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Estimation of biomass and sequestered carbon on farm forest plantations in northern New South Wales, Australia

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Abstract

Tree stem diameters were measured in a stratified random sample of plots in each of 19 forest plantation estates in northern New South Wales. The estates were 0.2–170 ha in area and the plantations were 1–10 years old, growing eucalypts, sub-tropical rainforest species or an exotic conifer, both in single-species and mixed-species plantations. A sample of trees was measured also for biomass and estate- and region-specific allometric relationships developed to predict tree biomass from tree diameter. With the stratified random sample data, the allometric relationships were used to predict the total amount of carbon sequestered in tree biomass, and its 95% confidence limit, across each estate. These results were compared with estimates made using an allometric relationship from Nova Scotia, Canada, and a stand-based relationship from Australia. Bias in estimates made using the region-specific or Nova Scotia relationships appeared to be unimportant if the confidence limit was $> 10\%$ of the estimate. Bias was greater using the stand-based relationship and was unimportant only if the confidence limit was $> 30\%$ of the estimate. It was concluded that using sampling intensities of around 2–4% of the estate area, the total carbon sequestered by an individual small plantation estate in the region could generally be estimated satisfactorily with a 95% confidence limit of about 30–40% of the estimate or better, with a minimum of about 10%. Generally, the younger the plantation estate, the higher was the sampling intensity necessary to achieve the same precision of estimate as in older estates. If small plantation owners in the region are intending to offer sequestered carbon for sale as carbon credits, it appeared it will be difficult for them to estimate carbon sequestration by their trees with a 95% confidence limit as low as the present Australian recommendation of 10% of the estimate. If owners pooled their estates in a cooperative, they should be better able to achieve the required confidence limit from the much larger, pooled estate. Analysis of organic carbon contents of soil below plantations and adjacent pasture paddocks suggested there was a decline in soil carbon with time following plantation establishment. Growers will need to account for these losses when estimating the total carbon sequestered by their plantations ecosystems.

Keywords: Biomass; Carbon; Sequestration; Allometry; Farm forestry; Soil carbon

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1. Introduction

At present, there is considerable interest in Australia and other countries in methods to estimate the biomass of and carbon sequestration by terrestrial plant ecosystems. These estimates are required to satisfy the requirements of the United Nations Framework Convention on Climate Change 1992, the Montreal Process 1994 and the Kyoto Protocol 1997 [1–8]. Governments need this information to report on the state of their national forests [9]. Individual forest owners need to quantify the amount of wood they have available or, if an open market for the sale of sequestered carbon develops, the amount of carbon they have available for sale as 'carbon credits'. In response to government initiatives in Australia [10], the area of forest plantations has been increasing rapidly over recent years, both on a broad industrial scale and as smaller plantings on farms.

If plantation owners are to sell carbon credits, they must have available an estimate of the quantity of carbon sequestered by their plantations. That must be accompanied by a statement of the certainty of that estimate so that it is defensible for both scientific and financial accounting purposes. The certainty of an estimate is usually expressed as a 'confidence limit'; this is often converted to a 'confidence interval', which gives the range within which the estimate is known to lie with some specific probability.

One of the more reliable ways to achieve an estimate of carbon sequestration by a plantations is to select a sample of trees from the plantation estate, measure their carbon content and use that information to estimate the amount of carbon sequestered in all the trees across the whole estate, together with the confidence limit of the estimate. In essence, estimation of carbon content of the sample involves estimation of the oven-dry biomass of the sampled trees and conversion of this biomass to a quantity of carbon, assuming a certain proportion of the biomass is carbon [8,11–15].

Estimation of the biomass of a sample of trees can be very difficult and expensive. At most, it involves felling the trees, excavating their root systems and drying and weighing the biomass. Such practices are impossibly expensive for any other than research purposes and much attention has been paid to the development of techniques to estimate tree biomass from easily measured tree characteristics. These techniques, known generally as 'allometry', involve relationships between tree above-ground biomass and (the easily measured) tree stem diameter and/or height and between tree below-ground biomass and above-ground biomass. Substantial research programs are usually undertaken to develop such allometric relationships for application with particular tree species in particular forest ecosystems.

As well as the amount of carbon sequestered in the tree biomass in a plantation, the owner must be concerned also with the organic carbon content of the soil. Most plantations being established at present in Australia are on former pasture land. The soil and site disturbance and change to a different crop species may all contribute to changes in soil organic carbon content over time following afforestation [16], although reforestation appears generally to have little affect on soil organic carbon [17]. Australian studies have suggested that soil organic carbon declines over some years following plantation afforestation on sites occupied formerly by pasture or native forest. However, by the end of a 20–40 year plantation rotation, soil organic carbon may have changed further to be ultimately higher or lower than its value at the time of plantation establishment, depending on the site and its management [18–21]. Whether there are gains or losses of soil organic carbon, forest owners will have to determine how large they are as part of their assessment of the amount of carbon they have available for sale as carbon credits from their plantations.

The present work was concerned with the development of techniques to allow estimation of the amounts of carbon sequestered in smaller forest plantation estates, being grown as part of farm enterprises in sub-tropical and temperate parts of northern New South Wales. These estates have been established for a variety of reasons, ranging from wood production to bio-diversity conservation to farm beautification. They consist of a variety of species, sometimes planted in mixtures and sometimes with several blocks of different species or species mixtures planted on the one estate. The work considers the estate sampling technique and the application of various 'allometric' techniques to estimate the biomass of the trees growing on each estate and, hence, the amount of carbon it has sequestered. It also considers briefly the soil organic carbon content on these estates, although in insufficient detail to assess their quantities across the whole of any of them.

2. Methods

2.1. Estates

Work in this project was carried out on 19 plantation estates in New South Wales, in the sub-tropical Northern Rivers and central north coast regions and the temperate New England. Table 1 lists basic information about the estates. The largest (18) was publicly owned, whilst the rest were privately owned farm estates. They varied in area over the range 0.2–170 ha. Some estates included several plantation areas of different ages; their age ranges at the time of measurement (in 1999) are shown in Table 1. Over all estates, plantation ages varied in the range 1–10 years. Some estates consisted of one species only, some had more than one species planted in separate blocks and some had mixtures of species in the same blocks. Eucalypts, sub-tropical rainforest species and an exotic pine species were included. Rainforest species were always planted in mixtures. The plantation types and the species present on each estate are indicated also in Table 1. Appendix A lists the names of all the species occurring on the estates. The wide range in estate sizes and species planted reflect the mixed motives that land-owners in the region have for the establishment of plantation estates.

On all the estates, sampling of the plantations was undertaken to allow estimation of the amount of carbon sequestered in the plantation trees across the whole estate. On six estates (6,7,10,12,14,19), samples of trees were felled and weighed to determine tree biomass and to establish allometric relationships to allow prediction of tree biomass on other estates. On all but four estates (15,17,18,19), measurements were made of the soil organic matter carbon content.

