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Incorporating Carbon Credits into Breeding Objectives for Plantation Species in Australia

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1. Introduction

Forest tree plantations can capture more carbon than most other land uses. For example, a radiata pine (*Pinus radiata* D. Don) or blue gum (*Eucalyptus globulus* Labill.) plantations in the Green Triangle region in south-eastern Australia can on average produce more than 20 $m^3ha^{-1}y^{-1}$ of wood, with a 19% and 25% rate of carbon sequestration, respectively (Polglase et al. 2008). As carbon trade is becoming a reality, there is a need to incorporate carbon credits into the economic models of plantation forestry for those major and some emerging species. Carbon sequestration needs to be considered as a biological trait and bio-economic models need to include its value. In this chapter we will show how carbon sequestration can be incorporated into the breeding objectives of Australian tree improvement programs for commercial plantation species.

The procedure for the development of a bio-economic model and setting up breeding objectives for plantation trees includes the following major steps (Ivković et al., 2010):

- specification of the production system, which includes, silvicultural management regime, and harvesting, transportation and processing systems;
- identification of the wood-flows, and sources of income and cost in a specified production system (i.e. plantation growing, processing or integrated production);
- determination of how different biological traits influence wood-flows, and incomes and costs in the production system (i.e. identification of the critical traits affecting production system to consider as breeding-objective traits);
- derivation of the economic value, or weight, defined as the value of unit trait change for each breeding objective trait for existing and future plantation production systems.

The economic weights for breeding objective traits are used to develop an optimal selection index that maximises the expected genetic gain and profitability of production (e.g. Ivković et al., 2006a). To incorporate carbon credits into breeding objectives and to derive economic weights for plantation species in Australia it is necessary to:

- consider current breeding objectives for major plantation species including *P. radiata*, *E. globulus* and other minor species;

- consider currently proposed carbon pooling and accounting systems for reforestation; and
- incorporate carbon credits for sequestration into existing breeding objectives for *P. radiata*, *E. globulus* and other minor plantation species

We used *P. radiata* as a model species for incorporating carbon credits into breeding objectives. The model should be applicable to other plantation species. Sensitivity analyses involving different carbon prices, discount rates, timber prices, and carbon accounting options were performed.

2. Current breeding objectives

There has been a substantial amount of work on developing bio-economic models and breeding objectives for *P. radiata* structural timber, and to a lesser extent for pulp and paper production (e.g. Apiolaza and Garrick, 2000; Greaves, 1999; Ivković et al., 2006a, 2006b). Only one study addressed the issue of genetic gains for carbon sequestration, a preliminary study of radiata pine plantations in New Zealand (Jayawickrama, 2001). In *E. globulus*, bio-economic models have been developed for pulp production (e.g. Borralho et al., 1993, Greaves et al., 1997). There has been only one study on integrating carbon into the breeding objectives for *E. globulus* (Whittock et al., 2007). There has also been recent interest in using *E. globulus* and *E. nitens* for solid timber production and the development of bio-economic models for such production systems (e.g. Nolan et al. 2005). Such bio-economic models are being developed for other (minor) tree species, as well (e.g. *E. cloeziana*, *E. dunnii, E. saligna*, *E. obliqua*, *E. pilularis*, *Corymbia maculata, C. citriodora*, and *E. diversicolor*). However, there are no formally defined breeding objectives for the alternative production systems and/or minor plantation species.

2.1 *Pinus radiata*

Preliminary estimates of gains in carbon sequestration, obtainable through genetic improvement, for radiata pine plantations in New Zealand were calculated by Jayawickrama (2001). Data on height, diameter and wood density from New Zealand progeny trials were used to estimate heritability and the phenotypic variance for stem dry-weight production. The amount of carbon sequestered in the stem, branches and roots of typical stands of unimproved radiata pine was simulated using the C_Change simulator (Beets, 2006; Beets et al., 1999). The amounts of carbon sequestered at the end of one rotation, and the long-term average over successive rotations were estimated. Carbon sequestered under a standard, "direct sawlog" management regime differed among regions, from 211 tonnes (t) at the end of a 28-year rotation in Canterbury to 322 t on the East Coast. The highest simulated genetic gain in long-term carbon sequestration for the standard regime was 29 t $ha^{-1}y^{-1}$, for a stand grown in the East Coast region, using seed from the best 10 of 1000 ranked parents.

Based on the highest estimated rate of carbon sequestration, and a value of NZ$20 per t of carbon, the extra carbon credits attributable to genetic improvement, under the direct sawlog regime, would be worth NZ$307 per ha. However, a low-cost "plant-and-leave" regime sequestered even more carbon than the standard sawlog regime. Therefore, owners of large post-1990 radiata pine plantings on converted farmland or pasture could gain large financial benefits from genetic improvement and/or management targeting increased carbon sequestration. Plantation growers in New Zealand are likely to aim for multiple objectives rather than for carbon sequestration alone and the trees would be selected on an optimised combination of objective traits.

