Carbon accumulation by native trees and soils in an urban park, Auckland

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Abstract: Carbon storage by trees and soil in urban areas is of increasing interest as a potential greenhouse gas mitigation measure. Our objectives were to (1) quantify carbon accumulation in above- and below-ground tree biomass, organic layer and mineral soil (0–5 cm) of a 27-year-old planted forest in Auckland and (2) compare the sequestration potential of urban trees with natural shrublands and forests in New Zealand. A mixed-species allometric equation for urban-grown native trees was developed on the basis of the tree biomass of 21 trees belonging to four species (*Corynocarpus laevigatus*, *Kunzea ericoides*, *Pittosporum eugenioides, P. tenuifolium*). Our allometric equation and a recently developed mixed-species equation for New Zealand native forest species produced similar results. A total of 45.9 Mg C ha^{-1} was stored in above- and below-ground tree biomass in our Auckland park, equating to an average annual carbon sequestration rate of 1.7 Mg C ha^{-1}. This rate is within the range reported for New Zealand shrublands. Despite the adverse conditions posed by some urban environments (e.g. poor-quality soil, contamination), planted urban forests can sequester carbon at similar rates to natural vegetation in New Zealand.

Keywords: allometric equations; carbon sequestration; planted forest; root biomass; tissue and wood chemistry

Introduction

Increased urbanisation is destroying natural ecosystems and degrading the environment of urban areas. To mitigate some of these problems local governments across the globe conduct large tree-planting projects (i.e. urban afforestation) to provide habitats and ecosystem services such as carbon (C) sequestration, microclimate regulation, noise and air pollution reduction, and stormwater attenuation (Auckland Council 2012; Gaffin et al. 2012; Oldfield et al. 2013).

Besides planted forests there are many small patches of remnant forest scattered throughout urban areas in New Zealand. For example, approximately 25% of Auckland's urban area consists of green spaces, dominated by urban parkland and reserves (Auckland Council unpublished 2012 report 'Urban Auckland green space GIS analysis'). All these areas of woody and herbaceous vegetation take up CO_2 for photosynthesis. Urban green space cover varies widely among cities but tends to be slightly higher in 'sprawling' Australasian and American cities compared with 'compact' European cities (Fuller & Gaston 2009).

A higher proportion of vegetated surfaces, together with favourable climatic conditions, may result in a higher potential for C uptake in New Zealand cities. Greater growth of tree seedlings in urban environments was reported by Searle et al. (2012) suggesting urban trees can grow faster than trees in rural settings. However, soils in urban areas are often compacted, have low organic matter content, and may be contaminated (US EPA 2011). Studies have shown that adverse soil conditions and the exposure to pollutants and higher temperatures may have a detrimental effect on tree growth and thus C uptake in urban forests (e.g. Pouyat et al. 1995).

In this study we had the opportunity to investigate the accumulation of carbon by trees and soils in a small, 27-year-old, planted, urban forest in Auckland. Our first objective was to quantify the amount of carbon accumulated in above- and below-ground tree biomass, organic layer and mineral soil (0–5 cm) in this planted forest. To do this we developed an allometric equation for urban-grown native New Zealand trees and compared this equation with allometric equations commonly used to estimate tree carbon stocks in natural forests in New Zealand. We also investigated the carbon allocation pattern among species and our second objective was to compare our results with the carbon storage/sequestration values of native and exotic tree species growing in rural New Zealand shrublands and forests. Our study contributes to the understanding of carbon storage in New Zealand vegetation.

Materials and methods

Study site and vegetation survey

The study site was in a small urban park (Newmarket Park, 36°51'54"S; 174°47'2"E) located north-east of the Newmarket suburb, Auckland City, New Zealand. The climate of Auckland is characterised by warm humid summers and mild wet winters with an average annual rainfall between 1000 and 1300 mm (NIWA 2012). The section of park under study was a steep (26°) south-east-facing slope at the edge of the park. This area contained 1.87 ha of native trees that had been planted in 1983 as a 'beautification' project on the site of a landfill that had been closed. The landfill was covered with a 3-m layer of soil and sediments on in situ Waitemata sandstone. The infill material was low in soil carbon (<0.3%) and nitrogen (<0.02%) concentrations. Soils with soil organic matter contents <1% are classified as 'severely impacted' and are considered unsuitable for green infrastructure (i.e. trees and urban forestry; US EPA 2011) without soil amelioration measures such as mulching.

