forests

MDPI

Article

Predicting Aboveground Biomass in Second Growth Coast Redwood: Comparing Localized with Generic Allometric Models

Anil Raj Kizha [1,*] and Han-Sup Han [2]

1 School of Forest Resources, University of Maine, Orono, ME 04469, USA
2 Department of Forestry and Wildland Resources, Humboldt State University, Arcata, CA 95521, USA; Han-Sup.Han@humboldt.edu
* Correspondence: anil.kizha@maine.edu; Tel.: +1-207-581-2851

Academic Editor: Timothy A. Martin
Received: 28 December 2015; Accepted: 19 April 2016; Published: 27 April 2016

Abstract: Biomass amounts predicted by generalized models are often not applicable for small regions. Localized allometric models were developed relating tree/biomass components to diameter at breast height (dbh) for coast redwood (*Sequoia sempervirens* (D. Don) Endl.) from an industrial timberland in northwestern California, USA. dbh for the candidate trees ranged from 2.54 cm to 84.07 cm. Biomass of tree components, such as bole, foliage, bark, live and dead branches, along with the total aboveground biomass (TAGB) were estimated. Other tree dimensions such as tree height, height to live crown, weight and volume of bole wood were also modeled. Localized allometric models were able to explain more than 93% of the variability for most of the tree components ($p < 0.001$). Biomass amounts predicted from the widely used generalized models were different from that estimated by the localized allometric model developed from this study. However, the results presented in this study should be used carefully to predict the biomass components, if applied outside the stated dbh range or stand conditions on which this study was based.

Keywords: biomass components; California redwood; northern California; *Sequoia sempervirens*; tree dimensions; tree volume estimation

1. Introduction

Predicting the biomass of various tree parts using allometric models is crucial in multiple disciplines including forest utilization, management, and ecology. An allometric equation is a formula that helps quantitatively explain the relationship between various tree (or biomass) components and measurable tree attributes. Allometric models can be applied to all trees regardless of size, as long as they are growing under the same conditions [1]. These models consist of measureable independent variables, such as tree diameter or height, and have been used to obtain structural and functional characteristics for estimating biomass, net primary production, and biogeochemical budgets for forest ecosystems [2,3]. Traditionally, the determination of aboveground tree biomass and structural tree dimensions (for instance height of the live crown, height of the tree, weight, and volume of bole) was conducted to ensure sustainable planning of forest resources [4] and to determine amounts of carbon and carbon sequestration rates [5,6]. Currently, biomass models are finding a wide variety of other applications. They have been applied in predicting crown fire behavior [7], estimating potential conditions for drought, insect and disease outbreaks [8], estimating tree volume in remote sensing [9], and determining productivity and actual amount of biomass recovered during forest harvesting operations [10,11].

The US Forest Service has compiled a list of the most well-known published diameter-based biomass models for major tree species throughout the nation [5,6,12–14]. Yet, most of these generalized regional models are not suited for stand specific estimates, resulting in a need for localized allometric models. The need for localized models becomes even more crucial when the species of interest have high timber value or when accurate estimates are needed for various research activities.

In northwestern California, redwood trees (*Sequoia sempervirens* (D. Don) Endl.) are a major commercial timber species. Redwood forests are found in 12 counties of California. However, more than 75% of the redwood forests are concentrated in three northern counties—Del Norte, Humboldt, and Mendocino [15]. From 1978 to 2011, on average, the price for redwood timber has increased by 2.4% annually. From 1984 to 2000, the price saw a rapid increase, at almost 10.2%. As a result, redwoods are today considered to be the most valuable tree species in California, and are extensively used for fencing, decking, and paneling [16]. Additionally, coast redwood trees are the tallest in the world, adding further significance from an ecological standpoint. The redwood forests are considered to have the highest terrestrial biomass levels on earth (>3000 $\mathrm{Mg \cdot ha^{-1}}$) [17–19]. However, there have hardly been any localized allometric models developed to predict the total aboveground biomass (TAGB) and other tree components for coast redwood. This might be due to the difficulties associated with destructive sampling. Today, the most widely used models for predicting biomass in redwoods are generic allometric models published on a national level scale developed for cedar and larch [5,6,12]. Other allometric models developed for predicting stem volume for redwood trees had diameter at breast height (dbh) less than 10 cm (n = 9) [17–19]. However, due to its narrow dbh range, the applicability of this model is very limited. Other studies done on coast redwood includes, determining mensurational relationships for estimating the gross volume and taper for bolewood using dbh [20–24]. The Forest Inventory and Analysis (FIA) also has models to estimate the tree gross volume for trees above 13 cm in diameter [22–25].

