EVALUATION OF METHODS FOR QUANTIFYING CARBON STORAGE OF URBAN TREES IN NEW ZEALAND

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Abstract

Quantified tree carbon storage can give a better understanding of how urban forests offset carbon emissions to contribute to climate change mitigation. An evaluation of methods available for quantifying urban tree carbon storage in New Zealand (NZ) was completed, with a sample of 57 trees of six native species. Carbon outputs from four NZ derived allometric biomass equations were compared together with the carbon storage outputs from i-Tree Eco. Total tree carbon storage for the sample was estimated to be 1,500kg - equivalent to the carbon emissions from driving 30,000km in a new car. Pohutukawa trees stored the most carbon per tree, 99 - 110kg on average, due to higher wood density and tree maturity. Carbon figures from i-Tree Eco were comparable to NZ methods, thus i-Tree is considered a suitable tree carbon calculation tool for application in NZ. Inclusion of species wood density and accounting for different tree growth structures, as done by i-Tree Eco, improves the accuracy of carbon storage estimations. Suggested strategies and targets for municipal urban forest management, including an i-Tree Eco assessment of Auckland's urban forest, have climate change mitigation potential and support enhanced provision of ecosystem services.

1. Introduction

1.1. Ecosystem Services

Many environmental functions of trees can be classified as ecosystem services because they benefit humans (Millennium Ecosystem Assessment, 2005). Urban trees in streets, gardens and parks - collectively the urban forest (Wilcox, 2012) - provide many ecosystem services to cities. These include removing air-borne pollutants (Nowak, Crane, & Stevens, 2006), reducing the urban heat island effect (Akbari, Pomerantz, & Taha, 2001) and offsetting carbon emissions through carbon storage and sequestration (Nowak & Crane, 2002a). Also, the viewing of urban forest landscapes is known to have relaxing effects, such as lowering blood pressure and heart rates (Tsunetsugu et al., 2013).

More than half of the world's population now live in urban environments (United Nations, 2011). The many ecosystem services of trees improve urban environmental quality by supporting both ecological and population health, which make trees a valuable resource to cities and their citizens (Escobedo et al., 2010; Jim & Chen, 2008; Young, 2010). Consequently, there is a growing interest in quantifying the ecosystem services of urban trees to develop a better understanding of the value of these services, in cities around the world (Roy, Byrne, & Pickering, 2012; Young, 2010).

Urban forest researchers have developed a series of methods, including the creation of multi-functional modelling tools for quantifying the different ecosystem services of urban trees (i-Tree, 2013a; Jim & Chen, 2008; Semenzato, Cattaneo, & Dainese, 2011).

1.1.1. Carbon storage

As part of the carbon cycle, trees transform carbon dioxide to biomass through photosynthesis (Equation 1) (Liu & Li, 2012). This function is beneficial to humans because it counteracts emissions of carbon dioxide (CO_2), a greenhouse gas. Anthropogenic carbon emissions have caused a 40% increase in atmospheric CO_2 concentrations in the last century, a change which is known to be causing global warming (IPCC, 2013).

$$\mathrm{CO_2 + H_2O \rightarrow Biomass + O_2} \quad (1)$$

The biotransformation of carbon dioxide is quantified as tree carbon storage, in kilograms, and over time as carbon sequestration, in kilograms per year (Nowak & Crane, 2002a). New Zealand has opted out of binding carbon targets of the Kyoto Protocol, but is still obligated to report on climate change mitigation measures regularly (Ministry of the Environment, 2010). Thus carbon storage data is of use in NZ for estimating carbon stocks to report under the Kyoto Protocol and for contributing to a better understanding of how trees offset carbon emissions.

1.2. Allometric Equations

Tree carbon storage can be quantified with allometric equations which relate tree dimensions to tree volume or biomass (Henry et al., 2011; Picard, Saint-André, & Henry, 2012). Initially developed for sustainable management of forest resources, allometric equations are now in demand for global carbon cycle studies of forest carbon storage and carbon emission reduction schemes (Henry et al., 2011).

A species allometric equation is developed through the destructive analysis of multiple trees of the same species. Tree dimensions such as height and diameter at breast height (DBH) are measured and the tree is cut up and divided into sections (stem, branches, foliage and roots) for weighing to determine its biomass (Beets et al., 2012; Henry et al., 2011; McHale et al., 2009; Picard, Saint-André, & Henry, 2012). Using linear regression, a relationship between tree dimensions and tree volume, biomass or carbon content can be derived – this is an allometric equation.