In 2010 the trees were cleared as the slope had to be restabilised, presenting the opportunity to obtain some trees for carbon analysis. We were only informed at short notice. This resulted in a number of constraints imposed by our lack of control over the research design. The vegetation survey described below had been carried out by contractors prior to

clearance of the urban forest and at some time previous to our involvement; by the time we reached the site much of it had already been cleared. We were given a brief opportunity to visit the site and identify trees we would like to analyse. The trees were extracted and stockpiled to the contractors' timetable and we were then given 3 days on which we could work on them. No bulk storage facilities were available to us, so all the basic measurement and sample collection was carried out on site. This is also why it was not feasible to separate the foliage from the branches.

The vegetation survey consisted of four transects parallel to each other, from the top of the slope to the bottom. Transect lengths varied from 35 to 50 m, depending upon the width of the vegetation at that point. All trees within 1 m of either side of the transect line were identified and their diameter at 1.4 m above ground measured. A general indication of tree height was recorded.

Tree selection

As part of the project, the contractors agreed to dig up, in their entirety, 21 trees of four native species to measure the above- and below-ground biomass accumulation. The chosen species – karaka (*Corynocarpus laevigatus*) (n = 6), kānuka (*Kunzea ericoides*) (n = 5), lemonwood (*Pittosporum eugenioides*) (n = 6), and kōhūhū (*P. tenuifolium*) (n = 4) – are all widely planted in the Auckland Region in revegetation and restoration projects (Wilcox 2012). *Kunzea ericoides* can grow into a canopy tree (up to 20 m) whereas the other species are smaller trees (up to 15 m) (Wardle 1991).

Due to access problems we were only able to select trees from certain areas. As far as was possible, individuals typical of the height and growth form for that species were selected. Thus, we ignored obviously suppressed individuals and trees on the edge that often had a different growth form to those in the interior.

Tree measurements and sample preparation

The trees were measured for their height as well as diameter at breast height (1.4 m; DBH) above what had been ground level. The root plate was cut off, and attached soil and stones carefully removed. In the extraction process, it was inevitable that fine and medium roots were lost. However, from our observations, the majority of the major roots were intact; usually it was the distal ends that were missing. The stem was cut up into manageable sections and the crown (including branches and leaves) separated; the crown was defined as the point at which multi-branching of leaf-bearing branches occurred. Disks were cut from the stem of each tree for more detailed laboratory analysis. Each part of the tree was weighed to an accuracy of 0.1 kg.

Each section of each tree was then chipped using a commercial tree chipper. Approximate 5-kg samples of wood chips from the roots, stem and crown of each tree were retained for laboratory analysis. The approach was to start the chipping, allow chips to begin to be produced, and then collect the subsequent 5 kg. This was to avoid any contamination between samples. The wood chip material was subsampled, freeze-dried, and then ground to a fine powder using a ultra centrifugal mill (ZM 200, Retsch GmbH, Haan, Germany).

Organic layer and mineral soil sampling

Organic layer (also called forest floor or O-horizon) and mineral soil samples were collected beneath 12 trees (n = 3 samples per tree species). The organic layer was sampled within 20 × 25 cm quadrats and mineral soil samples were taken with an auger from 0–5 cm depth. Mineral soil samples (only one sample per tree species) were also taken, at 50–55 cm depth, to estimate the amount of carbon stored at the time of tree planting. Soil bulk density was calculated as the quotient of soil dry weight (105°C, 48 h) and soil volume. The stone content of the infill material was less than 5%.