2.2. Tree biomass measurements

Tree biomass measurements were made of *Eucalyptus microcorys* (Estate 6), *E. grandis* (10), *E. saligna* (12), *E. nitens* (14), *Grevillea robusta* (7) and *Pinus radiata* (19). These six species were chosen to reflect the range and popularity of species being established in farm plantations in the region. Five or six trees of each species were sampled at random from across the whole estate, although sampling was restricted to ensure that it included trees covering broadly the range of ages and sizes of trees which occurred over the estate. Whilst it would have been desirable to sample rather more trees of each species to establish more statistically reliable allometric relationships for each, the resources available to the present study precluded doing so.

The selected trees were felled, divided into foliage, branches, stem wood and stem bark and weighed fresh. Sub-samples were dried to constant weight at 80°C to determine oven-dry weights. Roots with a diameter of 5 mm or greater were excavated carefully by hand digging and washing out with low pressure water and were also weighed fresh and dry.

2.3. Sampling to estimate estate-sequestered carbon

To undertake sampling on each estate, its plantation area was first stratified by forest type, plantation age and by productivity differences apparent to the eye (for example, where aspect of the plantation had an obvious effect on plantation productivity). The number of strata identified in the various estates varied in the range 1–6, but most commonly there were 2–4 in each estate.

Having stratified the area of each estate, at least two sample plots were located at random in each stratum. The diameter at breast height (1.3 m) over bark of all the trees in each plot was measured. Plot areas varied in the range 42–225 m^2, depending on plantation circumstances, but were most commonly in the range 100–150 m^2; the same plot area was used for the set of plots measured in any one stratum. The total number of plots measured in each estate varied in the range 2–12, but most commonly there were 6–10. Sampling intensity across the various estates (area of all plots sampled on the estate divided by estate total area) varied in the range 0.05–7.8%, but was most commonly 1–4%. Sampling intensities were selected somewhat arbitrarily and reflected the resources available to carry out the work.

2.4. Soil organic carbon content determination

On the 15 estates where soil organic carbon content was determined, paired sites were located. One of

Table 1
Characteristics of the plantation estates

Estate	Location °S, °E	Type[a]	Area (ha)	Age range (yr)	Species present[b]
Northern Rivers					
1	29°28′, 153°13′	Euc	6.3	2–5	1, 4, 5, 6, 7, 9, 13, 18, 19
2	28°39′, 153°23′	Rf and Euc	3.0	5–6	1, 3, 5, 7, 8, 9, 13, 14, 16, 17, 18, 31, 42, 44, 46, 47, 52, 53, 56, 57
3	28°41′, 153°27′	Rf	2.0	3–4	26, 30, 31, 33, 34, 36, 40, 41, 42, 43, 44, 47, 48, 52, 60, 65
4	28°40′, 152°34′	Euc	16.9	3	2, 4, 9, 10, 12, 14, 16, 35
5	28°40′, 153°23′	Rf	5.6	2–6	23, 24, 25, 27, 28, 29, 30, 31, 32, 33, 34, 36, 37, 38, 39, 40, 42, 44, 45, 46, 47, 48, 49, 51, 52, 53, 54, 55, 57, 59, 61, 62, 63, 64, 67
6	28°32′, 152°41′	Euc	43.0	5	4, 9, 13
7	28°38′, 153°20′	Rf	4.9	4–8	22, 25, 30, 34, 40, 41, 42, 44, 45, 46, 47, 49, 50, 51, 52, 53, 56, 58, 60, 63, 65, 67
Central North Coast					
8	32°26′, 151°32′	Euc	9.7	2	1, 8, 9, 18, 19, 56
9	31°52′, 152°22′	Euc	10.0	2	5, 8, 12
10	31°27′, 152°45′	Rf and Euc	8.2	2	5, 13, 17, 18, 22, 52, 56
11	31°44′, 152°42′	Euc	6.8	3	5, 13
12	32°01′, 151°58′	Euc	2.0	1–4	13, 18
13	32°12′, 152°17′	Euc	0.2	5	9
New England					
14	30°24′, 152°21′	Euc	4.4	2–7	11, 15, 21
15	29°46′, 151°40′	Euc	3.0	1–2	11, 21
16	30°34′, 152°07′	Euc	1.2	3	18, 22
17	30°59′, 151°35′	Con	0.4	10	66
18	30°59′, 151°35′	Euc	170.0	4–6	11
19	30°49′, 151°30′	Con	23.0	3–10	66

[a]Euc—eucalypt, Rf—sub-tropical rainforest species, Con—Exotic conifer.
[b]Species numbers and names given in Table 6.

each pair was inside the plantation, within the ripped row if ripping had been done, and one in an adjacent paddock deemed to be representative of the plantation before establishment. The paired sites were no more than 25 m apart. On two estates (4, 11), two pairs of sites were sampled.

At each site, soil was excavated to a depth of 1 m or bedrock, whichever was reached first. Using an 8 cm bulk density corer, soil samples were taken at every 10 cm depth. Rocks and gravel (> 2 mm diameter) were removed from each sample and the remaining soil ground and oven-dried for bulk density determination. Tests showed there was no detectable inorganic carbon in any of the samples. Organic carbon content of the samples was measured using a Leco elemental analyser (estimation error of 0.05% of the carbon in the sample). From this information, the amount of soil organic carbon per unit ground area was determined for each 10 cm soil layer.

3. Allometric relationships to predict tree biomass

3.1. Above-ground biomass

An 'allometric' model used commonly to describe the relationship between tree oven-dry biomass (W, kg) and tree diameter at breast height over bark (D, cm) is,

$$W = aD^b, \quad (1)$$

where a and b are parameters. Several authors [22–24] have reviewed the application of this and other allometric models. The model is usually fitted to the data using ordinary least-squares regression analysis after logarithmic transformation of the model to a straight line.

Fig. 1 shows the logarithmically transformed data, relating tree above-ground dry biomass to diameter, for the data of each of the five species for which biomass data were collected here. For each species, the relationship appeared close and linear. A covariance analysis showed there was no significant difference (at $p = 0.05$) between the slopes of the least-squares, straight-line fits to the data for the five species, but that the intercepts differed just significantly ($p < 0.05$). However, it was clear that the magnitude of the differences between the intercepts was so small as to be of little practical significance if the models are to be used generally in the region for prediction of above-ground biomass from measured tree diameter. Accordingly, the data from all five species were pooled and a single regression line determined across all five. The fit to the data of the pooled regression is shown in Fig. 1.