The development process is time-consuming, thus sample sizes are usually small and lead to a limited range of DBH values for which an equation is valid (Picard, Saint-André, & Henry, 2012). Composite equations, which combine equations with valid DBH ranges, are commonly used for carbon storage calculations (Nowak & Crane, 2002a). The customary power form of an allometric equation is shown in Equation 2: above-ground tree volume, biomass or carbon content, Y, is related to the DBH measurement or a DBH^2-Height composite, X, (Beets et al., 2012; Picard, Saint-André, & Henry, 2012).

$$Y = aX^b \qquad (2)$$

1.2.1. New Zealand Allometric Equations

Recent research in NZ has developed allometric equations for native forest species, from trees in natural forests and in urban environments. Beets *et al.* (2012) developed allometric relationships for 15 native hardwood species and a mixed-species equation from destructive analysis of trees from natural forests around NZ following thinning operations or windfall. A study by Schwendenmann & Mitchell (2013 under review) measured trees felled in an urban park in Auckland and developed two allometric relationships to quantify the carbon stored by the trees there. i-Tree Eco, an international tool for quantifying urban tree ecosystem services, was also available in NZ. However it's suitability for quantifying carbon storage of urban forests in New Zealand has not been verified.

1.2.2. i-Tree Eco

The US Forest Service, developed the Urban Forest Effects Model (UFORE) in the late 1990s which was adapted and rebranded as i-Tree Eco in 2006 (i-Tree, 2013a). i-Tree Eco is a comprehensive model that uses environmental data to quantify urban forest structure and a range of forest effects, or ecosystem services (i-Tree, 2013a). The model consists of several back-end databases: field tree data, species information, meteorological data, pollution data and pollutant valuation rates (i-Tree, 2013b). Collectively, these databases can quantify air pollution removal, carbon storage and sequestration, rainfall interception and the dollar valuation of these ecosystem services for a sample of urban trees (Nowak et al., 2008a; Nowak & Crane, 2002a; Nowak, Crane, & Stevens, 2006).

As an isolated island in the south-Pacific, New Zealand tree species and climatic conditions are different to US conditions that i-Tree Eco was established to model. Thus an evaluation of the carbon storage outputs of i-Tree Eco with outputs from NZ-developed methods (from Beets *et al.* (2012) and Schwendenmann & Mitchell (2013 under review) would provide valuable information about i-Tree's potential for use in NZ.

2. Objective

The aim of this project was to evaluate and compare methods of quantifying urban tree carbon storage available in New Zealand. Included in this aim was to determine the applicability of the i-Tree Eco model for quantifying carbon storage of urban trees in NZ.

This project hopes to develop an understanding of the capabilities of different methods and which tree characteristics influence carbon storage and its quantification. This evaluation could inform priorities for carbon storage research and support planning of NZ carbon offset schemes in the future.

3. Method

An area in Auckland's Wynyard Quarter was chosen for this study, which included a sample of urban trees for which carbon storage would be estimated (Figure 1). A complete inventory analysis of the area was undertaken, including 95 trees of seven NZ native species. An investigation of the availability and completeness of all data required to apply i-Tree Eco in New Zealand was carried out and discussed by Findlay (2013). Only data requirements directly related to quantifying carbon storage will be considered here: field tree data and species information, including allometric equations.

Figure 1: Case Study Area - Wynyard Quarter (Photo courtesy of Auckland Council.)

3.1. Field Tree Data

Tree measurements and data required by the i-Tree Eco Manual were recorded for the trees in Wynyard Quarter as this included all data required for NZ-developed allometric equations as well (i-Tree, 2013b). Standard tree measurements of DBH and of crown characteristics were taken with reference to the pictorial i-Tree field measurement guide produced by Barcham Tree Specialists UK (Sacre, 2010). The field tree data of species, DBH (cm), height (m), number of stems and tree condition (percent dieback or missing foliage) were recorded to establish a complete inventory of the study area (Figure 1). All trees species studied were evergreen, thus crown characteristics do not change seasonally, thus measurements taken in the New Zealand winter were representative of normal crown characteristics. Raw field measurements were taken using a measuring tape and Abney level, and data were converted to the required parameters using Microsoft Excel (e.g. stem circumference to stem diameter).