In Australia the Southern Tree Breeding Association (STBA), uses a 'bio-economic' model based on industry data and various sawmill performance studies to assess the relative importance of breeding objective traits (Ivković et al., 2006a, 2006b). A generic bio-economic model similar to that used by the STBA was created for the purpose of this study (**Table 1.**).

		Effect of 10% Trait Increase			
	Base	**MAI**	**SWE**	**BRS**	**MOE**
Wood flows (m^3/ha)					
pulplog	166	173	181	178	166
sawlog	555	620	540	543	555
green sawn timber	269	296	260	263	269
dry structural timber	182	200	176	178	182
sawmill residue (chip)	255	280	250	250	254
Total harvested volume	**721**	**793**	**721**	**721**	**721**
Costs NPV ($/ha)					
establishment	-2,047	-2,047	-2,047	-2,047	-2,047
ann. maintenance	-1,241	-1,241	-1,241	-1,241	-1,241
harvest	-1,628	-1,881	-1,628	-1,654	-1,628
transport	-973	-1115	-973	-973	-973
green mill	-2,149	-2,388	-2,093	-2,101	-2,149
dry mill	-1,673	-1,842	-1,619	-1,637	-1,673
Total costs	**-9,712**	**-10,514**	**-9,602**	**-9,654**	**-9,712**
Income NPV ($/ha)					
pulplog	1,952	2,030	2,057	2,013	1,952
sawlog	6,151	7,184	5,976	6,020	6,151
Total stumpage	**8,103**	**9,214**	**8,033**	**8,034**	**8,103**
sawn timber	10,724	11,815	10,378	10,402	11,547
other sawn products	1,046	1,152	1,012	1,023	1,046
sawmill residue chip	1,256	1,406	1,230	1,228	1,256
Total income	**14,979**	**16,403**	**14,677**	**14,667**	**15,801**
Income NPV – Costs NPV($/ha)					
Plantation growing	**2,214**	**2,930**	**2,144**	**2,119**	**2,214**
Percent NPV change		**32%**	**-3%**	**-4%**	**0%**
Integrated production	**5,267**	**5,889**	**5,075**	**5,013**	**6,089**
Percent NPV change		**12%**	**-4%**	**-5%**	**16%**

Table 1. Summary of the wood flows, costs and incomes per hectare for a generic integrated radiata pine production system at the base level and after increase in mean annual increment (MAI), sweep (SWE), branch size (BRS), and modulus of elasticity (MOE). Net present value (NPV) was calculated at 7% discount rate over one 30-year rotation.

The breeding objective traits, namely, mean annual increment (MAI), stem straightness or sweep (SWE), branch size (BRS), and wood stiffness measured by modulus of elasticity (MOE), were chosen based on their significant economic importance. For plantation growers, MAI (i.e. harvest volume) was the main driver of profit. For integrated production systems, MOE and MAI were more balanced in their relative importance. In section 4 of this chapter, we will incorporate carbon credits into this bio-economic model, which is expected to influence the breeding objective and decisions regarding selection of trees for establishing new plantations (e.g. Maclaren et al., 2008). Carbon sequestration in plantations is directly related to the amount of dry-weight of biomass accumulated and therefore the relative economic weights of traits related to growth (i.e. MAI and BRS) and wood density (i.e. MOE) and therefore dry weight yield of biomass.

2.2 *Eucalyptus globulus*

Economic breeding objectives for the production of kraft pulp from plantation grown *E. globulus* have been defined previously by several authors (e.g. Borralho et al., 1993; Greaves et al., 1997). The authors identified the same three biological traits (clearfall volume, wood basic density and kraft pulp yield) as having the greatest economic value. Those models considered only costs and/or incomes within a single rotation. More recently, Whittock *et al.* (2007) developed a model on a plantation estate scale, consisting of multiple stands and age classes, accounting for carbon sequestration in biomass and carbon revenues. The authors considered an *E. globulus* plantation estate that has been established on ex-pasture sites with the major expansion of the estate occurring after 1990. They examined the impact of carbon revenues associated with clearfall volume and basic density in an export chip production system. Income was calculated based on sale of wood chips, and carbon revenues were directly proportional to the biomass accumulation in the plantation estate. Whole tree growth was proportioned to merchantable volume increment and biomass allocated to roots, stem, branches, leaves and bark following methods by Madiera *et al.* (2002). Thinned material, stumps and roots were assumed to decay linearly over a 7-year-period.

