Long-term growth responses of *Eucalyptus globulus* to soil ripping, weed control and fertiliser application at establishment on a former agricultural site in South-eastern Australia

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ABSTRACT

Eucalyptus globulus is an important commercial pulpwood species in southern Australia, where approximately 450,000 ha have been established in the decade to 2005 with a nominal rotation length of 10–15 years. While there has been considerable research and development effort on establishment silviculture practices, there are few rotation-length studies of growth and yield responses.

The effects of soil ripping, weed control and fertiliser application at establishment on growth of *E. globulus* were evaluated to age 10 years on a former agricultural site at Buffalo River, north-eastern Victoria, Australia. The site has an average annual rainfall of 1110 mm and evaporation of 1240 mm. The soil is well drained and structured.

The effects of silvicultural treatments on tree survival had occurred mainly by the first year of growth and were dominated by weed control (75–90% survival compared to 10–60% where no weed control). An interaction between weed control and fertiliser resulted in greater mortality when fertiliser was applied without weed control. Ripping had no effect on survival. Consequently, stem volume growth per hectare was approximately 2 to 4 times greater in the weed-controlled treatments than in the no weed control treatments (c. 60 m^3 ha^{-1} at age 10 years).

Volume growth responses above the weed control only treatment (c. 140 m^3 ha^{-1} at age 10 years) were apparent from age 2 years, and by age 10 years were similar in the ripping and fertiliser treatments (44% and 55% respectively), and were additive (81%) in combination. Differences in growth between fertiliser treatments were attributed to N and P nutrition. Differences in growth between ripping treatments were associated with greater root abundance in the disturbed soil along rip lines.

The process-based CABALA forest growth model predicted basal area trajectories well for treatments with ripping and weed control, with or without fertiliser application. Growth in treatments with weed control, but no ripping, was not satisfactorily modelled.

INTRODUCTION

Australia's total plantation area of 1.74 million hectares (Mha) at December 2005 comprised 0.74 Mha (43%) hardwoods and 0.99 Mha (57%) softwoods (Parsons *et al.* 2006). Between 1995 and 2005, there was a rapid expansion (0.54 Mha) of the total hardwood area, particularly in southern Australia where *Eucalyptus globulus* (Labill.), total 0.45 Mha, was dominantly planted in Western Australia, South Australia and Victoria, and *E. nitens* (Deane and Maiden), total 0.14 Mha, dominantly planted in Tasmania. The *E. globulus* plantations have been mostly established on former agricultural land for pulpwood production over rotations of 10–15 years.

The plantation expansion has been supported by a considerable research and development effort on establishment silviculture, including soil cultivation, weed control and fertiliser application with the aim of developing cost-effective, site specific practices (Goncalves *et al.* 2004). Early experimental results clearly demonstrated the critical need to undertake weed control to achieve adequate survival and avoid plantation failure (e.g. Borschmann and Baker

1995). Growth responses to soil cultivation (ripping, mounding, discing) were usually apparent but the magnitude variable across different soils (e.g. Borschmann and Baker, 1995; Holz *et al*., 1999; Lacey *et al.* 2001, Duncan and Baker, 2004). Responses to fertiliser application on former agricultural sites (cf. unimproved sites, e.g. Mendham *et al.* 2002) while evident were less clear (e.g. Baker 1998, Bird *et al.* 2000). Among the many establishment techniques experiments there are few longer-term studies to allow detailed analysis of growth responses and confident financial analysis of alternative practices using observed rotation-length data.

This study describes growth responses to age 10 years of *E. globulus* to soil ripping, weed control and fertiliser application at establishment on a former agricultural (pasture) site at Buffalo River, north-eastern Victoria, Australia. Observations on soil morphological properties, soil nutrient availability, tree nutrition and root distribution, are used to explain the growth responses. The responses are further interpreted using the CABALA process-based forest growth model.

METHODS

Site description

The Buffalo River trial site (Latitude 36° 47′ 00″S, Longitude 146° 40′ 01″E) has a long-term average annual rainfall of 1110 mm and an average annual pan evaporation of 1240 mm. Average daily maximum and minimum temperatures are respectively 29.6 and 13.0°C in January and 11.4 and 1.9°C in July (Hutchinson, 1991). The site is 300 m above sea level, with an average slope of 3%. Soils are Red and Brown Dermosols (Isbell, 1996), alternatively classified as having non-calcareous Gradational Primary Profile Forms (Gn, Northcote *et al.* 1979), formed on Ordovician marine sediments. Prior to establishment of the trial the site was phalaris grass and subterranean clover pasture used for cattle grazing. These two species and sorrel were the dominant weeds during plantation establishment.