This study developed a localized allometric model for estimating TAGB in oven-dry kilograms (ODKg) for coast redwood in northwestern California based on the tree dbh. Regression models were also developed for other tree components such as bole (stem), bark, branch, foliage, live and dead branches using dbh in ODKg (Table 1). Tree dimension components such as height of the tree, height to live crown, weight and volume of bole were also regressed to develop allometric models. The allometric model developed by this study was further compared to the existing national level models and the models used in the FIA model [5,6,12,21–25].

Table 1. Description of tree components and dimensions used for the study to develop localized allometric models for coast redwood.

Tree/Biomass Components	Description
dbh	Diameter at breast height; measured in centimeters (cm).
Height (H)	Total height of the tree from the ground to tip of the crown; measured in meters (m).
Stump	Remaining portion (0.30 m above ground) of the stem after the tree is felled with roots still in the ground. For calculating TAGB, the biomass in stump was included in the bole.
Bole (stem)	Biomass in stump, bole and bark up to 2.54 cm top; measured in oven dry kilograms (ODkg).
Live branch	Biomass in living branches; measured in ODkg.
Dead branch	Biomass in dead branches; measured in ODkg.
Foliage	Biomass in entire foliage (both live and dead); measured in ODkg.
Wood weight	Biomass in bole (main stem) above the stump including bark; measured in ODkg.
Bark	Biomass in bark; measured in ODkg.
Total aboveground biomass (TAGB)	Biomass in all tree components including bole, branch (dead and live), and foliage; measured in ODkg.
Height to live crown base	Height from an imaginary horizontal line drawn across the stem from the bottom of the lowest live foliage of the live crown for trees and from the lowest live foliage of the lowest twig for saplings [25]; measured in m.
Volume	Volume of bole (including bark) above the stump up to the top 2.54 cm; measured in m^3.

2. Materials and Methods

2.1. Description of Coast Redwood

The coast redwoods (family: Cupressaceae), named after the color of their bark and heartwood, are evergreen, long-living (in some cases more than 2200 years), monoecious trees endemic to the Pacific temperate rainforest eco-region [26–28]. They naturally occur from southern Oregon to central California within a relatively narrow strip (50 km) along the Pacific Ocean [29,30]. Hence, these trees are also referred to California redwood. The coast redwoods thrive in the moist, humid coastal climate, where marine fog provides favorable conditions necessary for their growth. Exceptionally massive stands of redwoods occur in the central redwood forest, which ranges from southern Humboldt County to San Francisco Bay [28]. Redwood self-prunes well in dense stands and the base of the bole in natural conditions is strongly buttressed. The fibrous bark of the tree can reach up to 30 cm in thickness [31]. Old growth trees can attain heights of 61 m with many reaching over 91 m. Such trees could reach dbh of up to 610 cm [30].

2.2. Study Sites

The candidate trees used for this study were selected from an industrial timberland property approximately 15 km from the Pacific coast in Humboldt County, California (123°56′17″ W and 40°57′51″ N) (Figure 1). The dominant species in the study area consisted of even-aged second growth redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziessii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and tanoak (*Notholithocarpus densiflorus* (Hook. & Arn.) Rehd.), with stands averaging 60 years in age. The sites were located approximately 220 to 460 m above mean sea level with ground slopes ranging from flat terrain to 111% (48°). The climate for the region is characterized by summers averaging 29 °C, and winter being cool and wet averaging 8 °C. On average, the region receives 1200 mm of rain annually, mostly from December through April [32]. Furthermore, the study sites fall within the Pacific temperate rainforests ecoregion, which are amongst the richest and most diverse temperate forests in the world [33]. The study region probably has a fire return interval of less than 100 years [34]. However, after the fire suppression policies instigated in 1900s, fire occurrences have greatly reduced for at least the last 50 years [35,36]. According to forest management records, trees were planted via aerial seed spraying and the stands were not thinned.