In the study the tradable unit of CO_2 was the biomass equivalent of one metric ton of CO_2 (tCO_2e). Carbon was assumed to be 46% of oven-dry biomass, and a ton of carbon equivalent to 3.67 tCO_2. Carbon in wood products was considered lost immediately after harvest. 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} is tradable in 2012 (the 1st Kyoto Protocol commitment period) and a further 30 t CO_2e ha^{-1} is tradable in 2016 (a hypothetical second Kyoto protocol commitment period). The correlated response among breeding objectives with and without carbon revenues never fell below 0.86 in sensitivity analysis, and the mean was 0.93. Where economic breeding objectives for the genetic improvement of *E. 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 a minimal effect on the relative economic weights of the key economic traits, wood basic density and standing volume at harvest.

2.3 Other production systems and plantation species

The hardwood industry in Australia has been affected by a reduction in the harvest of native forests and competition from lower priced plantation softwood products. However, *Eucalyptus* species have desirable characteristics that most softwoods cannot match and the hardwood industry is moving to higher price, appearance and niche structural products (Nolan et al., 2005). Eucalypt plantations for solid wood, or for dual pulp and solid wood production are emerging as a new industry and more than 100,000 ha of eucalypt plantations are currently managed for sawlog production (DAFF 2007). The first step in the process of tree improvement is to clearly set the breeding and silvicultural objectives and formally determine the economic importance of different biological tree traits.

In eucalypt plantations for solid wood, different production systems are used, such as, unthinned and unpruned; thinned and unpruned, and thinned and pruned (i.e. sawlog regime) for different species. The choice of species and silviculture is mostly determined by the requirement to meet commitments to customers and minimise business risk. Further development of breeding objectives that will maximise returns on investment for different *Eucalyptus* species and production systems is still a priority of the emerging industry. Formal methodology of breeding-objective development, incorporating carbon credits, needs to be applied and the developed breeding objectives adopted by the industry. Yet, there has been only limited work reported on development of bio-economic models involving the plantation grown eucalypt resource (Hamilton 2007).

3. Carbon crediting mechanisms

Under Article 3.3 of the Kyoto protocol (UNFCCC 1997), to receive credits a forest must be planted after 1 January 1990 on land that was not previously forested. Article 3.4 of the Kyoto Protocol specifies that carbon sequestration due to “additional forest management activities” in existing managed forests could also be used to meet emission reduction targets. The Australian, New Zealand and Canadian Governments elected not to account for additional forest management activities, because managed forests may be a source of emissions, and the cost of sequestration measurement may exceed the benefit. However, the Australian Government may decide to cover in a future ETS all managed forests or only plantations.

For the ETS the Australian National Carbon Accounting System (NCAS) would generate carbon emission and removal estimates based on satellite images, climate and soil data, and extensive databases on forest type and management. The National Carbon Accounting Toolbox (NCAT) would use modelling capability of the NCAS to generate emission and removal estimates for reforestation at the project level.

To receive permits, forest growers would need to satisfy reporting and other obligations designed to ensure that the correct number of permits are issued and surrendered. They would also need to indicate the date of forest establishment and provide information about the location of the forest. They would need to provide maps based on NCAS data to assist stakeholders to determine the eligibility of their forests. An approach to reporting similar to the existing New South Wales Greenhouse Gas Reduction Scheme (http://greenhousegas.nsw.gov.au/) would be then used, which includes annual reporting with full verification at periodic intervals (i.e. every five years or following each international commitment period). Forest growers would be required to report any major changes to the emissions estimation plan as a result of changes to forest management or natural disturbances. The regulatory organisation would publish information about all forest registrations.

The Australian Government, Department of Climate Change and Energy Efficiency proposed two approaches to crediting reforestation activities: “full crediting” and “average crediting”. The full crediting approach reflects real annual changes in greenhouse gas emissions and removals as reported in Australia’s national forest inventory. However, this approach can create risks that, in any given year, severe droughts or fires could significantly and unexpectedly reduce the total number of permits available to forest growers and subsequently to the market. This approach also involves high compliance costs, as permits must be issued on an ongoing basis. On the other hand, this approach would expose forest entities to the full marginal carbon price at all times. The forests included in the ETS would, therefore, be managed for optimal carbon storage and wood production.

The Australian Government would more likely apply the more conservative average crediting approach. For a plantation the permit limit would be based on the average cumulative net greenhouse gas removals calculated at the end of rotation (i.e. prior to harvest) over, for example two long rotations (about 70 years). The net greenhouse gas removals would be based on the forest grower’s initial estimation plan and updated as necessary. Although forest growers would not be exposed to the full marginal carbon costs at all times, this approach would reduce the risks of non-compliance. The approach also involves lower compliance costs as permits would generally not need to be surrendered on harvest or following fire and then re-issued as the forest is re-established.