A photo of each tree was taken, which was used to verify field measurements entered into the spreadsheet and, later, when entered into the i-Tree Eco desktop program. This desktop program can be downloaded for free from the i-Tree website (www.itreetools.org) (i-Tree, 2013a). Data was spot-checked to identify unusual or missing values. Transcription errors were corrected by looking at photographs and cross-checking measurements with those of similar species and age where required. Consultation with a botanist on-site at Wynyard Quarter was done to verify species identification. Seven tree species were found in the area of Wynyard Quarter studied: nikau, pohutukawa, northern rata (referred to as rata), a pohutukawa-rata hybrid (referred to as hybrid), taraire, puriri and karaka.

3.2. Species Information

To quantify the carbon storage of a tree with i-Tree Eco, individual tree data must be allocated a package of species-specific data from the i-Tree Eco species database. For carbon storage, this database includes species information such as genus, leaf type, growth form and allometric relationships (i-Tree, 2013b; Nowak et al., 2002b). The species database can be updated to include additional species and new figures or equations from the literature for existing species.

Some work has been done at the University of Canterbury to incorporate NZ species information into i-Tree (Morgenroth, 2013). This is understood to have added some information for NZ species including manuka, pohutukawa, northern rata, totara, hebe, kaikawaka, red beech, kauri, puriri, titoki and karaka. i-Tree also has species information on genus-relatives of some common NZ urban trees which can be used when no species match is available. For example, nikau palm can adopt Norfolk Island palm species information as both are of the *Rhopalostylis* genus.

3.3. i-Tree Eco carbon quantification

i-Tree Eco uses forest-derived allometric equations to estimate carbon storage for urban trees (Nowak & Crane, 2002a; Nowak et al., 2002b). i-Tree Eco assessments use species allometric equations where possible or, where a species equation is not available, a genus-relative equation, or an average of hardwood or conifer equations are applied (Nowak et al., 2002b). There were no NZ native species allometric equations in the i-Tree Eco species database so the average hardwood equation was used. Its formula is not shown here because it is a complex equation that incorporates the carbon storage outputs from numerous hardwood allometric equations in the literature to find an average.

For accurate carbon estimates, species-specific allometric equations are favoured over generalised mixed-species equations (Henry et al., 2011). However, considering the process required to develop allometric equations, striving for this level of accuracy is not always practicable.

3.4. NZ allometric equations

Four NZ allometric equations were applied in this study, for comparison with each other and with the methods of i-Tree. Two were derived from Beets *et al.* (2012) and two from Schwendenmann and Mitchell (2013 under review).

3.4.1. Beets et al. 2012

The first equation (Equation 3) summed mixed-species allometric biomass relationships for stem and branch (≥10cm diameter), branch (<10cm diameter) and foliage carbon to estimate total above-ground tree carbon (Beets et al., 2012). These equations were developed from a sample of 60 trees of 15 different hardwood species

(Beets et al., 2012), with an estimated average wood density of 0.53g/cm^3 (Zanne et al., 2009).

$$Y = 1.62\times10^{-2}(DBH^2H)^{0.943} + 1.75\times10^{-2}(DBH)^{2.2} + TCF^*\times1.712\times10^{-2}(DBH)^{1.75} \quad (3)$$

Equation 4 was developed specifically for this study to better represent the carbon storage of the trees in Wynyard Quarter which have a variety of wood densities (Table 1). The higher wood densities of *Metrosideros* species pohutukawa, rata and the hybrid are notable. The stem and branches (≥10cm) contain the bulk of tree biomass. Therefore, accounting for species-specific wood density in this component will improve accuracy of carbon storage calculations, instead of using mixed-species biomass equations. Foliage and smaller branches (<10cm), are lesser components of total tree biomass so accounting for species-specific wood densities there are less important.

Table 1: Wood densities from Global Wood Density Database for tree species in Wynyard Quarter

Species	Wood density* (g/cm^3)
Pohutukawa	0.956
Hybrid	0.803
Rata	0.650
Puriri	0.573
Taraire	0.570
Karaka	0.530
Nikau	0.273

**(collated from Zanne et al., 2009)*

Equation 4 was a sum of Beets *et al.*'s (2012) mixed-species branch (<10cm) and foliage allometric biomass equations, the same used in Equation 3, and a modification of Beet *et al.*'s (2012) volumetric stem and branch (≥10cm) allometric equation. The volumetric allometric equation was multiplied by wood density (ρ_{wood}) and the biomass-to-carbon conversion factor (0.5) to calculate the stem and branch (≥10cm) carbon storage for each species. Volumetric allometric equations for branch (<10cm) and foliage were not developed by Beets *et al.* (2012) hence mixed species biomass equations were used unmodified.

