Carbon Storage in Young Growth Coast Redwood Stands

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Abstract
Carbon sequestration is an emerging forest management objective within California and around the world. With the passage of the California's Global Warming Solutions Act (AB32) our need to understand the dynamics of carbon sequestration and to accurately measure carbon storage is essential to insure successful implementation of carbon credit projects throughout the State. As the leader in forest carbon credit projects within the U.S., California's forest carbon protocols are being looked to as templates for successful carbon credit accounting. Coast redwood (*Sequoia sempervirens*) stands have the largest measured biomass per acre making the argument for use of the species in long-term carbon sequestration projects self evident. To date no direct measurement of both carbon fraction and wood density of coast redwood has been undertaken. With this study we tested the applicability of the current forest carbon project protocols set out by the Climate Action Reserve for forest carbon credit projects within California. Specifically we tested the applicability of a carbon fraction of 0.5 and a greenwood density of 0.34 g/cm^3 for coast redwood trees. Our main findings were that: 1) a species-average of 0.34 g/cm^3 significantly underestimated the wood density of the measured trees, 2) wood density varied predictably with tree height and wood type, 3) carbon fraction was significantly higher than the default 0.5, and 4) carbon fraction varied predictably in relation to wood type. Our results indicate that a simple approach to estimating carbon storage utilizing a carbon fraction of 0.5 and a species-average wood density underestimates carbon budgets in young growth redwood stands. Given the regional nature of carbon credit projects our results indicate that forest project protocols should be adjusted to allow for calculations that incorporate directly measured wood density and carbon fraction values within the forest carbon project area.

Key words: biomass, *Sequoia sempervirens*, carbon fraction, sequestration projects, wood density

Introduction

Carbon sequestration is emerging as an important goal for forestry. In order to make informed decisions related to managing forests for carbon sequestration it is necessary to have precise and empirically based estimates of carbon budgets (Brown 2002). Forest carbon budgets are typically determined by estimating the volume of a tree using species-specific allometric equations or genus-specific equations (Brown 2002, Jenkins and others 2003) to convert easily measured tree characteristics such as diameter at breast height into wood volume. The bone-dry wood density of the species is then used to convert this overall volume into tree biomass. Tree biomass is multiplied by a carbon fraction to estimate the mass of carbon contained in that tree. Species-specific values of carbon fraction are not widely available and therefore a

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generalized value of 0.50 is typically used (Brown 2002, Goodale and others 2002, Harmon and others 1990, Pacala and others 2001, Van Deusen and Roesch 2011).

Using a carbon fraction of 0.50 is problematic because carbon values that have been directly measured range from about 0.45 to 0.55 (Lamlom and Savidge 2003). The associated error with using 0.50 can therefore be as high as ten percent (Lamlom and Savidge 2003).

Another source of error in carbon budget estimates arises from variation in species specific wood density values from region to region. The default value for young growth redwood whole-tree basic wood density (called wood density hereafter) is 0.34 g/cm^3 (CAR protocol methodology - climateactionreserve.org), however regional estimates range from 0.32 g/cm^3 to 0.38 g/cm^3 (Luxford and Markwardt 1932) equating to deviations from the species average of 6 and 12 percent respectively.

Due to the longevity of the species and it's propensity to accumulate high levels of biomass (Busing and Fujimori 2005), young growth coast redwood forests have the potential to become significant carbon sinks for hundreds of years. Redwood stand volume production has been shown to be affected by stand density and structure implying that there is the potential to effect stand volume productivity with carefully planned silvicultural treatments (Berrill and O'Hara 2009). In addition to the high wood volume productivity within a stand of coast redwood, the wood products harvested from those stands has been shown to have long lifecycles (Highley and others 1995) allowing for long term carbon storage in wood products.

This study focuses on second growth coast redwood trees to pursue the following study objectives: 1) determine whether any differences in carbon fraction exist within three wood types of the tree bole at breast height; 2) determine whether any differences in density exist between the three wood types; 3) determine whether any carbon is lost due to oven drying; 4) develop methodology to precisely determine the carbon fraction of tree boles in young growth redwood; and 5) compare the directly measured values in the study area to the default values specified in standard methodologies (carbon fraction of 0.50 and wood density of 0.34 g/cm^3).

Methods

Study area and description

Tree cores were collected from coast redwood stands located at Railroad Gulch on Jackson Demonstration State Forest near Ft. Bragg, California. Redwood stands at this location regenerated naturally from stump sprouts and from seedlings planted after removal of the old growth stands around 1920 (Jackson 1991). Sample trees were randomly selected from a database created in 1982 when Railroad Gulch was divided into 14 contiguous blocks. A total of 42 trees were selected ranging in breast height age from 23 to 87, ranging in diameter from 13 to 86 cm and ranging in height from 5 to 45 m.