Trial design and establishment

The trial compared two levels each of soil ripping, weed control, and fertiliser application in a complete factorial randomised block design with three replicates. The ripping treatments were deep ripping along planting rows to 0.6 m depth (R+) and unripped (R-). The weed control treatments were herbicide applied along the planting rows (W+) and no weed control (W-). The fertiliser treatments were addition of N, P, K and B (F+), and no fertiliser (F-). Treatment plots were set out with 8 rows x 8 trees (3 x 3 m spacing), with one or two buffer rows of trees between each treatment plot.

The R+ treatment plots were contour ripped (3 m spacing) in April 1990 using a winged tine drawn by a bulldozer. The soil profile was dry, and the ripping operation effective as evidenced by soil surface ground heave approximately 0.6 m either side of the rip line. The W+ treatment plots received a pre-planting herbicide application in July 1990 of glyphosate (1.4 kg ha^{-1} active ingredient) and simazine (6.2 kg ha^{-1} active ingredient) in 270 L ha^{-1} of water sprayed in a 2 m swath along the planting line using a tractor mounted boom spray. A post-planting herbicide application of fluazifop-P (0.424 kg ha^{-1} active ingredient) in 400 L $ha^{-1}$of water was applied using a hand-held spot gun to a 1 m diameter circle around each tree in November 1990. Trees in the F+ treatment plots were planted with a 21 g NPK fertiliser tablet (20% N, 10% P, 5% K). The post-planting fertiliser treatment consisted of a banded (along the planting line) application of 500 g $tree^{-1}$ of NPKS fertiliser (8% N, 10.5% P, 10% K, 7.1% S) and 30 g per tree of ulexite (13% B) 2 months after planting; and a banded application of 1300 kg ha^{-1} of NPKS fertiliser (16.6% N, 6.6% P, 9% K, 11% S) 14 months after planting. Total N, P, K, S and B application was the equivalent of 265, 145, 175, 183 and 4 kg ha^{-1} respectively.

Eucalyptus globulus (Jeeralang, South Gippsland, Victoria seed source) seedlings were raised by a commercial nursery in 40-plug x 60 mL container trays, and were 200–250 mm tall and healthy at planting. Seedlings were planted in August 1990 into 200 x 200 x 200 mm spade-cultivated pits. In the ripped plots, the planting pits were made immediately adjacent to the rip line. In all treatments, the top 30 mm of soil from the pits was scalped and discarded to avoid herbicide (simazine) treated top soil coming in contact with the roots of the seedlings. In November 1990, trees were sprayed with carbaryl insecticide (0.1% solution) to control insect defoliation by wingless grasshoppers.

Measurements and data analysis

The inner 6 x 6 trees of each 8 x 8 tree treatment plot were measured for survival and total height (H, m) at ages 1.0, 2.0, 2.6, 4.4, 5.9, 7.5 and 10.5 years. The trees were also measured for diameter overbark at 1.3 m height (D, cm) from age 2.0 years. Survival, mean dominant height (mean height of the 6 largest-diameter trees per 36-tree measurement plot, equivalent to the mean height of the 200 largest diameter trees ha^{-1}), basal area (overbark) and stem volume (underbark to a small end diameter of 2 cm) in each plot were calculated from individual tree measurements. Stem volume (V, m^3) was calculated using a generalised individual-tree volume function developed for fast growing eucalypts ($V = 0.0054125 + 2.966 \times 10^{-5} D^2H$; Wong *et al.*, 1999).

Foliage samples (youngest fully expanded leaves from the upper one-third of the live crown) were collected from six co-dominant trees in each plot in June 1992 (age approximately 2 years, juvenile foliage) and May 1994 (age approximately 4 years, adult foliage). Samples were dried (70°C), finely ground, and analysed for total N (colorimetrically after Kjeldahl digestion), and S, P, K, Ca, Mg, Fe, Mn, Zn, Cu and B (by ICP-AES after digestion in nitric and perchloric acids).

Surface soil samples (0–10, 10–20 cm depth; thirty 25 mm diameter cores per sample) were collected from each replicate block of the trial in May 1990. Samples were air dried (40°C), sieved (< 2 mm) and analysed for pH (1:5 soil : water), total N (colorimetrically after Kjeldahl digestion), organic carbon (Walkley Black Method 6A1; Rayment and Higginson, 1992) and extractable P (colorimetrically after Bray and Kurtz No. 2 reagent, 1:7 soil : 0.03 M NH_4F in 0.1 M HCl, 40 s extraction; Bray and Kurtz, 1945).

Soil morphology was described according to the conventions of McDonald *et al.* (1998) in three pits (up to 3.5 depth) dug in inter-rows within the trial area in December 2001 (age 11 years). The effects of ripping on soil structure and root abundance was visually assessed in soil trenches (approximately 1.2 m deep) dug across and perpendicular to the planting lines in each of three unripped and three ripped treatment plots.