$$Y = (0.5\rho_{wood})4.83\times10^{-5}(DBH^2H)^{0.978} + 1.75\times10^{-2}(DBH)^{2.2} + TCF^*\times1.71\times10^{-2}(DBH)^{1.75} \quad (4)$$

Equation 4 calculates total tree above-ground carbon storage. Wood densities, ρ_{wood}, were found for each species in the Global wood density database (Table 1) (Zanne et al., 2009). Density values were applied to the stem and branch (≥10cm) volume equation, according to the species of tree in question, to calculate total tree biomass. The biomass to carbon conversion factor, 0.5, (Rowell, 1984) is a standard conversion used in estimating carbon storage from tree biomass (Beets et al., 2012; Escobedo et al., 2010; Nowak & Crane, 2002a; Nowak et al., 2002b).

For both Equation 3 and 4 the foliage components, the last terms, were multiplied by a tree condition factor (TCF), shown in Equation 5, to account for any tree dieback and missing canopy (from pruning) identified in field data collection. This adjustment was done in an effort to calculate tree carbon in a comparable manner to i-Tree. Tree condition was a data input for i-Tree and it was supposed that it was incorporated in carbon storage calculations.

$$^*TCF = \frac{(100 - \%\ Missing - \%\ Dieback)}{100} \quad (5)$$

Equation 4 was intended to provide a more accurate means of estimating total above-ground tree carbon storage in comparison with Equation 3. This is because the tree species in Wynyard Quarter had a range of wood densities, most of which exceeded the average wood density of trees in Beets *et al*'s study (2012).

3.4.2. Schwendenmann & Mitchell

Schwendenmann and Mitchell (2013 under review) developed two allometric biomass equations from a study of Newmarket Park. The first is a polynomial allometric equation which relates stand volume, V, to above-ground carbon storage. This polynomial equation was used to estimate stand carbon rather than individual tree carbon storage in Newmarket Park (Schwendenmann & Mitchell, 2013 under review). To apply it in Wynyard Quarter, tree volume was first calculated using Equation 6. This equation multiplies tree basal area by tree height, with a correction to convert DBH from centimetres to metres, to give volume (m^3).

$$V = 7.854\times10^{-5}(H.DBH^2) \quad (6)$$

Then individual tree volume figures were grouped by species to form species 'stand' volumes. These volumes (V) from Equation 6 were input into Equation 7 to estimate total carbon storage for each species. This approach was adopted to apply the Schwendenmann & Mitchell (2013 under review) polynomial biomass equation in a similar way to how it was developed. The equations compiled from Beets *et al.* (2012) can be applied appropriately to calculate individual tree biomass because of how they were developed. For reporting, all carbon storage data were grouped by species so that, by dividing by the number of trees in each group, the average tree carbon storage per species in Wynyard Quarter could be found and compared.

$$Y = -2533.5V^3 + 1323.2V^2 + 117.59V \qquad (7)$$

The second allometric equation used from the Newmarket Park study was a power equation for estimating biomass from DBH. It has three components which estimate stem and branches, foliage and root carbon storage in order (Equation 8). Note that Equation 8 includes the root component, in contrast to Equations 3, 4 and 7. Thus Equation 8 directly produces total above- and below-ground tree carbon storage figures.

$$Y = 2.30\times10^{-3}(DBH)^{3.3885} + 1.21\times10^{-2}(DBH)^{2.576} + 9.00\times10^{-3}(DBH)^{2.4966} \qquad (8)$$

All outputs from Equations 3, 4 and 7 were converted to total tree biomass using the IPCC root-to-shoot ratio of 0.25 (IPCC, 2003). This approach was adopted because of its widespread use in carbon storage studies, where above-ground biomass required conversion to total tree biomass (Liu & Li, 2012; Cairns et al., 1997: in Nowak et al., 2002b) and because it is also used by the IPCC, a consortium of leading international scientists (IPCC, 2003).

For a multi-stemmed tree, the chosen allometric equation was applied to each stem and the total from each stem summed to determine total tree volume or biomass. This approach, referred to here as the 'multi-stem summation method', mimics the structure of a stem that is connected to branches (large to small) and foliage, all of which store carbon.