Core extraction and processing

Two cores were taken perpendicularly to the bole axis at a 45° angle to slope aspect on opposite sides of sample trees. The increment corer was cleaned between trees to avoid contamination. A subset of four trees were selected for additional core extractions taken from halfway between base of live crown, at live crown and halfway between tree top and live crown. These cores were used for analysis of vertical variation in wood density. Cores were then placed in straws, sealed and labeled.

Ten cores for paired carbon and density analysis were cut in half lengthwise and divided up into three categories: 1) juvenile heartwood (first seven growth rings from pith); 2) mature heartwood (three growth rings away from sapwood heartwood boundary and showing no curvature of the growth rings); and 3) sapwood (determined by color). This resulted in 30 samples analyzed for density (10 of each wood type) with corresponding halves of segments analyzed for carbon. Ninety-six additional core segments were selected strictly for carbon analysis, however, these samples were not cut in half.

Core segment samples were ground into a fine powder which was placed into a sample tube with a two-stage cap to either permit or exclude airflow. To determine if differences in air-drying and oven-drying affected carbon fraction the tubes and wood powder were first air-dried in a vacuum chamber with desiccant then analyzed for carbon fraction. The same sample tubes were later oven dried at 65 ºC and then again at 105 ºC and carbon analysis was repeated each time to determine any potential loss of carbon due to volatilization of organic compounds.

Carbon fraction

Carbon fraction was determined by taking a 5 mg sample of wood powder from each of the 126 (42 of each wood type) sample tubes for the analysis of air-dried samples (Cai) then another 5 mg sample was taken from the same tubes after oven drying for the oven-dried carbon (Cov) samples at 65 ºC then again at 105 ºC. Mass lost due to oven drying was recorded for each sample at each stage. Each sample of wood powder was placed into a clean dry tin container (Costech Analytical Technologies, Inc.) that was first zeroed on a Metler Toledo microbalance. A CE Instruments NC 2100 Elemental Analyzer (Rodano, Milano, Italy) was used to quantify total carbon of each sample on a mass per mass basis using a calibration curve with an r^2 >0.9999. To ensure correct carbon values the air dried carbon fractions were adjusted by dividing the initial Cai value by one minus the result of subtracting the volatile carbon fraction (Cv) from the total mass lost fraction. Effectively this adjusted the initial carbon values to reflect the amount of residual moisture left in the wood powder.

Wood density

The volume of the samples (Vs) used to determine the density of wood was determined by zeroing a graduated cylinder of deionized water with a submerged capsule used to hold samples on an OHAUS Analytical Plus scale. The wood samples were then placed into the capsule and submerged into the water making sure to lower the capsule to the same level as it was zeroed. The reading on the OHAUS scale was recorded as the volume of the sample after determining the proper density of the water at room temperature (20 ºC), which was done by treating the scale reading as unitless and multiplying that reading by the density of water at 20 ºC (0.998199 g/cm^3) (Aleksandrov et al. 2004). Density samples were oven-dried at 105 ºC until a constant mass was achieved. Once the samples were stable their masses

(Ms) were recorded and the density determined by calculating (Ms+Cv*Ms)/Vs. This density value adjusts for the mass of volatile carbon lost during oven drying.

Statistical methods

The mean and standard error of carbon fraction for 42 samples for each of the three wood types were determined. Variation in carbon fraction was tested using a one-way analysis of variance ($\alpha = 0.01$) and significance of differences between the means of each wood type was determined using a Tukey-Kramer t-test (α=0.01). The mean and standard deviation of 10 replicates for each wood type were calculated and a one-way analysis of variance ($\alpha = 0.05$) was used to test for differences in density among wood types. A z-test was used to determine the significance of differences in the overall mean from 0.34 g/cm^3. The mean for Cai and the mean of Cov were compared using a paired t-test. Linear regression was used to test relationships between carbon fraction of each wood type and growth rate, diameter at breast height, height, height to live crown and length of live crown. One standard error is represented by values in parenthesis within the text and tables.

Results

Variation in carbon fraction between wood types

Analysis of carbon fraction for the three wood types showed that heartwood was consistently higher in carbon than sapwood and that mature heartwood was higher in carbon than juvenile heartwood samples (*table 1*). Means were significantly different between the three wood types using a Tukey-Kramer t-test ($p<0.0001$) and all were significantly different from a mean of 0.50 ($p<0.0001$).