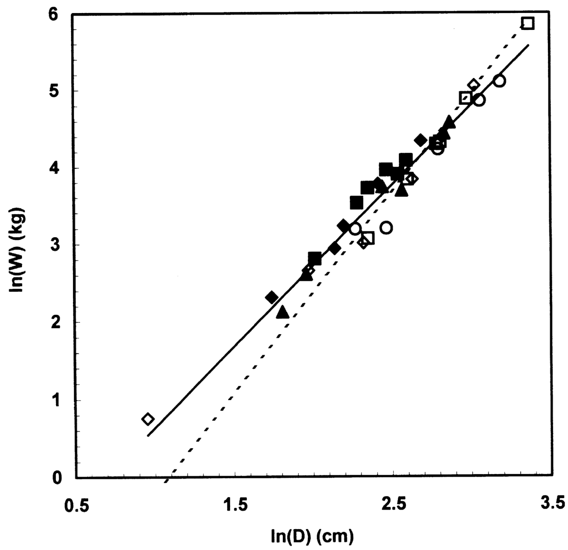

Fig. 1. Scatter-plot of logarithmically transformed data for above-ground oven-dry biomass (W), and tree diameter at breast height over bark (D) for individual tress of *E. microcorys* (■), *E. grandis* (◆), *E. saligna* (▲), *E. nitens* (◇), *Grevillea robusta* (□) and *Pinus radiata* (○) harvested in the present work. The fit to the data pooled across all six species is shown (——), together with an allometric model for Nova Scotia [25] (— — —), discussed later in the text. Note that ln(′) denotes natural logarithms.

Parameter values of the individual regression models and the pooled model are given in Table 2.

When model (1) is fitted in its logarithmic form and used to predict tree biomass from measured tree diameter, the predictions of biomass may be biased, because of the back-transformation from logarithms ('bias' means that on repeated measurement or estimation of something, the average of the measurements or estimates obtained differ from the true value). The degree of bias is likely to increase as the degree of the fit to the data of the logarithmic regression declines. Various methods have been proposed to correct for this bias [25,26]. For the present work, the bias correction factor of Snowdon [26] was used. This is the ratio of the average of the untransformed biomasses used to fit the model to the average of the fitted values from the logarithmic regression model, after back-transformation from logarithms. Predictions made using model (1) should be multiplied by this factor to remove the bias. The bias correction factors for the allometric models fitted here are shown in

Table 2
Allometric relationships established from tree oven-dry biomass data collected here

Species	No	*D*-range (cm)	Above-ground biomass			Total biomass			Root/shoot ratio (standard error %)
			a	*b*	Bias	a	b	Bias	
E. grandis	5	6–5	0.203	2.20	1.011	0.313	2.11	1.009	0.261 (7.5)
E. microcorys	6	8–13	0.238	2.15	0.999	0.246	2.22	1.000	0.227 (6.3)
E. saligna	6	6–18	0.167	2.21	1.003	0.238	2.18	0.991	0.304 (12.7)
E. nitens	6	3–21	0.274	2.00	1.098	0.515	1.76	1.014	0.278 (4.6)
G. robusta	6	11–29	0.035	2.74	0.992	0.030	2.90	0.999	0.282 (10.3)
P. radiata	6	7–24	0.186	2.11	1.029	0.204	2.15	1.032	0.217 (12.1)
Pooled			0.235	2.08	1.047	0.355	2.00	1.026	0.259 (4.4)

Parameter values (a, b) are shown for allometric models of the form (1). No refers to the number of trees measured and *D*-range to their range of diameters at breast height over bark. Bias refers to the bias correction factor [26] to be used when using the fitted models to predict biomass. Root/shoot ratio is the mean for a species of its root oven-dry biomass to its above-ground oven-dry biomass. The standard errors of the means are shown also.

Table 2. The factors are all close to unity, reflecting the close fit to the data evident in Fig. 1.

Analysis of information in other biomass studies [27,28] suggests that the allometric models fitted for a wide range of tree species across much of the world differ little in the slopes or intercepts of the fitted models. That is to say, it may be possible to apply allometric models fitted for certain tree species in one part of the world to predict satisfactorily tree above-ground biomass from stem diameter for a different species in another part of the world. Of course, there would be expected to be some bias in the predictions made under these circumstances. Judgement will then be needed to determine if the degree of bias is sufficiently small as to render the predictions useful despite the bias. This issue was explored in some detail in the present work, for obviously it would be useful for plantation owners in New South Wales to make predictions of biomass using a previously established allometric model, rather than having to undertake the biomass measurement necessary to derive such a model locally. Accordingly, for the estimates of the amounts of carbon sequestered in the trees across each estate which are determined finally here, comparisons will be made between estimates made using the locally derived allometric models (Table 2), estimates obtained using a model determined for native vegetation in Nova Scotia, Canada, and estimates obtained using models determined elsewhere in Australia.

3.2. Root and total tree biomass

Determination of total biomass is of interest in the present work, not just above-ground biomass. When measured root biomass was added to above-ground biomass, to provide total tree biomass for the trees sampled in this work, the scatter-plot of the data had a similar form to Fig. 1. The individual species and pooled data allometric relationships fitted to these total biomass data are given in Table 2. For any tree, predictions from tree diameter of root biomass can be found as the difference between the predicted values for total tree and above-ground biomass.

An alternative method to predict tree root biomass has some currency in work presently being undertaken in Australia and internationally to determine carbon sequestration by terrestrial vegetation [1,11,27]. This method determines the ratio of root oven-dry biomass to above-ground oven-dry biomass, commonly termed root/shoot ratio. Fig. 2 shows a scatter plot of root/shoot ratio against tree diameter for the data of each of the five species for which biomass data were collected here. Analysis of these data suggested there was no statistically significant relationship between the ratio and tree diameter for any of the

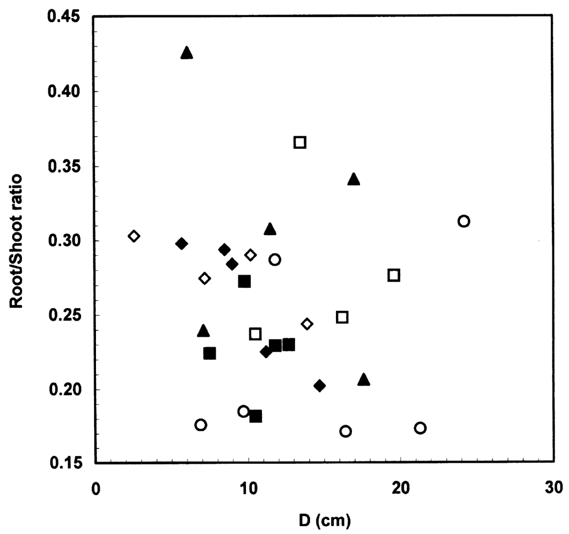

Fig. 2. Scatter-plot of root/shoot ratio and tree diameter at breast height over bark (D) for individual trees measured in this work. Symbols for different species as in Fig. 1.

species, nor was there any significant difference between the mean ratios for the five species. The mean ratio for each species, and when the data were pooled over all species, are given in Table 2, together with the standard errors of those means (standard error is a measure used in mathematical statistics to describe the variabiation in a set of data, root/shoot ratios in the present instance). Given this, once above-ground biomass has been predicted from tree diameter, using the allometric model (1), root biomass can be predicted as being 25.9% (the pooled root/shoot ratio in Table 2) of the predicted above-ground biomass.

