Agroforest Syst (2013) 87:689–698
DOI 10.1007/s10457-012-9589-2

Preliminary carbon sequestration modelling for the Australian macadamia industry

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Received: 20 September 2011 / Accepted: 5 December 2012 / Published online: 15 December 2012
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Abstract There is a need to accurately estimate the carbon sequestration potential of many of our agricultural and horticultural industries now that the Australian Government has introduced the Carbon Farming Initiative and is planning to introduce an emissions trading scheme in 2015. This study estimates that the carbon sequestration of macadamia plantations is around 3t CO_2e/ha/yr, and provides a methodology to assess the carbon footprint of the Australian Macadamia Industry. This study attempts to estimate the growth rate, and subsequently the sequestration rate of plantation grown *Macadamia* spp. through regression analysis of stem characteristics of destructively sampled *Macadamia integrifolia* var. 344. A volume increment curve was also derived using three common genetic varieties (A4, A16 & A42). This curve is used to extrapolate a carbon sequestration rate for the national macadamia plantation estate. Once volume estimates and sequestration rates are determined, an economic benefit of the carbon sequestration can be estimated by auditing the amount of carbon produced by activities such as "on farm" fuel use, fuel used in transport, and energy used in producing the product. In this way, a life cycle carbon budget can be developed that will aid the sustainable development of the macadamia and horticultural industries in Australia through the production of carbon credits from the carbon stored in the trees.

Keywords Carbon sequestration · Macadamia industry · Modelling · Carbon markets · Informing policy development

Introduction

This paper is the first part of an investigation into the carbon sequestration potential of the Australian macadamia industry, and has arisen from a need to develop information to enable sequestration modelling for plantation grown *Macadamia* spp. This research is needed to establish and enhance the sustainability of the industry from both economic and environmental perspectives, and assist the development of an appropriate industry policy in relation to climate change regulation. This in turn may improve the viability of an important Australian export market, and assist the ongoing development of Australia's international reputation for climate change action. The research for this paper is being conducted in parallel with

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research designed to provide an initial estimate of the farm gate carbon emissions of macadamia production. When combined with an industry emissions audit, this is expected to demonstrate that the macadamia industry does not follow the general trend of Australian agricultural emissions, and instead sequesters more carbon than it emits. This information is also likely to be relevant to Australia's other horticultural industries, and will ideally result in the development of an appropriate carbon audit framework and protocol for the wider Australian horticulture industry.

Macadamia integrifolia and *M. tetraphylla* are well known as horticultural species, despite being (in the case of *M. integrifolia*) considered rare in the wild (Harden et al. 2000). A range of natural and controlled hybrids with *M. tetraphylla* exist, with a wide variety of intermediate forms being apparent. They have been largely ignored to date by forestry circles (Bootle 1998; NCCP 1998; Ilic et al. 2000; Dimitriadis 2005) due probably to their low significance as a timber species. As a result, the information required to reliably estimate sequestration rates in macadamia plantations has not previously been available.

M. integrifolia (Maiden & Betche) is a member of the Proteaceae family. Tree form is a tree or tall shrub to 6–18 m tall, with a spread of 13 m. Adult leaves are whorled in 3's; margins are undulate, entire to spinose (an important differentiator from *M. tetraphylla*), and up to 14 cm long, as well as being sessile or on very short petioles. Flowers are a creamy pink to mauve, occurring in large racemes. The fruit consists of a fleshy green husk enclosing one seed; nuts are usually elliptical or spindle-shaped. (NCCP 1998; Harden et al. 2000). Both natural and controlled hybridisation with *M. integrifolia* generate numerous intermediate forms varying in spininess of leaves, colour of flower, size of nut and thickness of shell (NCCP 1998; Harden et al. 2000).

The Australian Macadamia industry

Macadamia nuts are Australia's only commercially significant native food product with the industry located principally around the northern New South Wales towns of Alstonville, Lismore and environs, and in Queensland around Gympie, Bundaberg, Rockhampton and the Atherton Tablelands. The industry is the largest of Australia's tree nut industries, and represents around 13 % (by tree numbers) of Australia's fruit and nut production (Australian Bureau of Statistics (ABS) 2008). It is also well run and it is thought that it has a small carbon footprint. According to 2005 data, the Australian Macadamia industry consists of over 900 growers who collectively farm 3.3 million nut-bearing trees on 17,000 hectares in Queensland and NE New South Wales (FAR 2005; ABS 2008; Australian Macadamia Society (AMS) 2008). This was worth a total of $146 million in 2004, but has declined to less than half this value according to 2007 estimates (Australian Macadamia Society). It is an ideal industry to assess the carbon stored in the trees with a view to monetizing this stored carbon through agricultural offsets through emerging markets within Australia such as the Carbon Farming Initiative (CFI).

