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Original article

Integrating revenues from carbon sequestration into economic breeding objectives for *Eucalyptus globulus* pulpwood production

Simon P. WHITTOCK[a]*, Gregory W. DUTKOWSKI[b], Bruce L. GREAVES[a], Luis A. APIOLAZA[c]

[a] School of Plant Science and CRC for Forestry, University of Tasmania, Private Bag 55, Hobart, Tasmania 7001, Australia
[b] PlantPlan Genetics Pty Ltd. Private Bag 55, Hobart, Tasmania 7001, Australia
[c] School of Forestry, University of Canterbury, Private Bag 4800, Christchurch, New Zealand

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Abstract – A system where carbon sequestration was directly dependent upon biomass production in a plantation was modelled to assess whether economic breeding objectives for the genetic improvement of *Eucalyptus globulus* were sensitive to potential revenues from carbon sequestration. Carbon dioxide equivalent accumulation in the biomass (CO_2e) of the Australian *E. globulus* plantation estate established between 2004 and 2012 was estimated. Total carbon dioxide equivalent (CO_2e) accumulation was in the order of ~146 t CO_2e ha^{-1}, of which 62 t CO_2e ha^{-1} were tradable in 2012 (the 1st Kyoto Protocol commitment period) and a further 30 t CO_2e ha^{-1} were tradable in 2016 (a hypothetical second Kyoto protocol commitment period). The correlated response of breeding objectives with and without carbon revenues (ΔcG_{H_1}) never fell below 0.86 in sensitivity analysis, and the mean was 0.93. Where economic breeding objectives for the genetic improvement of *Eucalyptus globulus* for pulpwood plantations are based on maximizing net present value by increasing biomass production, the consideration of carbon revenues in economic breeding objectives will have no significant effect on the relative economic weights of the key economic traits, wood basic density and standing volume at harvest.

***Eucalyptus globulus* / genetic improvement / economic breeding objectives / environmental services / carbon sequestration**

Résumé – Intégration des recettes de séquestration du carbone dans des objectifs d'amélioration économique pour la production de pâte à papier avec *Eucalyptus globulus*. Un système où la séquestration du carbone était directement dépendante de la production de biomasse en plantation a été modélisé pour déterminer si des objectifs d'amélioration économique pour l'amélioration génétique d'*Eucalyptus globulus* réagissaient sur des revenus potentiels à partir de la séquestration du carbone. Le dioxyde de carbone gaz équivalent de l'accumulation de biomasse (CO_2e) par des plantations australiennes d'*Eucalyptus globulus* crées entre 2004 et 2012 a été estimé. L'accumulation de dioxyde de carbone (CO_2e) était de l'ordre de ~146 t CO_2e ha^{-1}, dont 62 t CO_2e ha^{-1}, étaient commercialisables en 2012 (période correspondant aux engagement du premier protocole de Kyoto) et 30 t CO_2e ha^{-1} supplémentaires étaient commercialisables en 2016 (hypothétique second protocole de Kyoto). La réponse correspondant aux objectifs d'amélioration avec et sans recettes de carbone (ΔcG_{H1}) n'est jamais tombée sous 0,86 en analyse de sensibilité, et la moyenne était 0,93. Là où les objectifs d'amélioration économique pour l'amélioration génétique d'*Eucalyptus globulus* pour des productions de pâte à papier étaient basées sur maximalisation de la valeur actuelle nette par un accroissement de la production de biomasse, la prise en compte des recettes du carbone dans des objectifs d'amélioration économique n'aura pas d'effets significatifs sur le poids économique relatif de ces traits économiques, densité de base du bois et volume de bois sur pied à la récolte.

***Eucalyptus globulus* / amélioration génétique / objectifs économiques d'élevage / services pour l'environnement / séquestration du carbone**

1. INTRODUCTION

Returns from genetic gains made in a breeding program are partially dependant upon the value of products and services provided by improved populations [9]. Intensively managed plantations must be highly productive, economically efficient, supply an increasing range of products, and maintain a high standard of sustainability. The guiding principles for achieving these goals in the Australian context are set out in documents such as the Australian Government's 2020 vision for forestry [10], the Montreal Protocol [25], and the Australian Forestry Standard [2]. The importance of sustainable management of forest industries was highlighted in the Millenium Ecosystem Assessment [33]. While economists continue to favour the use of market based instruments over policy mechanisms for the management of environmental issues [14, 17, 35–37] it is likely that markets for ecosystem services will expand. The establishment of markets for ecosystem services will provide a mechanism by which the environmental impacts of, or services provided by plantations may influence plantation economics.

