-based models of forest growth 25 years ago. This remains an active area of research and emerging research and simplifying assumptions about wood properties drawing on the pipe model (e.g Deckmyn *et al.* 2006) and hydraulic constraints (e.g. Magnani et al.2000) or even simpler phenomenological formulations (e.g. Deleuze and Houllier 1998) may provide an the necessary formulations for linkage to existing production models.

Assessment of forest health impacts

With the increase globally in forest investment and the increase in global forest commodity trade, pests pose an increasingly real economic threat to the plantations. In addition great uncertainly exists as to how project climate change may influence pest distributions and ultimately impacts of plantation growth and value. Process-based models of forest growth provide can potentially provide important link between distributional and epidemiological of pests and diseases and the impacts on production. The effect of a pest attack will depend upon the frequency of attack, the time of year of infection and the tree vigour at that time. Integration of these factors within process-based models however requires that models represent the longer effects of changes in allocation, photosynthetic up-regulation and growth that occur following crown or tree damage (e.g Pinkard *et al.* 2006a,b). Some aspects of pest attack, for example reduced light interception due to loss of leaf area, are easily accommodated into models of forest growth although where models rely heavily on big-leaf assumptions (e.g 3-PG) this may not be possible. Other impacts of pest attack such as changes in allocation patterns, the change in nutrient and carbon storage pools and the loss of meristematic tissue, particularly leaf buds, may present more significant modelling challenges.

Conclusion

Process-based models have largely met the promises of a decade ago. The increasingly competitive, changeable and complex world of commercial forestry is creating further opportunities for their uptake. Furthermore the range and number of commercial applications of process-based models (some highlighted in this review) will provide increase confidence for others to utilise these models to support forest management and inventory. While there is future opportunities to apply process-based models in areas such as wood properties prediction and the assessment of forest health impacts, the physiological and process complexity inherent in these responses may present a challenge for models and modellers to provide realistic predictions without making models so complex and input intensive as to be useless for widespread commercial applications. Without a doubt progress will occur when appropriate emergent relationships and simplifications are found, in the same way as has occurred in forest growth modelling.

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References

ABARE - Jaakko Poyry 1999, Global Outlook for Plantations, ABARE Research report 99.9, Canberra

Almeida,A.C., 2003. Application of a process-based model for predicting and explaining growth in Eucalyptus plantations. PhD Thesis, The Australian National University, 232 pp.

Almeida, A. C., Landsberg, J. J., Ferreira, T. C., and Fonseca, S. 2004a. Estabilishment and application of Eucalyptus potential productivity in Brazil using a process-based model. In: Borralho, N. (Ed.), Eucalyptus in a Changing World. Proc. of IUFRO Conf., 11-15 October 2004. Aveiro, Portugal, pp. 225-232

Almeida,A.C., Landsberg,J.J., Sands,P.J., 2004b. Parameterisation of 3-PG model for fast-growing Eucalyptus grandis plantations. For. Ecol. Manage. 193, 179-195.

Almeida,A.C., Landsberg,J.J., Sands,P.J., Ambrogi,M.S., Fonseca,S., Barddal,S.M., Bertolucci,F.L., 2004c. Needs and opportunities for using a process-based productivity model as a practical tool in Eucalyptus plantations. For. Ecol. Manage. 193, 167-177.

Almeida,A.C., Maestri,R., Landsberg,J.J., Scolforo,J.R.S., 2003. Linking process-based and empirical forest models in Eucalyptus plantation in Brazil. In: Amaro,A., Tomé,M. (Eds.), Modelling Forest Systems. CABI, Wallingford, UK, pp. 63-74

Battaglia M (2005) 'Application of CABALA to predict growth under irrigation in the Coal River Valley Tasmania.' CSIRO Client Report 1583, Hobart.

Battaglia,M., Sands,P., White,D., Mummery,D., 2004. CABALA: a linked carbon, water and nitrogen model of forest growth for silvicultural decision support. For. Ecol. Manage. 193, 251-282.

Battaglia,M., Sands,P.J., 1998. Process-based forest productivity models and their application in forest management. For. Ecol. Manage. 102, 13-32.

Battaglia M, Sands PJ 1998b Application of sensitivity analysis to a model of Eucalyptus globulus plantation productivity. Ecol. Model. 111, 237-259.

Battaglia M, Sands PJ. 1997 Modelling site productivity of Eucalyptus globulus in response to climate and site factors. Aust. J. Plant Phys. 24, 831-850.

Bergh J, Freeman M, Sigurdsson B, Kellomäki S, Laitinen K, Niinistö S, Peltola H, Linder S (2003) Modelling the short-term effects of climate change on the productivity of selected tree species in Nordic countries. For. Ecol. Manage. 183, 327-340.

Coops,N.C., 1999. Improvement in predicting stand growth of Pinus radiata(D.Don) across landscapes using NOAA AVHRR and landsat MSS imagery combined with a forest growth process model (3-PGS). Photogram. Eng. Rem. Sens. 65, 1149-1156.