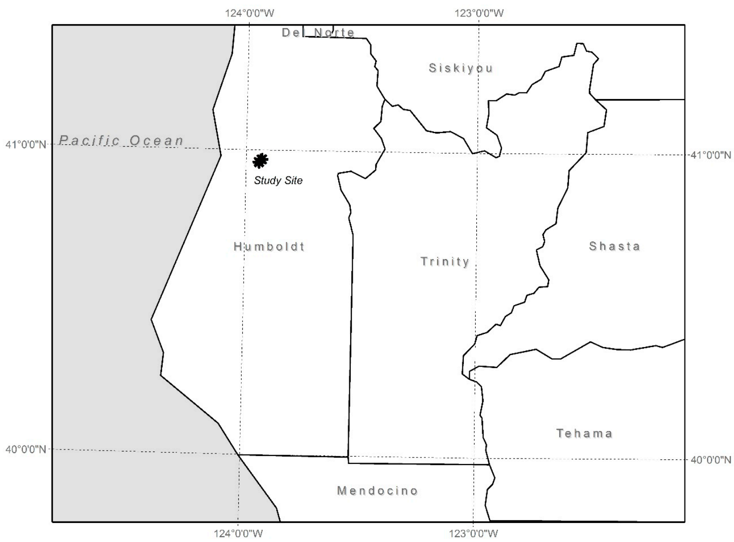

Figure 1. The locations of the study site used to develop the localized allometric models for coast redwood (*Sequoia sempervirens*) in Humboldt County, CA, USA. The stand was situated in an industrial timberland property.

2.3. Sampling Procedures and Data Collection

A stand inventory was done at 10% sampling intensity using 11 m line transects for 0.04 ha fixed-radius circular sampling plots and recorded species, height, and dbh for all standing trees over 2.54 cm (Table 2). The sample plots were evenly spaced at 76 m on transects lines drawn at random azimuths. The average basal area and dbh for the redwood trees in the two stands were 3.14 $m^2 \cdot ha^{-1}$ and 21.89 cm, respectively. The average tree density was around 296 trees per hectare with an average dbh of around 10 cm (both these values includes all species).

Table 2. Summary of stand conditions (A and B) and inventory for the localized redwood allometric model study on a per hectare basis.

Stands	Tree Types	A	B
Ground slope range (%)		3–37	0–50
Average slope (%)		22	31
Basal area ($m^2 \cdot ha^{-1}$)	C	9	9
	H	4	2
	D	0.4	1
	SD	0.5	2
Trees density (Number of trees ha^{-1})	C	75	84
	H	45	42
	D	17	23
	SD	126	194
Average dbh (cm)	C	35	37
	H	31	25
	D	14	14
	SD	9	10

C—Conifer species, H—Hardwood species, D—Dead trees, SD—Small-diameter trees (hardwood and conifer species below 15.24 cm dbh).

Twenty-nine trees, spanning a range of dbh from 2.54 cm to 84.07 cm (Table 3), were selected for destructive sampling following the methods outlined by Monserud and Marshall [37]. The stand inventory showed that this diameter range encompassed 99% of the redwood trees in the study site. A minimum of two trees were selected from all dbh classes observed in the sample plot inventories. Candidate trees excluded those that were open grown, obviously deformed, defected, and diseased. Trees were selected across two stands so that concentrations of either species or size classes in one stand were avoided. Moreover, trees that were adjacent to recent clear-cuts were given priority in the candidate tree selection process because the various tree components were more effectively recoverable (Table 1). Other non-candidate trees were cleared from the area to assist the feller with landing the candidate trees while reducing breakage. Trees selected for sampling were felled at the soil surface by a professional faller into nearby roadways or clearings to reduce stem breakage and loss of crown components in an attempt to facilitate sampling techniques. Sampling was initiated by compartilizing the tree into bole, branches (live and dead), and foliage.