Growth modelling

Observed growth in the R -/+ by F -/+ treatments receiving weed control was compared with predictions using CABALA Version 2.1 a daily time-step linked carbon, water and nitrogen process-based forest growth model (Battaglia *et al.*, 2004). The model requires parameters/data for species, site, climate and (silvicultural) regime. *E. globulus* species parameters distributed with Version 2.1 were used. Daily climate data were taken from SILO Data Drill (http://www.bom.gov.au/silo) for the trial location. Silvicultural regime specifications for planting (e.g. espacement) and N fertiliser application were input according to actual values and dates. Site N-availability variables (C, N, pH) for the surface 0–10, 10–20 and 20–50 cm of soil were determined from the analyses of the soil samples.

Comparisons of observed and modelled growth were made primarily using stand basal area, CABALA's conventional mensuration output variable that is most closely related through mean tree diameter and stand density to the allometric (power) relationships within CABALA that are used to distribute assimilated carbon (and therefore biomass) amongst tree components. While tree height and stand volume (a function of stand basal area and stand height) might also have been used, growth predictions for ages greater than 6 years departed markedly from observed values suggesting that the tree diameter-height relationship is inappropriate for the study site. CABALA's competition-dependent self-thinning rule was over-ridden, and tree density trajectories with age were forced to approximate observed densities by imposing an annual thinning from below.

RESULTS

Tree growth responses in relation to silviculture and site factors

During the study period (1990–2001) annual rainfall was 1160 mm, similar to the long-term average of 1110 mm. Annual rainfall varied from 1490 mm (1992, trees aged 2 years) to 760 mm (1997, trees aged 7 years). Average monthly rainfall varied from 50 mm in March (range 3–120 mm) to 150 mm in September (range 53–330 mm). Monthly rainfalls less than 10 mm occurred variously in February, March, April, May, October and December.

The effects of silvicultural treatments on tree survival occurred within the first year from planting, with relatively little subsequent change attributable to intra-specific competition-induced mortality to age 10 years (**Table 1**). The silvicultural effects were dominated by weed control, with survival greater in the W+ treatments (75 to 90 %) than in the W- treatments (10 to 60%). An interaction between weed control and fertiliser application arose because fertiliser promoted weed growth in the W-F+ treatments and the increased inter-specific competition resulted in greater tree mortality. Ripping had no effect on survival to age 10 years.

By age 10 years, basal area and stem volume were approximately 2 to 4 times greater in the W+ treatments than in the W- treatments (**Table 1**), largely because of greater survival. However, an average increase of 14% in mean dominant height (**Table 1**) in the W+ treatments also contributed to this volume response. The weed control by fertiliser interaction on survival was mirrored in basal area and volume, although relatively less. For example, at age 10 years survival in the W-F- and W-F+ treatments averaged 51 and 15% respectively, whereas volume averaged 64 and 60 m^3 ha^{-1} respectively. An interaction between ripping and weed control treatments on volume responses to age 7.5 years (and earlier for mean dominant height and basal area) arose because there was no response to ripping in the W- treatments.

Where weeds were controlled, the volume growth response at age 10 years (i.e. increased volume above R-W+F- treatment) to ripping alone was 64 m^3 ha^{-1}, to fertiliser application alone was 80 m^3 ha^{-1}, and to ripping and fertiliser application combined was 117 m^3 ha^{-1}. However, these treatment effects were statistically additive and on average ripping contributed 57% and fertiliser 43% of the combined response. Differences in volume growth trajectories between treatments were discernible from age 2 years (**Figure 1**). Relative responses to treatments calculated on a cumulative growth basis expectably declined with age; for example the ratio of volumes in R+W+F+ to R-W+F- treatments was respectively 6.5, 2.5 and 1.8 at ages 2.6, 5.9 and 10.5 years. Likewise, relative responses calculated on a periodic annual increment (PAI) basis between successive measurements also declined with age; for example the ratio of PAIs in R+W+F+ to R-W+F- treatments was respectively 6.3, 1.5 and 1.5 at ages 2.0–2.6, 4.4–5.9 and 7.5–10.5 years. At least for the W+ treatments, the volume growth trajectories indicated continue divergence to age 10 years; that is absolute responses (m^3 ha^{-1}) increased with age and result from approximately linear height and basal area growth (**Figure 1**).

Table 1 Survival, mean dominant height, basal area and volume of *Eucalyptus globulus* to age 10 years in response to ripping (R -/+), weed control (W -/+) and fertiliser application (F -/+) treatments.

