CARBON REVENUES AND ECONOMIC BREEDING OBJECTIVES IN *EUCALYPTUS GLOBULUS* PULPWOOD PLANTATIONS

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ABSTRACT

This paper investigates the integration of carbon revenues into production system models used to define economic breeding objectives for the genetic improvement of *Eucalyptus globulus* pulp-wood plantations. A model was used to estimate that carbon dioxide equivalent accumulation in biomass in the Australian *Eucalyptus globulus* plantation estate established between 2004 and 2012 was in the order of ~146 t CO_2e ha^{-1}, of which 62 t CO_2e ha^{-1} were tradable in 2012 and a further 30 t CO_2e ha^{-1} were tradable in 2016. By considering a system where revenues for carbon sequestration are directly dependant upon biomass production in a plantation, it was possible to determine whether economic breeding objectives for the genetic improvement of *E. globulus* will be sensitive to the revenue from carbon sequestration. The correlated response of breeding objectives with and without carbon (ΔcG_{H_1}) never fell below 0.86 in sensitivity analysis, and the mean was 0.93. As such, where economic breeding objectives for the genetic improvement of *Eucalyptus globulus* for pulpwood plantations are based on maximizing NPV by increasing biomass production, the consideration of carbon in economic breeding objectives will provide no significant gains in NPV.

INTRODUCTION

Definition of an economic breeding objective is accomplished by (1): specifying the production system, then (2): identifying sources of income and costs, (3): indentifying biological traits that influence income and costs, and (4): determination of the economic value or weight of each trait in the objective (Ponzoni 1986). Economic breeding objectives for the production of pulpwood or kraft pulp from plantation grown *E. globulus* have been defined previously (Borralho *et al.* 1993; Greaves *et al.* 1997). Both authors identified the same three biological traits (clearfall volume, wood basic density and kraft pulp yield) as having the greatest economic value. The recent advent of carbon dioxide (CO_2) trading schemes adds a source of income separate to the production of pulpwood to the plantation system. Such schemes allow a grower to trade any permanent increase in the carbon density per hectare on their estate.

While most of the carbon in a forest is held below ground (Malhi *et al.* 1999), it has been shown that in a plantation system most of the change in carbon density per hectare is associated with changes in perennial woody biomass (Madeira *et al.* 2002). Therefore changes in the productivity of plantations will affect the amount of revenue achievable for carbon sequestration in that plantation.

There has been considerable effort expended on the genetic improvement of *E. globulus* for pulp-wood plantations (Volker and Orme 1988; Borralho *et al.* 1993; Greaves *et al.* 1997; Borralho and Dutkowski 1998; Harbard *et al.* 1999; Kerr *et al.* 2001), and it is expected that the use of improved genotypes will increase harvested volume and dry matter production. Increasing harvested volume and dry matter production through genetic improvement is likely to result in an increase in the amount of woody biomass per unit area of plantation, and therefore increase the amount of carbon held per hectare in a plantation (Jayawickrama 2001).

The most widely publicised carbon-trading scheme is that outlined in the Kyoto Protocol. This provides a mechanism for the trade of 90% of any increase in carbon density per hectare during a commitment period in forests established on land not forested prior to 1990 (Watson *et al.* 2000). The first commitment period is set down for the period 2008 and 2012 and further contiguous commitment periods are envisaged for the period following 2012 (ie. 2012 – 2016). To date, the published models used to describe *E. globulus* pulpwood plantation production systems in economic breeding objectives only consider costs and incomes within a single rotation. Long-term carbon sequestration in biomass and therefore carbon revenues, will be the result of multiple sites of different ages within an estate (Dean *et al.* 2004). Therefore, in order to assess the impact of carbon revenues on the economic breeding objectives for *E. globulus* pulpwood plantations, the breeding objective must be scaled up to include multiple sites at different stages within their rotations.

In Borralho, N., *et al.* (2004). Eucalyptus in a Changing World. Proc. of IUFRO Conf., Aveiro 11-15 October 2004

The current paper investigates the impact of carbon revenues from the first two commitment periods (2008 –2012 and 2012 – 2016) on the economic weights for clearfall volume and wood basic density, and the correlated response of breeding objectives including and excluding carbon revenues. Income was calculated based on the sale of woodchips for export from Australia, and carbon revenues were directly proportional to biomass accumulation in the plantation estate. As such, carbon revenues calculated in this study are extremely sensitive to biomass production, and therefore, the sensitivity of the economic breeding objective to carbon revenues will probably be higher than would be expected in reality. Therefore, if the carbon revenues in the scenario presented here do not have a large impact on the correlated response of the economic breeding objectives including and excluding carbon revenues, then the real effect of carbon revenues will be negligible.

