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Compilation of publications on *Eucalyptus grandis* physiology
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Public

Compilation of publications on *Eucalyptus grandis* physiology:

The basis for a formal review with particular reference to the calibration of physiologically-based growth models for use as plantation management tools in S.E. Queensland

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Project B4: Modelling production and wood quality

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Introduction

The expansion of the hardwood plantation estate in Queensland is essential for the meeting of Australian national targets for afforestation over the next 20 years. Insufficient land availability in southern, temperate Australia and in the traditionally-planted humid coastal zone has forced the prospectus-driven commercial plantation sector to expand increasingly into regions more marginal for plantation establishment, e.g. the subtropical 700 – 1000 mm rainfall zone (Loxton and Forster 2000). In these regions, production is limited by low water availability and high evaporative demand (Sands et al. 1999), there is no history of plantation establishment, and few if any useful data exist pertaining to growth estimates or site indices for species of potential interest.

Plantation establishment has grown rapidly in the tropical and subtropical region over the last three years, and accompanying this a significant amount of research has been undertaken covering a wide range of taxa, sites and silvicultural treatments (e.g. Lee et al. 1999; 2001). However, longer-term knowledge of eucalypt silviculture in these regions, necessary to drive selection and management decisions, is both very limited and restricted primarily to *Eucalyptus grandis* (Birk and Turner 1992; Cromer and Jarvis 1990; Doley 1978) and *E. camaldulensis* (Blake 1980; Facanha et al. 1983). Consequently, for the estimation of plantation performance in the immediate future, predictive models may constitute the most useful tools.

In particular, there is an increasing potential for physiologically-based models to be used as powerful predictive tools in plantation selection and management (Battaglia and Sands 1997, 1998a; Coops 1998a). While several such models have been used in the context of predicting performance, few have been routinely applied to decision-making in plantations (Sands 1988; Battaglia and Sands 1998; Sands et al. 2000). Managers require models with attributes such as simplicity of structure and of use, ease of validation within the relevant context, flexibility in terms of the questions they can address and a capacity to operate using readily available input data (Sands 1988). However, for most physiological models, while input data such as weather records are easily obtained, other data required to set parameters and to validate models for new situations or species often are not. These parameters may include physiological responses to light, water-use efficiency characteristics, and growth rates. They may be obtained through physiological research, from growth plots or from the literature.

Eucalyptus grandis is an important plantation species in both South Africa and South America, where it has and continues to be the subject of a considerable research effort, particularly in relation to its water-use characteristics (e.g. Dye 1996, Bevilaqua and Blake 1997, Esprey *pers. comm.*, Almeida *pers. comm.*). Despite the extensive work of Cromer et al. (1993; 1995), *E. grandis* has received on the whole much less attention in Australia. However, it remains arguably the most researched of the tropical/subtropical eucalypts in a field where there exists a dearth of both basic and applied physiological knowledge. This is particularly apparent when compared to the much better understood temperate commercial species (e.g. *E. globulus*, *E. nitens*). While *E. grandis* is considered primarily a pulp species in Australia, it is increasingly being considered for solid wood products in South America in response to periodic downturns in pulp and paper markets (Lima et al. 2000). The substantial processing challenges for the industry presented by these short-rotation crops have resulted in heightened interest in the taxon's physiology in recent years. Although the species has long been considered to possess significant potential for plantations in Australia, its variable performance across sites is well established (Cromer et al. 1991). It thus provides an excellent starting point to consider the usefulness of predictive models, both in terms of the quantity of available information, and the known limitations of traditional empirical approaches to modelling its growth.

Two physiological models potentially suitable for application to *E. grandis* are PROMOD (Battaglia and Sands 1997) and 3-PG (Landsberg and Waring 1997, Sands and Landsberg 2002). These are process-based models developed specifically for use as forest management tools. Sands (2001a) compares the performance of these models as tools for site selection. Both are generic models in the sense that application to a species requires the development of a set of parameters that characterise the species. However, many parameters in PROMOD are derived from physiological experiments, e.g. gas-exchange measurements, while those required for 3-PG are stand-level parameters often not accessible to direct measurement. The two models use very similar site and climatic input data.

Both 3-PG and PROMOD can be used to screen sites on the basis of potential productivity, to predict stand development (but in radically different ways), and to determine which factors are likely to be limiting production. Both can be applied spatially to predict productivity across a landscape. 3-PG and PROMOD have been implemented in various ways, but both have been similarly implemented in Microsoft Excel in a format particularly convenient for parameter estimation and testing (Sands 2001b, Sands 2002).

In preparation for the adaptation of these models to *E. grandis*, a substantial literature search of publications relevant to *E. grandis* physiology, effects of silviculture and climatic conditions on growth and development of *E. grandis* stands, the availability of *E. grandis* growth data, and prior application of growth models to *E.* grandis has been carried out. This material will be used as the basis of a review of *E. grandis* physiology, and for the adaptation of the two models to this species. The Appendix of this report is a compilation of the material to hand at the time of writing (July 2002).

Reference list

Battaglia, M. and Sands, P. (1997). Modelling site productivity of *Eucalyptus globulus* in response to climatic and site factors. *Aust. J. Plant Physiol.* 24: 831-850.