The biomass of the organic layer was estimated by oven-drying the material at 105°C for 48 h after removing a homogeneous subsample for carbon analysis. Mineral soil samples and the forest-floor subsamples were oven-dried at 40°C and ground (ZM 200, Retsch GmbH, Haan, Germany). Mineral soil samples were passed through a 2-mm sieve before grinding.

Wood density and carbon analysis

The discs, sections of roots, and crown samples were weighed, air-dried, and reweighed. The volume of the disc and root sections was determined by water displacement. The samples were then dried at 105°C until constant weight was achieved (typically 4 days) to estimate both fresh density and dry wood density.

Plant and soil material were analysed for carbon concentration by dry combustion using an elemental analyser (True Spec, LECO Corporation, St. Joseph, Michigan, USA). Every 10th sample was analysed twice. The analytical precision was 1.3% for plant and 0.15% for soil material.

Proc GLM (SAS version 9.2, SAS Institute Inc., Cary, NC, USA) was used to identify differences in tree and tissue characteristics among species.

Tree and stand carbon accumulation and sequestration

Tree felling is often not an option to derive tree carbon stocks, particularly in urban areas. However, in this case we were provided with mostly complete trees that had been mechanically extracted from the ground. The amount of carbon stored in each tree component was estimated by multiplying carbon concentrations and the mass (dry weight) of a given component. The total tree carbon is the sum of carbon stored in above- and below-ground tree components. The proportion of below-ground carbon to total tree carbon was calculated as the quotient of root carbon and total carbon stocks.

From these data we were also able to develop an allometric equation that could be applied to the rest of the trees in Newmarket Park. We also had other survey data on planted forests in the Auckland Region, many planted during the same time period. From these data, species-specific growth curves were constructed to estimate individual tree heights for the measured trees.

The amount of carbon stored in the organic layer was calculated as the product of carbon concentration and the dry weight of the organic layer. Mineral soil carbon density (Mg C ha^{-1}) was estimated by multiplying soil carbon concentration with bulk density and soil depth. The amount of carbon stored at 50–55 cm depth (carbon density at the time of tree planting = baseline carbon density) was subtracted from the carbon density at 0–5 cm depth to calculate the accumulation of soil carbon since planting.

Results

Tree and tissue characteristics and carbon allocation on a per-tree basis

Comparisons between species are shown in Table 1. Tree height and dry biomass differed among tree species. Marked differences were also found in the ratios of fresh to dry weight and wood densities. Carbon concentration in stem, root, and crown tissue ranged between 43.3% and 49.6%, with crown tissue (branches + leaves) tending to have the highest carbon concentration independent of tree species. The carbon concentration in all tissue components was highest in *Kunzea ericoides*.

Carbon accumulation on a per-tree basis varied between 15 and 62 kg with *Pittosporum eugenioides* having accumulated four times more carbon over the past 27 years than *Corynocarpus laevigatus*. The amount of carbon accumulated in the root biomass accounted for 16–23% of total tree carbon. This did not relate to any of the other measured variables and is probably species specific.

Organic layer and mineral soil carbon

Carbon concentration and density (Table 1) in the organic layer was significantly higher beneath *Kunzea ericoides* than under the other tree species. Carbon concentration in the mineral soil ranged from 5.3% to 7.3%. Carbon density in the top 5 cm varied between 23 and 32 Mg C ha^{-1} with the highest amount of carbon measured under *Pittosporum tenuifolium*.

Allometric equations based on Newmarket Park data

There are several allometric equations available for estimating biomass and carbon stocks in natural New Zealand forest systems (e.g. Coomes et al. 2002; Beets et al. 2012). However, we initially carried out a standard statistical analysis of the data without any a priori assumptions as to the nature of the relationship between tree dimension and tree carbon content. In particular we were interested in whether we could find an equation that could be applied to all the species for which we had biomass data. The best relationship was found using a polynomial function ($r^2 = 0.8737$, $F = 38.2$, d.f. = 3 and 16, $P < 0.001$) of the following form:

Table 1. Summary of comparisons among species for the tree and soil characteristics at Newmarket Park, Auckland, New Zealand. Values are means ± standard deviation. Significance * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns – no significant difference.