4. Estate-wide carbon sequestration

4.1. Estimation method

As described in Section 2.3, individual tree diameters at breast height were measured in a stratified random sample of plots taken from the plantation area of each of the 19 plantation estates considered here. For each of those plots, the total amount of carbon sequestered in the biomass of the trees on the plots was determined as follows. First, the above-ground oven-dry biomass of each tree in the plot was predicted from its diameter using an allometric model as discussed in Section 3.1. Root oven-dry biomass was then predicted from the predicted above-ground biomass using an average root/shoot ratio as discussed in Section 3.2. The amount of carbon sequestered in the above-ground parts of each tree was then assumed to be 50% of the predicted above-ground biomass and in the roots as being 49% of predicted root biomass. These proportions of carbon have been found appropriate to apply generally in Australian trees [13,14], with little difference between different tree taxa. These proportions of carbon in above-ground biomass agree quite well with the values of 49% and 47% reported for *Pinus taeda* [29] and *Populus spp* [12], respectively. The estimates of the amounts of carbon sequestered in each tree in each plot were then summed to give an estimate of the total amount of carbon sequestered in the total tree biomass of the plot.

Once a total amount of sequestered carbon had been estimated for each plot measured on an estate, the information was used to estimate the total carbon sequestered in the biomass of all trees across the entire estate, together with a 95% confidence limit about the estimate. A standard statistical procedure for stratified random samples [30, pp. 47–48] was used to determine the estimates and their variances (variance is another measure, closely related to standard error, used in mathematical statistics to describe the variation in a set of data). Note that this procedure assumes that the amount of carbon sequestered in the tree biomass in each plot in an estate is measured without error. In fact, because allometric models and Australia-wide mean proportions of biomass carbon were used to estimate the carbon amounts, they are subject to the errors in those models and proportions. Incorporation of such errors into estate-wide estimates has been considered [23], but was not done here since it was considered those errors would be negligibly small when compared with the sampling error of plots across strata.

For each estate, several different estate-wide estimates of carbon sequestered in tree biomass were determined. Each of those estimates was based on the application of a different allometric model to estimate individual tree above-ground biomass. The different models applied were:

- A species/estate-specific allometric model, which was applied in four of the estates (6,12,14,19) on which tree biomass data had been collected. In these four cases, the estate-wide carbon estimate was made only for that part of the estate which consisted of the species for which the biomass data had been collected. The allometric model for above-ground biomass and mean root/shoot ratio used in these cases were the species-specific cases given in Table 2. Because these models were determined specifically for the species and estate concerned, it was considered that their application to those species and estates should yield estate-wide estimates of amounts of carbon sequestered with the minimum bias and maximum precision (that is lowest confidence limit) possible.

- A region-specific allometric model for above-ground biomass and mean root/shoot ratio was applied to all species across all estates. This was the pooled model and mean given in Table 2, which were based on all the biomass data collected for the five selected species in the region. In doing this, these models were being applied to all species found in all the estates, even though they were determined using data from five species only.
- The Nova Scotia, Canada, allometric model for above-ground biomass, alluded to earlier, was applied in each estate. It was considered appropriate to use for comparison in the present work because it was derived using a much more comprehensive and substantial data set than is used in most work which has established allometric models appropriate for particular species and regions. The Nova Scotia model was determined from a data collection of above-ground biomass of 765 individual coniferous and hardwood trees and woody understorey shrubs native to the region [31]. Its form was identical to (1) and it used the pooled data collected for all species. Its parameter values were $a = 0.060$ and $b = 2.59$. Its fit to the biomass data measured in the present work is shown as the dashed line in Fig. 1. It is obvious from the figure that some bias will be introduced in predictions of tree biomass when the Nova Scotia model is applied to New South Wales trees, particularly for smaller diameter trees. The importance or otherwise of that bias will be considered in detail later. Unfortunately no estimate was made in the Nova Scotia work of the bias correction factor for back-transformation of values from logarithms, although the closeness of the fit to the data reported there ($r^2 = 0.997$) suggests that the bias would be small. For the present work, estimates were made using the Nova Scotia model without any bias correction. When it was applied here, the Nova Scotia model was coupled with the region-specific mean root/shoot ratio, shown as the pooled mean in Table 2, to estimate total biomass.
- Allometric models developed elsewhere in Australia [27] to predict above-ground biomass. These models were stand-based, rather than individual tree based. They have exactly the same functional form as (1), but predict above-ground oven-dry biomass (kg ha^{-1}) for an entire stand from stand basal area (total cross-sectional area at breast height of trees in the stand, m^2 ha^{-1}). There were two such models, one for eucalypt species (parameter values were $a=3912, b=1.147$) and one for *Pinus radiata* ($a = 1565, b = 1.254$). In applying these models, plot total above-ground biomass was determined directly, after first determining plot basal area, rather than summing estimates for individual trees. These above-ground biomass estimates were then coupled with the region-specific mean root/shoot ratio, shown as the pooled mean in Table 2.

4.2. Estate-wide estimates

Applying the methods described in Section 4.1, Table 3 gives the estate-wide estimates, and there 95% confidence limits expressed as a percentage of the estimates, of carbon sequestered in tree biomass for the 19 estates.

The estate-wide estimates of the total amount of carbon sequestered in the tree biomass differ greatly, over a range of about 1–2000 tonnes, reflecting particularly the wide range of estate sizes and tree ages on the estates. The 95% confidence limits of the estimates also differ widely, varying from as little as 9% of the estimate to nearly 600%.