Agroforestry systems and horticulture

There are numerous examples around the world of how agroforestry systems can be used to sequester carbon in annual and perennial crop-tree combinations, and how this carbon sequestration can provide payment for environmental services (Montagnini and Nair 2004). However, as far as we are aware this is the first time such an approach (carbon sequestration) has been described for macadamia plantations with a view to attaching a monetary value to this sequestration. Stem volumes, wood density, root-to-shoot ratios are all well described; as are the forestry allometric equations that can be applied to macadamia trees (West 2004).

Carbon farming initiative

Carbon Farming is a carbon offsets scheme or carbon credit scheme being established by the Australian Government to provide new economic opportunities for farmers, forest growers and landholders and help the environment by reducing carbon pollution (Australian Government Department of Climate Change & Energy Efficiency). The Carbon Farming Initiative (CFI) in Australia includes: (1) Legislation to establish a carbon crediting mechanism, (2) Fast-tracked development of methodologies for offset projects, and (3) Information and tools to help farmers and landholders benefit from carbon markets. Carbon Offsets or Carbon Credits represent an abatement of GHGs which can be achieved by: (1) Reducing or avoiding emissions, for example, through capture and destruction of methane emissions from landfill or livestock manure; or (2) Removing carbon from the atmosphere and storing it in soil or trees, for example, by growing a forest or reducing tillage on a farm in a way that increases soil carbon. The carbon credits or offsets are usually purchased and used by individuals or companies to cancel out or offset the emissions they generate during their day-to-day life or normal course of business, for example, by consuming electricity or catching a plane. Carbon credits can be used to offset emissions voluntarily or to meet regulatory requirements. Offset projects established under the CFI will need to apply methodologies approved by the Australian Government. They will contain the detailed rules for implementing and monitoring specific abatement activities and generating carbon credits under the scheme. Methodologies can be developed and proposed by private project proponents, as well as government agencies. The Australian Government is working with industry and other stakeholders, state government officials and technical experts to develop offset methodologies that have broad application. These methodologies are expected to be approved and rolled out progressively from November 2011. An independent expert committee, the Domestic Offsets Integrity Committee, has been established to assess offset methodologies proposed under the scheme and provide recommendations to the Minister for Climate Change and Energy Efficiency on their approval. The Committee will ensure that methodologies are rigorous and lead to real abatement. Once approved CFI methodologies will be published on the CFI website. Australia announced the framework for a national emissions trading scheme in December 2008 and has introduced a carbon tax in 2011 as a precursor to an emissions trading scheme in 2015. The framework establishes that forests or plantations that were established after 1990 on land that was cleared before 1990 may be eligible to sell sequestration that is generated after 2008. Macadamia industry census (2008) data establishing the post 1990 macadamia plantings is presented in Fig. 1. It is assumed for this estimate that all plantings occurred on previously cleared land and are therefore eligible for inclusion in the trading scheme. The aim of this study is therefore to establish a robust methodology for estimating carbon storage in the macadamia industry by using forestry allometric equations that estimate tree biomass and growth, together with density and carbon conversions to estimate carbon sequestration in the macadamia trees. This sequestration can then be used by the macadamia industry to apply for carbon offsets if the industry wishes to do so. This is part of a broader aim to assess and decrease industrial emissions of GHGs through agricultural and forestry offsets.