Battaglia, M. and Sands, P. J. (1998). Process-based forest productivity models and their application in forest management. *Forest Ecology and Management* 102: 13-32.

Bevilaqua, E. and Blake, T. J. (1997). Modelling growth and ecophysiological responses of *Eucalyptus grandis* clones in Minas Gerais, Brazil. *Journal of Tropical Forest Science* 9: 505-513.

Blake, T. J. (1980). Effect of coppicing on growth rates, stomatal characteristics and water relations in *Eucalyptus camaldulensis* Dehn. *Australian Journal of Plant Physiology*, 81 - 87.

Birk, E. and Turner, J. (1992). Response of flooded gum (*E. grandis*) to intensive cultural treatments: biomass and nutrient content of eucalypt plantations and native forests. *Forest Ecology and Management* 47: 1-28.

Coops, N.C., Waring, R.H., Landsberg, J.J. (1998a). Assessing forest productivity in Australia and New Zealand using a physiologically-based model driven with averaged monthly weather data and satellite-derived estimates of canopy productivity. *For. Ecol. Manage*. 104, 113-127.

Cromer, R. N. and Jarvis, P. G. (1990). "Growth and biomass partitioning in *Eucalyptus grandis* seedlings in response to nitrogen supply." Austral. J. Plant Physiol. 17: 503-515.

Cromer, R. N., Cameron, D. M., Lennon, S., Rance, S. J., Ryan, P. A. and West, P. (1995). Response of *E. grandis* to fertilizer and irrigation, to five years of age., CSIRO Division of Forestry.

Cromer, R. N., Cameron, D. M., Rance, S. J., Ryan, P. A. and Brown, M. (1993). "Response to nutrients in *Eucalyptus grandis*. I. Biomass accumulation." Forest Ecology and Management 62: 211-230.

Cromer, R. N., Ryan, P. A., Booth, T. H., Cameron, D. M. and Rance, S. J. (1991). Limitations to productivity of *Eucalyptus grandis* plantations in sub-tropical Australia. Third Australian Forest Soils and Nutrition Conference.

Doley, D. (1978). "Effects of shade on gas exchange and growth in seedlings of *Eucalyptus grandis* Hill ex Maiden." Aust.J. Plant Physiol. 5: 723-38.

Dye, P. J. (1996). "Response of *Eucalyptus grandis* trees to soil water deficits." Tree Physiology 16: 223-238.

Facanha, J., Oliva, M. A., Lopes, N. F., and de, B. N. F. (1983). Germination/growth relation in eucalypt species under water stress. *Revista-Arvore* **7**, 177 - 187.

Landsberg, J. J. and Waring, R. H. (1997). "A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning." Forest Ecology and Management 95: 209-228.

Lee, D.J., Nikles, D.G. and Dickinson, G.R. (2001) Prospects of eucalypt species, including interspecific hybrids from South Africa, for hardwood plantations in marginal subtropical environments in Queensland, Australia. Southern African Forestry Journal 190: 89-94.

Lee, D.J., Nikles, D.G. and Walker, S.M. (1999). Strategy and progress on the genetic improvement of hardwood timber species in Queensland. In: Langridge, P., Barr, A., Auricht, G., Collins, G., Granger, A., Handford, D. and Paull, J. (eds.) 11th Australian Plant Breeding Conference Proceedings, Adelaide, 19-23 April 1999 – Volume 2.

Lima, J.T., Breese, M.C. and Cahalan, C.M. (2000) Variation in wood density and mechanical properties in *Eucalyptus* clones. In: The future of eucalypts for word products - Proceedings of IUFRO meeting, Launceston, Australia, 19-24 March.

Loxton, I., and Forster, S. (2000). “Brigalow Research Station Technical Report 1999-2000,” Rep. No. Q100098. Queensland Beef Industry Institute, Department of Primary Industries, Queensland, Theodore.

Sands, P. (1988). “Resource modelling: its nature and use.” Mem. Ent. Soc. Can. 143: 5-10.

Sands, P.J. (2001a). Productivity models - a comparative analysis. Technical Report No. 55 (M. Cherry and C. Beadle Eds) pp 51-54. (CRC-SPF, Hobart, Tasmania).

Sands, PJ. (2001b). 3PGpjs 1.1 – a User-Friendly Interface to 3-PG, the Landsberg and Waring Model of Forest Productivity. Technical Report. No. 29, CRC Sustainable Production Forestry, Hobart.

Sands, PJ. (2002). PROMOD Excel – a User-Friendly Interface to PROMOD. Technical Report. No. 88, CRC Sustainable Production Forestry, Hobart.

Sands, P.J. and Landsberg, J.J. (2002). Parameterisation of 3-PG for plantation grown *Eucalyptus globulus*. *Forest Ecology and Management*, 163: 273-292

Sands, P.J., Rawlins, W. and Battaglia, M. (1999). Use of a simple plantation productivity model to study the profitability of irrigated *Eucalyptus globulus*. *Ecological Modelling*, 117:125-141.