It is interesting also to consider the results if the data for all 19 estates are combined across their total area of 325 ha and the data from the 146 measured sample plots considered as a stratified random sample across that total area, with the estates themselves being considered as an additional stratification factor. If this is done, the sampling intensity across the entire 325 ha was 0.6% of the entire area. When the

Table 3
Estate-wide estimates of carbon sequestered by the tree biomass on each estate (tonne) as determined using different allometric models (1 = Species/estate-specific, 2 = Region-specific, 3 = Nova Scotia, 4 = Australian stand-based)

Estate	Weighted age (yr)	Sampling intensity (%)	Allometric model			
			1	2	3	4
1	3.9	2.2		165 (13)	154 (15)	237 (14)
2	5.3	1.6		87 (24)	75 (24)	129 (27)
3	3.3	2.0		27 (86)	21 (96)	37 (93)
4	3.0	0.6		46 (64)	29 (68)	52 (70)
5	2.9	1.6		65 (28)	50 (30)	90 (31)
6	5.0	0.4		671 (26)	619 (28)	903 (29)
E. microcorys only	5.0	0.4	195 (43)	177 (42)	149 (45)	230 (48)
7	5.6	3.8		72 (29)	65 (37)	98 (32)
8	2.0	1.6		4 (79)	2 (75)	4 (92)
9	1.5	0.9		29 (34)	19 (31)	35 (33)
10	2.0	1.1		71 (61)	56 (67)	91 (68)
11	3.0	0.7		202 (64)	182 (73)	302 (71)
12	2.7	7.8		16 (20)	13 (22)	20 (22)
E. saligna only	2.1	6.1	7 (41)	7 (40)	5 (43)	8 (45)
13	4.5	4.2		2 (493)	1 (591)	2 (538)
14	2.8	4.7		16 (27)	17 (30)	23 (31)
E. nitens only	2.5	3.3	14 (33)	14 (32)	14 (36)	20 (36)
15	1.3	2.6		2 (53)	1 (64)	2 (60)
16	2.5	4.4		10 (9)	7 (11)	13 (10)
17	9.5	4.5		20 (9)	18 (11)	17 (10)
18	5.5	0.05		2023 (9)	1700 (13)	2652 (10)
19	5.8	0.5		472 (20)	483 (17)	393 (20)
P. radiata only	5.8	0.5	442 (17)	472 (20)	483 (17)	393 (20)

The 95% confidence limit, as a percentage of the estimate, is shown in parentheses after each estimate. The 'weighted age' (see later in text) of the plantations on each estate and the sampling intensity on each estate are shown also.

region-specific allometric model was then applied to estimate carbon sequestration by tree biomass in each sample plot, an estimate was obtained of 3991 tonnes of carbon sequestered over the entire 325 ha, with a 95% confidence limit of 6.4% of the estimate. Whilst that confidence limit might be reduced by increasing the sampling intensity, the result suggests that generally across larger estate areas, the variation in plantation growth within strata is such that 95% confidence limits might be obtained which are perhaps within the range 5–10% of the estimate.

For the four estates in which it was possible to apply the species/estate-specific allometric models to predict tree biomass, there is little evidence that any appreciable advantage was gained by using those models rather than using the region-specific allometric model. The estimates of sequestered carbon differ between the species/estate- and region-specific models in some of the estates. However, the 95% confidence intervals (a confidence interval is the range between the estimate *less* the confidence limit and the estimate *plus* the confidence limit) for the species/estate-specific estimates overlap the corresponding intervals for the region-specific model. For example, the species/estate-specific estimate for *Pinus radiata* in Estate 19 was 442 tonne carbon, with a 95% confidence interval of 425–459 tonne (442 ± 17). The corresponding region-specific estimate was 472 tonne carbon, with a 95% confidence interval of 452–492 tonne (472 ± 20). Those two confidence intervals (425–459 and 452–492) overlap, suggesting there is no real (statistically significant in mathematical statistics terms) difference between the two estimates. This suggests that the amount of bias introduced by using the region-specific model, rather than the species/estate-specific models, is insufficient to be of practical importance. However, the information in Table 3 suggests also that if the sampling intensity in those estates was increased to the extent that the 95% confidence limits for the species/estate-specific models were reduced to perhaps as little as 10% of the estimate, then the bias introduced by using the region-specific model might be sufficient that the respective 95% confidence intervals no longer overlapped. That is to say, the bias introduced by using the region-specific model would then be sufficient to be of practical importance.

When comparing results derived from the region-specific and the Nova Scotia allometric models, it appeared that the bias introduced by applying the Nova Scotia model (see Fig. 1) was generally insufficient to produce an estimate of sequestered carbon lying outside the 95% confidence interval for the region-specific models. Cases where it did (9,15–18) were all estates in which the estimate of total carbon sequestered was relatively small or the 95% confidence limit of the region-specific estimate was relatively small (say less than about 10% of the estimate). This suggests that the bias arising from use of the Nova Scotia model might generally be too large only if the estate is very small or the sampling intensity used is sufficiently high to produce confidence limits less than about 10% of the estimate.

Use of the stand-based, Australian allometric models produced estimates outside the 95% confidence interval of the region-specific estimates in 10 of the 19 estates. This suggests that the bias arising from use of the stand-based models might be too large whenever sampling intensities are sufficient to produce confidence limits less than about 30% of the estimate.

4.3. Sampling intensity

The results in Section 4.2 showed a very wide range in the magnitude of the 95% confidence limits of the estate-wide carbon estimates. Consideration was given to what estate factors might lead to those differences. For each of the 19 estates, the coefficient of variation of the estate estimate was determined for the results obtained with the region-specific allometric model. The coefficient of variation is the standard deviation (another measure of variation in a data set used in mathematical statistics, closely related to standard error and variance) of the estate estimate divided by the estimate. It is a variable used commonly in mathematical statistics to compare variation in different populations, when they differ widely in the magnitude of the value estimated for the population from a sample. It is related closely to the percentage confidence limits determined here, which are simply the coefficients of variation multiplied by the appropriate value of Student's 't' (a variable defined in mathematical statistics specifically for the calculation of confidence limits) for the sample size used in each estate.

In examining these results, the data for estate 13 were excluded. That was a very small estate (only 0.2 ha in extent) and only two plots were sampled in it. These happened to differ widely in the amounts of carbon sequestered in the tree biomass, leading to the extraordinarily high 95% confidence interval of 493% of the estate carbon estimate (Table 3). It was felt that sampling in that estate had been so inadequate that its results were inappropriate to consider in the present context. Given that, the coefficients of variation in the remaining 18 estates were inspected in relation to the following estate factors, estate age, the estimate of sequestered carbon for the whole estate, the estate-sequestered carbon per unit area of the estate, the estate area, the sampling intensity used in the estate, the area of the sample plots established in the estate, the total area sampled across the estate and the plantation type on the estate (species monoculture, mixed eucalypt or plantations with rainforest species). Because some estates included plantation areas of different ages, an average weighted age was determined for those estates, the weighting being based on the areas of plantations of different ages on the estate. The weighted average ages of the estates are given in Table 3. Also shown in Table 3 are the sampling intensities that were used in each estate.