3.4.3. Evaluation of methods

The tree field data were applied to Equations 3, 4, 7 and 8 using a Microsoft Excel spreadsheet to calculate carbon storage. Trees where the DBH had been measured below the 1.37m standard height (due to short stems or bulges at branch junctions at 1.37m height) were omitted. This was necessary so that the NZ equations could validly be applied: equations from Beets *et al.* (2012) in particular were developed to represent tree volume or biomass from the standard DBH measurement only. This eliminated all nikau and a number of multi-stemmed trees, leaving 57 trees eligible for analysis. Only i-Tree outputs for the 57 eligible trees were included in the analysis.

The i-Tree Eco study of Wynyard Quarter was completed by Findlay (2013). Carbon storage outputs from i-Tree Eco were entered into the Microsoft Excel spreadsheet to enable comparative analysis with carbon estimates from Equations 3, 4, 7 and 8. Spot-checking of spreadsheet data against data in the i-Tree Eco desktop program was done to identify and correct any transcription errors.

4. Results

In this comparative study of methods for estimating carbon storage in NZ, the total carbon stored by the 57 trees at the time of measurement was estimated to be at least 1,500kg, with an upper estimate of 1,773kg from Equation 4. Carbon offset is equivalent to 30,000-35,000 km in a new car (Sloane, 2012), or a return passenger flight from Auckland to London (Virgin Atlantic, 2013; World Atlas, 2013). Pohutukawa trees stored the most carbon, 99-110kg per tree on average, and taraire stored the least carbon with 2.2-3.0 kilograms per tree on average. Of the 57 trees analysed in Wynyard Quarter, 48% of total carbon was stored by rata (n=17), 33% by pohutukawa (n=5) and the remaining 19% of carbon stored by the hybrid, taraire, karaka and puriri trees (n=35). Data represented in graphs show bars of standard error.

i-Tree, Equation 4 and 8 produced comparable carbon storage figures for each tree species (Figure 2). However differences and trends among carbon storage estimation methods emerged when data were grouped by species type: the *Metrosideros* genus group of pohutukawa, rata and the hybrid (Figure 3) exhibit different trends to the other hardwood species, puriri, taraire and karaka (Figure 4). Equation 3 estimated very similar carbon storage for puriri, taraire and karaka but less carbon for pohutukawa, rata and the hybrid species by 30-35% on average. This was expected as the equation was developed with trees of average wood density 0.53g/cm^3, similar to karaka and taraire. Thus this equation could not accurately represent the denser wood of the *Metrosideros* species (0.650 - 0.956 g/cm^3).

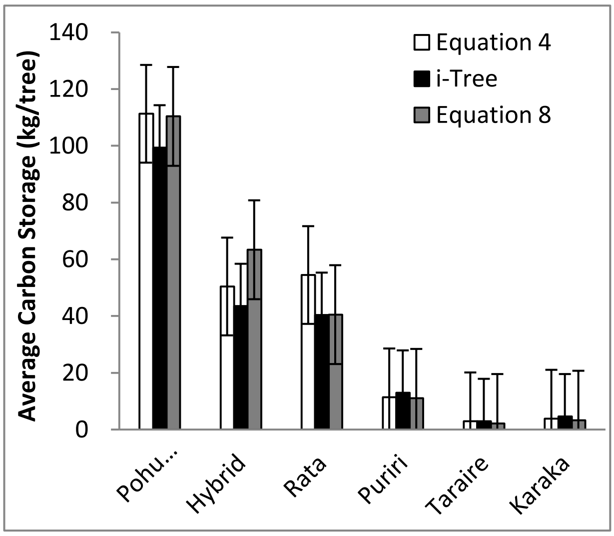

Figure 2: Carbon storage estimates by method from Wynyard Quarter study

Equation 7 estimated carbon storage within the range of other estimates for puriri, taraire and karaka but for pohutukawa, rata and the hybrid, large negative values were produced. Calculated species stand volumes for *Metrosideros* trees were greater than $1.2m^3$ which is considered to be outside of the valid range for this equation.

Tree carbon storage estimates for the pohutukawa, rata and the hybrid species (Figure 3) were more variable than the other hardwood species (Figure 4) among the methods used in this study. *Metrosideros* trees in Wynyard Quarter were also much older, hence larger trees in contrast to the younger and predominantly single-stemmed puriri, karaka and taraire trees.

i-Tree Eco estimated higher carbon storage for puriri and karaka when compared with the other NZ-derived methods (Figure 4). However i-Tree Eco estimates were consistently within the range of standard error for the two comparable methods, Equation 4 and 8.