Table 3. Distribution of candidate trees by diameter and height class, which were used to predict the biomass and other tree components for coast redwood (*Sequoia sempervirens*) on industrial timberlands.

		Diameter at Breast Height (cm)									
		1–10	**11–20**	**21–30**	**31–40**	**41–50**	**51–60**	**61–70**	**71–80**	**81–90**	**Total**
Height (m)	1–5	3									3
	5–10	1									1
	11–15	1	2								3
	16–20		2	2	1	1					6
	21–25			1	1						2
	26–30						1				1
	31–35				2	3			2	1	8
	36–40					1	1	2		1	5
	Total	5	4	3	4	5	2	2	2	2	29

2.4. Bole Measurements

The bole was divided into 1.52 m sections from the bottom to the top of the live crown. For each section, the large- and small-end diameters were measured (to the nearest centimeter) until the top 2.54 cm. The outer bark diameter was measured at the stump top (0.31 m above the ground) and ground level, to account for stump volume (Table 1). A millimeter caliper was used to measure bark thickness, at the same location where the outside bark diameter was measured. Finally, length to the tip of the crown and diameter at the tip were recorded. To obtain bole wood densities, three sample disks (approximately 2.54 cm thick) were cut from the lower, middle, and upper portions of the bole. The bark was removed from the wood, and both components were sent to the lab for further analysis.

2.5. Branch Measurements

The crown was divided into three equal sections from the base to the tip of the tree. Within each section, the largest and two randomly selected sample branches were removed with a chainsaw [38]. To facilitate measurements, all branches were cut into portions of approximately 1–2 m in length and then weighed in the field for calculating the fresh weight. The branches were further classified as dead and live. The dead branches were below the live crown and were leafless, and brittle. The live branches constituted from the first live branch up till the tip of the crown.

"Branch-summation" was the approach taken to estimate the branch-level measurement. Samples of live and dead branch on the stem were measured for basal diameter to the nearest 0.25 cm using calipers. In addition, length, and distance from the tip of the tree top to the branch node were also measured. The fresh weights of all sample branches less than 15 cm were measured in the field. Bigger samples of branches removed were labeled and kept, while the rest were discarded. During sampling, each branch location was marked on the stem to avoid double counting. The tree was then rolled over to measure branches on the other side. If a branch was missing due to breakage, the branch basal diameter was measured at the stem and branch weight was later estimated using regression models developed for the measured branches.

2.6. Laboratory Measurements

The volume and density of wood (debarked discs/cookies) were calculated using the water displacement method. The volume of wood was determined from the volume of water displaced when submerged. The wood density was estimated as the oven dry weight divided by the volume. Drying was done at a temperature of 105 $\pm$ 2 °C and the dry weight of the samples were achieved when the change of weight was less than 0.2% within a 60 m period [39]. Additionally, the wood density and bark to wood weight ratio was calculated for each tree by averaging the specific gravities obtained from respective cookies of the tree bole. Needles, branches, wood discs, and bark were weighed separately to calculate the specific dry to fresh weight ratios.

The branch weights were regressed against their respective basal diameter, length, and distance from the tree top, for estimating the weight of each unsampled component for every branch. These regression models were developed combining measurements from all trees and was transformed using natural logarithm. The oven dry weights for unsampled tree components were calculated by multiplying fresh weight with dry/wet ratio of each sample component [4]. The total oven dry biomass of each stem was then calculated by summing the dry biomass over all stem sections. The biomass in each section (*i.e.*, bole, foliage, bark, live, and dead branches) were summed to obtain the TAGB for each tree. The bole wood volume was estimated using Smalian's formula, which was later converted to weight by applying the specific gravity of stem wood cookies (dry weight/wet volume) derived from water displacement.