To account for natural disturbances such as fire, disease outbreak, insect attack, storms or severe drought, the permit limit could be reduced by an amount proportional to the risk, i.e., the “risk of reversal buffer”. A delay in applying the risk of reversal buffer would mean that the forest entity would receive the full allocation of permits during forest establishment when costs are greatest. In addition, during the early years of forest growth the amount of total carbon storage and therefore potential carbon that could be lost due to natural disturbance is relatively low. This approach would generally remove the need to require the surrender of permits in the event of natural disturbances. Permits would be issued for each tonne of net greenhouse gas removals and would only be issued after trees have grown. The permits would be issued up to a limit, incorporating a risk of reversal buffer. An example of the average crediting approach is given in **Fig. 1**.

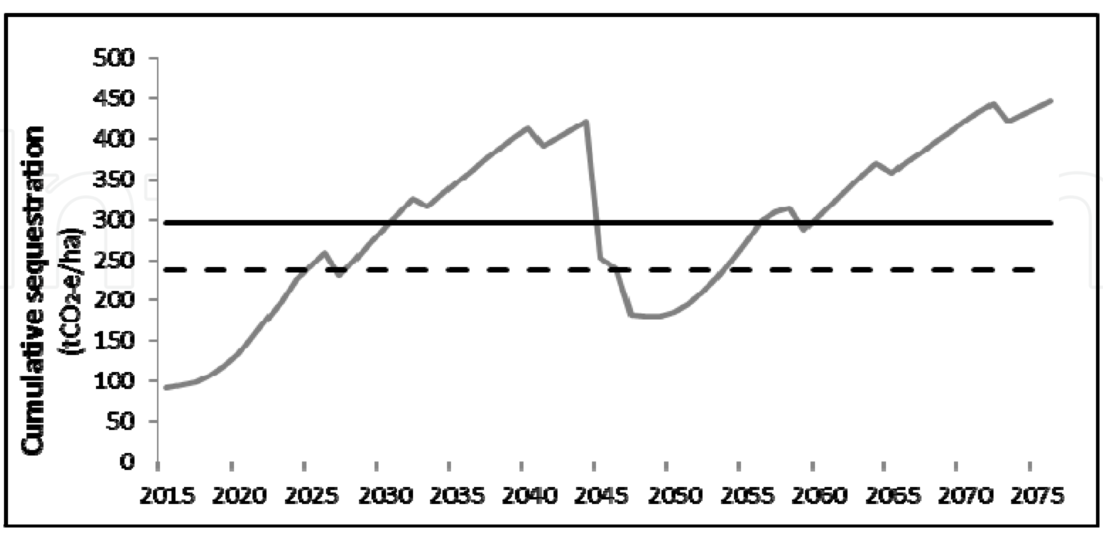

Fig. 1. Diagram of the cumulative carbon sequestration over two rotations and the average crediting approach for a hypothetical *P. radiata* plantation, generated using the FullCam package (Richards et al., 2005). The solid horizontal line represents the permit limit and the dashed line marks the risk of reversal buffer.

4. Incorporating carbon credits into plantation production systems – Example of radiata pine in Australia

Besides volume production and wood quality, breeding and more generally silviculture need also to optimise carbon sequestration. To incorporate carbon credits into breeding objectives we developed a bio-economic model that described the role of carbon crediting in profitability of a radiata pine production system. The model considered the current and future plantation resource, actual and intended silvicultural management regimes, costs and incomes, different discount rates and carbon prices, and different carbon accounting options. Using the methodology previously developed for radiata pine in Australia (Ivković *et al.* 2006a), the objectives were to:

1. Determine future areas of new (i.e. converted from other land uses) and replanted radiata pine plantations that will be established, and on which improved trees will be deployed;
2. Develop a bio-economic model incorporating credits for carbon sequestration in radiata pine plantations;
3. Estimate economic weights for breeding (and silviculture) objective traits based on the production system model incorporating carbon credits;
4. Perform sensitivity analyses by altering the main production system and carbon accounting model assumptions.

4.1 Future area of new plantations

The coverage of additional forest management activities in the future ETS would determine if the genetic improvement will contribute to carbon sequestration in newly established areas only, or also in re-established existing plantations. Currently, in Australia, there is a steady trend of relatively low establishment of new areas of softwood plantations, including radiata pine plantations. Long-term predictions are generally difficult, and the projections of plantation area were generally overestimated (e.g. Ferguson et al. 2002), when compared with the actual plantation area expansion reported by the NPI (2010). The development of the softwood plantation estate was strongly supported by the government during 1970s and 1980s. However, ownership of state owned plantations has been changing to private. In 2009, the area of new plantations established on land not previously used for plantation forestry was 43,231 hectares of hardwoods and 6,427 hectares of softwoods.