Treat-ment	**Survival (%)**							**Mean dominant height (m)**							**Basal area (m^2 ha^{-1})**						**Volume (m^3 ha^{-1})**					
	Age (years)							**Age (years)**							**Age (years)**						**Age (years)**					
	1.0	**2.0**	**2.6**	**4.4**	**5.9**	**7.5**	**10.5**	**1.0**	**2.0**	**2.6**	**4.4**	**5.9**	**7.5**	**10.5**	**2.0**	**2.6**	**4.4**	**5.9**	**7.5**	**10.5**	**2.0**	**2.6**	**4.4**	**5.9**	**7.5**	**10.5**
R-W-F-	65	64	64	61	61	58	57	0.7	1.4	2.7	5.6	7.7	11.2	17.4	0.0	0.1	0.9	2.5	4.3	9.1	0.03	0.43	2.57	8.20	19.4	60.0
R-W-F+	11	10	10	10	10	10	10	0.8	2.6	4.3	8.7	10.6	13.6	22.1	0.1	0.3	1.1	2.1	3.2	5.6	0.20	0.70	4.10	9.60	18.4	48.0
R-W+F-	80	78	78	78	78	77	75	1.0	2.9	4.8	8.7	10.6	15.0	20.3	0.3	1.6	5.0	9.0	12.1	18.9	0.77	3.70	17.9	38.1	68.4	144
R-W+F+	90	92	92	91	85	85	81	1.5	4.8	6.9	11.3	13.6	17.6	23.5	1.3	5.1	10.5	14.8	18.5	25.3	3.23	14.3	46.8	76.4	121	224
R+W-F-	48	48	47	47	45	45	44	0.7	1.2	2.9	6.1	8.3	12.3	18.6	0.0	0.2	1.0	2.7	4.7	9.7	0.00	0.43	2.77	9.20	22.1	67.6
R+W-F+	23	21	21	20	20	20	20	0.9	2.9	4.9	8.1	10.6	14.6	21.2	0.1	0.6	1.7	3.3	5.0	8.7	0.27	1.37	5.87	14.2	28.5	71.2
R+W+F-	98	98	98	96	91	93	89	1.2	4.0	6.0	10.6	12.9	17.4	22.7	0.6	3.5	8.7	13.6	17.3	24.4	1.63	8.90	36.3	68.1	113	208
R+W+F+	94	94	94	93	89	85	84	1.8	5.5	7.6	12.0	13.9	17.4	23.9	2.4	7.9	14.0	18.0	21.4	29.0	5.87	24.2	66.4	96.4	145	261
Significance[1]																										
R	NS	NS	NS	NS	NS	NS	NS	***	**	***	NS	**	*	NS	***	***	***	**	*	*	***	***	***	***	**	*
W	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***
F	***	**	*	**	**	**	**	***	***	***	***	***	***	***	***	***	***	**	*	NS	***	***	***	***	**	*
R*W	NS	NS	NS	NS	NS	NS	NS	**	**	*	*	NS	NS	NS	***	***	**	*	NS	NS	***	***	***	**	*	NS
R*F	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	*	NS	NS	NS	NS	NS	**	*	NS	NS	NS	NS
W*F	***	***	**	**	**	**	**	***	NS	NS	NS	NS	NS	NS	***	***	***	**	**	*	***	***	***	***	**	*
R*W*F	*	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS
RMS[2]	125	184	199	187	165	173	159	0.008	0.10	0.09	0.54	0.40	0.91	1.99	0.03	0.20	1.07	2.69	5.06	13.1	0.136	1.86	22.7	60.5	210	1142

[1] Significance of difference between treatments: NS=not significant, * = $p< 0.05$, ** = $p< 0.01$, *** = $p < 0.001$.

[2] Residual Mean Square (df = 14) from analysis of variance.