		Corynocarpus laevigatus ($n = 6$)	*Kunzea ericoides* ($n = 5$)	*Pittosporum eugenioides* ($n = 6$)	*Pittosporum tenuifolium* ($n = 4$)	*P*
Tree height	(m)	6.7 ± 0.5	11.3 ± 0.4	10.5 ± 0.6	9.2 ± 0.4	***
Tree diameter	(cm)	12.0 ± 0.8	12.3 ± 2.3	15.0 ± 0.6	13.6 ± 1.3	*
Tree biomass (dry weight)	(kg)	46.2 ± 10.5	89.6 ± 15.3	166.1 ± 25.5	113.6 ± 39.4	**
Proportion of total biomass						
Crown	(%)	30.3 ± 2.9	15.8 ± 1.1	20.1 ± 1.4	22.5 ± 2.6	**
Stemwood	(%)	51.1 ± 2.6	71.7 ± 1.6	60.1 ± 2.8	62.5 ± 1.9	***
Roots	(%)	18.6 ± 3.0	12.5 ± 1.4	19.7 ± 1.7	15.0 ± 2.3	ns
Root-to-shoot ratio		0.23 ± 0.04	0.19 ± 0.05	0.25 ± 0.09	0.29 ± 0.08	**
Wood density						
Stemwood	(g cm^{-3})	0.47 ± 0.01	0.68 ± 0.01	0.63 ± 0.00	0.66 ± 0.01	***
Roots	(g cm^{-3})	0.50 ± 0.01	0.70 ± 0.01	0.65 ± 0.04	0.71 ± 0.07	**
Carbon concentration						
Crown	(%)	44.9 ± 1.4	49.6 ± 1.5	46.6 ± 0.4	47.6 ± 0.6	***
Stemwood	(%)	45.2 ± 0.1	47.0 ± 0.3	45.9 ± 0.2	45.6 ± 0.1	***
Root	(%)	43.4 ± 2.4	46.3 ± 1.2	43.8 ± 1.7	44.7 ± 0.5	ns
Tree carbon content	(kg $tree^{-1}$)	15.1 ± 3.2	33.5 ± 5.8	62.1 ± 9.5	42.9 ± 15.0	**
Proportion of total tree carbon						
Stemwood + crown	(%)	76.7 ± 4.0	84.5 ± 1.7	77.6 ± 1.9	82.2 ± 2.8	**
Roots	(%)	23.4 ± 4.0	15.5 ± 1.7	22.4 ± 1.9	17.8 ± 2.8	***
Organic layer[1]						
Biomass (dry weight)	(Mg ha^{-1})	16.6 ± 3.1	22.5 ± 4.1	15.8 ± 3.5	16.2 ± 4.2	ns
Carbon concentration	(%)	37.4 ± 1.6	40.5 ± 0.7	34.2 ± 5.5	33.5 ± 1.5	**
Carbon density	(Mg C ha^{-1})	6.2 ± 0.8	9.1 ± 1.3	5.4 ± 1.6	5.5 ± 1.1	***
Mineral soil[1]						
0–5 cm						
Carbon concentration	(%)	5.8 ± 0.4	5.7 ± 0.7	5.3 ± 0.5	7.7 ± 0.4	***
Carbon density	(Mg C ha^{-1})	25.5 ± 1.7	25.2 ± 3.2	23.3 ± 2.0	32.3 ± 1.5	***
50–55 cm						
Carbon concentration	(%)	0.5	0.8	0.8	1.9	***
Carbon density	(Mg C ha^{-1})	2.9	5.3	5.3	12.9	***

[1] $n = 3$ per tree species

Tree carbon content (kg tree^{-1}) = −2533.5 volume^3 + 1323.2 volume^2 + 117.59 volume, where volume (m^3) = tree height × tree basal area.

This polynomial function was then used to estimate the carbon storage at the stand level using the transect data.