As the existing short rotation pulpwood plantations in Australia are harvested, funds will be increasingly redirected towards replanting rather than hardwood estate expansion. Meanwhile, the inability to attract investments for the longer rotation plantations will limit the expansion of the softwood sector. There may be some scope for limited expansion of the softwood plantations to areas that do not prove suitable for second rotation hardwood replanting. The trend of a steady but low rate of establishment of softwood plantation estate is expected to continue. The trend for the softwoods has followed approximately the low estimate of plantation expansion provided by the "Plantations of Australia: Wood Availability 2001-2044" report (Ferguson et al., 2002).

For the purpose of modelling in this study, we assumed an average annual softwood plantation expansion of 6,500ha (min=5,000 and max=10,000), of which radiata pine would comprise 75%. We also assumed a normal, regulated, radiata pine plantation estate of

750,000 ha that will expand over the next two rotations (i.e. 60 years). Such a regulated, so called "normal", forest had equal areas in each age-class up to the rotation length of 30-years. The regulated plantation estate initially had an annual area of clearfelling and planting of 25,000 ha. Forest productivity across the carbon pool was assumed constant and sustainable (i.e. non-declining yield or volume harvested is equal in annual volume increment from growth).

4.2 Bio-economic model

We assumed an integrated forestry production system including plantation growing and sawmill processing components, as described in Ivković et al. (2006a). The bio-economic model had a structure which is summarised in **Table 1.,** but it is a detailed model with approximately 250 production system components (i.e. input parameters). For example, for plantation growing wood flows, details included harvested volume by operation (i.e. 3 thinnings and clear fall), by roundwood category and by 5 cm sawlog diameter classes. For sawmill production systems the wood flow details included sawlog volumes by 5 cm diameter classes and bark percentages, green mill productivity and recovery by diameter and by heart- and sap-wood classes, green mill product output (volumes of green board, chip, fines and shavings), kiln productivity and recovery (i.e. shrinkage volume loss), dry mill productivity and recovery (i.e. planing and docking volume loss), finished product volumes etc.

Variable costs for a forest grower included land rental costs, establishment and maintenance costs (i.e. site preparation, plants and planting, fertilisation, weed and wildling control, annual land and maintenance costs), harvesting, chipping and haulage costs by product type (i.e. pulplog, whole tree chip, preservation sawlog, plylog and recovery log). Variable costs for a sawmill included sawlog procurement (mill gate), mill yard costs, debarking, green and dry mill, kiln cost by board class, and chipping costs.

Incomes for a forest grower included royalties for whole tree chip, pulpwood, preservation, and sawlog by 5 cm diameter classes. Incomes for a sawmill are obtained from sale of finished product (i.e. structural machine graded and visual grades), boards standard and wide, flooring, linings, mouldings, scantlings, treated material etc. and sawmill residues, less marketing costs.

On the base model structured as described above the effects of four breeding objective traits were superimposed. Those four traits had different effects on different production system components and those effects are described below. A discounted cash-flow analysis was then applied to calculate net present value (NPV) of the system before and after a 10% increase of breeding objective traits.

Mean annual increment (MAI), was defined as the average annual increment in volume in cubic metres per hectare per year (m^3 ha^{-1} y^{-1}) evaluated at the end of rotation. To estimate the effects of increasing MAI on the total merchantable volume and sawlog distribution obtained from thinnings and final felling, industry data and the South Australian yield tables (Lewis *et al.* 1976) were used for interpolation. An increase in MAI affected green timber recovery due to changes of diameter distribution. It also impacted carbon revenues, and in turn the economic weight for volume production relative to basic density, within the modelled production system. Whole tree growth was proportional to merchantable volume increment and allocation of biomass to roots, stem, branches, leaves and bark (see next section).

Stem straightness or sweep (SWE) was defined as the maximum deviation of log axis from straight line over a length of the log in units of millimetres per metre (mm/m). Sweep was not considered to have an impact on carbon revenues because the trait does not affect the tree biomass.

The average branch size (BRS) had a major effect on log and timber grade estimated. The effect of branch size on carbon revenues was through its effect on proportion of debris after harvest.

Stiffness of clear wood (measured as Modulus of Elasticity, MOE), had a major effect on timber grade. The effect of MOE on carbon revenue was through its relationship with wood density. It was assumed that there was a slope of b=0.8 for relationship between MOE and wood density (Ivković et al. 2009). Green volume multiplied by basic wood density (defined as ratio of dry weight over green volume) determines the dry weight biomass production. Wood density was included in log specifications and therefore affected carbon accounting.