Sands, P.J., Battaglia, M. and Mummery, D. (2000). Application of process-based models to forest management: Experience with PROMOD, a simple plantation productivity model. *Tree Physiology*, 20: 383-392

Appendix : Compilation of References

Alexander, T. G. and Thomas, T. P. (1985). Physical Properties of Soils in Relation to Eucalypt Growth, Kerala Forest Resarch Institute, Divsion of Soil Science.

Attiwell, P. M. and Adams, M. A., Eds. (1996). Nutrition of Eucalypts, CSIRO Publishing.

Baldwin, P. J. and H. T. L. Stewart (1987). "Distribution, Length and Weight of Roots in Young Plantations of *Eucalyptus grandis* W-Hill Ex Maiden Irrigated with Recycled Water." Plant and Soil 97(2): 243-252.

Barnard, E. L., T. Geary, et al. (1987). "Basal Cankers and Coppice Failure of *Eucalyptus grandis* in Florida." Plant *Disease* 71(4): 358-361.

Battaglia, M. and Sands, P. (1997). Modelling site productivity of *Eucalyptus globulus* in response to climatic and site factors. *Aust. J. Plant Physiol.* 24: 831-850.

Battaglia, M. and Sands, P. J. (1998). Process-based forest productivity models and their application in forest management. *Forest Ecology and Management* 102: 13-32.

Battaglia, M. and Sands, P.J. (1998). Application of sensitivity analysis to a model of *Eucalyptus globulus* plantation productivity. *Ecological Modelling* 111: 237-259.

Battaglia, M., Beadle, C. and Loughead, S. (1996). Photosynthetic temperature responses of *Eucalyptus globulus* and *Eucalyptus nitens. Tree Physiology* 16: 81-89.

Battaglia, M., D. Mummery, and A. Smith. (2001). Economic analysis of site survey and productivity modelling for the selection of plantation areas. *Forest Ecology and Management* (in press).

Battaglia, M., Sands, P.J. and Candy, S.G. (1999). Hybrid growth model to predict height and volume growth in young *Eucalyptus globulus* plantations. *Forest Ecology and Management*, 120: 193-201.

Beadle, C. L. and Turnbull, C. R. A. (1992). Comparative growth rates of *Eucalyptus* in native forest and plantation monoculture. *Growth and water use of forest plantations*. Calder, I. R., Hall, R. L. and Adlard, P. G., John Wiley and Sons: 318-331.

Benyon, R. G. (1999). "Nighttime water use in an irrigated *Eucalyptus grandis* plantation." *Tree Physiology* 19(13): 853-859.

Bevilaqua, E. and Blake, T. J. (1997). Modelling growth and ecophysiological responses of *Eucalyptus grandis* clones in Minas Gerais, Brazil. *Journal of Tropical Forest Science* 9: 505-513.

Birk, E. and Turner, J. (1992). Response of flooded gum (*E. grandis*) to intensive cultural treatments: biomass and nutrient content of eucalypt plantations and native forests. *Forest Ecology and Management* 47: 1-28.

Boden, D. I. (1987). The use of actual evapotranspiration and a hydrological model to predict the growth of *Eucalyptus grandis* in South Africa. Institute of Commercial Forestry Research (ICFR).

Boden, D. I. (1991). "The relationship between soil water status, rainfall and the growth of *Eucalyptus grandis*." *South African Forestry Journal* 156: 49-55.

Bonny, L. (1991). Growth of a *Eucalyptus grandis* plantation following intensive silvicultural treatments applied in the first six years. Sydney, Forestry Commission of NSW.

Bradstock, R. (1981). “Biomass in an age series.” *Aus. For. Res*. 11: 111-127.

Bredenkamp, B. V. and H. E. Burkhart (1990). “An Examination of Spacing Indexes for *Eucalyptus grandis*.” *Canadian Journal of Forest Research* 20(12): 1909-1916.

Burgess, I. P. (1988). “Provenance trials of *Eucalyptus grandis* and *E. saligna* in Australia.” Silvae Genetica 37: 5-6.

Byrne, G. F. (1989). “Above-Ground Dry-Matter Accumulation by *Eucalyptus grandis* and Its Relation to Standard Meteorological Data.” *Agricultural and Forest Meteorology* 46(1-2): 65-73.

Calder, I. R. (1992). “Deuterium tracing for the estimation of transpiration from trees. Part 2: Estimation of transpiration rates and transpiration parameters using a time-averaged deuterium tracing methods.” *Journal of Hydrology* 130: 27-35.

Calder, I. R., Swaminath, M. H., Kariyappa, G. S., Srinivasalu, N. V., Srinivasa Murthy, K. V. and Mumtaz, J. (1992). “Deuterium tracing for the estimation of transpiration from trees Part 3. Measurements of transpiration from *Eucalyptus* plantation, India.” *Journal of Hydrology* 130: 37-48.

Carvalho, R., Furtini-Neto, A.E., Santos, C.D. dos, Fernandes, L.A., Curi, N., Rodrigues, D. de C., de C. Rodrigues, D. and dos Santos, C.D. (2001) Silicon-phosphorus interactions in soils cultivated with eucalyptus under greenhouse conditions. *Pesquisa Agropecuaria Brasileira* 36 (3), 557-565.