Materials and methods

The study was conducted at Deenford Macadamia Plantations near Knockrow, north-eastern NSW. One 25 year old stand of *M. integrifolia var. 344* was sampled using destructive measurement techniques, with material being obtained from a thinning operation. A second stand of 17 year old *var. 344* was also surveyed for height and diameter growth, as was a mixed 10 year old stand of vars. A4, A16 & A42. The *Var. 344* stands were planted with a stocking rate of 357 stems per hectare, and the A series hybrids were planted in contiguous rows with a stocking rate of 250 stems per hectare (Greg James, pers. comm.). The A series hybrids had not yet achieved a sufficient degree of growth to close their canopies at either their actual stocking rates, or at the stocking rate of their neighbouring stands. Their diameter data has therefore been directly compared with the older and more densely stocked stands without modification, on the assumption that basal area increments remain comparable due to lack of competition effects. Height data is

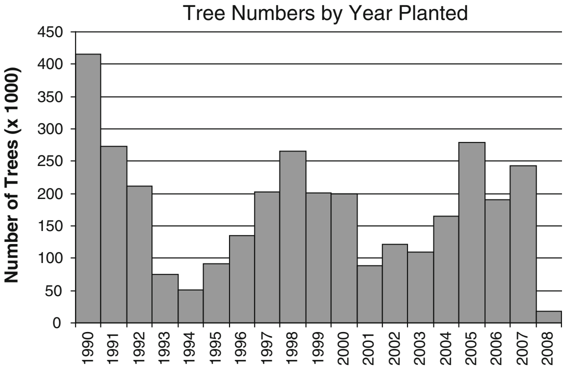

Fig. 1 Macadamia tree census according to year planted (AMS 2008)

also compared directly, ignoring any varietal variability, on the assumption that early height increment is likely to be more similar than not.

The soil of the study site forms part of the Wollongbar landscape group, consisting of deep, well drained kraznozems, probably of Gn3.11 or Gn4.11 Northcote soil group (Morand 1994). The terrain consists of an East facing slope with a fall of approximately 1, and experiences an autumn dominated rainfall of 1,730 mm per annum (Bureau of Meteorology, BOM). The average temperature is 19.3 °C with a daily range of 10.2 °C, an average annual maximum of 28.2 °C, and an annual average minimum of 8.4 °C (BOM). Temperature records from 1963 to 2009 from the Centre for Tropical Horticulture at Alstonville, northern New South Wales, near the study site indicate a strong seasonality in warming, with winters increasing by 1.5 °C over this period (~0.31 °C/decade)(Olsen 2011). Flush development for macadamia's trees hedged 25 days prior to the winter solstice decreased by about 17 days from 1963 to 2008, whilst for hedging at the summer solstice there was no trend.

Diameter and height measurements were recorded in the non-destructively sampled stands by systematically measuring every 2nd tree, excluding edge trees, using a diameter tape and an inclinometer. Thinning in the 25 year old stand was conducted in a systematic manner, removing every second tree from every second row, resulting in a 25 % thin. The 30 cm height was marked with paint prior to felling, and subsequently used to permit accurate direct height measurements. Heights and diameters (over bark) of 36 thinned trees were measured post felling using a tape measure and diameter tape. Heights of standing trees were estimated using a Sunto inclinometer, with measurement difficulties meaning that only top heights were measured for multi stemmed trees. Sample disks were removed from thinned trees at heights of 1.3 m and 5.3 m, and re-sawn to provide 2 outer and 2 inner-wood blocks of approximately 30 mm^3. The blocks were oriented across the disk to capture the greatest degree of eccentricity within the log as was possible, resulting in an ability to characterise variation due to uneven growth characteristics. Blocks from the centre of the disk were cut directly adjacent to the pith, whilst perimeter blocks were obtained from 3/4 of the distance from pith to bark in order to obtain a weighted density sample suitable for averaging with the centre samples. No sapwood banding was visible, but the medullary ray tissue was noticeably spongy when directly adjacent to the bark. This spongy tissue extended to a depth of around 5 mm, and was not included in the basic density samples

Bark samples were obtained with a chisel from heights of 1.3 and 5.3 m above ground, and then trimmed to retain only material with a complete profile. Bark thickness was measured using a Vernier calliper on a cut surface prior to bark removal. Samples were weighed on an electronic balance with a resolution of 0.001 g to obtain green mass and volume (using the water displacement method), and subsequently dried at 103 °C in a wood drying oven until no further reduction in mass was evident (~3 days). Samples were then re-weighed to obtain oven-dry mass.