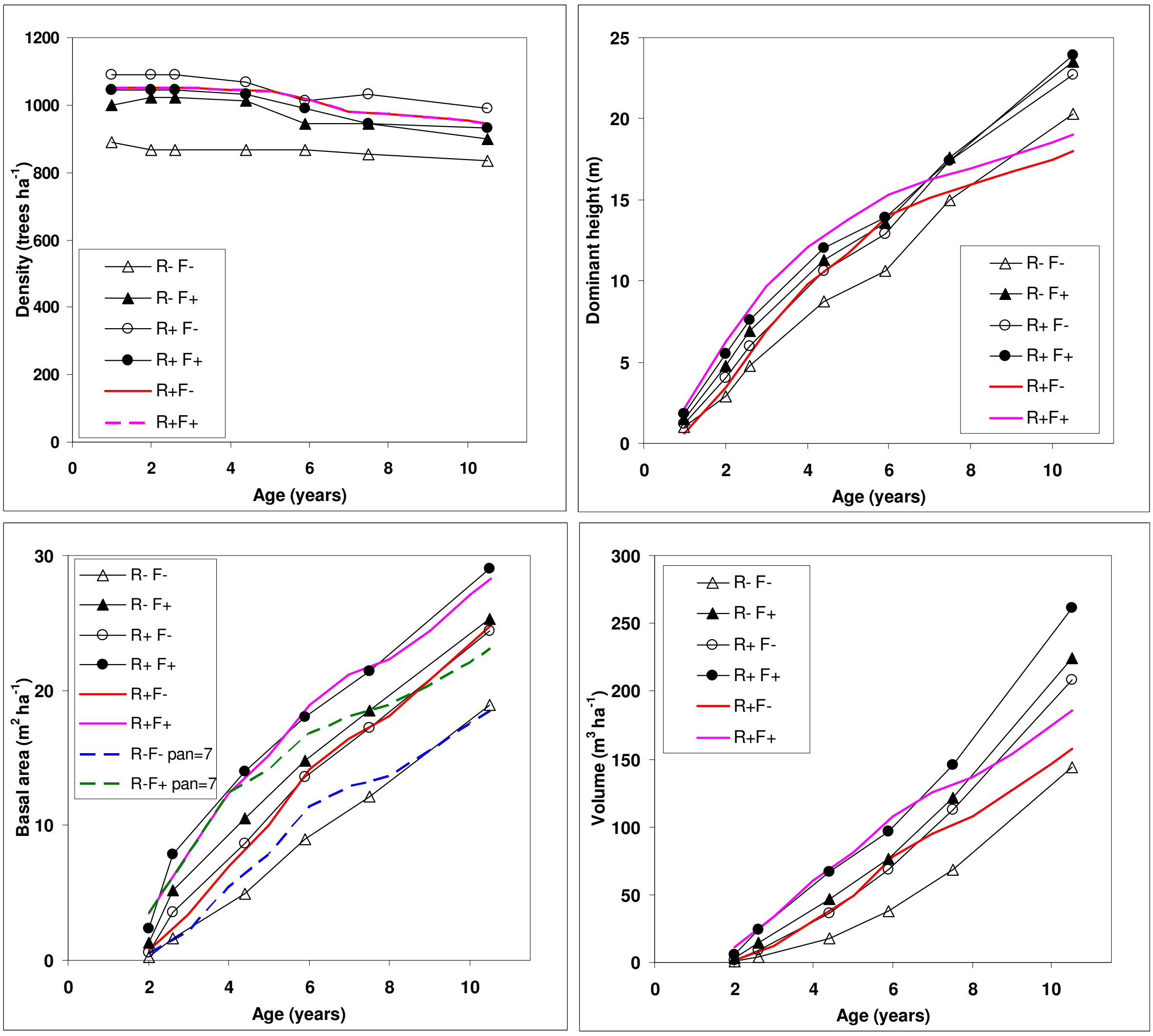

Figure 1 Survival, mean dominant height, basal area and volume of *Eucalyptus globulus* to age 10 years in response to ripping (R -/+) and fertiliser application (F -/+) treatments where weeds were controlled. Example CABALA model predictions are superimposed (see text).

On average, the surface soil (0–10, 10–20 cm) had a pH of (4.6, 4.8), total N (2.8, 1.3 g kg^{-1}), organic C (29, 12 g kg^{-1}), C : N ratio (10, 9) and extractable P (7.6 and 6.5 mg kg$^{-1,}$ respectively). Although the site was expected to be relatively fertile because of its agricultural history, the concentrations of available P in the soil were low by agronomic standards and P fertiliser would have been recommended for continuing pasture production.

Ripping or weed control treatments did not affect nutrient concentrations in foliage. The observed tree growth responses to fertiliser application correlated with apparent improved tree nutrition as assessed by nutrient concentrations in juvenile foliage at age 2 years (**Table 2**). Application of the NPKS and B fertilisers increased N, S, P, K, Zn and B concentrations but decreased Ca, Mg, and Cu concentrations. Using diagnostic/interpretative values for juvenile foliage for young (age < 2 years) *E. globulus* plantations from Dell *et al.*, 2001, the observed concentration changes for K, Ca, Mg, Zn and Cu were not nutritionally significant. The increases in concentrations of N (from 16.2 to 21.9 mg kg^{-1}) and of P (from 1.1 to 2.1 mg kg^{-1}) in response to fertiliser compared to the minimum adequate values of 25 and 1.3 mg kg^{-1} respectively suggest that P and N were the nutrients primarily associated with the growth response. By age 4 years (approximately 3 years after the last fertiliser application) there was no effect on concentrations of N or P in adult foliage, and higher concentrations of B and lower concentrations Cu in foliage in the fertiliser treatments were not nutritionally significant (**Table 2**). However, for B, they indicate continued availability from the more slowly soluble calcium borate in the ulexite.