Tree characteristics which positively influence tree carbon storage can be interpreted from these data. The *Metrosideros* trees in Wynyard Quarter - pohutukawa, rata and hybrid - are distinguished from the other hardwood species by greater wood density (Table 1) and greater tree age. When Wynyard Quarter was redeveloped in 2011, a number of mature pohutukawa and rata trees were transplanted from other sites, and the remainder of the trees were planted as saplings.

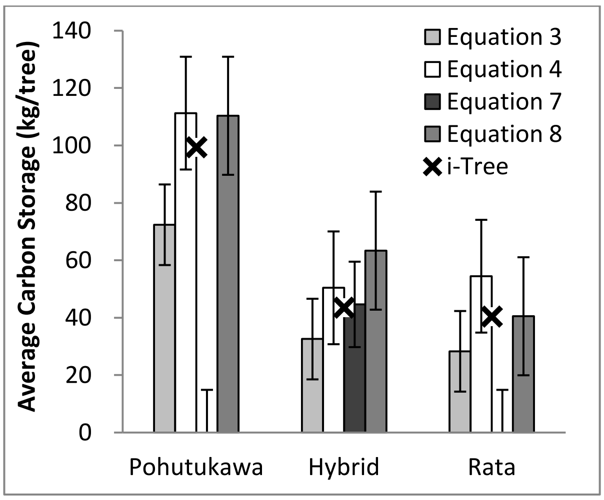

Figure 3: Average tree carbon storage for *Metrosideros* species by method: pohutukawa, rata and hybrid.

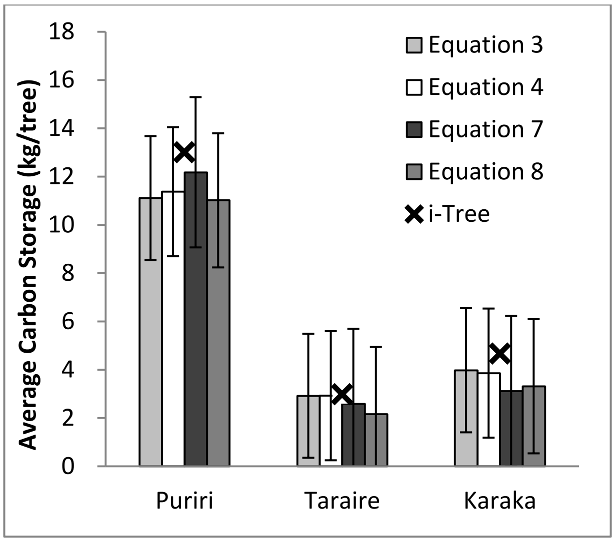

Figure 4: Average tree carbon storage for puriri, taraire and karaka by method

No nikau were included in the comparative analysis of carbon storage estimation methods because DBH measurements could not be taken at the standard height of 1.37m. Lower measurements of stem diameter are done when stems are shorter than 1.37m or to avoid bulges or diverging branches at 1.37m height. In Wynyard Quarter, nikau trees were immature with the bulb of fronds often emerging at ground level or otherwise stems were less than 20cm high, and root masses likely smaller than in a mature nikau. i-Tree estimated carbon storage for nikau in the area studied to be 59kg for the 31 trees, an average of 1.4kg per tree. Enright (1985) studied mature nikau biomass and found the equivalent of 1.7kg of carbon in the fronds and 2.3kg of carbon per metre of stem (using standard 0.5 biomass to carbon conversion factor). Based on Enright's biomass data, the carbon storage estimates from i-Tree seem realistic; however validation from destructive analysis or applying a palm allometric equation is recommended.

Nikau has a much lower wood density relative to other trees, $0.273g/cm^3$ (Table 1). Lower wood density means nikau contribute less carbon than other species in Wynyard Quarter, given the same biomass. Nikau also has an atypical tree structure compared to that of hardwood trees which Equations 3, 4, 7 and 8 and i-Tree were designed to model.

Only two hybrid trees were found in this study of Wynyard Quarter. In an effort to best represent the structure of the two individual trees, the larger one was modelled using pohutukawa species information and the juvenile with rata species information. For the hybrid, an average rata and pohutukawa wood densities, 0.803g/cm^3, was applied in Equation 4 (Zanne et al., 2009).