Stem volume was calculated using a combination of Newtons and Smalians formulae to the 5.3 m mark, and assuming the remainder of the stem followed a conical form (after West 2004). The 0–0.3 sectional volume was calculated as a cylinder, with the presence of micro-buttressing/soil erosion making direct measurement difficult. This will likely cause an underestimation of volume, however the short length of the butt section is expected to minimise this error (Philip 1994). Bark volume was obtained by calculating the basal area of the bark as the difference between the over and under bark diameter measurements and calculating volume in the same way as stem volume. Values in between measurement points were extrapolated using separate linear functions for the lower and upper stem, and assuming that bark thickness was zero at the tip, in a manner similar to that proposed by Husch et al. (2002) and Specht et al. (2000).

Macadamia timber has been reported as being hard and dense, with a Basic Density (BD) of 800–1,000 kg/m^3, of fine texture, and with pronounced medullary rays (see Dimitriadis 2005), indicating that macadamia trees can store significant amounts of carbon. Measurements of Basic Density (BD) was conducted according to the water displacement method (Ilic et al. 2000), using the formulae tabled in Table 1 (Bootle 1998). The basal area of multiple leader trees was calculated using the quadratic summed diameter at breast height (QSDBH). Samples for bark density (BD) were obtained at breast height in accordance with Ilic et al. (2000). Samples were also obtained from a height

Table 1 Formulae used in analysis of Macadamia stem form and properties

Green density	$\text{Green Density} = \frac{\text{Green mass}}{\text{Green volume}}$
Basic density	$\text{BD} = \frac{\text{Oven dry mass}}{\text{Green volume}}$
Quadratic summed diameter	$D = \sqrt{\sum_{i=1}^{n} \text{DBH}^2}$

of 5.3 m (approximately half way up the stem) in order to identify the degree of variability in BD due to height.

A formula for estimating stem volume (over bark and under bark) as well as bark volume of the 25 year old stand was developed using multivariate regression of the form: $y = b_1x_1 + b_2x_2 \ldots + e$. Factors were identified with a backwards stepwise elimination approach (Vanclay 1994), with elimination criteria being $p > 0.1$. Eliminated factors were reintroduced and re-eliminated where co-linearity was suspected. Potential parameters were deliberately restricted to those which are readily obtainable using basic measurement tools, with parameters being considered in both unmodified form and in various transformations. Regression statistics were calculated in MS Excel and the null hypothesis $(H_0 = \Delta x \neq \Delta y)$was tested at both regression and parameter level using the F and P statistics from the regression analysis table, subject to acceptable model evaluation as recommended in Vanclay (1994). The over-bark volume model was then recalibrated against a sub-dataset, and benchmarked against the remaining data. The under-bark volume was not benchmarked, as it followed the same form as the over-bark model, and was based on modified over-bark measurements. The derived formulae were then applied to survey results from two neighbouring stands to further benchmark the models. The mixed 10 year old *M. tetraphylla* hybrid stand was not adequately represented by the models, and stem volumes for this stand were estimated using the formulae of a cone and cylinder. The default expansion factors for estimating carbon volume from stem volume are tabled in Table 2. Above and below ground expansion factors were not assessed for this study, and the default factors are therefore applied. A factor of 0.5 is the generally accepted biomass to carbon conversion ratio in Australia (Gifford 2000; Australian Greenhouse Office (AGO) 2002), however this estimate is based on a limited suite of predominantly *Eucalyptus* species (Gifford 2000). This author noted in particular that the carbon contents of sapwood, heartwood and bark warranted further exploration in a wider range of species. Fourteen random samples of wood and bark were therefore submitted to the Southern Cross University Environmental Analysis Laboratory (EAL) for analysis using a LECO CNS2000 instrument. The wood was not differentiated into sap and heartwood due to the absence of a visually distinct sapwood band.

Table 2 Summary of default formulae and factors used to estimate carbon sequestration

Generic stem volume	$\text{Stem volume}(\text{m}^3) = \frac{\pi \times (\text{Diameter}(\text{cm}(\text{under bark}))/200)^2 \times \text{Height}(\text{m})}{3}$
Above ground expansion factor	Above ground volume (m^3) = 1.25 × stem volume
Root to Shoot ratio	Total volume (m^3) = 1.25 × above ground volume
Basic Density	Biomass (t) = total volume × 0.5 t/m^3
Biomass to carbon	C(t) = biomass × 0.5
CO_2 expansion factor	CO_2 (t) = C × 3.67

It is recognized that the carbon sequestration value is a preliminary estimation and is based upon a number of assumptions. A key assumption is the non-species specific nature of the default expansion factors used in this study. We have assumed they are the same for all species of tree.