Christie, S. I. and Scholes, R. J. (1995). “Carbon storage in *Eucalyptus* and pine plantations in South Africa.” *Environmental Monitoring and Assessment* 38: 231-241.

Clearwater, M. J. and F. C. Meinzer (2001). “Relationships between hydraulic architecture and leaf photosynthetic capacity in nitrogen-fertilized *Eucalyptus grandis* trees.” *Tree Physiology* 21(10): 683-690.

Clemens, J., Kirk, A. and Mills, P. (1978). “The resistance of waterlogging and an ethylene-releasing substance on *E. robusta*, *E. grandis* and *E. saligna*.” *Oecologia* 34: 125-131.

Comer, C. W. and Rockwood, D. L. (1985). Screening of *Eucalyptus* species for coppice productivity. 1984 Southern Forest Biomass Workshop, Asheville, NC USA.

Coops, N.C. and Waring, R.H. (2001). Estimating Maximum Potential Site Productivity and Site Water Stress of the Eastern Siskiyous using 3-PGS. *Canadian Journal of Forest Research* 31: 143-154.

Coops, N.C., Waring, R.H., Landsberg, J.J. (1998). Assessing forest productivity in Australia and New Zealand using a physiologically-based model driven with averaged monthly weather data and satellite-derived estimates of canopy productivity. *For. Ecol. Manage*. 104, 113-127.

Coops, N.C., Waring, R.H. and Landsberg, J.J. (1998). The development of a physiological model (3-PGS) to predict forest productivity using satellite data. In: G. Nabuurs, T. Nuutinen, H. Bartelink, & M. Koorhonen, eds. Forest Scenario Modelling for Ecosystem Management at Landscape Level. pp. 173 -191. EFI Proceedings.

Criddle, R.S., Church, J.N., Hansen, D., Mitchell, A.K., Puttonen, P., Stoehr, M. and Hawkins, B.J. (2000) Respiratory parameters define growth rate, species distribution and adaptation to temperature. *Journal of Sustainable Forestry* 10(1-2): 115-123.

Cromer, R. N. and Jarvis, P.G. (1989). "Allocation of Dry-Matter in *Eucalyptus grandis* Seedlings in Response to Nitrogen Supply." *Annales Des Sciences Forestieres* 46: S680-S683.

Cromer, R. N. and P. G. Jarvis (1990). "Growth and Biomass Partitioning in *Eucalyptus grandis* Seedlings in Response to Nitrogen Supply." Australian Journal of Plant Physiology 17(5): 503-515.

Cromer, R. N., Cameron, D. M., Lennon, S., Rance, S. J., Ryan, P. A. and West, P. (1995). Response of *E. grandis* to fertilizer and irrigation, to five years of age., CSIRO Division of Forestry.

Cromer, R. N., Cameron, D. M., Rance, S. J., Ryan, P. A. and Brown, M. (1993). "Response to nutrients in *Eucalyptus grandis*. I. Biomass accumulation." Forest Ecology and Management 62(1-4): 211-230.

Cromer, R. N., Cameron, D. M., Rance, S. J., Ryan, P. A. and Brown, M. (1993). "Response to Nutrients in *Eucalyptus grandis*.2. Nitrogen Accumulation." Forest Ecology and Management 62(1-4): 231-243.

Cromer, R. N., Ryan, P. A., Booth, T. H., Cameron, D. M. and Rance, S. J. (1991). Limitations to productivity of *Eucalyptus grandis* plantations in sub-tropical Australia. Third Australian Forest Soils and Nutrition Conference.

Darrow, W. K. (1984). "Biomass production of *Eucalyptus grandis* in South Africa planted at various close espacements: Two-year results." *South African Journal of Forestry* 131: 34-39.

Davidson, N. J., Battaglia, M. and Beadle, C. (1995). Photosynthesis of *Eucalyptus nitens* is reduced by mild frosts. Eucalypt plantations, improving fibre yield and quality. Proc. CRCTHF-IUFRO Conference, Hobart, CRC for Temperate Hardwood Forestry: Hobart.

Dawson, T. E. and Pate, J. S. (1996). "Seasonal water uptake and movement in root systems of Australian phraeatophytic plants of dimorphic root morphology: a stable isotope investigation." *Oecologia* 107: 113-20.

Doley, D. (1978). "Effects of shade on gas exchange and growth in seedlings of *Eucalyptus grandis* Hill ex Maiden." *Aust.J. Plant Physiol*. 5: 723-38.

Doley, D. (1982). "Photosynthetic productivity of forest canopies in relation to solar radiation and nitrogen cycling." *Aust. For. Res*. 12: 245-61.

Dudley, N. S. and Fownes, J. H. (1993). "Preliminary biomass equations for eight species of fast-growing tropical trees." *Journal of Tropical Forest Science* 5(1): 68-73.

Dye, P. J. (1987). Estimating water use by *Eucalyptus grandis* with the Penman-Monteith equation. Forest Hydrology and Watershed Management, Vancouver, International Association of Hydrological Sciences (IAHS).

Dye, P. J. (1996). "Response of *Eucalyptus grandis* trees to soil water deficits." *Tree Physiology* 16(1-2): 233-238.