There was no evidence in these data of any relationship existing between estate coefficient of variation in sequestered carbon and any of the estate factors, with the exception of weighted average age of the estate. That relationship is shown in Fig. 3. It was found it could be expressed as

$$c = 100 \sin^2(pA^q), \tag{2}$$

where c was the coefficient of variation (%), A was weighted average age (yr) and p and q were parameters. Model (2) was fitted by ordinary least-squares linear regression after transformation

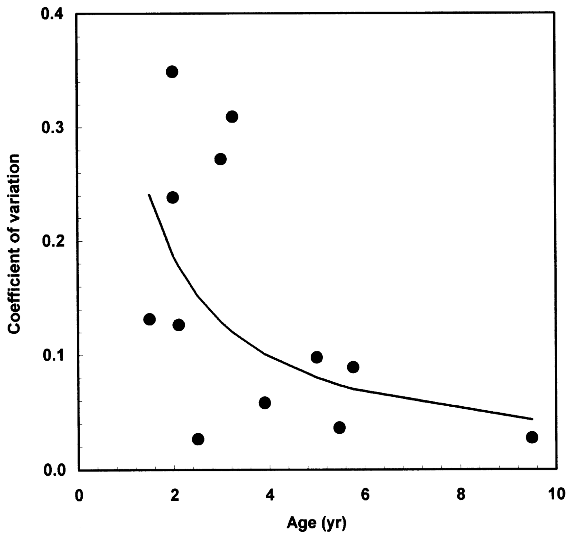

Fig. 3. Scatter-plot of estate coefficients of variation in estimates of amount of carbon sequestered across estates, derived using the region-specific allometric model, against estate weighted average age. The fit to the data of model (2) is shown (—).

of c as $\sin^{-1}\sqrt{(c/100)}$, a transformation considered in mathematical statistics to be generally appropriate for proportions to ensure normality of their distribution, and logarithmic conversion of both sides of the model. The fit to the data yielded estimates for the parameters of $p = 0.0577$ and $q = -0.425$, was statistically significant ($p < 0.05$ at least) and explained 28% of the variation in the dependent variable. The fitted model is shown in Fig. 3.

The information in Fig. 3 shows there was a tendency for coefficient of variation, hence the confidence limit of the estimate of sequestered carbon, to decline as plantation age increased. This tendency for younger plantations to exhibit more variation probably results from small-scale variations (perhaps over distances as short as a few metres) in site characteristics (such as soil water availability or fertility) across the estate. As plantations age, the trees become larger and access site resources over larger areas so the initial size variations due to these small-scale site variations are evened out. The implication for the present work is that sampling intensity would need to be greater in younger plantations to achieve a similar precision of estimate, of the estate-sequestered carbon, as is possible in older plantations.

Table 4
Assumptions used in the simulation study to determine the effects of sampling intensity on the precision of estimate of the amount of carbon sequestered in Estate 4

Stratum	Area (ha)	Plot mean sequestered carbon amount (kg)	Standard deviation of mean carbon amount (kg)
1	8.77	29.2	24.8
2	1.74	42.2	25.7
3	3.77	34.6	5.3
4	2.65	56.5	27.7

The effect of sampling intensity on the precision of the estimate was explored further using the information obtained from estate 4 as an example. This estate was 16.9 ha in area, composed of 3-year old blocks of various eucalypt species, sometimes in mixtures, and with a few individuals of a rainforest species in some blocks. Based on the species present, four strata were recognised across that estate and two sample plots were measured in each stratum. When the region-specific allometric model was used to predict above-ground biomass in the sample plots, Table 3 shows it was estimated there was 46 tonnes of carbon sequestered in the trees on the estate with a large (64%) 95% confidence limit about the estimate. This is consistent with the larger confidence limits found generally in younger plantations, as discussed in previous paragraphs.

A simulation study was carried out for estate 4 to estimate the effect on the confidence limit of its estimate of estate-sequestered carbon as sampling intensity changed across the estate. Table 4 shows the assumptions on which the simulation study was based. The values there were derived from the data measured in the estate. In carrying out the simulation for a particular sampling intensity across the estate, it was assumed that the number of plots (each of an area of 133 m^2) selected in each stratum was proportional to the stratum area and that the plot-sequestered carbon amounts were distributed normally within any stratum, with means and standard deviations as specified in Table 4. Simulations were carried out for a variety of sampling intensities varying over the range 1–7.5%. Fig. 4 shows how the confidence limit of the estimate

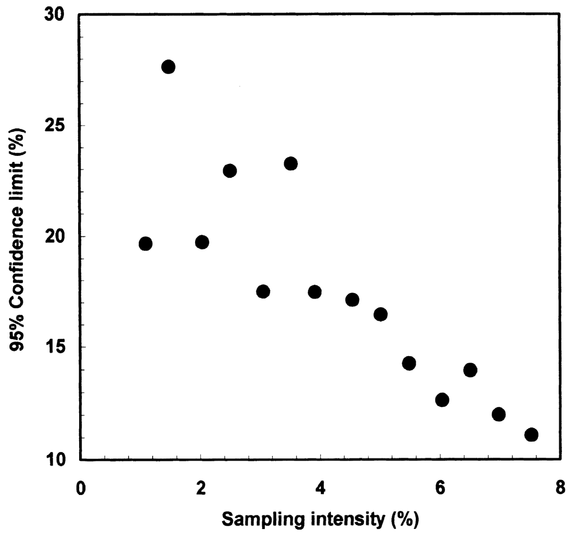

Fig. 4. Scatter-plot of 95% confidence limit of the estate-sequestered carbon estimate (as a proportion of the estimate) against sampling intensity, as determined in the simulation study carried out for estate 4.

Table 5
Soil organic carbon content to 50 cm depth from paired soil samples taken from plantation estates and adjacent implanted paddocks; the age of the plantations is also shown

Property	Plantation age (yr)	Soil organic carbon to 50 cm depth (tonne ha^{-1})	
		Paddock	Plantation
1	5	174	176
2	5	196	157
3	3	330	271
4 Sample 1	3	109	90
4 Sample 2	3	93	99
5	3.5	163	173
6	5	160	134
7	7	248	340
8	2	84	123
9	2	82	87
10	2	118	176
11 Sample 1	3	129	205
11 Sample 2	3	136	132
12	4	94	54
13	5	198	125
14	7	211	209
16	3	181	222

of estate-sequestered carbon varied with sampling intensity in these simulations.

The results of Fig. 4 suggest that the 95% confidence limit of the estate-sequestered carbon estimate would tend to decline as sampling intensity increased, a trend that would be expected normally. However, for the young Estate 4, it appears that even with a sampling intensity of 7.5% (which would involve establishing 95 sample plots across the estate if 133 m^2 plots were being measured), the 95% confidence limit would still be slightly in excess of 10% of the estate estimate. It is unlikely that, for any practical purpose, the estate owner would be able to afford the expense of establishing and measuring that many sample plots. Of course, fewer larger plots could be established. However, whatever plot size was used, this sampling intensity would involve measurement of tree diameters on a total of nearly 1.3 ha of plantation area.

5. Soil organic carbon

Table 5 lists the results obtained from sampling soil at paired sites from plantations and adjacent paddocks on 15 estates. Results are shown for the total soil organic carbon to 50 cm depth. The shallowest soils were 50 cm in depth and the deepest were over 1 m, although soil sampling never went below 1 m. The organic carbon in the top 50 cm constituted 74–100% of the total carbon in the profiles to bedrock or 1 m depth. Results are reported here for the top 50 cm only, to avoid confusion by reporting results to variable soil depths.