Results

Wood/bark carbon content and basic density

LECO carbon analysis results were 46.3 % carbon $(\pm 0.28\ \%)_{95\ \%\ \text{confidence}}$ for wood, and 47.4 % $(\pm 0.46\ \%)_{95\ \%\ \text{confidence}}$ for bark. These results show that the carbon fraction of the wood is 3.7 % less than the generally accepted value (50 %), with the bark fraction being 2.6 % less.

Basic density of the wood was 650 kg/m^3 $(\pm 4.78\ \text{kg/m}^3)_{95\ \%\ \text{conf}}$ at 1.3 m, and 668 kg/m^3 $(\pm 5.56\ \text{kg/m}^3)_{95\ \%\ \text{conf}}$ at 5.3 m. No significant difference was identified between the outer and inner samples of 1.3 m and 5.3 m disks using a 2-tailed, paired t test. A significant difference was identified between the pooled 1.3 m and 5.3 m samples however, with basic density increasing by 2.8 % at the 5.3 m measurement point (approximately half way up the stem). The bark Basic Density was 533 kg/m^3 and 531 kg/m^3 for 1.3 m and 5.3 m samples, ±0.40 and 0.33 kg/m^3, respectively at the 95 % confidence level. A high degree of variation existed between the sample pairs, and a significant difference also existed between the 1.3 m and 5.3 m Green Density readings. A two tailed, paired *t* test found no difference comparing the 1.3 m and 5.3 m bark samples however. One outlier lay above 700 kg/m^3, and 2 outliers lay below 400 kg/m^3, and were removed due to identification as measurement errors.

Stem volume

Stem diameters (over bark) were measured every meter, from 0.3 m through to 5.3 m. Multiple leaders were converted to an equivalent single stem diameter using the quadratic summed diameter transformation tabled in Table 1. The diameter data ranges are plotted in Fig. 2.

The outliers shown in Fig. 2 were assessed to ascertain their cause. Both data points are assessed as valid according to Chauvenet's criterion. A further assessment of stem form indicated that the 2.3 m outlier (Tree 22) appeared to be a legitimate data point, whilst the 1.3 m outlier generated by Tree 27 appears to be caused by a measurement anomaly (data not shown). It is likely that this outlier was caused by a measurement or transcription error, and as this data point has a high leverage in the regression, it was excluded from further analysis.

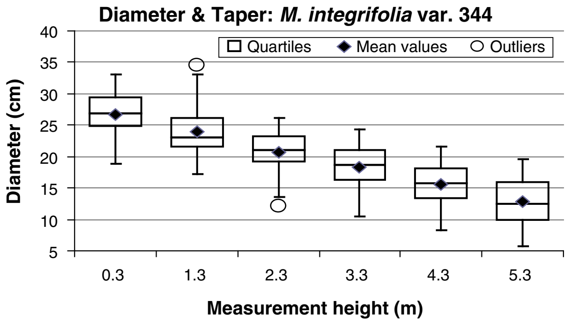

Fig. 2 Quadratic Mean Diameter (*over bark*) versus height for 25 year old *Macadamia integrifolia* var. 344. [*Outliers* represent data lying more than 1.5 × the inter quartile range from the 1st and 3rd quartiles]

The diameter at breast height over bark (DBHOB) and height distributions for the 3 surveyed stands are shown in Fig. 3. The increase in diameter of the 17 year old stand over the 25 year old stand was found to be significant at the 95 % confidence level, but its cause was not ascertained. The mean stem height of the 25 year old *M. integrifolia* var. 344 stand was 10.2 m, ±0.25 m$_{\alpha=0.05}$. Twenty-eight percent of sampled trees contained double leaders at 1.3 m, and the average height difference of these leaders was 0.38 m, or 3.56 % less than the top height.

The nature of the crowns was such that the accurate measurement of multiple leaders on standing trees is likely to be highly difficult for taller trees. Stem volume analysis was therefore restricted to the height from the tallest stem in order to maximise the useability of the results.