Dye, P. J. and Olbrich, B. W. (1992). Heat Pulse observations of *Eucalyptus grandis* transpiration in South Africa. Growth and Water Use of Forest Plantations. Calder, I. R., Hall, R. L. and Adlard, P. G., John Wiley and Sons: 216-225.

Dye, P. J. and B. W. Olbrich (1993). “Estimating Transpiration from 6-Year-Old *Eucalyptus grandis* Trees - Development of a Canopy Conductance Model and Comparison with Independent Sap Flux Measurements.” *Plant Cell and Environment* 16(1): 45-53.

Dye, P. J., Olbrich, B. W. and Calder, I. R. (1992). “A comparison of the Heat Pulse Method and Deteurium Tracing Method for measuring transpiration from *Eucalyptus grandis* trees.” Journal of Experimental Botany 43 (248): 337-343.

Eastham, J., Rose, C. W., Cameron, D. M., Rance, S. J., Talsma, T. and Charles-Edwards, D. A. (1990). “Tree/pasture interactions at a range of tree densities in an agroforestry experiment. II Water uptake in relation to rooting patterns.” *Aust. J. Agric. Res*. 41: 697-707.

Eastham, J., Rose, C. W., Cameron, D. M., Rance, S. J., Talsma, T. and Charles-Edwards, D. A. (1990). “Tree/pasture interactions at a range of tree densities in an agroforestry experiment. III Water uptake in relation to soil hydraulic conductivity and rooting patterns.” *Aust. J. Agric. Res*. 41: 709-718.

Facanha, J., Oliva, M. A., Lopes, N. F., and de, B. N. F. (1983). Germination/growth relation in eucalypt species under water stress. *Revista-Arvore* **7**, 177 - 187.

Fan, S. and Blake, T. J. (1997). “Comparison of polyethylene glycol 3350 induced osmotic stress and soil drying for drought simulation in three woody species.” *Trees* 11: 342-348.

Flanagan, L. B. and Ehrlinger, J. R. (1991). “Stable isotope composition of stem and leaf water: applications to the study of plant water use.” *Functional Ecology* 5: 270-277.

Folster, H. v. and Khanna, P. K. (1997). Dynamics of Nutrient Supply in Plantation Soils. *Management of Soil, Nutrients and Water in Tropical Plantation Forests.* Nambiar, E. K. S. and Brown, A. G. Canberra, CSIRO: 339-378.

Haigh, H. (1966). “Root development in the sandy soils of Zululand.” *Forestry in South Africa* 7: 31-36.

Henri, C. J. (2001). “Soil-site productivity of *Gmelina arborea*, *Eucalyptus urophylla* and *Eucalyptus grandis* forest plantations in western Venezuela.” *Forest Ecology and Management* 144(1-3): 255-264.

Herbert, M. A. (1990). “Fertilizer Site Interactions on the Growth and Foliar Nutrient Levels of *Eucalyptus grandis*.” *Forest Ecology and Management* 30(1-4): 247-257.

Hoad, S. P. and R. R. B. Leakey (1994). “Effects of Light Quality on Gas-Exchange and Dry-Matter Partitioning in *Eucalyptus grandis* W Hill Ex Maiden.” *Forest Ecology and Management* 70(1-3): 265-273.

Hoad, S. P. and R. R. B. Leakey (1996). “Effects of pre-severance light quality on the vegetative propagation of *Eucalyptus grandis* W Hill ex Maiden - Cutting morphology, gas exchange and carbohydrate status during rooting.” *Trees-Structure and Function* 10(5): 317-324.

Honeysett, J. L., Beadle, C. L. and Turnbull, C. R. A. (1991). “Evapotranspiration and growth of two contrasting species of eucalypts under non-limiting and limitinga water availability.” *Forest Ecology and Management*.

Hopmans, P., Stewart, H. T. L., Flynn, D. W. and Hillman, T. J. (1990). “Growth, biomass production and nutrient accumulation by seven tree species irrigated with municipal effluent at Wodonga, Australia.” *Forest Ecology and Management* 30: 203-211.

House, S. M. (1999). Calibration of 3-PG for *Eucalyptus grandis* using Shell data at Toolara, SE Queensland., QFRI, Draft Report, Gympie.

Hunter, I. (2001). “Above ground biomass and nutrient uptake of three tree species (*Eucalyptus camaldulensis*, *Eucalyptus grandis* and *Dalbergia sissoo*) as affected by irrigation and fertiliser, at 3 years of age, in southern India.” *Forest Ecology and Management* 144(1-3): 189-199.

Hutchinson, M.F., Houlder D., Nix, H.A. and McMahon, J.P. (1997). ANUCLIM Version 1.5. CRES, ANU, Canberra. Published at http//cres20.anu.edu.au/software/anuclim.html

Johnson, I. G. and Stanton, R. R. (1993). Thirty years of eucalypt species and provenance trials in New South Wales. Survival and growth in trials established from 1961 to 1990. Sydney, Forestry Commission of New South Wales. Research Division.

Kallarackal, J. (1992). Water use of eucalypts in Kerala. *Growth and water use of forest plantations.* Calder, I. R., Hall, R. L. and Adlard, P. G., John Wiley and Sons: 290-297.