MATERIALS AND METHODS

Area planted, tree growth and silviculture. Planting figures from Australia's National Plantation Inventory (2003) were used to establish planting rates for the estate. The rate of establishment of new *E. globulus* plantation areas between 2004 and 2016 was extrapolated from the NPI data, assuming that *E. globulus* made up 60% by area of all hardwood planting (National Forest Inventory 2004). A quadratic growth curve was assumed, as defined by clearfall merchantable volume at the end of a ten-year rotation. Whole tree growth was proportional to merchantable volume increment. Allocation of biomass between different tree components (roots, stem, branches, leaves, bark) followed that described by Madeira *et al.* (2002) for 6 year old *E. globulus* trees. Allocation was assumed to remain unchanged over time. A 1-year fallow period was assumed between harvests and replanting of a site. Estimates of the estate area occupied by plantations established between 2004 and 2016, total CO_2 equivalent (CO_2e) sequestration and CO_2e sequestration per hectare were obtained. When coppice was used to produce the second rotation crop, the new stems began to grow immediately following harvest of the first rotation crop. It was assumed that there was no stump mortality and that the initial growth was the same as in the first rotation crop. Thinning of the coppice from between 10 and 20 stems per stump, to one or two stems per stump at the age of 2 years was assumed to remove ~60% (Table 1) of the living above ground biomass at that site. The remaining stems then grew at a rate that resulted in the same harvest volume as was obtained in the seedling rotation. The root biomass of a coppiced tree was maintained unchanged from the end of the seedling rotation, throughout the coppice rotation after which the stumps and roots decayed. Biomass in harvest residue (harvested logs were assumed to be debarked on site), thinned material, stumps and roots, was assumed to decay linearly over a 7-year period (Watson *et al.* 2000).

The production system. The production system modeled the export of *E. globulus* wood chips from Australia. The system used was similar to that described by Whittock *et al* (2004), but described only a single seedling derived rotation, and incorporated more detail of the transport and processing of roundwood. Unlike the production systems described in Borralho *et al.* (1993) and Greaves *et al.* (1997) conversion of woodchips to pulp was not considered. Costs for growing, harvesting, transport and chipping were included. Growing costs were proportional to the area planted, harvest costs proportional to clearfall volume and transport costs proportional to transport distance and harvest volume. Harvest and chipping losses were accounted for. Revenue was earned for an oven dry metric ton of wood chips for export. All costs and revenues were discounted to the present. The production system was used to define economic breeding objectives including and excluding carbon revenues. The overall aim of the breeding objectives was to maximize the net present value (NPV) per hectare of growing *E. globulus* in plantation. The NPV of plantings between 2004 and 2012 (to the end of the first commitment period) was calculated over the period 2004 to 2021 so that the revenue from sold timber from all the plantings in the period 2004 – 2012 were considered. In the case of the second commitment period (2012-2016) NPV was calculated over the period 2004 – 2025. All costs and incomes were discounted to the present (2004). All costs and prices are presented in Australian dollars.

Carbon revenues. Under the system outlined in the Kyoto Protocol the tradable unit of carbon is one metric ton of CO_2e. Carbon was assumed to make up 46% of oven dry tree biomass (Pate and Arthur 2000). Every ton of biomass carbon is equivalent to 3.67 tons CO_2 (Watson *et al.* 2000). Ninety percent of carbon sequestered in each commitment period (2008 – 2012 and 2012 – 2016) in forests established on land not forested prior to 1990 is eligible to be traded. A base price of \$8.00 t^{-1} CO_2e was calculated by converting the prices in US dollars for Kyoto pre-compliant CO_2 sequestration given in Lecocq (2004) to Australian dollars. Much of the Australian *E. globulus* plantation estate has been established on ex-pasture sites (Mendham *et al.* 2003), with the major expansion of the estate occurring after 1990 (National Forest Inventory 2003). Therefore, all new areas planted after 2004 were considered eligible to sequester carbon. In keeping with the default IPCC approach, carbon in wood products was not considered, and all carbon in biomass sold was lost to the system immediately upon harvest (Watson *et al.* 2000).

Table 1. Model base values, and minima and maxima for model variables in the sensitivity analysis of the estate model based production system