Over bark volume: 25 yo M. integrifolia

Over bark volume was found to be related to diameter and height through the regression (Fig. 4):

$$y = 0.000386842 \times \mathrm{QSDBH}(ob)^2 + 0.008927399 \times h - 0.1113647657$$

The null hypothesis was rejected, with combined regressor's of QSDBH and top height returning an r^2_{adj} value of 0.937. Individual coefficient of significance levels are tabled in Table 3. The plot of the over bark volume regression is shown in Fig. 4, with the trend line of the fit following a 1:1 slope, and passing approximately through the origin. The data distribution does not suggest the presence of heteroskedasticity,

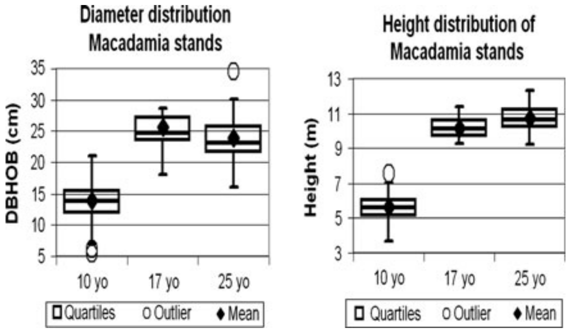

Fig. 3 Diameter and height distribution of sampled 10, 17 and 25 year old Macadamia stands. [*Error bars* denote the maximum and minimum range, or 1.5 × the inter quartile range, whichever is the lesser value. The 10 year old stand consisted of 3 different *tetraphylla/integrifolia* hybrids, whilst the 17 & 25 yo stands consisted of *M. integrifolia* var 344]

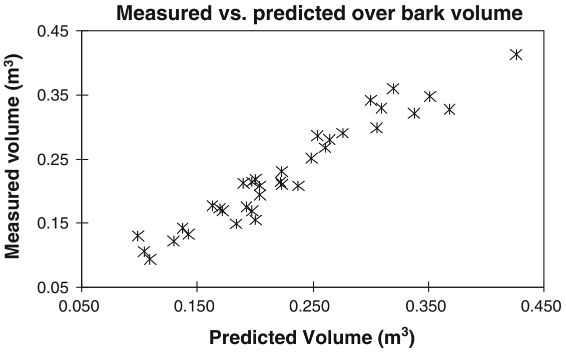

Fig. 4 Plot of calculated over bark volume versus predicted volume

with stem volume vs height regressions and statistical residual analyses providing no further suggestion of a serious violation of regression assumptions.

Bark

The average double sided bark thickness of the 25 year old stand was 7.9 mm ± 0.39 mm $_{95\ \%\ \mathrm{conf.}}$ at 1.3 m, and 5.8 mm ± 0.38 mm $_{95\ \%\ \mathrm{conf.}}$ at 5.3. The relative thickness of the bark increased from 4 % of stem diameter at 1.3 m to 5.7 % of stem diameter at 5.3 m.

Under bark volume: 25 yo *M. integrifolia*

Under Bark Volume was also found to be significantly related to diameter and height, with the regression following the form.

$$y = 0.0093005 \times \mathrm{QSDBH}(ub)^2 + 0.0003578 \times h - 0.1178482$$

Regression analysis of these coefficients returned an r^2_{adj} value of 0.939 and a P significance value of 3.62E^{-16} (data not shown). Stem volume versus height and QSDBH regressions with an analysis of residuals (data not shown) indicate that the data may not be normally distributed, but the normal probability plot shows that the deviation from normality is not great, and resultant errors are not likely to be significant.

Regression model evaluation

The regression model was evaluated by recalibrating the over bark model to a sub-dataset and fitting the revised model to the remaining data points. The data set was split at $n = 20$, with 15 data points being retained for validation (data not shown). No sorting or selection criteria were applied. The residuals of the resulting model were assessed for gross modelling assumption violations with the mean of the 15 residuals being −0.0012, with $\sigma = 0.0174$. The normal probability plot and histogram show that the smaller data set resulted in a poorer approximation of a normal distribution, however this error was not found to invalidate the model. The model was found to fail completely in trees significantly smaller than those measured however, with $\hat{y} = 0$ when $d = 10$ cm and $h = 4.8$ m. The model was not tested against completely independent data due to the lack of a suitable dataset.