4.2.1 Carbon stocks and carbon revenue models

The FullCAM Carbon Accounting Model (Version 3.0, Richards et al., 2005) models carbon stocks for pasture-to-plantation conversion and over subsequent rotations. The package is a component of the National Carbon Accounting Toolbox Version 1.0 (http://www.climatechange.gov.au/en/government/initiatives/ncat/ncat-toolbox-cd.aspx). FullCAM calculates the gross annual increments in stem volume from yield tables and multiplies the increments by the wood density of the corresponding annual growth sheaths. Wood density can be either estimated from breast height outerwood density samples, or predicted from the site mean air temperature, nitrogen fertility, tree stocking and stand age (Beets et al., 2007a). The product of growth increment and wood density determines annual increments in stem wood carbon. Expansion factors are used to convert those increments in stem wood carbon to estimates of the increments of other tree components, including stem bark, branches, foliage, and roots (Beets et al., 1999; Beets et al., 2007b).

Biomass losses due to tree component mortality are then estimated. For needles, litter fall is based on the needle retention score for the plot. Branch mortality is based on tree stocking and crown occupancy. Thinning and harvesting related losses are based on the estimated reduction in live stem volume. Decay functions are applied to the dead material, thus affecting estimates of the required carbon pools. The modelling system provides point estimates of carbon stocks for each of the required pools. Given complete stand tending regime, the modelling system outputs a carbon yield table over a full rotation and predicts carbon stock changes for the stand.

In this study, the research version of FullCAM was used to predict carbon stock yield on a hypothetical one hectare plot in the Australian Green Triangle region. Estimates of carbon stocks and the effects of carbon credits were obtained over 2 rotations (1. pasture to pine plantation and 2. second rotation of pine plantation). Those carbon stocks were matched with a generic production system described above.

Costs related to carbon accounting can vary widely (and inversely) to the scale of the enterprise, but they generally include: initial set-up cost, registration and lawyers fees (assumed ~\$10 ha^{-1}), ongoing monitoring and accounting annual costs, (assumed ~\$40 $ha^{-1}yr$) and carbon pooling costs (assumed ~\$2.50 $ha^{-1}yr^{-1}$).

For forestry systems that include harvested products, but are also managed for carbon, the average stock approach is usually adopted to estimate the value of carbon (Maclaren, 2000; Baalman and O'Brien, 2006). For forests managed in a regulated way over multiple rotations the carbon stock that may be claimed for credits is approximately half the carbon stock at harvest (Fig. 1). The approach yields results equivalent to a carbon pool that is managed as a normal forest with an equal forest area in every age-class up to the rotation length. For example, a 30,000 ha forest estate with stands managed on a 30-year rotation, would have 1,000 ha stands in each age-class. The assumptions were also that the forest productivity across the carbon pool is the same and that the forest is managed to yield a constant sustainable harvest (non-declining yield), based on volume control, i.e., the annual forest volume harvested.

While most of the carbon in a plantation is below ground, carbon stock per ha and its partitioning to roots and woody biomass depends on survival, tree age, irrigation regime, and nutrient status. Nevertheless, an increase in woody biomass results in an increase in the carbon stored in the plantation. In this study, carbon revenues were considered to be directly proportional to the biomass accumulation in the plantation estate. The effect of breeding objective traits (MAI, SWE, BRS and MOE) on a radiata pine production system was determined as described above. Effects of those breeding objective traits on carbon revenues were proportional to their effects on dry bio-mass production per hectare. The tradable unit of CO_2 was the biomass equivalent of one metric ton of CO_2 (1 tCO_2e). In the FullCAM model carbon was assumed to make up 50% of oven dry tree biomass, and every ton of biomass carbon is equivalent to 3.67 tCO_2. A base price of \$25.0 t^{-1} CO_2e was assumed. In the base model, carbon in wood products was not considered, and all carbon in biomass sold was lost to the system immediately upon harvest.

To estimate the increase of carbon storage in wood products the TimberCAM version 1.15.5 model was used (CRC for Greenhouse Accounting, 2004). The model tracks the carbon stored in wood products through their life cycle from harvest through to manufacture, service and disposal. Harvested log removals were allocated to various wood product categories, which all had an estimated service life. All carbon was accredited to the forest grower, regardless of the fate of wood product. Volumes of each major wood product were as listed in Table 1, and described in more detail in Ivković et al. (2006a).