Table 1—*Carbon fractions and associated standard errors for each wood type - juvenile heartwood (HWj), mature heartwood (HWm) and sapwood (Sw) - for two drying methods, air dried and oven dried to 105 ºC. Forty two samples were used for each wood type for each drying method.*

Drying	HWj	HWm	Sw
Oven dried	0.5179 (0.00096)	0.5235 (0.00098)	0.5047 (0.00096)
Air Dried	0.5371 (0.00107)	0.5443 (0.00104)	0.5305 (0.00105)

Linear regression of Cai on the tested variables showed a significant negative relationship between carbon fraction of mature heartwood and average growth rate ($p = 0.026$, $r^2 = 0.134$)). The relationship is described by the following equation: Cai (HWm) = 55.051 – 1.503*AveGrowth. AveGrowth is the average growth of the sample in cm/growth ring. No significant relationships existed between carbon fraction of juvenile heartwood or sapwood and any of the variables tested. Linear regression of Cov on the above tree variables showed no significant relationships for any of the tested variables. An ANOVA on wood types and carbon fraction resulted in an adjusted r^2 of 0.41 for Cai and 0.64 for Cov ($p<0.0001$).

Oven-dried versus air-dried methods

A paired t-test showed significant differences ($p<0.0001$) in carbon fractions between air-dried wood powder samples and oven-dried wood powder samples (*table*

1). Mean differences for carbon fractions between air and oven dried samples were: 0.0192 for HWj, 0.0208 for HWm and 0.0258. The volatile fraction between air dried and oven dried carbon samples (to 65 ºC) was not significantly different from the volatile carbon fraction of samples dried at 105 ºC therefore the 105 ºC values are reported for incorporation with wood density dried to the same temperature.

Density of wood types and overall wood density

Wood density was significantly different for sapwood found above the live crown (ALC) versus below live crown (BLC) but not significantly different for heartwood by location in tree or between juvenile and mature heartwood. The mean wood densities of sapwood by location in tree (ALC or BLC) were: 0.300 g/cm^3 (0.017) ALC, and 0.372 g/cm^3 (0.017) BLC. The mean wood density for heartwood was 0.382 (0.010). The mean for heartwood and below crown sapwood were significantly (p=0.010, α=0.05) higher than the 0.34 g/cm^3 value for bone-dry density of redwood. The average of sapwood density sample values resulted in a mean of 0.351 g/cm^3 (0.014).

Carbon density comparison

The average values for the combination of carbon fraction and wood density (carbon density) are given below (*table 2)*. Significant differences existed between directly measured values of carbon density and the default values for carbon density obtained by multiplying a wood density for redwood of 0.34 g/cm^3 by the default carbon fraction of 0.50 (p<0.05). Only the ALC sapwood carbon density was close to the resulting value (default value).

Table 2—*Comparison between default and measured values for carbon densities and standard errors for two wood types found within the boles of young growth redwood trees measured above live crown (ALC) and below live crown (BLC).*

Wood type	Location	Default value (g C/cm^3)	Measured values (g C/cm^3)	Difference (%)
Heartwood	ALC	0.17	0.2052 (0.0037)	20.70
Sapwood	ALC	0.17	0.1591 (0.0061)	-6.41
Heartwood	BLC	0.17	0.2076 (0.0037)	22.12
Sapwood	BLC	0.17	0.1973 (0.0074)	16.06

Discussion

Carbon fraction variation

The significant variation in carbon fraction between the three wood types indicated that using an overall average for carbon fraction, even a species specific one, may lead to underestimates of the carbon fraction of young growth redwood. There are few studies that have directly measured carbon fraction in trees (Chow and Rolfe 1989, Elias and Potvin 2003, Lamlom and Savidge 2003, Lamlom and Savidge 2006, Thomas and Malczewski 2007), potentially explaining the reliance on a general carbon fraction of 0.50 to convert dry biomass to carbon mass despite the inherent inaccuracy of utilizing such an average to predict carbon fractions of unmeasured species. The overall measured mean of carbon fraction in young growth redwood is significantly greater than the 0.50 value that is often used for trees (Brown 2002, Goodale et al. 2002, Harmon et al. 1990, Pacala et al. 2001, Van Deusen and Roesch 2011).

The differences in wood characteristics such as density, shearing strength and extractive content between old-growth redwood and young growth redwood (Resch and Arganbright 1968), make extrapolation of the values from this study to old-growth redwood inadvisable. The higher extractive content in old-growth redwood would most likely result in higher carbon fraction of the stem compared to young growth as extractives can be made up of as much as 66 percent carbon (Resch and Arganbright 1968). Wood type explained a good deal of the variation found in the tree boles with an adjusted r^2 of 0.41 for Cai predicted by wood type and an adjusted r^2 of 0.64 for Cov predicted by wood type. The difference in r^2 between the two drying methods indicated volatile compounds may vary independently from structural carbon components such as lignin and cellulose. Though the causes of carbon fraction variation within tree boles are not well understood (Elias and Potvin 2002, Lamlom and Savidge 2003), it is clear from the data that volatile organic compounds are a significant portion of the overall carbon fraction.