An estimate of the carbon sequestration rate of Macadamia plantations

The model was used to estimate the average stem volume in the 10, 17, and 25 year old stands. Stem volume in the 10 year old stand was estimated using frusta of cylinder below breast height, and cone above breast height, whilst its bark volume was calculated as a constant percentage (8.58 %) of total stem volume. The results are shown in Table 4 and default values for expansion factors, root to shoot ratio, basic density, carbon fraction and conversion factor (Table 5). Table 6 summarises the conversion factors used to

Table 3 Over bark volume regression coefficients and values

Multiple R	R^2	Adj R^2	SE	Obs	F	Sig F
0.969784319	0.940481626	0.936761728	0.017236866	35	252.8245497	2.4798E−20
	Coefficients	SE	t stat	P value	Lower 95 %	Upper 95 %
Intercept	−0.113647657	0.041543189	−2.735650747	0.01006968	−0.198268365	−0.0290269
QSDBH^2	0.000386842	2.02104E−05	19.14070415	4.37442E−19	0.000345675	0.00042801
Top height	0.008927399	0.004229135	2.11092776	0.042683373	0.000312932	0.01754187

Table 4 Stem volume and total CO2 estimates in tonnes for plantation Macadamia trees

		Volume (m^3/tree)			CO_2e/tree
		Over bark	Under bark	Bark	
10yo	Mean	0.0198	0.0181	0.0017	0.033705
	Confidence (95 %)	n/a	n/a	n/a	
17yo	Mean	0.1625	0.1481	0.0143	0.276387
	Confidence (95 %)	17.00 %	17.37 %	13.21 %	
25yo	Mean	0.2020	0.1852	0.0167	0.343904
	Confidence (95 %)	11.31 %	11.48 %	9.47 %	

The 17 and 25 year old trees were *M. integrifolia,* whilst the 10 year old trees consisted of several *M. tetraphylla* hybrids. [The factors in 5 were used to derive total CO_2]

n/a = not available

Table 5 Summary of conversion factors used to convert stem volume to total CO2

	Wood	Bark
Above ground expansion factor	1.25	
Root to shoot ratio	1.25	
Basic density	0.65	0.533
Carbon fraction	46.30 %	47.40 %
CO_2 conversion factor	3.67	
Combined factor	1.72576	1.44874

Table 6 MMF model coefficients for estimating stem volume versus age

MMF model: $y = (a*b + c*x\text{^}d)/(b + x\text{^}d)$

Coefficient	Over bark	Under bark
a=	0	0
b=	47591923	31688386
c=	73.55737	67.67044
d=	6.70408	6.54456

derive total tonnes CO_2/tree from bark volume and under bark stem volume. This data was used to produce an MMF model equation (Table 6) with the resulting data fitted using Curve Expert (Hyams 2005) as shown in Fig. 5.

Applying the sequestration vs age estimate in Fig. 5 to the post 1990 planting statistics suggested that Australian Macadamia plantations will sequester around 51 thousand tonnes of CO_2e in 2008/09 and 56 thousand tonnes in 2010/11, assuming no new plantings.

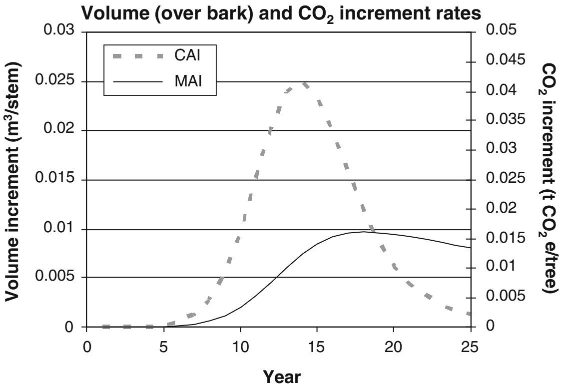

Fig. 5 Stem volume (*over bark*) and CO_2 increment rates. The Current Annual Increment (CAI) is the estimated growth occurring in a given year, and the Mean Annual Increment (MAI) is the average growth rate to a given year