2.7. Statistical Analysis

The tree components estimated in this study were bole (stem), bark, foliage (needle), live and dead branches from which the TAGB was estimated. Allometric models were also developed for tree dimensions, such as height to live crown, total height of the tree (H), weight, and volume of bole (Table 1). Before establishing the allometric model, scatter plots were used to check whether the relationships between transformed independent and dependent variables were linear. Several transformation models were developed and compared; however, logarithmic transformed models with base 10 were selected [40]. Therefore, all allometric models reported for this study used logarithmic transformation with base 10 of various tree components, dimensions and dbh as independent variables for the regression. The logarithmic transformation equalized the variance over the entire range of biomass components and satisfied the assumptions of linear regression [4,41,42]. Multi-collinearity was tested using a tolerance value greater than 0.1 and variance inflation factor less than 10. Eleven models similar to the published biomass equations were developed for predicting respective biomass and tree dimensions in SAS statistical program version 9.3 [43]. Models were transformed back to the original units and corrected for bias using a correction factor (CF) for each model [44]. The R^2 reported for the regression model was calculated before it was back-transformed. The general form of allometric models reported was:

$$\log_{10}(\mathrm{B}) = \mathrm{a} + \mathrm{b}\log_{10}(\mathrm{dbh}) + \mathrm{CF}$$

where: B—Total biomass of the tree component (ODKg) or tree dimensions; dbh—Diameter at breast height (cm); log to base 10 a; b—Regression coefficients; Correction factor—CF $= \frac{\mathrm{SE}^2}{2}$; SE—standard error.

3. Results and Discussion

Eleven allometric coefficients were developed for coast redwood to predict biomass in various tree components and other structural tree dimensions by sampling trees from an industrial timberland (Table 4).

The TAGB estimated for this study, averaged at 910.56 ODKg and ranged from 1.20 to 3018.40 ODKg ($n = 29$). The average height of the candidate trees was 26.09 m, ranging from 9.45 to 34.05 m ($n = 26$, the three saplings were not included). The logarithmic transformed model (based on dbh) provided a highly significant ($p < 0.001$) fit for the all tree components (Figure 2) and met all of the assumptions for regression. Additionally, the residual plots and quantile-quantile (Q-Q) plots were also inspected to confirm the validity of the model. All components were estimated in ODKg based on log to the base of 10 and produced R^2 values ranging from 55% to 99% for the log transformed models (Table 4). Biomass for dead branches ($R^2 = 0.58$) and the height to live crown using dbh ($R^2 = 0.55$) explained the least amount of variability among the various tree components and dimensions reported.

When dbh was modeled for predicting the specific gravity and bark to stem wood ratio, very low R^2 values ($\leqslant 0.04$) were generated and did not meet several assumptions of normality for regression.

The specific gravity of the wood estimated for the study ranged between 0.37 and 0.48, which fell in the range for the Cupressaceae family (*i.e.*, median specific gravity 0.43) estimated by Chojnacky *et al.* [6]. Interestingly, during the development of this database no redwood trees were included [6]. While the oven-dry weight for wood (comprising merchantable sawlog) and volume of bole were estimated from a timber production point of view, TAGB and other tree component models were generated considering the ecological significance of the species in the region.

The destructive sampling techniques used to create allometric model for this study did not completely sample the crown. Instead, the total biomass of the crown was estimated by regressing branch weight based on basal diameter and other parameters, rather than crown mass ratio [4,37].