The second allometric equation developed for Newmarket Park is based on a power function. This equation has three components (stem and branches, crown and roots) and combined these components such that we could estimate either the above-ground carbon or the total tree carbon. The equation took the form:

Tree carbon content (kg C) = $0.0023DBH^{3.3885}$ + $0.0121DBH^{2.5276}$ + $0.009DBH^{2.4966}$.

This corresponds to: stem and branches + crown + root.

Both the polynomial (Proc GLM) and power function (Proc POWER) were developed using SAS version 9.2 (SAS Institute Inc., Cary, NC, USA). The variables were tree volume and tree diameter, respectively.

Comparison with the allometric equations of Beets et al. (2012)

Beets et al. (2012) developed allometric equations (using power functions) for New Zealand forest tree species on the basis of biomass data of approximately 140 trees. The authors also demonstrate that, for improved precision, parameterisation of the species-specific equations varies between species (Beets et al. 2012). Power functions are the most widely used functions for allometric equations (Picard et al. 2012), but in our analysis we found that a polynomial function provided the best estimation of total tree carbon content. It is thus important to compare our results with those that used allometric equations based on power functions.

Presented in Table 2 are results for both above-ground and total carbon based on our (destructive) analysis together with a set of additional analyses. The 'Beets general mixed-species equation' (Beets et al. 2012) is expressed as:

Tree carbon content (kg C) = 0.0162 $(DBH^2 \times Height)^{0.943}$ + 0.0175 $DBH^{2.2}$ + 0.0171 $DBH^{1.75}$.

The 'Beets modified equation' is based on the above equation but using a species-specific '*a*' parameter (a_{sp}). In our study we did not separate foliage from branches thus we retained values for a_{sp} based on those presented in Beets et al. (2012). There is clearly much variability between species for a_{sp}, with no obvious patterns. However, hardwood and softwood species tend to have different wood characteristics. In our study we only had hardwood species thus, for the branches and foliage terms, we used the mean a_{sp} based on the hardwood species listed in Beets et al. (2012). We identified that variation in the a_{sp} value of the 'stem and branch carbon' term has the greatest effect on overall tree carbon estimation; this also corresponded to our 'trunk' measurement. For each of our species, we developed, through successive approximation, a 'stem and branch carbon' a_{sp} value, which was used to estimate the carbon content of each individual of a species.

Tree carbon content (kg C) = a_{sp} $(DBH^2 \times Height)^{0.936}$ + 0.0197 $DBH^{0.936}$ + 0.0148 $DBH^{1.595}$.

The a_{sp} was modified until the sum of the carbon content for individuals of that species was equivalent to the measured above-ground value (see Table 2 for the a_{sp} values).

Stand carbon accumulation and sequestration rates

The vegetation survey included 12 species that had been planted. *Kunzea ericoides* was present in the replanted area but not along the four transects. Tree density varied considerably among species, reflecting differing survival rates or initial densities (Table 3). Over the 27 years of its existence this forest stand accumulated a total 45.9 Mg C ha^{-1} in above- and below-ground tree biomass (Table 3). The tree carbon sequestration rate was 1.7 Mg C ha^{-1} year^{-1}, with considerable differences among species (Table 3). Including the amount of carbon stored in the organic layer (6.5 Mg C ha^{-1}) and mineral soil (0–5 cm; 20.2 Mg C ha^{-1} corrected for mineral soil carbon density at the time of tree planting), a total of 72.7 Mg C ha^{-1} was stored in this 27-year-old urban park (Table 3).

The 'Newmarket power function' and 'Beets general equation' were also applied to the Newmarket Park vegetation survey data to estimate overall carbon accumulation at the site (Table 4).

Discussion

Carbon concentrations of tree tissues and carbon accumulation on a per-tree basis

The higher carbon concentration in crown tissue is explained by the high proportion of foliage. Leaves and needles have

Table 2. Comparison of the measured carbon content with the estimated carbon content derived from allometric equations. a_{sp} = species-specific 'a' parameter.