Kallarackal, J. and C. K. Somen (1997). “An ecophysiological evaluation of the suitability of *Eucalyptus grandis* for planting in the tropics.” *Forest Ecology and Management* 95(1): 53-61.

Kalma, S. J., Thorburn, P. J. and Dunn, G. M. (1998). “A comparison of heat pulse and deuterium tracing techniques for estimating sap flow in *Eucalyptus grandis* trees.” *Tree Physiology* 18: 697-705.

Kirschbaum, M. U. F. (1991). “Effects of Photon Flux-Density on Nutrient Productivity in *Eucalyptus grandis* Seedlings.” *Australian Journal of Plant Physiology* 18(3): 307-315.

Kirschbaum, M. U. F. and D. Tompkins (1990). “Photosynthetic Responses to Phosphorus-Nutrition in *Eucalyptus grandis* Seedlings.” *Australian Journal of Plant Physiology* 17(5): 527-535.

Kirschbaum, M. U. F., D. W. Bellingham, et al. (1992). “Growth Analysis of the Effect of Phosphorus-Nutrition on Seedings of *Eucalyptus grandis*.” *Australian Journal of Plant Physiology* 19(1): 55-66.

Laine, E. and A. David (1994). “Regeneration of Plants from Leaf Explants of Micropropagated Clonal *Eucalyptus grandis*.” *Plant Cell Reports* 13(8): 473-476.

Landsberg, J.J. and Gower, S. T. (1997). Applications of Physiological Ecology to Forest Mangement. San Diego, Academic Press.

Landsberg, J.J. and Hingston, F. J. (1996). “Evaluating a simple radiation/dry matter conversion model using data from *Eucalyptus globulus* plantations in Western Australia.” *Tree Physiology* 16: 801-808.

Landsberg, J.J. and Waring, R. H. (1997). “A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning.” *Forest Ecology and Management* 95: 209-228.

Landsberg, J.J. (1998). Assessing forest productivity in Australia and New Zealand using a physiologically-based model driven with averaged monthly weather data and satellite-derived estimates of canopy productivity. *For. Ecol. Manage*. 104, 113-127.

Landsberg, J.J., Johnson, K.H., Albaugh, T.J., Allen, H.L. and McKeand, S.E. (2000). Applying 3-PG, a simple process-based model designed to produce practical results, to data from loblolly pine experiments. *For. Sci*. (in press).

Lang, A. R. G. and McMurtrie, R. E. (1992). “Total leaf areas of single trees of *Eucalyptus grandis* estimated from transmittances of the sun's beam.” *Agricultural and Forest Meteorology* 58: 79-92.

Law, B.E., Waring, R.H., Anthoni, P.M. and 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 Maitre, D.C. and Versfeld, D.B. (1997). “Forest evaporation models: relationships between stand growth and evaporation.” *Journal of Hydrology* 193: 240-257.

Le Roux, D., Stock, W. D., Bond, W. J. and Maphanga, D. (1996). “Dry mass allocation, water use efficiency and 13C in clones of *Eucalyptus grandis*, *E. grandis* x *camaldulensis* and *E. grandis* x *nitens* grown under two irrigation regimes.” *Tree Physiology* 16: 497 - 502.

Lee, D., Ryan, P., and Nikles, G. (1997). Provenance variation of *Eucalyptus cloeziana* exhibited at Pomona in South eastern Queensland. *In* “Overcoming impediments to reforestation : tropical forest rehabilitation in the Asia-Pacific region, proceedings of the 6th International Workshop of Bio-Refor, Brisbane, Australia” (E. J. K. e. al.], ed.). Brisbane, Qld. : BIO-REFOR, 1998., Australia.

Lesch, W. and D. F. Scott (1997). “The response in water yield to the thinning of *Pinus radiata*, *Pinus patula* and *Eucalyptus grandis* plantations.” *Forest Ecology and Management* 99(3): 295-307.

Leuning, R. (1990). “Modeling Stomatal Behavior and Photosynthesis of *Eucalyptus grandis*.” *Australian Journal of Plant Physiology* 17(2): 159-175.

Leuning, R. (1995). “A critcal appraisal of a combined stomata-photosynthesis model for C_3 plants.” *Plant, Cell and Environment*. 18: 339-355.

Leuning, R., Wang, Y. P. and Cromer, R. N. (1990). Model simulations of spatial distributions and daily totals of photosynthesis in *Eucalyptus grandis* canopies. Shell Hardwood Plantation Development Project. Final Report, CSIRO Division of Forestry and Forest Products.

Leuning, R., Wang, Y. P. and Cromer, R. N. (1991). “Model simulations of spatial distributions and daily totals of photosynthesis in *Eucalyptus grandis* canopies.” *Oecologia* 88: 494-503.

Lima, W. d. P., Zakia, M. J., Libardi, P. L. and Filho, A. P. d. S. (1990). “Comparative evapotranspiration of eucalyptus, pine and natural 'Cerrado' vegetation measured by the soil water balance method.” *Piracicaba, IPEF International* 1: 5-11.