4.3 Economic weights for breeding objective traits

Introduction of carbon credits (scenarios NCP vs. MCP defined in the caption of Table 2) increased the base NPV per hectare from \$2,485 to \$3,818 and from \$5,913 to \$7,246 for plantation growing and integrated production systems, respectively. The relative importance of genetic improvement in different traits also changed. For the plantation growing component of the production system the importance of MAI and MOE (via wood density) increased relative to that of SWE and BRS. For an integrated production system, including both plantation growing and sawmill processing, there was also an increase in the importance of MAI and MOE relative to the importance of SWE and BRS. However, the difference was less than for the plantation growing, because of the high influence of value adding in the sawmill component of the production system (Table 2).

Production system	Scenario	Base	MAI	SWE	BRS	MOE
Plantation Growing	NCC	$2,485	$3,290 32%	$2,424 -2.5%	$2,378 -4.3%	$2,485 0%
	MCP	$3,818	$4,830 27%	$3,739 -2.1%	$3,721 -2.5%	$3,984 4.4%
Integrated Production	NCC	$5,913	$7,111 20%	$5,732 -3.1%	$5,628 -4.8%	$7,252 23%
	MCP	$7,246	$8,652 19%	$7,065 -2.5%	$6,971 -3.8%	$8,751 21%

Table 2. The average NPV per hectare of a generic radiata pine production system over two 30-year rotation before (Base) and after a 10 % increase in the four breeding objective traits at a discount rate of 7%. The values are for production system without carbon credits (NCC) and with a medium carbon price of \$25 × $tCO2e^{-1}$ incorporated (MCP).

The change in NPV ha^{-1} y^{-1} per unit trait change, i.e., economic weight (EW) for MOE increased greatly (i.e., from \$0 to \$145), after carbon credits were accounted for in the model (scenarios for plantation growing NCC vs. MCP defined in the caption of Table 3). However, the EW for MAI for integrated production system showed higher rate of increase (from \$499 to \$585) than that of MOE (from \$1,164 to \$1,309), indicating that carbon revenue can change the relativity of EWs for MAI and MOE. At the same time the EW of SWE remained unchanged while that of BRS became less negative both for plantation growing and integrated production (Table 3). These changes in EWs were examined in more detail in the next section.

4.3.1 What-if scenarios

When carbon price was increased from \$10 per tCO_2e (scenario LCP, Table 3) to \$40 per tCO_2e (scenario HCP, Table 3), it increased EW of MOE for plantation growing significantly (i.e., from \$58 to \$231). This was because there was no premium for wood quality of logs and the EW for MOE of a plantation grower was based exclusively on carbon price. However, for an integrated production system the EW of MAI increased at a higher rate (i.e., from \$533 to \$637) than that of MOE (i.e., from \$1,222 to \$1,367), which affected the relativity of two EWs. This was because of the very high absolute value of EW for MOE in an integrated production system. The increase in carbon price did not affect the EW for SWE, but it had made the EW for BRS slightly less negative (Table 3).

Discount rate had less influence on cash flows that occurred earlier in the rotation(s), such as carbon credits, than on revenue from the final harvest. For plantation growing the EW for MOE was based exclusively on carbon credits, but when discount rate increased from 4% (scenario LDR, Table 3) to 10% (scenario HDR, Table 3) it influenced the EW of MOE (i.e. a decrease from \$203 to \$108) less than that of MAI (i.e. a decrease from \$785 to \$247). Therefore the relative weight of MOE to MAI increased from 26% to 44%. For integrated

Production system	*Scenario*	**MAI**	**SWE**	**BRS**	**MOE**
Plantation Growing	**NCC**	$335	$-60	$-215	$0
	LCP	$369	$-60	$-207	$58
	MCP	$421	$-60	$-195	$145
	HCP	$473	$-60	$-182	$231
	LDR	$785	-$141	-$514	$203
	HDR	$247	-$29	-$82	$108
	LTP	$228	-$3	-$77	$145
	HTP	$614	-$124	-$312	$145
	WPI	$425	-$75	-$194	$153
Integrated Production	**NCC**	$499	$-177	$-572	$1,164
	LCP	$533	$-177	$-564	$1,222
	MCP	$585	$-177	$-551	$1,309
	HCP	$637	$-177	$-539	$1,396
	LDR	$1,574	-$530	-$1,504	$3,414
	HDR	$247	-$63	-$223	$593
	LTP	$253	-$36	-$241	$858
	HTP	$916	-$318	-$862	$1,806
	WPI	$589	-$206	-$550	$1,338