Discussion

Over 50 thousand tonnes of CO_2e is being sequestered by post 1990 Macadamia plantations each year, with an average sequestration rate of about 3 tonnes of CO_2e/ha/yr. This is equivalent to about 5 % of the total GHG emissions from the horticulture industry (Australia's National Greenhouse Accounts 2009). Whilst the potential for converting this sequestration into carbon credits may be limited with fewer than 10 % of growers managing plantations of more than 10,000 trees, we have estimated that 10 t CO_2e/ha/yr is also sequestered by the shell and husk of the macadamia nut (Murphy et al. 2008). This improves the sequestration to 13 t CO_2e/ha/yr. At $23 a tonne the potential value of this sequestration is over $5 million dollars per annum. The prevalence of smaller operators within the industry is likely to add to compliance and management costs of running sequestration projects, and would require careful consideration. However, the carbon sequestration could be managed by a company which audits the sequestration for the industry as a whole, through the CFI after subtracting emissions.

The key sources of direct and indirect emissions from horticulture are; (1) fuel and electricity = ~70 % of total emissions; (2) nitrogenous fertilizers and animal manures = ~20 %; and (3) Waste and refrigerant loss to the atmosphere = ~10 % of total emissions (unpublished). To accurately monetise the real economic value of the carbon stored in the macadamia plantations these emissions must be subtracted from the tree carbon and carbon stored in the husk and shell. However, we have roughly estimated that fuel and electricity usage from two farms in the northern rivers region is equivalent to about 1 t CO_2e/ha/yr and if carbon stored in the shell and husk can be valued and stored in soils for example the total sequestration should be around 12 t CO_2e/ha/yr giving an economic return of about $4.7 million dollars per annum if this methodology is accepted by the Government Regulator.

The real economic value of the sequestration may however lie in the ability to assist market positioning of macadamia produce. The market price of macadamia nuts has dropped due to a current global oversupply, and Australian nuts are therefore competing on quality and desirability. The ability to confidently demonstrate good environmental credentials may assist this end. A search of the literature indicates that further research is also required to inform accurate carbon modelling in macadamia plantations. The results of basic density testing show that this variety of Macadamia has a significantly lower BD than was suggested by the available literature. The lack of referenced sources negated the ability to determine the provenance from which the reports came however, leaving the possibility that 0.65 t/m^3 represents an appropriate value for plantation grown macadamia spp, and that the previous data came from wild provenances. The estimates of carbon content for both wood and bark were both close to 3 % of the recommended default value. Further research into this value would improve statistical confidence for the species; however the proximity of the results to the default value suggests that greater gains in accuracy may result from other research avenues. One such area likely to benefit from further research is in the estimation of expansion factors. *Macadamia* spp. are known to have a large network of fine surface roots, accompanied by a proteoid root structure, and a shallow taproot on grafted species (Firth et al. 2003). Keith et al. (2000) note that massive variation in root to shoot ratios may occur, and failed to identify any previous research into appropriate values for either the Proteaceae family as a whole, or any of the *macadamia* species in particular. This appears to be the first instance of a published growth model for any of the *Macadamia* species. It is not expected that this model is sufficiently accurate for detailed modelling. It is however believed that it provides a starting point for further validation and adaptation.

Conclusions

This estimate of sequestration appears to be the first instance of a horticultural industry in Australia acting to capture the potential value of the sequestration it generates. This is worth around $1.3 million annually for the carbon stored in the trees, and higher if carbon in the shell and husk is included. The Australian horticultural industry has a strong international reputation for quality and high standards. This sequestration estimate represents the first step of an industry carbon audit process that may help secure the reputation and industry value in the face of increasing competition and recognition of agriculture's effects on the climate (IPCC 2007). However, further research on default expansion factors, variations in growth of different species and hybrids used, and research into the management and regional variability of soils and the trees is warranted. This study also does not consider the emissions profile of the industry in any detail. This emissions profile will require consideration before making any specific environmental claims for macadamia orchards, beyond the stated sequestration estimate. Also this carbon sequestration estimate will vary over the coming decades as temperatures increase further and variations in photosynthesis affect carbohydrate reserves in macadamia orchards (Olsen et al. 2008).

Acknowledgments This research has been greatly aided by help from Andrew Heap and Kim Jones (Australian Macadamia Society), Greg and Cliff James of Deenford Macadamia farm in the Northern Rivers region of NSW, and Peter Leihn from the NSW Greenhouse Gas Abatement Scheme/Green Power.

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