Assumption	Units	Base	Min	Max
E. globulus	% *E. globulus*	60	48	72
Area 2002	area planted 2002	51026	39344	59016
Area 2003	area planted 2003	32601	28241	34517
Bark allocation	% bark in total biomass	8	6	10
Stem allocation	% stem in total biomass	56	45	67
Root allocation	% root in total biomass	21	17	25
Carbon in biomass	% carbon in total biomass	46	37	55
Coppice	% coppice	0	0	40
Thinned	% thinned	60	48	72
Clearfell volume	m^3 ha^{-1}	250	200	300
Clearfell basic density	t m^{-3}	0.54	0.43	0.64
Specific gravity	t m^{-3}	1.03	0.82	1.24
Bark	% havested	13	10	16
Area loss	%	3	2	4
Harvest loss	%	2	2	2
Chipping loss	%	5	4	6
Lease cost	\$ ha^{-1} a^{-1}	300.00	240.00	360.00
Establishment cost	\$ ha^{-1}	1,000.00	800.00	1200.00
Maintenance cost	\$ ha^{-1} yr^{-1}	80.00	64.00	96.00
Harvest cost	\$ m^{-3}	11.00	8.80	13.20
Transport flagfall	\$ t^{-1}	4.00	3.20	4.80
Transport distance cost	\$ t^{-1} km^{-1}	0.10	0.08	0.12
Haul distance	km	75.00	60.00	90.00
Chipping and loading costs	\$ t^{-1}	27.00	21.60	32.40
Selling price	\$ t^{-1}	168.00	134.40	201.60
Annual discount rate	% yr^{-1}	10	8	12
Carbon price	\$ t^{-1} CO_2e	8.00	6.40	9.60
σ_a volume	m^3	38.00	30.40	45.60
σ_a density	t m^{-3}	0.02	0.02	0.02
$r_{vol:den}$		-0.10	-0.12	-0.08

Correlated response. Where two traits have a non-zero genetic correlation, selection on one trait will lead to a genetic change in the other (Weller 1994). Similarly, where traits in different economic breeding objectives have non-zero genetic correlations, selection on one objective will lead to a genetic change in the other. For two breeding objectives the correlated response in objective 1 (H_1) when selection is based on an index derived to maximize response on breeding objective 2 (H_2) is calculated as the regression of H_1 on H_2 (eg. Apiolaza and Garrick 2001):

$$\Delta cG_{H_1} = b_{H_1H_2}\Delta G_{H_2}$$

$$= \frac{\mathrm{Cov}(H_1, H_2)}{\mathrm{Var}(H_2)}\Delta G_{H_2}$$

$$= \boldsymbol{v}_1'\boldsymbol{G}w\left(w'\boldsymbol{G}w\right)^{-1}\Delta G_{H_2}$$

where $\boldsymbol{v_1}$ and $\boldsymbol{w}$ are the vectors of economic weights for H_1 and H_2 respectively, $\boldsymbol{G}$ is the additive covariance matrix for objective traits and ΔG_{H_1} is the direct response for breeding objective H_1. The first breeding objective (H_1) contained two traits: harvest volume and basic density. The second breeding objective (H_2) included the same two traits, but the revenues for carbon sequestration in the plantation estate altered the economic weights for volume and basic density.

Sensitivity analysis. Sensitivity analysis consisted of Monte Carlo simulation of 100000 iterations varying the plantation estate parameters by ±20% (with an even distribution) using Crystal Ball® (Decisioneering). Minima and maxima for model variables in the sensitivity analysis are shown in Table 1. The ranges of forecasts between the 5th and 95th percentiles (the central 90% of all forecasts) are reported in Table 2. Sensitivities of forecasts to variation in model variables were calculated as a percentage of total variance in forecast values contributed by each assumption, but are not reported here.

RESULTS AND DISCUSSION

Estate and carbon revenue. It was estimated that biomass accumulation in forests established between 2004 and 2016 was equivalent to 45 t C ha^{-1} (Table 2). Long-term CO_2e sequestration in the biomass component of the Australian *E. globulus* plantation estate established between 2004 and 2016 (34507 hectares) assuming no change in productivity over time was 146 t CO_2e ha^{-1} (Table 2). The addition of carbon revenues produced a change in NPV (ΔNPV) per hectare of \$216 ha^{-1} (Table 2) in the first commitment period, and \$287 ha^{-1} (Table 2) when the carbon revenues of the first and second commitment periods were combined.

The economic weights for volume and basic density excluding carbon revenues in the first commitment period were \$14.20 m^{-3} and \$14.93 kg^{-1} m^{-3} respectively, and the ratio of the economic weight per unit volume for volume and the economic weight per unit basic density was 0.95. Inclusion of first commitment period carbon revenues altered the economic weights for volume and basic density to \$15.06 m^{-3} and \$15.33 kg^{-1} m^{-3} respectively, with a greater emphasis on volume (the ratio of the economic weight per unit volume for volume and the economic weight per unit basic density was 0.98). When the second commitment period is considered the economic weights without carbon were \$17.59 m^{-3} and \$18.50 kg^{-1} m^{-3} for volume and basic density respectively without carbon revenues, and \$18.74 m^{-3} and \$19.03 kg^{-1} m^{-3} including carbon revenues, but the ratios between the weights for volume and basic density did not differ from the first commitment period.