Deckmyn G, Evans S, Randle TJ. 2006 Refined pipe theory for mechanistic modeling of wood development. Tree Phys. 26, 703-717.

Deleuze, C., and Houllier, F. 1998. A simple process-based xylem growth model for describing wood microdensitometric profiles. J. Theor.l Biol. 193, 99-113.

Dye,P.J., 2001. Modelling growth and water use in four Pinus patula stands with the 3-PG model. S. African For. J. 191, 53-63.

Dye,P.J., Jacobs,S., Drew,D., 2004. Verification of 3-PG growth and water-use predictions in twelve Eucalyptus plantation stands in Zululand, South Africa. For. Ecol. Manage. 193, 197-218.

Esprey,L.J., Sands,P.J., Smith,C.W., 2004. Understanding 3-PG using a sensitivity analysis. For. Ecol. Manage. 193, 235-250. 121pp

FAO-Rome; 2003 State of the World's Forests 2005, Food and Agriculture Organisation of the United Nations, Rome 2003, 166pp.

FAO-Rome; 2005 State of the World's Forests 2005, Food and Agriculture Organisation of the United Nations, Rome 2005, 166pp.

Fritts HC, Vagaonv EA, Sviderskaya IV, Shashkin AV (1991) Climate variation and tree-ring structure in conifers: empirical and mechanistic models of tree-ring width, number of cells, cell size, cell-wall thickness and wood density. Climate Res. 1, 97-116.

Kirschbaum MUF (1999) CenW, a forest growth model with linked carbon, energy, nutrient and water cycles. Ecol. Modell. 118, 17-59

Landsberg,J.J., 2003a. Modelling forest ecosystems: state-of-the-art, challenges and future directions. Can. J. For. Res. 33, 385-397.

Landsberg,J.J., 2003b. Physiology in forest models: history and the future. FBMIS 01, 46-63.

Landsberg,J.J., Waring,R.H., 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. For. Ecol. Manage. 95, 209-228.

Law,B.E., Waring,R.H., Anthoni,P.M., Aber,J.D., 2000. Measurements of gross and net ecosystem productivity and water vapour exchange of a Pinus ponderosa ecosystem, and an evaluation of two generalized models. Global Change Biol. 6, 155-168

Le Roux D., Stock, W.D., Bond, W.J. and Mapphanga, D., 1996 Dry mass allocation, water use efficiency and d13C in clones of Eucalyptus grandis, E. grandis x camaldulensis and E. grandis x nitens grown under two irrigaton regimes. Tree Physiology 16, 497-502.

McMurtrie,R.E., Rook,D.A., Kelliher,F.M., 1990. Modelling the yield of Pinus radiata on a site limited by water and nitrogen. For. Ecol. Manage. 30, 381-413.

Magnani F, Mencuccini, Grace JC 2000 Age-related decline in stand productivity: the role of structural acclimation under hydraulic constraints. Plant, Cell Env. 23, 251-263.

Pinkard EA, Battaglia M, Mohammed CL 2006a Influence of defoliation and nitrogen application on photosynthetic processes and growth of young plantation-grown Eucalyptus globulus. Tree Physiology in press

Pinkard, E.A., Baillie, C.C., Patel, V., Paterson, S., Battaglia, M., Smethurst, P.J., Mohammed, C.L., Wardlaw, T. and Stone, C. 2006b Growth responses of Eucalyptus globulus Labill. To nitrogen application and severity, pattern and frequency of artificial defoliation. For. Ecol. Manage. 229:378-387.

Sands,P.J., 2002. 3PGpjs - a user-friendly interface to 3-PG, the Landsberg and Waring model of forest productivity. Cooperative Research Centre for Sustainable Production Forestry and CSIRO Forestry and Forest Products Technical Report No. 29, Edition 2.2, 1-22. Hobart, Australia, CRC for Sustainable Production Forestry and CSIRO, Forestry and Forest Products.

Sands,P.J., Battaglia,M., Mummery,D., 2000. Application of process-based models to forest management: experience with ProMod, a simple plantation productivity model. Tree Physiol. 20, 383-392.

Sands,P.J., Landsberg,J.J., 2002. Parameterisation of 3-PG for plantation grown Eucalyptus globulus. For. Ecol. Manage. 163, 273-292.

Waring,R.H., McDowell,N., 2002. Use of a physiological process model with forestry yield tables to set limits on annual carbon balances. Tree Physiol. 22, 179-188.

Williams,K., Ryan,P., Coops,N., Storey,R., Claridge,J., Grundy,M., 2002. Estimating the productivity of Forest Systems in Southeast Queensland (An application of forest model 3-PG). Publication No 2/, 1-177. A report for the RIRDC/L&W Australia/FWPRDC Join Venture Agrforestry Program.