Economic breeding objectives for the production of kraft pulp from plantation grown eucalypts have been defined previously [6, 15]. Both authors identified the same three biological traits (clearfall volume, wood basic density and kraft pulp yield) as having the greatest economic value. Definition of an economic breeding objective is accomplished by (1): specifying the production system, then (2): identifying sources of

* Corresponding author: Simon.Whittock@utas.edu.au

income and costs, (3): identifying biological traits that influence income and costs, and (4): determination of the economic value or weight of each trait in the objective [31]. The recent advent of carbon dioxide (CO_2) trading schemes, such as that outlined in the Kyoto Protocol, adds a source of income, separate to the production of pulpwood, to the plantation system. Project based carbon sequestration 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 [22], 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 [21]. Genotype, survival, tree age, irrigation and nutrient status all affect biomass (and therefore carbon) partitioning (see [3, 4, 24, 29, 32]).

There has been considerable effort expended on the genetic improvement of *E. globulus* for pulpwood plantations [6, 7, 15, 16, 19, 38]. Borralho et al. [5] estimated gain in dry matter production attributable to tree improvement activities in *E. globulus* to range from 20 to 47% in Portugal. Increased productivity of *Eucalyptus* sp. plantations directly attributable to genetic improvement in the form of provenance selection and breeding was demonstrated by Pallett and Sale [28]. An increase in the amount of woody biomass per unit area of plantation, results in an increase in the amount of carbon stored per hectare in a plantation [18].

A project based carbon trading scheme was defined by Watson et al. [39]. 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 [39]. The first commitment period is set down for the period 2008−2012 and further contiguous commitment periods are envisaged for the years following 2012 [39]. 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 [8, 12]. In order to assess the impact of carbon revenues on economic breeding objectives for *E. globulus* pulpwood plantations, the production system must be scaled up to include multiple sites at different stages within their rotations.

The work presented in the current paper investigates the impact of carbon revenues on the economic weights for clearfall volume and wood basic density, and the correlated response of breeding objectives 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 very sensitive to expected biomass production. Therefore, the sensitivity of economic breeding objectives to carbon revenues will probably be higher than would be expected in reality. In this scenario, if carbon revenues do not have a large impact on the correlated response of economic breeding objectives including and excluding carbon revenues, the real effect of carbon revenues on economic breeding objectives will be negligible.

2. MATERIALS AND METHODS

2.1. Modelling the area planted, tree growth and silviculture

Planting figures from Australia's National Plantation Inventory [NPI, 26] were used to establish planting rates for the forest 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 [27]. A negative curvilinear function was fitted to the planting figures for 2000−2003 and extrapolated to give estimates of the establishment of new areas of *E. globulus* between 2004 and 2016. Only plantings after 2004 were considered in calculations of carbon sequestration and revenue, as it is not possible to influence plantations already established. Growth was 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. [21] for 6-year old *E. globulus* trees. Allocation was assumed to remain unchanged over time. A 1-year fallow period was assumed between the harvest and the 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. In some cases coppice is used to produce the second rotation crop in Australian pulpwood plantations. In a coppice rotation the new stems were assumed to begin growing immediately following harvest of the first rotation crop. It was assumed that there was no stump mortality and that initial growth was the same as in the first rotation crop. Thinning of the coppice from between 10 and 20 stems per stump [41], to one or two stems per stump at the age of 2-years was assumed to remove ~60% (Tab. I) 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 original 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 [39]. A schematic representation of the system used to calculate the biomass accumulation in the *E. globulus* estate is shown in Figure 1.

2.2. The production system

The production system modelled the net present value (NPV) of *E. globulus* wood chips for export from Australia. The system used was adapted from the "ChipEx" model (Greg Dutkowski, pers. com.), which was similar to that described in Whittock et al. [42], but incorporated more details of the transport and processing of roundwood. The NPV per hectare of growing *E. globulus* to produce wood chips for export on a ten-year rotation, on the basis of the whole estate modelled was calculated where:

$$NPV = I - C, \tag{1}$$

$$I = \frac{R}{\left(1 + \frac{d}{100}\right)^q}, \tag{2}$$

where

$$R = Sold \times p \tag{3}$$

Table I. Assumptions in the production system, abbreviations used to represent them and their units.