Models for estimating TAGB and foliage were developed using 29 trees, while all other tree components were estimated using 26 trees because the additional three trees were 1–3 years old saplings (dbh below 6.35 cm) (Table 3). Regressions done on the live, and dead branch components using 29 trees lowered the R^2 from 0.88 to 0.79 and 0.57 to 0.13 respectively. The high reduction in R^2 for the dead branches were due to low sampling population for the saplings. Consequently, for these biomass components, models having 29 observations were also not included in the final results. Allometric models developed for other species, like *Cordia alliodora*, have also shown similar trends, with trees (saplings) with diameter lesser than 5 cm not generating reasonable prediction (R^2 = 0.02) [45]. This possibly suggests that dbh might not perhaps be a good indicator of biomass components and tree dimensions for small diameter trees. Enquist [46] explains that fitting data for shrubs and saplings (with relatively few branches) can result in different exponents from trees. Additionally, the very concept behind scaling theories is based on sample populations being consistent across size classes; fitting models to sub-sets of data is contrary to that principle [44,47,48]. Hence, the dbh range for TAGB and foliage was 2.54–84.07 cm and for all other tree components and dimensions were 8.25–84.07 cm.

Table 4. Localized allometric regression models developed to predict biomass and other tree components for coast redwood (*Sequoia sempervirens*) from industrial timberlands. All components were expressed in oven dry kilograms (ODKg); except for total height (H) and height to live crown (m) and volume of bole (m^3). The number of observations for all components was 26, except for total aboveground biomass (TAGB) and foliage (n = 29). All models and their parameters were significant at $p < 0.001$.

	Intercept	dbh [a]	H [b]	R^2	Adjusted R^2	RMSE [c]	CF [d]
TAGB	−0.8252	2.2607		0.9878	0.9874	0.1036	0.0054
Biomass Components							
Bole (stem) [e]	−0.9180	2.2931		0.9740	0.9729	0.1118	0.0062
Live branch	−1.8562	2.0382		0.8804	0.8754	0.2242	0.0251
Dead branch	−3.5952	2.3257		0.5766	0.5589	0.5948	0.1769
Foliage	−1.3094	1.5819		0.9386	0.9364	0.1669	0.0139
Bark	−1.9063	2.4469		0.9787	0.9779	0.1076	0.0058
Tree dimensions							
Wood [f]	−0.9553	2.2613		0.9710	0.9698	0.1167	0.0068
Height	0.4943	0.5808		0.8511	0.8449	0.0725	0.0026
Volume of bole [g]	−3.5879	2.2859		0.9690	0.9677	0.1220	0.0074
Height to live crown	−0.1241		0.8791	0.6715	0.6572	0.1176	0.0069
Height to live crown	0.3275	0.5034		0.5529	0.5335	0.1372	0.0094

[a] dbh—diameter at breast height in centimeters; [b] H—total tree height in meters; [c] RMSE—root mean square error; [d] correction factor, $CF = \frac{SE^2}{2}$, where SE is the standard error; [e] Biomass in stump, bole and bark up to the top 2.54 cm diameter; [f] Biomass in bole (main stem) including bark above the stump; [g] volume of bole including bark above the stump.