Equation 8 did not incorporate species wood density as an input variable. Wood densities in the Newmarket Park study ranged from 0.59 – 0.77 g/cm^3 (Schwendenmann & Mitchell, 2013 under review). Though it estimated the highest carbon storage over the other methods for the hybrid trees, it estimated comparable carbon storage values for all other species.

5. Discussion

5.1. i-Tree Eco in NZ

i-Tree Eco produces comparable carbon storage figures to NZ methods for quantifying tree carbon storage. For the 57 trees studied in Wynyard Quarter, i-Tree Eco produced carbon figures within the range of standard error of estimates from Equations 4 and 8. i-Tree Eco could thus be used with NZ urban forests to produce indicative information for city planners and decision-makers on tree carbon stocks to inform urban tree policy and climate change emissions strategies.

i-Tree Eco carbon storage estimates for palm species need to be verified because the equations i-Tree Eco uses currently do not include any specific palm allometric equations (Nowak & Crane, 2002a). Estimating palm carbon storage using the equations derived from hardwood trees is not ideal because of their structural differences. The GlobAllomeTree database contains a number of palm allometric equations which could be evaluated to identify an applicable equation or composite suitable for i-Tree Eco (FAO, 2013). This resource was not used in this study as the intention was to compare NZ methods for carbon storage and no NZ equations are in this database. Including specific palm allometric equations into the i-Tree Eco model would give greater accuracy and confidence in palm carbon storage outputs. This would be useful for urban tree carbon storage quantification for nikau in NZ and in regions such as Hawaii and California where palms are common.

The average hardwood allometric equation in i-Tree Eco produces realistic carbon storage figures for NZ tree species found in Wynyard Quarter. Compared to NZ allometric equations, it is also applicable for a wide range of DBH values and accounts for species factors such as wood density. Thus, i-Tree Eco has wider applications and potentially greater accuracy than existing carbon calculation methods available in NZ.

5.2. Allometric equations

Tree characteristics such as density and the DBH-Height relationship of sampled trees are expressed in an allometric equation when measurements from other trees are applied to them. Of trees in the same species, different environmental stresses (forest compared to urban) or levels of maturity can result in rather different tree forms and allometric characteristics. So even with species-specific allometric equations, which are largely more accurate tools for estimating tree carbon storage, there are still errors in their estimations. Nowak *et al.* (2002a) admit a lack of information around the errors in allometric equations which makes it impossible to account for them fully. Some errors in carbon storage estimates can be reduced by considering attributes that vary among trees and contribute to tree carbon storage.

5.2.1. Tree growth structure

Tree growth structure should be represented appropriately by allometric equations, accounting for typical number of stems and shape or distribution of crown volume. Trees that naturally grow multiple stems below breast height have different natural allometric relationships that single-stemmed trees – this affects carbon storage estimates. Also, some tree species have different structural forms as juveniles and when mature, such as the native lancewood (*Pseudopanax crassifolius)*.

Pohutukawa trees have an ‘umbrella’ crown structure and multiple stems, which is a different form to typical hardwood trees such as karaka or puriri, which are single-stemmed with spherical or conical crown structure. Another contrasting example is the nikau palm, which has a cylindrical stem and frond-like foliage.

The ‘multi-stem summation method’ used with Equations 3, 4 and 8 produced sensible carbon storage estimates. To verify this rationale for modelling carbon storage in multi-stemmed trees, a comparison of actual biomass with estimated biomass for a sample of multi-stemmed trees, such as pohutukawa, could be completed. Collaboration between arborists and researchers could support the development of allometric equations for multi-stemmed tree species in NZ.

As mentioned for i-Tree Eco, allometric equations for palm species would produce more accurate carbon storage estimates, incorporating specific wood density and the palm tree structure in allometric relationships. Nikau and pohutukawa are a common urban tree species in NZ. Thus, verified and accurate methods for calculating carbon storage for these and other species with atypical growth structures have value for future urban tree carbon studies in NZ.

5.2.2. Forest- and urban-derived methods

No clear difference between urban- and forest-derived allometric equations was found in this study. However, the classification of ‘urban-derived’ is vague and requires clarification. Allometric equations from Beets *et al.* (2012) and i-Tree (Nowak et al., 2002b) are known to be derived from analysis of natural forest trees. The trees felled for Schwendenmann and Mitchell's study (2013) were in an urban park in Auckland City, thus Equation 8 is by definition urban-derived. However, environmental stresses in a stand of trees in an urban park are likely to be less extreme than for single exposed trees or those growing in urban streets. The trees studied in Wynyard Quarter were growing in a waterfront courtyard or along Jellicoe Street spaced 1-3m apart. They are likely to be subject to harsher urban environmental stresses than any of the trees for which allometric equations used here were developed.