Table 2 Mean foliar nutrient concentrations for *Eucalyptus globulus* at ages 2 and 4 years in response to fertiliser application (F -/+) treatments.

Age (years)	Treatment	N ($g\ kg^{-1}$)	S	P	K	Ca	Mg	Fe ($mg\ kg^{-1}$)	Mn	Zn	Cu	B	Al
2	F-	16.2	1.6	1.1	8.3	8.9	2.8	33	1888	13	4	13	141
	F+	21.9	1.9	2.1	9.4	6.5	2.0	36	2085	16	2	20	125
	Significance[1]	***	***	***	*	***	***	NS	NS	***	***	***	**
4	F-	22.7	1.6	1.8	12.2	7.1	1.7	55	1041	19	11	15	71
	F+	21.5	1.6	1.7	12.2	5.6	1.6	57	996	20	10	19	64
	Significance[1]	NS	NS	NS	NS	**	NS	NS	NS	NS	**	**	**

[1] Significance of difference between treatments: NS=not significant, * = $p< 0.05$, ** = $p< 0.01$, *** = $p < 0.001$.

Soil profile texture increases slightly from clay loam (A_{11} horizon) to clay loam (heavy) (B_{23} horizon). Structure varies from weak coarse to weak medium polyhedral large peds parting to weak fine/medium granular smaller peds. The soil appears well drained as evidenced by absence of bleaching, and with mottling only occurring beneath 2 m depth in one profile. There are very few coarse fragments, and there are no morphologically identifiable pans or impeding layers to root growth, at least to 3.5 m depth, as evidenced by the presence of roots (size class 2-3, abundance 1, McDonald *et al.* 1998) at 1.5 m depth in all profiles, and roots observed to 3.5 m depth in two of three profiles. Nonetheless, roots were relatively abundant at the A–B horizon interface (35 cm depth), which is consistent with development of an agriculture-induced pan.

Given the soil's apparent favourable depth, texture, structure and drainage for tree growth, the magnitude of the growth response to ripping was unexpected. However, the growth response was associated with an apparent improvement in soil physical properties for root growth observed around the rip line across an area of approximately 1 m width and 0.6–0.9 m depth. Here, the soil was more finely structured and friable and there was a greater abundance of fine roots than in the soil immediately adjacent. These differences were not apparent where the soil was not ripped. Thus the growth response to ripping may be attributed at least to improved soil conditions allowing more rapid root growth and occupation of a potential rooting zone, if not in addition, access to a greater rooting zone volume. It may also be speculated that the contour ripping used in the study would have promoted infiltration of rainwater into the soil profile near the trees, particularly that which might have otherwise been lost to run-off. Evidence of this is that (open) rip lines in some soils fill with water after intense rainfall.

Modelled growth

From initial model runs it was evident that CABALA-predicted growth (e.g. to age 10.5 years) and the shape (curvilinearity) of the growth trajectory was sensitive to: (i) total soil depth (specified in the model in three user-defined horizons) and therefore potential storage of plant available water, (ii) a scalar (specified 0 to 1) used to reduce the modelled soil N mineralisation rate for the proportion of the soil humus pool involved in mineralisation, and (iii) the interaction of these two variables. Moreover, it was evident that an *a priori* specification of soil depth based (simply) on presence of roots observed to at least 3.5 m in soil pits, was not appropriate.

Therefore, the modelled growth response to soil depth (in 0.5 m increments from 0.5 to 3.5 m) by the N mineralisation scalar (values of 0.1, 0.2, 0.3, 0.4, 0.5, 1.0) was explored and compared to observed growth (at ages 5.9 and 10.5 years) in the R+F- and R+F+ treatments (i.e. where based on the observed growth responses any physical soil restriction had been removed, or at least reduced). The optimum fit to observed basal area resulted for a total soil depth of 2 m (Upper Horizon 1: 0–0.5 m depth, Middle Horizon + Lower Horizon: 0.5–2.0 m depth) and an N mineralisation scalar = 0.4 (**Figure 1**). The relatively uniform texture of the soil profile (clay loam, plant available water estimated to be 180 mm m^{-1} depth) facilitated the exploration of the effect of soil depth in the model simply by varying the total thickness of Middle Horizon + Lower Horizon.