	Measured	Polynomial	Power	Beets general	Beets modified	a_{sp}
Above-ground carbon (kg C)						
Corynocarpus laevigatus	69.8	86.6	111.8	101.3	69.8	0.0161
Kunzea ericoides	143.0	171.9	120.1	139.2	143.1	0.0223
Pittosporum eugenioides	290.9	271.8	260.4	230.4	290.1	0.0283
Pittosporum tenuifolium	144.6	116.5	108.1	104.2	144.2	0.0318
Total (kg C)	648.3	646.7	600.4	575.0	647.1	
Total-tree carbon (kg C)	802.2	799.0	738.9	766.7[1]	805.6[2]	

[1]This value is calculated from the assumption that roots represent 25% of the carbon content.
[2]This value is calculated from our observation that roots on average comprise 19.8% of tree carbon.

Table 3. Stem density, basal area, carbon accumulation and sequestration of trees, organic layer and mineral soil carbon density (0–5 cm). Stem density and basal area result from the vegetation survey. The tree carbon values were estimated using the 'polynomial function' derived from biomass data of 21 trees felled in Newmarket Park, Auckland, New Zealand.

Species	Stem density[1] (ha^{-1})	Basal area ($m^2\ ha^{-1}$)	Carbon accumulation (Mg C ha^{-1})	Carbon sequestration (kg C $ha^{-1}\ year^{-1}$)
Alectryon excelsa	75	1.4	4.19	155.2
Coprosma repens	50	0.6	0.78	28.9
Coprosma robusta	61	0.2	0.07	2.6
Corynocarpus laevigatus	28	0.3	0.22	8.1
Macropiper excelsa	28	0.02	0.002	0.1
Melicytus ramiflorus	301	2.4	3.90	144.4
Myoporum laetum	28	0.1	0.02	0.7
Myrsine australis	25	0.02	0.003	0.1
Pittosporum eugenioides	570	4.8	10.21	378.1
Pittosporum tenuifolium	464	4.0	7.65	283.3
Schefflera digitata	165	1.4	1.48	54.8
Vitex lucens	418	7.1	17.35	642.6
Tree total	**2212**	**22.3**	**45.9**	**1699.1**
Organic layer			**6.5 ± 1.9**	
Mineral soil				
0–5 cm			26.6 ± 4.0	
50–55 cm^2			6.4 ± 4.0	
Mineral soil total			**20.2 ± 1.9**	
Stand total			**72.7**	

[1]Many trees were multi-stemmed, each stem having been measured. This measure was used rather than reporting tree density.
[2]Carbon density at the time of planting (= baseline carbon density). This value was subtracted from the carbon density at 0–5 cm depth to calculate the total stand carbon accumulation since planting.

Table 4. Site estimation of carbon content at Newmarket Park, Auckland, New Zealand. Values derived from three allometric equations are provided for both individual species and overall estimate of carbon.

Species	Polynomial	Newmarket power (Mg C ha^{-1})	Beets general
Alectryon excelsa	4.19	3.50	2.54
Coprosma repens	0.78	1.11	0.84
Coprosma robusta	0.07	0.17	0.18
Corynocarpus laevigatus	0.22	0.44	0.33
Macropiper excelsum	0.002	0.01	0.01
Melicytus ramiflorus	3.90	4.54	3.66
Myoporum laetum	0.02	0.05	0.06
Myrsine australis	0.003	0.01	0.02
Pittosporum eugenioides	10.21	9.21	8.43
Pittosporum tenuifolium	7.65	7.77	6.69
Schefflera digitata	1.48	2.70	1.77
Vitex lucens	17.35	17.65	12.04
Total carbon	**45.9**	**47.2**	**48.8**[1]

[1]This allometric equation only estimates above-ground carbon, and has been corrected for an assumed 25% root carbon.

been reported to have higher carbon concentrations compared with stem wood and roots (e.g. Bert & Danjon 2006; Mello et al. 2012). Stem-wood carbon concentrations measured in the four New Zealand native tree species (45.2–47.0%) were at the lower end of values reported for angiosperms from across the globe (47.7 ± 0.3%) (Thomas & Martin 2012). In most New Zealand studies a constant conversion factor of 0.5 is used to convert dry biomass into carbon stocks (e.g. Beets et al. 2012; Carswell et al. 2012). Using the general default value of 0.5, the carbon accumulation of individual trees in Newmarket Park would have been overestimated by 3.0–4.8%. This illustrates the need to obtain species-specific data on tree tissue carbon.