Table 2. Forecast means and values for the 5th and 95th percentiles (the central 90% of all forecasts fall within the range shown) following sensitivity analysis. Values are for new areas planted between 2004 and 2016

FORECAST	Units	Mean	5%	95%
ESTATE				
Seedling area	ha	3148.64	1502.55	6239.78
Coppice area	ha	596.02	60.65	1452.02
Biomass total	Mt	3.68	1.63	7.29
CO_2e ha^{-1} long term	t CO_2e ha^{-1}	146.05	90.69	218.32
CO_2e ha^{-1} 2012	t CO_2e ha^{-1}	62.35	37.95	94.47
CO_2e ha^{-1} 2016	t CO_2e ha^{-1}	29.70	16.18	48.02
CO_2 revenue				
CO_2 revenue 2012	M\$	\$7.87	\$3.06	\$16.18
CO_2 revenue 2016	M\$	\$2.88	\$0.79	\$7.24
(H_2 - $H1$) 2012 ΔNPV	M\$	7.87	3.06	16.18
(H_2 - H_1) 2012 ΔNPV ha^{-1}	\$ ha^{-1}	215.76	121.25	346.01
(H_2 - H_1) 2016 ΔNPV	M\$	10.74	3.87	23.34
(H_2 - H_1) 2016 ΔNPV ha^{-1}	\$ ha^{-1}	287.08	157.18	467.66
ECONOMIC WEIGHTS				
H_1 2012 Volume	\$ m^{-3}	14.20	5.15	25.66
H_1 2012 Basic density	\$ kg^{-1} m^{-3}	14.93	9.51	21.79
H_2 2012 Volume	\$ m^{-3}	15.06	5.87	26.67
H_2 2012 Basic density	\$ kg^{-1} m^{-3}	15.33	9.84	22.28
H_1 2016 Volume	\$ m^{-3}	17.59	6.28	32.26
H_1 2016 Basic density	\$ kg^{-1} m^{-3}	18.50	11.45	27.61
H_2 2016 Volume	\$ m^{-3}	18.74	7.24	33.63
H_2 2016 Basic density	\$ kg^{-1} m^{-3}	19.03	11.89	28.23
CORRELATED RESPONSE				
ΔcG_{H_1} 2012		0.93	0.87	0.97
ΔcG_{H_1} 2016		0.93	0.86	0.97

Coppice crops in the second rotation are likely to change the dynamics of woody biomass in an *E. globulus* plantation. In a coppice crop the stumps are allowed to resprout following the first rotation harvest, and the rootstock is retained as living biomass. In *E. globulus*, up to 20 stems are produced by each stump (Whittock *et al.* 2003), and thinning to one or two stems per stump after the first 2 years of growth is required to produce an economically viable pulpwood crop. Such thinning removes a large percentage of the above ground biomass from each plant,

resulting in a large build up of decaying biomass in the plantation. Therefore the dynamics of carbon storage will differ between seedling and coppice crops in an *E. globulus* plantation. However, while coppicing was considered as a variable in this study, plantation dynamics over a longer period of time than that considered here (2004 – 2025) would have to be studied to fully assess the impact of coppicing on carbon accumulation in the plantation estate.

Correlated response. The changes in the economic weights of the traits harvest volume and basic density because of carbon revenue in either commitment period (2012 or 2016) result in the correlated response of H_1 to selection based on H_2 (ΔcG_{H_1}) being 0.93. As the correlated response of H_1 to selection based on H_2 is so high, it is unlikely that some of the assumptions in the model (i.e. no age dependant change to within tree biomass allocation) will affect the overall conclusions.

CONCLUSIONS

Tree breeding is a long-term enterprise and the impact of decisions made today will not be seen for at least 20 years (Greaves *et al.* 1997). It would be redundant to consider tree improvement in terms of carbon sequestration if the only period in which carbon could be traded was between 2008 and 2012. However, if in the future the carbon density on a site is increased above the level of 2008-2012, then that carbon could potentially be traded. In order that the carbon sequestered to 2012 is maintained in the longer term, further contiguous commitment periods following 2008-2012 must be envisaged. It is possible that in subsequent commitment periods carbon sequestered in forest products will be included in the calculations of the amount of carbon tradable in forest sector (Pingoud and Lehtilä 2002). This should increase the NPV of alternative objectives, because models of carbon sequestration incorporating processing of wood and wood products have already shown positive carbon balances (Apps *et al.* 1999; Côté *et al.* 2002). Therefore, even though the initial Kyoto commitment period is too soon and too short for tree improvement to address directly, it is possible

that future tree improvement in the direction of increasing carbon sequestration per hectare in *E. globulus* plantations could have an effect on carbon revenues. However, as the correlated response to selection of an economic breeding objective without carbon when selection is based on an economic breeding objective including carbon sequestration is so high (between 0.86 and 0.97) in a system designed to be maximise carbon revenues relative to biomass production, inclusion of carbon revenues in economic breeding objectives for *Eucalyptus globulus* is unnecessary.

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