Assuming these optimised values for soil depth and the N mineralisation scalar, and assuming that they had not been affected by ripping, the effect of <u>not</u> ripping was then explored by comparing observed growth in the R-F- and R-F+ treatments with modelled growth where (i) a root-impeding pan of arbitrary 'hardness' (specified 1 to 10) was imposed – in the model the pan is defined to be between the Upper Horizon and Middle Horizon and reduces the available water beneath this depth, and (ii) where the potential maximum annual vertical root growth was reduced. Neither varying pan hardness, or varying maximum root growth, or these in combination provided satisfactory fits to observed basal area growth simultaneously to the R-F- and R-F+ treatments across ages (see example Pan = 7 in **Figure 1**). Particularly, the modelled basal area trajectories were strongly curvilinear compared to observed linear growth.

Selected variables predicted by CABALA for R+F- and R+F+ treatments at ages 5 and 10 years are shown in Table 3. Run-off (including drainage beyond the rooting zone) was approximately one-third of rainfall. The trees were rarely drought-stressed, there being only 30 days in 10 years, confined to the first summer and in the R+F- treatment, where pre-dawn leaf water potential was less than -3.0 MPa. There was a significant loss of N from the site from age 0–10 years: 95 kg/ha in the R+F- treatment and 300 kg/ha in the R+F+ treatment. The difference between these indicates that 205 of the 260 kg ha^{-1} N (80%) applied in fertiliser were lost. Nonetheless, fertiliser application resulted in an early difference in leaf area index that continued to age 10 years. Maximum root depth (2.0 m) was attained earlier (age 2.4 years) in the R+F+ treatment than in the R+F- treatment (age 3.2 years). Thus the absolute growth difference (biomass) resulting from difference in leaf area between treatments that resulted from fertiliser application was established by and large within a few years from planting. Thereafter, net primary production was similar.

DISCUSSION

Soil cultivation, weed control and fertiliser application are common silvicultural practices in plantation forestry, and because they represent a significant proportion of the growing costs of plantations there is a continuing effort directed to understanding responses to better enable site-specific application of treatments. There is much experimental (including the present study) and practical experience of the importance of control of competing vegetation (weeds) during plantation establishment, and applied research effort now focuses on development of environmentally acceptable and cost effective herbicides and methods of application (Jenkin and Tomkins 2006). Likewise, there is increasing knowledge and practical experience in measurement of the nutrient status of trees, of nutrient limitations in particular soils, and in the prediction of fertiliser responses from plant and soil analysis (e.g. Dell *et al.* 2001, Mendham *et al.* 2002).

In contrast, tree growth responses to soil cultivation are understood only in general terms (e.g. reduced soil strength for more rapid root growth, fracturing of an impeding pan, enhanced mineralisation and nutrient availability from soil organic matter), and prediction of responses with site-specific application is imprecise. Thus in the recent expansion of Australia's hardwood plantations, soil cultivation (commonly ripping and mounding) is generally practised regardless whether any soil limitations, other than morphologically obvious impediments to roots such as hardpans, are in fact present on particular sites. This approach arises because of both the difficulty (and therefore cost) in the measurement and description of soil properties, exacerbated by spatial variability, and of interpreting soil properties and the potential for their amelioration in relation to growth. Indeed the present study is illustrative of the problem.

Table 3 Selected variables predicted by CABALA for R+F- and R+F+ treatments. Annual values are for ages 4.5–5.5 and 9.5–10.5 years.

Variable	**Unit**	**Age 5 years**		**Age 10 years**	
		R+F-	**R+F+**	**R+F-**	**R+F+**
Rainfall (actual)	(mm $year^{-1}$)	945		1180	
Run-off		330	240	420	400
Transpiration		490	510	560	570
Leaf area index		1.8	2.5	3.0	3.3
Above-ground biomass	(Mg ha^{-1})	34	54	93	110
Below-ground biomass		7	11	18	21
Gross primary production	(Mg ha^{-1} $year^{-1}$)	49	55	58	58
Net primary production		30	31	29	27
Litterfall		1.3	3.3	2.6	3.6

The storage and availability of water and nutrients in soils to meet the potential growth demands of trees (genetic and climatic effects) is greatly influenced by and interacts with root occupancy of the soil horizontally and vertically. Because of these interactions, a process-based modelling approach is necessary to understand growth in relation to soil properties, and responses to cultivation. CABALA was generally successful in the present study in modelling growth where a putative physical constraint to root growth had been reduced by ripping. However, the present simple conceptualisation of soil physical constraints to root growth will require further development to better model responses to soil cultivation (not only ripping, but also mounding). Particularly, the interacting spatial effects of the cultivation tool(s) and the pattern of cultivation with the natural spatial variability of soils will need to be addressed.

The present study challenges generalisations that growth response to fertiliser application on former agricultural sites (assumed to be fertile), and growth response to soil ripping on apparently favourably structured soils (at least as assessed from morphological characteristics) may be rare (e.g. Goncalves *et al.* 2004).