Table 3. Economic weights - the average NPV ha^{-1} per unit trait change for: mean annual increment (MAI in $m^3y^{-1}ha^{-1}$), sweep (SWE in $mm{\times}m^{-1}$), branch size (BRS in cm), and modulus of elasticity (MOE in GPa) at a discount rate of 7%. The values are for a production system with no carbon credits (scenario NCC) and with low carbon price of $\$10{\times}tCO_2e^{-1}$ (LCP), medium carbon price of $\$25{\times}tCO_2e^{-1}$ (MCP), high carbon price of $\$40{\times}tCO_2e^{-1}$ (HCP), low discount rate of 4% (LDR), high discount rate of 10% (HDR), low timber price (60% of prices given in Table 1), high timber price (140% relatve to prices given in Table 1) and with carbon storage in wood products included (WPI).

production the relative increase was much less (from 217% to 240%). For SWE and BRS, the traits less affected by carbon credits, EWs increased relative to those of MAI and MOE with the increase in discount rate. On the other hand, for a single-rotation production system that did not include carbon credits the EWs, all traits decreased at relatively the same rate with an increase in discount rate (Ivković et al., 2006b).

The increase in round-wood and timber price from 60% to 140% of the base price for plantation growing given in Table 1. did not affect the EWs for MOE ($145), however, the EW for MAI increased from $228 to $614 (Table 3). Therefore the importance of MOE relative to MAI decreased from 64% to 24%. For the integrated production, the increase in EW was greater for MOE than for MAI, i.e., from $858 to $1,806 and from $253 to $916, respectively. The EWs for form and branching (i.e. SWE and BRS) became more negative with the increase in timber price (Table 3.). Similar results were also obtained for a single-rotation production system that did not include carbon credits (Ivković et al., 2006b).

If carbon sequestration in wood products is included in the ETS the NPV of plantation growing and integrated production would significantly increase from $2,485 to $3,908 and

$5,913 to $7,336, respectively. However, this did not seem to significantly change the relative weighting for the four breeding objective traits (scenario WPI, Table 3).

5. Conclusion

Genetically improved germplasm may be deployed both in areas of new plantation and in re-established areas previously under pine plantations. However, the latter may not be eligible to receive carbon credits under the proposed future ETS. The economic weights for breeding objective traits should be calculated as an average for the plantations that are receiving and those that are not receiving carbon credits, weighted by their respective projected plantation areas.

The area of new softwood plantation establishment is currently predicted to be small (i.e., approximately 19%) relative to the area of re-established plantations in the current Australian estate (NPI 2010). Therefore the introduction of carbon credits may only slightly affect the overall breeding objective in the short term. In the long term, consequences of the introduction are more difficult to predict because they rely on various assumptions about plantation expansion.

The analyses on a per hectare basis performed in this study show clearly an increase in the relative importance of biomass production with the introduction of carbon credits. In the case that increases in carbon sequestration resulting from tree breeding and genetic improvement will be accounted for both newly established and re-established plantation areas, the importance of MAI and MOE is expected to increase relative to SWE and BRS. However, the increase in relative value of those traits would also depend on a range of factors: such as changes in rotation length, and accounting for longevity of carbon in the wood products.

Based on the modelling of radiata pine plantations in New Zealand the optimum rotation length is expected to increase with the introduction of carbon credits (e.g. Maclaren *et al.*, 2008). For a production system with rotation length extended from 30 to 35 years the economic weights for MOE are expected to decrease relative to that of other traits (Ivković *et al.* 2006b). However, as the price of carbon increases, regimes with minimum silvicultural intervention and even longer rotations may become more profitable.

Revenue from sales of carbon credits significantly increased the profitability of the radiata pine production system on a per hectare basis. The inclusion of these potential revenues increased the relative economic weights on traits MAI and MOE (i.e., wood density) that determine dry weight of biomass and in turn carbon yield per hectare. Carbon credits are cash flows that occur early in the first rotation, as opposed to the later cash flows from the final harvest and subsequent rotations, and therefore an increase discount rate had less influence on carbon credits. However, the relative economic weights in the production system model with carbon credits behaved similarly to a production system model without carbon credits when discount rate changed (Ivković 2006b).

There is no doubt that for any given production system an increase in growth rate and wood density resulting from genetic improvement will increase carbon storage in stems, products and soil (e.g., Polglase et al., 2008). Although there may have been some losses in wood density due to negative genetic correlation between the two traits (e.g., Wu et al., 2010), genetically improved radiata pine trees can certainly capture more carbon because their biomass production is higher on average.

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This book is dedicated to global perspectives on sustainable forest management. It focuses on a need to move away from purely protective management of forests to innovative approaches for multiple use and management of forest resources. The book is divided into two sections; the first section, with thirteen chapters deals with the forest management aspects while the second section, with five chapters is dedicated to forest utilization. This book will fill the existing gaps in the knowledge about emerging perspectives on sustainable forest management. It will be an interesting and helpful resource to managers, specialists and students in the field of forestry and natural resources management.