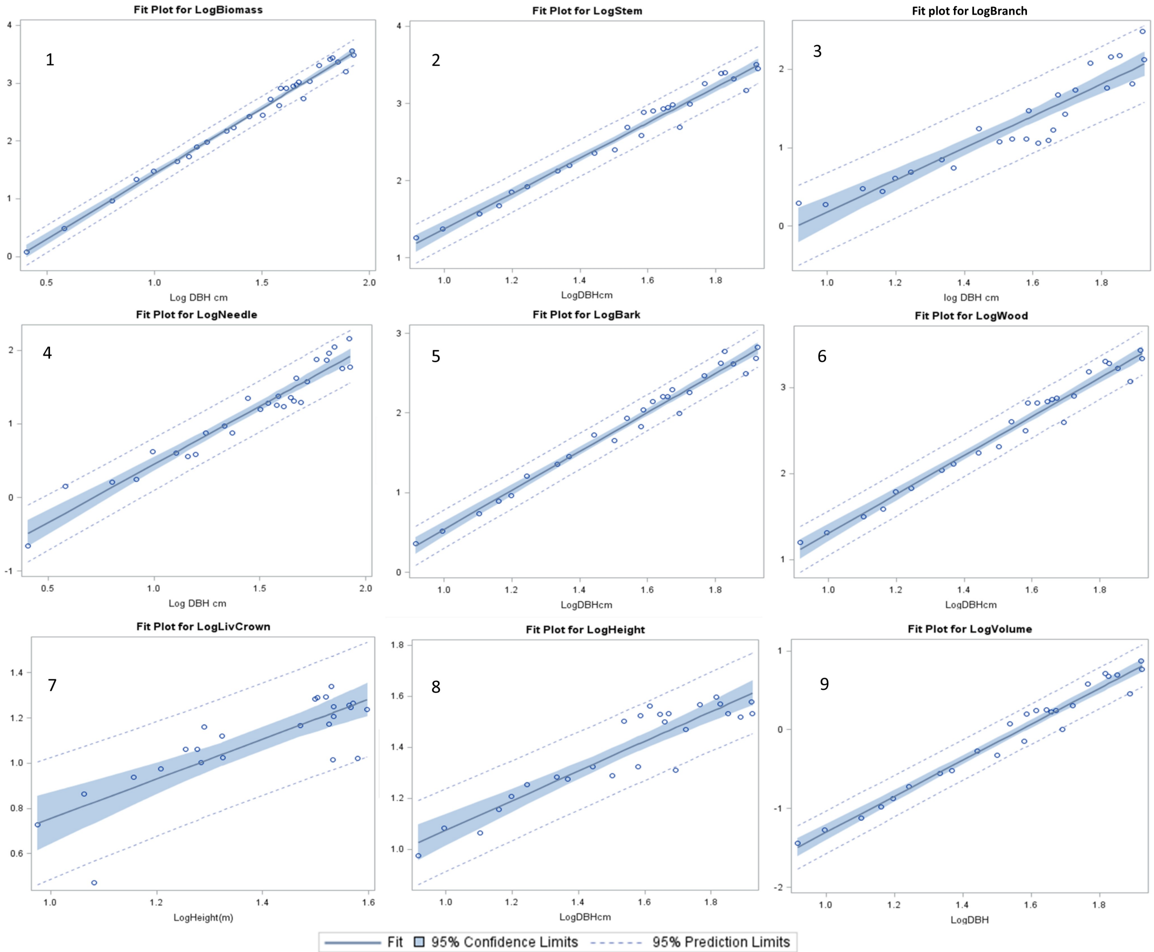

Figure 2. The logarithmic regression transformation for selected tree components for coast redwood (*Sequoia sempervirens*), including (**1**) total aboveground biomass; (**2**) bole; (**3**) live branch; (**4**) foliage; (**5**) bark and tree dimensions; (**6**) weight of wood; (**7**) height to live crown; (**8**) height of tree; and (**9**) volume of bole. All models were significant ($p < 0.001$).

3.1. Model Selection

Attempts were made to develop models for estimating TAGB and volume of bole wood based on both dbh and H. However, both these models only had a slight increase in R^2, (around 2% increase compared to R^2 for the model only with dbh) and it had higher Akaike Information Criterion (AIC) (~134) than the dbh based model (AIC~108), suggesting that the model with both dbh and H was a bad fit. Or in other words, H did not contribute more to the reduction in mean square error than the loss of a degree of freedom cost. Additionally, dbh and H of trees are usually highly correlated for trees from the same site [49]. Coon's [50] efforts on validating existing biomass models for Douglas-fir uncovered a strong bias for managed stands where the relationship between H and dbh had been manipulated through thinning and fertilization. For estimating the height to live crown, the allometric equation using H as the independent variable was able to explain more variance ($R^2 = 0.88$) as compared to dbh ($R^2 = 0.50$). However, the dbh model was also reported, as dbh is a convenient independent variable that can be easily measured in the field.