Fig. 5 shows a scatter plot, for the paired sites, between plantation age and the proportional difference in soil organic carbon content to 50 cm depth between paddock and plantation. Although there appears to be a negative trend in the data, the ordinary least-squares straight line fit to the data showed it was not significant ($p > 0.05, r^2 = 0.20$). However, the trend suggested that plantations of 2 years of age had an average of about 17% more soil organic carbon than the adjacent paddock. This declined progressively with plantation age, until there was no difference at about 4 years of age and an average of about 23% less soil organic carbon in the plantation by 7 years of age. The implication of these results is that the pre-planting cultivation tended to incorporate surface organic material into the

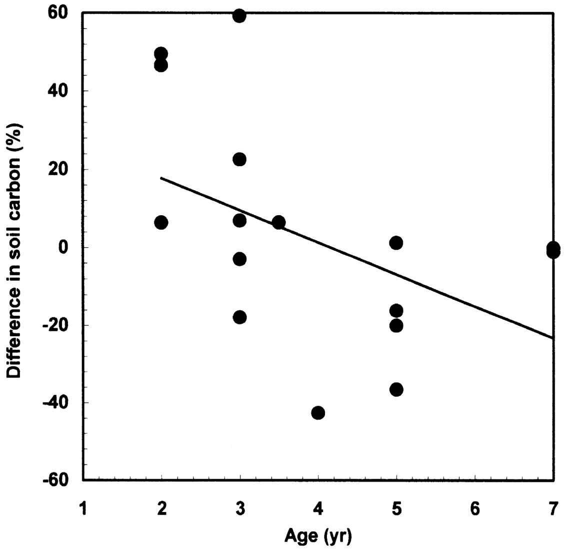

Fig. 5. Scatter plot of the proportional difference in soil organic carbon content, to 50 cm depth, between paddock and plantation at the 17 paired sites measured on 15 estates, plotted against plantation age. The solid line shows the ordinary least-squares straight-line fit to the data.

soil, initially increasing soil organic carbon content. With time, there was then a progressive decline in soil organic carbon in the plantation until the soil beneath it contained less organic carbon than the adjacent paddock. However, it must be recognised that the results found here were not significant statistically. As well, there is likely to be further uncertainty in the results because soil sampling was restricted to only one soil profile in each sample pair and did not take account of the high degree of variation that soils often exhibit even over distances of a few metres.

The amounts of soil organic carbon reported in Table 5 (to 50 cm depth) are probably within the range 13–165 tonne ha^{-1} reported in pasture paddocks to 30 cm depth in soils measured widely across forest plantation sites in Australia [20]. In that work, soils under plantations which showed a loss of 20% or more of their soil organic carbon by 7 years of age tended to still have 10–20% less soil organic carbon at the end of a 40 year plantation rotation than at its start. Given these conclusions from [20], the implication of the present results is that soils under plantations in the region considered here may show a net loss of soil organic matter during a plantation rotation. Based also on the biomass yields of plantations reported in [20], a net loss of about 20% of soil organic carbon would reduce the net amount of carbon in the whole plantation ecosystem at the end of the plantation rotation by about 15–20%. That is to say, plantation owners would need to reduce the amount of carbon they could offer for sale as carbon credits, to allow for the losses of soil organic carbon from the plantation ecosystem.

If the 17 estimates of amount of soil organic carbon to 50 cm depth in plantations in Table 5 are considered to be a random sample of the soils of the region, the data can be used to suggest the level of soil sampling which might be necessary to achieve a desired confidence limit about estimates of soil organic carbon. Those 17 values have a mean of 163 tonne carbon ha^{-1}, with a 95% confidence limit of 23% of the mean. If a 95% confidence limit of 10% of the mean was desired, the data suggest that a sample size of about 77 would be required to achieve this. For a 95% confidence limit of 5% of the mean, a sample size of about 300 would be required.

6. Discussion and conclusions

The methods described in the present work appear to be appropriate generally for plantation owners who wish to make defensible estimates of the amount of carbon sequestered by their plantation estates. To make those estimates, an estate needs to be stratified into areas of appreciably different productivity, principally on the basis of plantation age, the species planted, and gross site affects which might substantially influence productivity (such as aspect or soil type). Of course, the more detailed the stratification, the more precise is likely to be the estimate of the amount of carbon sequestered by the estate, but the more tedious and expensive will be the mapping of the strata and determination of their areas; some balance would have to be drawn by the owner between these two issues in stratifying an estate. Sample plots would then be established at random over the estate, with at least two plots in each stratum (or statistical computation of the precision of the final estimate would be impossible) and the diameter at breast height over bark of all the trees in the plots measured. The size of the plots would not be of particular importance (plots used in the present work generally varied in area over the range 100–150 m^2), rather it would be the combination of plot size and total number of plots sampled which should be considered. This would determine the total area of the estate sampled, hence the sampling intensity (area sampled divided by total estate area). The greater the sampling intensity, the higher would be the likely precision of the final estimate. However, given some desired sampling intensity, the estate owner would need to balance plot size and number to ensure that the sample adequately represented the estate circumstances.

Once these data have been collected, allometric relationships which predict tree oven-dry biomass from diameter would be used to predict total tree biomass on each plot and these estimates combined with well-established factors to convert biomass amounts to amounts of carbon. Computation of the estimate of the total amount of carbon sequestered over the estate and its confidence limit would then require application of standard statistical techniques (described in texts such as 25).

The present work considered the issue of what allometric models might be appropriate to apply in a particular estate. Whilst research has suggested there is considerable commonality of models across different species in different parts of the world, differences do exist so that there may be some bias introduced into the estate-sequestered carbon estimates if an allometric model developed for one species in one part of the world is applied to another species elsewhere in the world. The important issue then is whether or not the degree of bias is sufficiently large that it renders an estimate inappropriate. The more precisely, hence the narrower the confidence interval, the owner wants the estimate, the more heed will have to be given to the degree of bias inherent in the allometric model being used.

The present work dealt with young (1–10 year old) plantation estates in temperate and sub-tropical regions of northern New South Wales. The effects were considered of applying an allometric model derived from a completely different forest type in a completely different part of the world (a model derived for hardwood and softwood species native to Nova Scotia, Canada). The results suggested that the bias involved in doing this was insufficient to render inappropriate the estate estimate of the amount of carbon sequestered, unless a 95% confidence limit of less than about 10% of the estimate was adequate. Interestingly, the bias inherent in two allometric models developed elsewhere in Australia for eucalypts and *Pinus radiata*, models which predicted tree biomass of whole stands (from stand basal area) rather than individual trees, appeared to introduce appreciably more bias in estimates of sequestered carbon when applied in northern New South Wales than the model from Nova Scotia. The results suggested that the Australian models would be inappropriate to use in northern New South Wales, unless a 95% confidence limit of more than about 30% of the estimate of sequestered carbon was considered appropriate.