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LITERATURE CITED

Baker, T.G. (1998) Growth response of *Eucalyptus globulus* on ex-agricultural sites to second-season fertilizer application. In Proceedings IUFRO Conference Environmental Forest Science. Kyoto University, Japan. pp. 251–252.

Battaglia, M., Sands, P., White, D. and Mummery, D. (2004) CABALA: a linked carbon, water and nitrogen model of forest growth for silvicultural decision support. Forest Ecology and Management 193, 251-282.

Bird, P.R, Jowett, D.W, Jackson, T.T, Kearney, G.A, Waters, M.J and Measki, B. (2000) Early growth responses of blue gums on the basaltic plains to ripping, mounding and fertiliser application. Australian Journal of Experimental Agriculture 40, 987–994.

Borschmann, R. and Baker, T. (1995) Provenance selection, establishment and productivity of eucalypt plantations for north-east Victoria. In Proceedings of the Institute of Foresters of Australia, 16th Biennial Conference, Ballarat, Australia. pp. 253–262.

Bray, R.H. and Kurtz, L.T. (1945) Determination of total, organic and available forms of phosphorus in soils. Soil Science 59, 39–45.

Dell, B., Malajczuk, N., Xu, D. and Grove, T.S. (2001) Nutrient Disorders in Plantation Eucalypts. 2nd Edition, ACIAR Monograph 74, Australian Centre for International Agricultural Research, Canberra, Australia.188 p.

Duncan, M.J. and Baker, T.G. (2004). Early-age cultivation, weed control and fertiliser responses in eucalypt plantations on six contrasting sites in East Gippsland, Victoria. In N.M.G. Borralho, J.S. Pereira, C. Marques, J. Coutinho, M. Madeira and M. Tome (eds), Eucalyptus in a Changing World, Proceedings IUFRO Conference, Aveiro, 11-15 October. RAIZ, Instituto Investiacao da Floresta e Papel, Portugal. pp. 241-248.

Goncalves, J.L., Stape, J.L., Laclau, J.P. Smethurst, P. and Gava, J.L. (2004). Silvicultural effects on the productivity and wood quality of eucalypt plantations. Forest Ecology and Management 193, 45-61.

Holz, G.K., Smethurst, P.J. and Pongracic, S. (1999). Responses to cultivation in eucalypt tree-farms in south-eastern Australia. In Proceedings of the Institute of Foresters of Australia, 18th Biennial Conference, Hobart, Australia. pp. 161–164.

Hutchinson, M.F. (1991) The application of thin plate smoothing splines to continent-wide data assimilation. In Data Assimilation Systems. BMRC Research Report No.27, Bureau of Meteorology, Melbourne, Australia. pp. 104–113.

Isbell, R.F. (1996) The Australian Soil Classification. CSIRO, Collingwood, Australia. 143 p.

Jenkin, B.M. and Tomkins, B. (2006). The Use of Chemical Pesticides by the Australia Plantation Forest Industry. Forest and Wood Products Research and Development Corporation, Melbourne, Australia. 183 p.

Lacey, S.T., Brennan, P.D. and Parekh, J. (2001) Deep may not be meaningful: Cost and effectiveness of various ripping tine configurations in a plantation cultivation trial in eastern Australia. New Forests 21, 231–248.

Mendham, D., Smethurst, P., Holz, G., Menary, R., Grove, T., Weston, C., Faunt, K., Baker, T. (2002). Soil analyses as indicators of phosphorus response in young eucalypt plantations. Proceedings Soil Science Society of America Journal 66: 959-968.

McDonald, R.C., Isbell, R.F., Speight, J.G., Walker, J. and Hopkins, M.S. (1998) Australian Soil and Land Survey: Field Handbook. 4th Edition. Inkata, Press, Melbourne, Australia, 198 p.

Northcote, K. H. (1979). A Factual Key for the Recognition of Australian Soils. 4th edition. Rellim Technical Publications, Coffs Harbour, Australia, 56 p.

Parsons, M., Gavran, M. and Davidson, J. (2006) Australia’s Plantations 2006. Bureau of Rural Science, Department of Agriculture, Fisheries and Forestry. 56 p.

Rayment, G.E. and Higginson, F.R. (1992) Australian Laboratory Handbook of Soil and Water Chemical Methods. Inkata Press, Melbourne, Australia. 330 p.

Wong, J., Baker, T.G., Duncan, M.J, Stackpole, D.J. and Stokes, R.C. (1999) Individual Tree Volume Functions for Plantation Eucalypts. Report No. 1999/037, Centre for Forest Tree Technology, Department of Natural Resources and Environment, Melbourne, Australia. 12 p.