Loxton, I., and Forster, S. (2000). "Brigalow Research Station Technical Report 1999-2000," Rep. No. Q100098. Queensland Beef Industry Institute, Department of Primary Industries, Queensland, Theodore.

Mabvurira, D. and J. Miina (2002). "Individual-tree growth and mortality models for *Eucalyptus grandis* (Hill) Maiden plantations in Zimbabwe." *Forest Ecology and Management* 161(1-3): 231-245.

McAlpine, J.R. (1970). Estimating pasture growth periods and droughts from simple water balance models. In "XI International Grasslands Congress", Surfers Paradise, Queensland (Ed. M. J. T. Norman) pp. 484-487.

Medhurst, J. L., Battaglia, M., Cherry, M. L., Hunt, M. A., White, D. A. and Beadle, C. L. (1999). "Allometric relationships for *Eucalyptus nitens* (Deane and Maiden) Maiden plantations." *Trees* 14: 91-101.

Medlyn, B. E. (1996). "Interactive effects of atmospheric carbon dioxide and leaf nitrogen concentration on canopy light use effciency: a modeling analysis." *Tree Physiology* 16: 201-209.

Mensforth, L., Thorburn, P. J., Tyerman, S. D. and Walker, G. R. (1994). "Sources of water used by riparian *Eucalyptus camaldulensis* overlying saline groundwater." *Oecologia* 100: 21-28.

Michelozzi, M., Johnson, J. D. and Warrag, E. I. (1995). "Response of ethylene and chlorophyll in two eucalyptus clones during drought." *New Forests* 9: 197-204.

Mielke, M. S., Oliva, M. A., de Barros, N. F., Penchel, R. M., Martinez, C. A. and de Almeida, A. C. (1999). "Stomatal control of transpiration in the canopy of a clonal *Eucalyptus grandis* plantation." Trees 13: 152-160.

Mousa, A. and Keady, E. (1998). Plantation volume growth summaries from growth plots in Queensland. Brisbane, DPI Forestry.

Mummery, D. and Battaglia, M. (2000). Applying PROMOD spatially across Tasmania with sensitivity analysis to screen for prospective *Eucalyptus globulus* plantation sites. *Forest Ecology and Management* 140:51-63.

Myers, B. J., Benyon, R.G. Theiveyanathan, S., Criddle, R.S., Smith, C.J., and Falkiner, R.A (1998). "Response of effluent-irrigated *Eucalyptus grandis* and *Pinus radiata* to salinity and vapor pressure deficits." *Tree Physiology* 18(8-9): 565-573.

Myers, B. J., Theiveyanathan, S., O'Brien, N. D. and Bond, W. J. (1996). "Growth and water use of *Eucalyptus grandis* and *Pinus radiata* plantations irrigated with effluent." Tree Physiology 16: 211-219.

Olbrich, B. W. (1991). "The Verification of the Heat Pulse Velocity Technique for Estimating Sap Flow in *Eucalyptus grandis*." *Canadian Journal of Forest Research* 21(6): 836-841.

Olbrich, B., Leroux, W.D., Poulter, A.G., Bond, W.J. and Stock, W.D. (1993). "Variation in Water-Use Efficiency and Delta-C-13 Levels in *Eucalyptus grandis* Clones." *Journal of Hydrology* 150(2-4): 615-633.

Ozkurt, N., Gulbaba, A.G., Ozkurt, A. and Tufekci, S. (1998) Phenological observations on *Eucalyptus* (*E. camaldulensis* and *E. grandis*). Teknik Bulten Orman Bakanligi Dogu Akdeniz Ormancilik Arastirma Enstitusu No 8, 46pp.

Rance, S. J., Cromer, R. N., Cameron, D. M. and E.R., W. (1990). Response of young *Eucalyptus grandis* to fertilizer treatments. I Biomass, leaf area, volume and wood density. Shell Hardwood Plantation Development Project. Final Report, CSIRO Division of Forestry and Forest Products.

Rockwood, D. L. and Dippon, D. R. (1989). “Biological and economic potentials of *Eucalyptus grandis* and slash pine as biomass energy crops.” *Biomass* 20: 155-165.

Sands, P. (1988). “Resource modelling: its nature and use.” *Mem. Ent. Soc. Can*. 143: 5-10.

Sands, P.J., Battaglia, M. and Mummery, D. (2000). Application of process-based models to forest management: Experience with PROMOD, a simple plantation productivity model. *Tree Physiology*, 20: 383-392

Sands, P. J., R. N. Cromer, et al. (1992). “A Model of Nutrient Response in *Eucalyptus grandis* Seedlings.” Australian Journal of Plant Physiology 19(5): 459-470.

Sands, P.J. (1995). “Modelling canopy production. II. From single-leaf photosynthetic parameters to daily canopy photosynthesis.” *Aust. J. Plant Physiol*. 22: 603-614.

Sands, P.J. (1996). “Modelling canopy production. III. Canopy light-utilisation efficiency and its sensitivity to physiological and environmental variables.” *Aust. J. Plant Physiol*. 23: 103-114.

Sands, P.J. (2001). Productivity models - a comparative analysis. Technical Report No. 55 (M. Cherry and C. Beadle Eds) pp 51-54. (CRC-SPF, Hobart, Tasmania).