McHale *et al.* (2009) highlight the uncertainty in applying allometric equations from natural forests to quantify urban forest carbon storage, noting urban environments can render different physical form of trees a different allometric relationship for the same species (Ward & Johnson, 2007). Urban carbon storage studies have identified the need for urban-derived allometric equations (McHale et al., 2009; Ward & Johnson, 2007). However, Semenzato *et al.* (2011) suggest the development of site-specific biomass equations is more pertinent. As a planning tool however, these suggestions are impractical both in terms of the time and resources required for development and the redundant greater accuracy of outputs.

5.3. Wood density and Age

Wood density and age demonstrated a strong influence on tree carbon storage capability. These characteristics had a compound effect in the sample of trees in Wynyard Quarter: the mature trees also had the densest wood. The five transplanted pohutukawa trees stored 33% of the total carbon of the 57 trees studied in Wynyard Quarter.

Influence of tree age on carbon storage can be seen in the results from Equation 3, where each tree was modelled as having the same wood density. The older trees, transplanted to Wynyard Quarter as mature trees, stored more carbon as they were taller and had greater stem diameters than other trees planted as saplings.

The carbon storage estimates from Equation 4 – which accounted for species-specific wood density – showed the positive effect of denser wood on calculated carbon storage: an increase of over 30kg per tree on average following the wood density correction was observed among trees in Wynyard Quarter. Tree species such as pohutukawa naturally have greater biomass per unit volume ($0.956 g/cm^3$) and thus store greater amounts of carbon than species with lesser wood densities (when applying biomass-to-carbon conversion factor of 0.5).

5.4. Managing urban forests

Mature trees are important constituents of carbon stocks, for mitigation of carbon emissions. However, recent changes to the NZ Resource Management Act (RMA) have removed some protection for trees (Ministry for the Environment, 2013). The research herein has shown how a mature, well-established tree, such as the pohutukawa in Wynyard Quarter, can provide greater ecosystem services to urban populations than a younger tree. A quantitative understanding of the ecosystem services provided by urban trees, enabled by i-Tree analysis for example, could prevent negative long-term impacts of the new RMA policy. Furthermore, such data can communicate to politicians and other decision-makers the value of urban forests and the imperative to protect urban forest resources to sustain provision of ecosystem services.

Strategic planting of urban trees can support provision of a range of ecosystem services in addition to carbon storage. In Auckland, tree and shrub wood density data could be included in council planting guidance documents, such as Lewis *et al.* (2010). Including this information in a simple way (as a carbon storage factor, perhaps) could encourage users to consider the potential climate change mitigation benefits of their planting choices. Planting of tree species with high wood densities ($0.80\text{-}0.96 g/cm^3$) that are suited to the environment and are long-lived would increase carbon storage potential and the climate change mitigation capacity of an urban forest.

New Zealand carbon storage data from urban forests could also be used to report under the Kyoto Protocol, which requires regular updates on national measures for mitigating climate change (Ministry of the Environment, 2010). TR2009/083 recommends species for different stormwater management practices (Lewis et al., 2010). Trees planted in bioretention cells and tree pits can contribute to stormwater management as well as climate change mitigation through carbon storage. However, choosing a range of species to support biodiversity is also recommended in planting schemes (Lewis et al., 2010).

An i-Tree analysis of Auckland's urban forest would quantify carbon storage and other ecosystem services such as carbon sequestration and air pollution removal. This could establish an understanding of the city's carbon stocks and highlight ways to enhance provision of ecosystem services to support Auckland's transition toward becoming the world's most liveable city (Auckland Council, 2012).

6. Conclusions

Of the carbon storage calculation methods studied, three produced comparable results for the 57 trees studied in Wynyard Quarter. This included i-Tree Eco, which is considered an appropriate tool for quantifying urban carbon storage of NZ trees for simple applications.

Development of allometric equations with inputs for tree wood density, and the evaluation and verification of methods for representing different tree growth structures would collectively improve the accuracy of existing methods for estimating carbon storage in NZ. Results from this study showed that greater the age and the wood density of a tree the greater its carbon storage capacity. Suggested strategies and targets for municipal urban forest management in New Zealand have climate change mitigation potential through offsetting carbon emissions.

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8. Disclaimer

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