The present results showed also that the precision of estimates of estate carbon tended to decline as plantation age declined. It was suggested that this reflects the increased variation of tree growth across an estate that occurs in its early stages than at later ages. This means that an owner will generally have to use more measurement resources in a younger estate to achieve the same precision of estimate that could be obtained in older estates. However, in the present work, using estate sampling intensities which averaged around 2–4%, it was found possible generally to estimate the total carbon sequestered by the estate with a 95% confidence limit of about 30–40% of the estimate or better, with a minimum of about 10%.

Owners of small plantation estates may choose not to market the carbon sequestered on their estates individually. Rather, they may develop some cooperative arrangement to market the total amount of carbon sequestered across all their estates to achieve economies of scale in their operations; their interest then would be in the confidence limit about the estimate of that total. For the total 325 ha in the estates considered here and with a sampling intensity of 0.6% of their total area, their total estimated carbon sequestered was 3991 tonne with a 95% confidence limit of 6.4%. This limit was lower than that for any individual estate (Table 3), as might be expected when all the samples taken are pooled across the total area. There are in fact more plantation estates in the region than those considered in the present study; if all the estates in the region were to pool their estates and market their carbon cooperatively, they may be able to estimate their total sequestered carbon with an even lower confidence limit. Similar work in farm estates in north Queensland [32], with a similar sampling intensity, estimated there was 8950 tonne carbon sequestered in above-ground tree biomass (equivalent to about 11,270 tonne carbon in the total biomass, using a 25.9% root/shoot as given in Table 2) over 1620 ha of plantations, with a 95% confidence limit of 16% of the estimate. This was a higher confidence limit than determined in the present work, even though it related to a much greater plantation area. However, the plantations in that case were generally younger (2–5 years) than those measured here (1–10 years), which the present results suggest will lower precision of the estimate. As well, no stratification of the plantations was carried out before sampling which would have been expected also to improve precision.

Present recommendations in Australia [11] are that forest owners who are considering entering the market for sequestered carbon should attempt to estimate the carbon sequestered by trees on their estate with a 95% confidence limit of no more than 10% of the estimate. The present work suggests that this will be very difficult to achieve in young, small plantation estates. Furthermore, it appeared that use of any other than a species/estate-specific allometric model may introduce unacceptably large bias in estimates with this degree of precision. The present results suggested that plantation establishment in the region may be accompanied by some net loss of soil organic carbon over the plantation rotation. Plantation growers would have to take account of this decline when assessing the net amount of carbon they may have available for sale as carbon credits from their plantation. If owners are unable to afford the cost of measuring soil organic carbon content, they may at least have to assume some maximum loss, based on studies like the present, by which they reduce the amount of carbon they have available to sell.

In a market for carbon credits, it is important to note also that forest owners will have to monitor their plantations at regular intervals, perhaps of about 5 years, to keep track of the changes with time in the amount of carbon sequestered both in trees and soil. If the amount of carbon declines with time, owners will have to buy back carbon credits to make up the shortfall. If it increases, they will be able to offer for sale the extra. In effect, all carbon credit sales will be based on changes over time of the amount of carbon sequestered in plantations. The present work was concerned only with estimation of sequestered carbon in a plantation estate on a single occasion. Estimates of change with time will be based on repeated measurements of the estate. The size of the confidence limit about estimates of change may be lower than that about a single estimate at one time, but this will depend on how the sampling is done in the re-measurement. Advanced texts on forest measurement provide information on estimation of change and its confidence limit [30, pp. 175–183]. Provided the degree of bias is consistent between estimates at different times, it should play little part in the estimate of change, which would then be based on the difference between two estimates with similar bias.

A rough estimate can be made here of the likely costs involved in undertaking a sampling program, by professional measurement teams, to estimate the carbon sequestered at any one time in plantations of the nature of those considered here. In this project, the cost of measuring the tree diameters on a sample plot averaged about $US350 and of determining the amount of soil organic carbon at one point averaged about $US400, including staff travel and accommodation. Suppose it was desired to estimate the carbon sequestered in trees and soil across the total 350 ha of the estates considered here, with a 95% confidence limit of 5–10% of the estimate. The present results suggest this would need measurement of about 150 tree plots and about 80 soil sites, making a total cost of about $US85,000 that is about $US240 ha^{-1}.

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Appendix.

Table 6 presents a list of species and estate numbering.

Table 6

Eucalyptus and Corymbia	
1	*Eucalyptus acmenoides*
2	*E. amplifolia*
3	*E. cloeziana*
4	*E. dunnii*
5	*E. grandis*
6	*Corymbia henryii*
7	*C. intermedia*
8	*C. variegata/citriodora*
9	*E. microcorys*
10	*E. moluccana*
11	*E. nitens*
12	*E. paniculata*
13	*E. pilularis*
14	*E. punctata*
15	*E. regnans*
16	*E. resinifera*
17	*E. robusta*
18	*E. saligna*
19	*E. siderophloia*
20	*E. teretecornis*
21	*E. viminalis*
Sub-tropical rainforest species	
22	*Acacia melanoxylon*
23	*Acmena ingens*
24	*A. smithii*
25	*Agathis robusta*
26	*Argyrodendron trifoliolatum*
27	*Ailanthus triphysa*
28	*Alphitonia excelsa*
29	*A. petriei*
30	*Araucaria bidwillii*
31	*A. cunninghamii*
32	*Argyrodendron actinophyllum*
33	*A. trifoliolatum*
34	*Castanospermum australe*
35	*Casuarina cunninghamii*
36	*Cedrela odorata*
37	*Cinnamomum oliveri*
38	*Darlingia darlingiana*
39	*Diploglottis australis*
40	*Dysoxylum fraserianum*
41	*D. muelleri*
42	*Elaeocarpus grandis*
43	*Melicope elleryana* (syn *Euodia*)
44	*Flindersia australis*
45	*F. bennettiana*
46	*F. brayleyana*
47	*F. schottiana*
48	*F. xanthoxyla*
49	*Geissois benthamii*
50	*Glochidion ferdinandi*
51	*Gmelina leichardtii*
52	*Grevillea robusta*
53	*Harpullia pendula*
54	*H. hillii*
55	*Lomatia fraxinifolia*
56	*Lophostemon confertus*
57	*Melia azedarach*
58	*Parachidendron pruinosum*
59	*Planchonella australis*
60	*Podocarpus elatus*
61	*Polyscias elegans*
62	*P. murrayi*
63	*Rodosphaera rodanthema*
64	*Stenocarpus sinuatus*
65	*Toona ciliata*
Exotic conifers	
66	*Pinus radiata*
67	Species not identified

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