Description	Abbreviation	Units
Assumptions		
Clearfall standing under-bark volume	VOL_{cf}	m^3 ha^{-1}
Clearfall basic density	BD	OD t m^{-3}
Selling price	p	\$ OD t^{-1}
Specific gravity	S	
Bark (proportion by weight)	b_h	proportion
Area loss (fraction of plantation area)	L_a	proportion
Harvest loss (fraction of harvest volume)	L_h	proportion
Rotation age	q	years
Discount rate (annual, compounding)	d	%
Haul distance	Haul	km
Lease cost	C_L	\$ ha^{-1} q^{-1}
Establishment costs	C_E	\$ ha^{-1}
Maintenance costs	C_M	\$ ha^{-1} q^{-1}
Harvest cost per hectare	C_H	\$ ha^{-1}
Transport flagfall per green ton loaded	F	\$ t^{-1}
Transport distance cost	C_d	\$ t^{-1} km^{-1}
Chipping loss (fraction of chipped volume)	L_c	proportion
Chipping and loading cost per green ton	C_c	\$ t^{-1}
Calculations		
Under-bark volume after harvest and area losses	VOL_{lo}	m^3 ha^{-1}
Harvested green weight of logs with bark	$Load$	t ha^{-1}
Sold chips	$Sold$	OD t ha^{-1}
Harvest cost per unit volume	C_v	\$ m^{-3}
Transport cost per green ton	C_{th}	\$ t^{-1}
Per hectare transport cost	C_{tw}	\$ ha^{-1}
Per hectare processing cost	$Mill$	\$ ha^{-1}
Revenue from sale of chips (undiscounted)	R	\$ ha^{-1}
Costs (discounted to establishment)		
Discounted lease costs	$^{PV}C_L$	\$ ha^{-1}
Discounted maintenance costs	$^{PV}C_M$	\$ ha^{-1}
Discounted harvest and processing costs	$^{PV}C_H$	\$ ha^{-1}
NPV Income	I	\$ ha^{-1}
NPV costs	C	\$ ha^{-1}
Net present value per hectare	NPV	\$ ha^{-1}

and

$$Sold = (1 - L_c) \times VOL_{lo} \times BD \tag{4}$$

and

$$VOL_{lo} = VOL_{cf}\,(1 - L_a)\,(1 - L_h)\,. \tag{5}$$

The present value of costs discounted to the start of the rotation was:

$$C = {}^{PV}C_L + {}^{PV}C_M + {}^{PV}C_H + C_E, \tag{6}$$

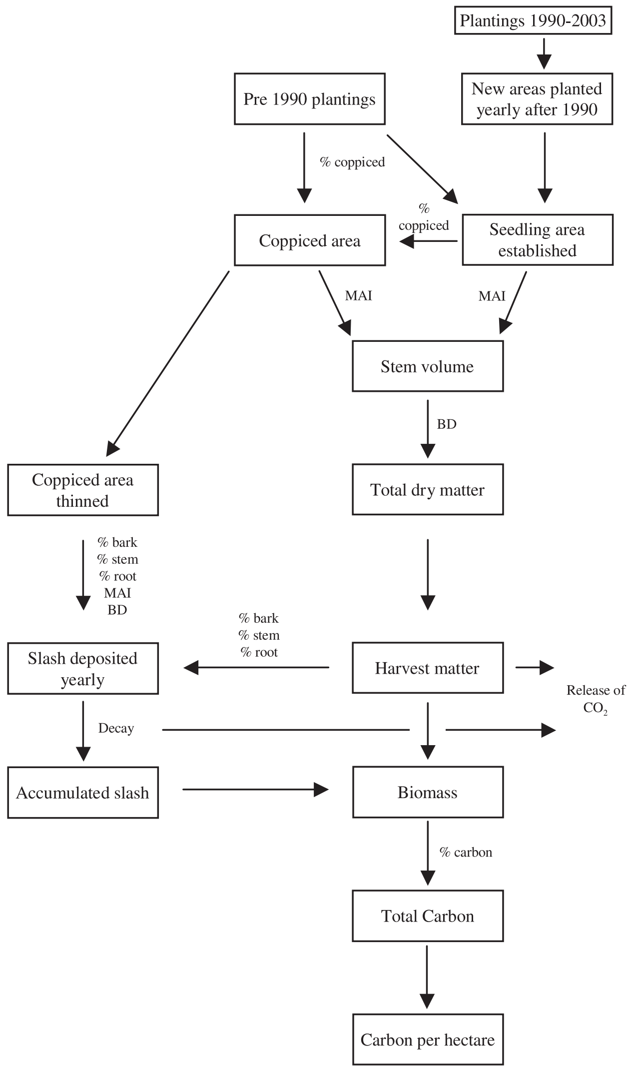

Figure 1. A schematic representation of the model used to calculate biomass accumulation in the Australian *E. globulus* plantation estate.

where

$$^{PV}C_L = \frac{C_L\left(1 - \left(1 + \frac{d}{100}\right)\right)^{-q}}{\frac{d}{100}}, \tag{7}$$

$$^{PV}C_M = \frac{C_M\left(1 - \left(1 + \frac{d}{100}\right)\right)^{-q}}{\frac{d}{100}}, \tag{8}$$

$$^{PV}C_H = \frac{(C_{th} + Mill + C_H)}{\left(1 + \frac{d}{100}\right)^q}, \tag{9}$$

$$C_{th} = Load \times C_{tw}, \tag{10}$$

$$Load = VOL_{lo} \times S \times (1 - b_h)\,, \tag{11}$$

$$Mill = C_c \times VOL_{lo} \times S, \tag{12}$$

$$C_H = VOL_{cf} \times C_v, \tag{13}$$

and

$$C_{tw} = F + (C_d \times Haul)\,. \tag{14}$$

All symbols are defined in Table I.

Unlike the production systems described in Borralho et al. [6] and Greaves et al. [15] 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. The production system model was used to define economic breeding objectives both including, and excluding carbon revenues. The overall aim of the breeding objectives was to maximize the 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 year 2004. All costs and prices are presented in Australian dollars.

2.3. Carbon revenues

The tradable unit of CO_2 is the biomass equivalent of one metric ton of CO_2 (1 t CO_2e). Carbon was assumed to make up 46% of oven dry tree biomass [29]. Every ton of biomass carbon is equivalent to 3.67 t CO_2 [39]. 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 (US\$ 5.52 t^{-1} CO_2e, 2004) to Australian dollars at the current exchange rate for December 2003. Much of the Australian *E. globulus* plantation estate has been established on ex-pasture sites [23], with the major expansion of the estate occurring after 1990 [26]. The model considered all new areas planted after 2004 eligible to sequester carbon. In keeping with the default approach of the Intergovernmental Panel on Climate Change in the first commitment period, carbon in wood products was not considered [39], and all carbon in biomass sold was lost to the system immediately upon harvest.

2.4. Correlated response

Where two traits have a non-zero genetic correlation, selection on one trait will lead to a genetic change in the other [34, 40]. 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 one (H_1) when selection is based on an index derived to maximize response on breeding objective two (H_2) is calculated as the regression of H_1 on H_2 (e.g. [1]):

$$\Delta c G_{H_1} = b_{H_1 H_2} \Delta G_{H_2} \tag{15}$$

$$= \frac{Cov\,(H_1, H_2)}{Var\,(H_2)} \Delta G_{H_2} \tag{16}$$

$$= v' \boldsymbol{G} w \,(w' \boldsymbol{G} w)^{-1} \,\Delta G_{H_2} \tag{17}$$

where $\boldsymbol{v}$ 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.

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

Assumption	Units	Base	Min	Max
E. globulus	% *E. globulus*	60	48	72
Area 2002	area planted 2002	51 026	39 344	59 016
Area 2003	area planted 2003	32 601	28 241	34 517
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
Clearfall volume	m^3 ha^{-1}	250	200	300
Clearfall 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	1 200.00
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

2.5. Sensitivity analysis

Sensitivity analysis consisted of Monte Carlo simulation of 100 000 iterations varying assumptions by ± 20% (with a uniform distribution – see Tab. II) using Crystal Ball® [13]. Minima and maxima for model variables in the sensitivity analysis are shown in Table II. The ranges of forecasts between the 5th and 95th percentiles (covering the central 90% of all forecasts) are reported in Table III. Sensitivities of key forecasts to variation in model variables were calculated as a percentage of total variance in forecast values contributed by each assumption, and are reported in Table IV.