Sands, P.J. and Landsberg, J.J. (2002). Parameterisation of 3-PG for plantation grown *Eucalyptus globulus*. *Forest Ecology and Management*, 163: 273-292

Sands, P.J., Rawlins, W. and Battaglia, M. (1999). Use of a simple plantation productivity model to study the profitability of irrigated *Eucalyptus globulus*. *Ecological Modelling*, 117:125-141.

Sands, PJ. (2001). 3PGpjs 1.1 – a User-Friendly Interface to 3-PG, the Landsberg and Waring Model of Forest Productivity. Technical Report. No. 29, CRC Sustainable Production Forestry, Hobart.

Sands, PJ. (2002). PROMOD Excel – a User-Friendly Interface to PROMOD. Technical Report. No. 88, CRC Sustainable Production Forestry, Hobart.

Schonau, A. P. G. (1984). “A Factorial Thinning Experiment in *Eucalyptus grandis*.” *Commonwealth Forestry Review* 63(4): 285-295.

Schonau, A. P. G. (1984). “Silvicultural Considerations for High Productivity of *Eucalyptus grandis*.” *Forest Ecology and Management* 9(4): 295-314.

Schubert, T. H., Strand, R. F., Cole, T. G. and Macduffie, K. E. (1988). “Equations for predicting biomass of six introduced tree species, island of Hawaii.” *Research Note Pacific Southwest*. 401.

Scott, D. F. and Lesch, W. (1997). “Streamflow responses to afforestation with *Eucalyptus grandis* and *Pinus patula* and to felling in the Mokobulaan experimental catchments, South Africa.” *Journal of Hydrology* 199: 360-377.

Sheriff, D. W. and Nambiar, E. K. S. (1991). “Nitrogen nutrition, growth and gas exchange in *Euclayptus globulus* Labill. seedlings.” *Aust. J. Plant Physiology* 18: 37-52.

Silva, W. da, Silva, A.A. da, Sediyama, T., Cardoso, A.A., da Silva, W. and da Silva, A.A (1999) Biomass and leaf area of *Eucalyptus citriodora* and *Eucalyptus grandis* seedlings as affected by soil water content and competition with *Brachiaria brizantha*. *Pesquisa Agropecuaria Gaucha* 5(1): 29-36.

Silva, W. da, Silva, A.A. da, Sediyama, T., Freitas, R.S. d, da Silva, W., da Silva, A.A. and de Freitas, R.S. (2000) Nutrient uptake by seedlings of two eucalypt species in response to different soil water contents and competition with *Brachiaria brizantha* plants. *Cienca e Agrotecnologia* 24(1): 147-159.

Snow, V. O., Bond, W. J., Myers, B. J., Theiveyanathan, S., Smith, C. J. and Benyon, R. G. (1999). “Modelling the water balance of effluent-irrigated trees.” *Agricultural Water Management* 39: 47-67.

Specht, R. L. and Specht, A. (1989). “Canopy structure in *Eucalyptus*-dominated communities in Australia along climatic gradients.” *Acta Oecologia* 10(2): 191-213.

Tandon, V. N., Pande, M. C. and Singh, R. (1988). “Biomsss estimation and distribution of nutrients in five different aged *Eucalyptus grandis* plantation ecosystems in Kerala State.” *Indian Forester* 114(4): 184-199.

Turner, J. (1986). “Organic matter, accumulation in a series of *Eucalyptus grandis* plantations.” *Forest Ecology and Management* 17: 231-242.

Turner, J. and Lambert, M. (1983). “Nutrient cycling within a 27 year old *Eucalyptus grandis* plantation in New South Wales.” *Forest Ecology and Management* 6: 155-168.

Waring, R.H. (2000). A process model analysis of environmental limitations on growth of Sitka spruce plantations in Great Britain. *Forestry* 73: 65-79.

Waring, R.H., Landsberg, J.J. and Williams, M. (1998). Net primary production of forests: a constant fraction of gross primary production? *Tree Physiol.* 18, 129-134.

Warrag, E. I., Lesney, M. S. and Rockwood, D. L. (1989). “Comparative greenhouse study of *Eucalyptus grandis* in vitro plantlets and half-sib seedlings, I. Net photosynthesis.” *Plant Cell Reports* 8: 497-499.

West, P. W., Lennon, S. M. and Cromer, R. N. (1995). Modelling growth of *Eucalyptus grandis* plantations with FOREST-BCG. Hobart, CSIRO Division of Forestry.

Williams, J., Prebble, R. E., Williams, W. T. and Hignett, C. T. (1983). “The influence of texture, structure and clay mineralogy on the soil moisture characteristic.” *Aust. J. Soil Res*. 21: 15-32.

Williams, K., Ed. (1999). Workshop on the Forest Model 3-PG - its use, evaluation, the wide-scale versions and matters arising. Brisbane, DNR, Forest Ecosystem Research and Assessment.

Willigen, v. C. and Panmenter, N. W. (1998). “Relationship between growth and xylem hydraulic characteristics of clones of *Eucalyptus* spp. at constrasting sites.” *Tree Physiology* 18: 595-600.