Densities

Differences in wood density between wood types in redwood have been reported (Luxford and Markwardt 1932, Resch and Arganbright, 1968) but were not detected with our small sample size. Significant differences in wood densities from 0.34 g/cm^3 ($p<0.05$) imply that utilization of an average density for young growth redwood may not be appropriate for all regions or for all stand structures. More studies into the factors controlling wood density in young growth redwood are needed in order to create accurate wood density prediction models to aid in predicting overall carbon stocks. The correlation of lower wood density to position in live crown of young growth redwood was not unexpected. Resch and Arganbright (1968) and Sillett and others (2010) found similar trends in old growth redwood implying that this trend is a species trait. The wood densities found in the study area are close to the 0.38 g/cm^3 value reported by Luxford and Markwardt (1932) for Mendocino implying that despite the relatively small sample size the wood density numbers found in this study may be representative for the region.

Loss of carbon during oven drying

The loss of carbon during oven drying at 65 ºC and 105 ºC is a significant finding. The methodology for carbon measurement in woody tissues commonly calls for oven drying (Lamlom and Savidge 2003). Studies have found that oven drying can lead to the loss of carbon, however, they have either used very high temperatures (Lamlom and Savidge 2003, Thomas and Malczewski 2007) or have not directly measured differences in total carbon before and after oven drying (Beakler et al. 2007). Oven drying wood at temperatures as low as 65 ºC and potentially lower (Beakler and others 2007) can lead to the loss of carbon. This suggests that oven drying should not be used in determining carbon fraction. Instead utilizing vacuum desiccation as outlined by Lamlom and Savidge (2003) or freeze drying as outlined by Thomas and Malczewski (2007) would be most appropriate. Kiln dried wood is typically processed at temperatures near 65 ºC (Beakler and others 2007) so the oven-dried carbon fractions from this study is appropriate for estimating carbon budgets for young growth redwood lumber. The oven dried values from this study are close to the value of 0.512 used by Wilson et al. (2010) indicating some consistency in carbon fraction of young growth kiln dried redwood. Timber production has been proposed as a potential method for increasing the amount of carbon stored by a given area of forest land (Skog 2008), however, it is important to understand the differences between carbon fractions of kiln dried lumber and that of live trees for accurate carbon accounting.

Improved methodology

The methodology presented in this study resulted in more precise and accurate carbon fraction values then the standard methodology. Measuring both carbon fraction and wood density is necessary in determining accurate values for a given species or location as these characteristics can be highly variable across species and regions (Chave et al. 2009, Lamlom and Savidge 2006). Lamlom and Savidge's (2003) methodology works well in a laboratory setting but the destructive nature of the methodology does not allow for comparison of carbon fractions over time. The ability to measure stand conditions over time along with carbon fraction and wood density, could be very helpful in explaining some of the environmental factors impacting those two variables. It is important that future studies into carbon fractions of tree species utilize either the vacuum desiccation methods suggested by Lamlom and Savidge (2003) or the freeze drying method described by Thomas and Malczewski (2007). Additionally the loss of carbon due to oven drying must be accounted for both in total carbon fractions and in the wood density values in order to ensure accurate carbon stock estimates.

Comparison of measured values to default values

The difference between the values suggested by the CAR protocols (0.17 g C/cm^3) and the values measured directly in this study were as high as 22 percent of the default estimate (*table 2*). The debate over improving carbon budget estimation seems to focus almost entirely on improvements in volume estimation (Jenkins et al 2003, Van Deusen and Roesch 2011). This study, however, clearly indicates the magnitude of the error that can be introduced into carbon budget estimates if variation in carbon and wood density are not addressed. The current methodology (CAR) to estimate forest carbon budgets in redwood calls for the use of values that underestimate the amount of carbon stored within redwood trees. It is likely that the default values for other species could result in overestimates of their respective carbon budgets. For example it is known that hardwoods have carbon fractions that are typically lower than 0.50 (Lamlom and Savidge 2003) and therefore utilizing a default value of 0.50 for estimates of hardwood tree carbon will systematically overestimate the amount of carbon contained within many hardwood species. Additionally there is the likelihood that tree species within some regions will have lower wood densities than the species average and therefore local estimates of carbon sequestration rates will be biased when the species average us used. To alleviate these potential biases it will be necessary to measure carbon fractions of tree species found in California and to accurately estimate the regional and stand level variations in wood density that are known to occur.

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