The amount of carbon accumulated in individual trees differed considerably among tree species (Table 1). Small tree size and low wood density explain the low amount of carbon stored in *Corynocarpus laevigatus*. Total-tree carbon accumulation is also influenced by species-specific allocation strategies (e.g. Campioli et al. 2010). A higher proportion of stem and root biomass resulted in higher tree carbon stocks in *Kunzea ericoides*, *Pittosporum eugenioides* and *P. tenuifolium*. The allocation into slowly decomposable carbon pools such as stems and roots also implies that the carbon sequestration capacity of these species in the long term is higher than the

carbon sequestration capacity of *Corynocarpus laevigatus*.

Roots as a percentage of total tree biomass and the root-to-shoot ratio in our study were in general lower than the values reported by Phillips and Watson (1994) and Hart et al. (2003). For example, live fine and coarse roots were 22% of total live hard beech (*Nothofagus truncata*, 6–80 cm in diameter) biomass with a root-to-shoot ratio of 0.28 (Hart et al. 2003). The total root biomass in six 14-year-old *Pinus radiata* trees (21–31 cm in diameter) represented 30% of the total tree biomass and had a root-to-shoot ratio of 0.43 (Phillips & Watson 1994). *Kunzea ericoides* (32 years old, 12.7 cm in diameter) growing in the East Coast hills had a root biomass (roots > 2 mm) of 20.1 kg tree^{-1} (Watson et al. 1995) compared with 15.4 kg tree^{-1}at Newmarket Park. Owing to the lack of species-specific root biomass data, a root-to-shoot ratio of 0.25, based on the IPPC guidelines for mature temperate broadleaved forests, is often used to account for below-ground biomass in New Zealand trees (e.g. Beets et al. 2012).

Some of the differences in root biomass can be explained by variations in root extraction methods or data collection methods. Our lower root biomass and root-to-shoot ratio may partly be explained by an underestimation of fine roots due to the root extraction procedure. However, trees grown in urban environments may allocate less biomass and carbon to roots. A recent study showed that urban-grown *Quercus rubra* seedlings had a lower root-to-shoot ratio than seedlings grown in remote areas (Searle et al. 2012). The decrease in biomass allocation to roots has been explained by higher growth temperatures in urban areas (Searle et al. 2012). Chen et al. (2013) associated lower fine root biomass in urban *Pinus massoniana* forests with higher N depositions in urbanised areas.

Comparison with carbon sequestration rates elsewhere in New Zealand

Carbon accumulated in above- and below-ground tree biomass at Newmarket Park (45.9 Mg C ha^{-1}) was within the range reported for New Zealand shrubland studies. For example, Coomes et al. (2002) estimated 48.6 ± 13.5 Mg C ha^{-1} (above- and below-ground biomass) in *Leptospermum scoparium – Coprosma propinqua* dominated shrublands growing north of Christchurch. An above-ground biomass of 34 Mg C ha^{-1} was reported for different types of New Zealand shrubland (Beets et al. 2009 cited in Carswell et al. 2012). Between 12 and 31 Mg C ha^{-1} were estimated in overseas urban forests under similar climatic conditions to Newmarket Park (Davies et al. 2011; Hutyra et al. 2011; Strohbach & Haase 2012).