Table III. 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 of first rotation plantation established between 2004 and 2016.

Forecast	Units	Mean	5%	95%
Estate				
Mean seedling area planted	ha yr^{-1}	3 148.64	1 502.55	6 239.78
Mean coppice area established	ha yr^{-1}	596.02	60.65	1 452.02
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				
$(H_2 - H_1)$ 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

3. RESULTS AND DISCUSSION

3.1. Estate and carbon revenue

If the Australian Government were to ratify the Kyoto Protocol, much of the Australian *E. globulus* plantation estate established on land previously cleared for agriculture would qualify to sequester CO_2 [39]. Even without the numerical requirements for the Kyoto Protocol of a minimum of 55 nations representing 55% of industrialised worlds 1990 CO_2 emissions being met in November 2004, and despite criticisms that the effect of the Kyoto Protocol on climate change will be trivial to non-existent [36], a considerable trade in non-Kyoto compliant carbon had already been established in 2004 [20].

It was estimated that biomass accumulation in forests established between 2004 and 2016 was equivalent to 45 t C ha^{-1} (Tab. III). Long-term CO_2e sequestration in the biomass component of the Australian *E. globulus* plantation estate established between 2004 and 2016 (estimated to be a total of 34 507 ha, assuming no change in productivity over time) was 146 t CO_2e ha^{-1} (Tab. III). The addition of carbon revenues produced a change in NPV (ΔNPV) per hectare of $ 216 ha^{-1} (Tab. III) in the first commitment period, and $ 287 ha^{-1} (Tab. III) 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} ha^{-1} and $ 14.93 kg^{-1} m^{-3} respectively (Tab. III), 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} ha^{-1} and $ 15.33 kg^{-1} m^{-3} respectively (Tab. III), 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). In the second commitment period the economic weights without carbon were $ 17.59 m^{-3} ha^{-1} and $ 18.50 kg^{-1} m^{-3} for volume and basic density respectively (Tab. III) without carbon revenues, and $ 18.74 m^{-3} ha^{-1} and $ 19.03 kg^{-1} m^{-3} including carbon revenues (Tab. III), but the ratios between the weights for volume and basic density did not differ from the first commitment period.

The use of coppice crops in the second rotation is 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. When *E. globulus* coppices, up to 20 stems are produced by each stump [41], 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. However, while coppicing was included as a variable in this study, its effect on carbon sequestration in plantations was small in the forest area considered, over the period considered (2004−2025). Longer timescales would have to be studied to fully assess the impact of coppicing on carbon accumulation in the plantation estate.

In sensitivity analysis 97% of the total variation in the amount of carbon accumulated per hectare in the estate (CO_2e ha^{-1} 2012, Tab. IV) was contributed by changes in the biomass allocated to the stem, basic density, clearfall volume and the percentage of carbon in biomass (46%, 17%, 17%, and 17% respectively, Tab. IV). Sensitivity analysis showed that variation in the difference in NPV in 2012 between scenarios with and without carbon revenues (97%, $(H_2{-}H_1)$ 2012 ΔNPV ha^{-1}, Tab. IV) was also driven by changes in the biomass allocated to the stem, basic density, clearfall volume and the percentage of carbon in biomass (35%, 13%, 13% and 13% respectively, Tab. IV) with changes in the price per unit CO_2e and the annual discount rate applied (13% and 10% respectively, Tab. IV) contributing significant percentages of the variation. Increasing the biomass allocation to the stem resulted in a reduction in the amount of CO_2e sequestered per hectare because the stem is the portion of the tree harvested and in this case, all carbon in harvested biomass was assumed released immediately upon harvest. However, it is unlikely that biomass allocation to the stem of the tree in plantations will vary to the extent (± 20%) applied in the sensitivity analysis.

Table IV. The sensitivity results for key output variables presented as a percentage of total variation, based on 100 000 iterations varying input variables by ± 20% with an even distribution. All variables contributing greater than 1% of variation are shown. At least 95% of all variation for each forecast is shown.