The sequestration rate of 1.7 Mg C ha^{-1} year^{-1} determined for Newmarket Park was within the range of values reported for New Zealand shrublands. The rate of carbon sequestration for young (age < 50 years) *Kunzea ericoides* and coastal broadleaved stands was 2.3 Mg C ha^{-1} year^{-1} (Carswell et al. 2012). A carbon sequestration rate of 2.1 ± 0.2 Mg C ha^{-1} year^{-1} for approximately 40-year-old *Leptospermum scoparium – Kunzea ericoides* stands across six sites was reported by Trotter et al. (2005). In contrast, the sequestration rate of a *Pinus radiata* plantation forest over a rotation cycle is about 8 Mg C ha^{-1}year^{-1} (Maclaren 2000). Our sequestration rate was lower than the average sequestration rate of 2.8 C ha^{-1}year^{-1} by urban trees in the United States (Nowak et al. 2013).

The slightly lower sequestration rates for the planted forest at Newmarket Park can partly be explained by the comparatively low tree density. Only 2212 stems ha^{-1} were measured in the stand. In contrast, tree density in a naturally regenerating *Kunzea ericoides* stand of similar age was 17 330 stems ha^{-1} (Carswell et al. 2012). Growth rates might also have been reduced as trees were planted on soils and sediments characterised by very low carbon and nitrogen contents. Despite these adverse conditions this planted urban forest sequestered carbon at a similar rate to natural vegetation in New Zealand.

The amount of carbon stored in the organic layer (5–9 Mg C ha^{-1}) at Newmarket Park was slightly higher than values measured across 10 urban forests sites (2–6 Mg C ha^{-1}) in Auckland (Wang 2012). Higher organic (litter) layer carbon stocks (8.9 ± 2.2 Mg C ha^{-1}) were found in the *Leptospermum scoparium – Coprosma propinqua* dominated shrublands investigated by Coomes et al. (2002). For two species, *Corynocarpus laevigatus* and *Kunzea ericoides,* the organic layer- and mineral-soil-associated carbon pools exceeded the amount of carbon stored in tree biomass. Carbon stored in soil can exceed above-ground carbon and the importance of soil carbon storage has recently been highlighted in a study on carbon stock in urban ecosystems (Edmondson et al. 2012). Our results suggest that the amount of soil organic carbon is tree species dependent. The effect of tree species on carbon accumulation in soils is explained by the quality and amount of litterfall and root residues (e.g. Finzi et al. 1998; Schulp et al. 2008). The fact that *Kunzea ericoides,* which had the highest carbon stock in the organic layer, did not have the highest tree biomass stocks implies that there are differences in litter decomposition rates between species.

Comparison of allometric equations

The polynomial function worked well when applied over the whole Newmarket Park dataset, despite the varying timber characteristics. However, for individual trees the accuracy varied considerably. Our polynomial function requires only diameter and height. As these tree characteristics are easy to measure, tree carbon storage across a wider scale could be evaluated. Still, this allometric equation has to be further improved by measuring additional tree species and sites. Using this allometric equation for trees outside the diameter range of trees investigated in this study may not provide reliable carbon values, as polynomial functions are subject to large errors when extrapolated outside the measured range (Picard et al. 2012).

The comparison between our measured tree carbon content and other allometric equations revealed that the more generalised equations did less well at estimating tree carbon content than did the more 'optimised' equations. The 'Beets general mixed-species equation' with an added 25% for root carbon provided a good approximation of the measured total-tree carbon values. This suggests that where both height and diameter measurements are available, this equation would be a good approach for non-destructively estimating total carbon content of a New Zealand mixed forest. Surprisingly this allometric equation did least well at estimating the above-ground carbon, underestimating by some 11%. If height data are not available, then an allometric equation based on power functions and diameter may well prove to be reasonably robust as shown for North American tree species (Jenkins et al. 2004).

The other feature to emerge from these results is that, except where the equations are species-specific, these equations are quite imprecise at estimating the carbon content of individual trees at a site. However, when applied to the overall site estimation, the applicable equations all provided a similar range of values (Table 4). It might be expected that the 'polynomial' and 'power' functions would provide a similar outcome as they are based on local data. Interestingly, the 'Beets general

equation' produced a similar result, suggesting the wide applicability of this equation. If many more species can be parameterised then, clearly, using species-specific allometric equations will be the optimal solution.

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