		Forecasts				
Assumptions	Units	CO_2e ha^{-1} 2012	$(H_2 - H_1)$ 2012 ΔNPV ha^{-1}	ΔcG_{H_1} 2012	*NPV* H_1 2012	*NPV* H_2 2012
Area 2002	area planted 2002			1	3	3
Area 2003	area planted 2003				–1	–1
Stem allocation	% stem in total biomass	–46	–35	16		
Carbon in biomass	% carbon in total biomass	17	13	–6		
Coppice	% coppice	2	2			
Clearfall volume	m^3 ha^{-1}	17	13		6	7
Clearfall basic density	t m^{-3}	17	13	13	35	35
Specific gravity	t m^{-3}			11	10	9
Lease cost	\$ ha^{-1} a^{-1}				–3	–3
Establishment cost	\$ ha^{-1}				–2	–2
Chipping and loading costs	\$ t^{-1}			–4	–3	–3
Selling price	\$ t^{-1}			40	35	34
Annual discount rate	% yr^{-1}		–10		–1	–1
Carbon price	\$ t^{-1} CO_2e		13	–6		

Therefore increasing volume production and clearfall basic density in plantations will increase the amount of CO_2e sequestered in plantations and also increase the value of a crop in a situation where the value of CO_2 sequestered in plantations can be traded.

3.2. 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 (95% of the forecasts ranged between 0.86 and 0.97 (Tab. III). In sensitivity analysis 40% (Tab. IV) of the variation in the correlated response of breeding objectives was due to variation in the price obtained for wood chips. Increasing the price obtained for woodchips increased the correlated response by decreasing the relative value of carbon revenues. Increasing the price obtained per unit CO_2e sequestered had a small negative impact on the correlated response of breeding objectives, contributing 6% of variation in sensitivity analysis (Tab. IV). 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. This is supported by the results of the sensitivity analysis of NPV for each breeding objective in the first commitment period (2008−2012). In each breeding objective (excluding and including CO_2 revenue), changes in the unit price of woodchips for export, and the basic density at clearfall both contributed over 69% of the variation, with the remainder being made up by changes in the same set of variables (NPV H_1 2012 and NPV H_2 2012, Tab. IV). It is noteworthy that changes in the unit price of CO_2e contributed less than 1% of the variation in NPV of the breeding objective including carbon revenues in 2012.

4. CONCLUSIONS

A breeding objective for woodchip production is a close approximation of an objective for biomass production. This simple system was investigated firstly because an economic breeding objective for wood chip export with some level of acceptance within the field of genetic improvement of *E. globulus* in Australia was available, and secondly, there was a well defined system already available for the assessment of the quantity of carbon in a plantation and payment for the service provided [39]. Thus, the work presented here illustrates the process that would be required for exploration of the impact of carbon sequestration on breeding objectives with which carbon sequestration is less highly correlated, or alternatively investigate the impact of other environmentally-related potential components of a wood chip breeding objective, such as that of sterility, delayed flowering, water usage, or site nutrient balance. However, calculations of the value, and systems for the trade of such ecosystem services have not been defined in the case of eucalypt plantations.

Consideration of a system where revenues for carbon sequestration were directly dependant upon biomass production in a plantation, allowed assessment of the impact of any potential revenue from carbon sequestration on economic breeding objectives for the genetic improvement of *E. globulus*. In this study the revenue calculated for carbon sequestration did not take into account emissions from the use of fossil fuels or soil disturbance in forestry operations, or the implementation costs of a carbon sequestration program. Implementation costs can be significant, including, for example, marketing the program, establishing the conditions for payments, negotiating contracts, processing claims for subsidies, assessing tax liabilities, or monitoring the compliance and performance of landowners with respect to carbon sequestration practices or quantities [37].

Tree breeding is a long-term enterprise and the impact of decisions made today will not be seen for at least 20 years [15]. 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 site average of 2008−2012, then that carbon could potentially be traded. In order that the carbon "stored" 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 [30]. This could increase the NPV of alternative objectives, because models of carbon sequestration incorporating processing of wood and wood products have already shown positive carbon balances (e.g. [11]). 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 a marginal effect on carbon revenues. In this study the correlated response to selection of an economic breeding objective without carbon revenues when selection is based on an economic breeding objective including carbon revenues was found to be very high (95% of predictions between 0.86 and 0.97) in a system designed to maximise carbon revenues relative to biomass production. Therefore, inclusion of carbon revenues in economic breeding objectives for *E. globulus* appears unnecessary at this time.

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