3.2. Comparing with Previous Studies

The results of this study were not compared with the models developed by Fujimori [17] due to its limited dbh range (less than 10 cm) and the study being carried out in a different ecological conditions (*i.e.*, old growth stand). However, the model developed in this study was compared with the widely used model to predict TAGB for coast redwood trees (Equation (1)) [12] and recently developed (Equation (2)) [6]. The models developed by Jenkins *et al.* [12] for Equation (1) were initially modeled for a species group called "Cedar–Larch" and consisted of meta-data from five genera of trees. The recently developed model had three subsets of equations for the Cupressaceae family based on the median specific gravity (*i.e.*, 0.29, 0.34 and 0.43) [6]. For this comparison, Equation (2) which has median specific gravity of 0.43, was chosen because the specific gravity for wood in this study averaged 0.40.

$$\ln\,(TAGB) = -2.0336 + 2.2592\ln\,(dbh) \tag{1}$$

$$\ln\,(TAGB) = -2.6327 + 2.4757\ln\,(dbh) \tag{2}$$

where ln—natural log to base "e" (2.7182); TAGB—total aboveground biomass in ODKg; *dbh*—diameter at breast height (cm).

Results showed the national generalized models had different effects when compared to the localized equation developed for the study. While Equation (1) tended to underrepresent TAGB by approximately 14%, Equation (2) over-represented (Figure 3). The deflection from the values predicted by the localized equation increased with increments in dbh. However, the values of "b" coefficient from both generic models were found to be very similar to the value developed in this study (2.2592 and 2.4757 *vs.* 2.2607). The minimal change could be attributed to the 'local' influence in this study compared to the more extensive area and wider range of species used for the nationalized model. Previous research has also recorded this inconsistency for other species while estimating TAGB using generalized models for local regions [51,52]. Additionally, comparisons were done with the models used by the FIA to predict biomass present in the bolewood [22–24]. The results showed that FIA models under represented biomass in bole by around 24%.

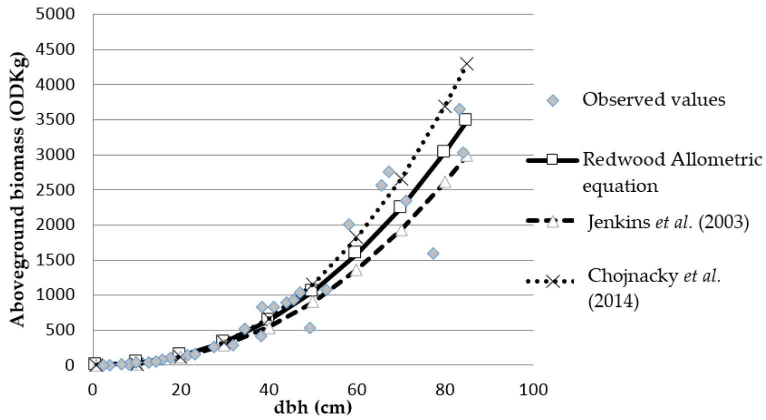

Figure 3. Graph of localized allometric models compared with Jenkins *et al.* [12] and Chojnacky *et al.* [6] for predicting total aboveground biomass of coast redwood in Oven Dry Kilogram (ODKg) against dbh (diameter at breast height).

Berrill *et al.* [53] reported that in redwood trees several factors, such as H, crown ratio, and H: dbh ratio were often affected to different degreees by stand density which must therefore impact the TAGB and other biomass components. Thus, the model provided in this study may be more suitable for research and management decisions for the second growth even-aged timberstands.

The study site represented a typical industrial timberland in the region based on species composition, terrain features and basal area factors. Models for estimating biomass for other species have also been done on small sampling area, and population size, especially for artificially planted industrial timberland in temperate regions where species variability is lesser when compared to natural tropical forest having higher variability among and within species. The case is also similar for single species than for a group of species [1]. Sampling area in natural habitats has also been as low as with 19 tree [4,54,55]. Cole and Ewel [45] developed allometric models for four species, *Cedrela odorata*, *Cordia alliodora*, *Hyeronima alchorneoides*, and *Euterpe oleracea*, from data drawn from an 8 ha study site. One of the probable reasons for this limitation could be the high cost of sampling larger populations. Additionally, the previous two studies done to estimate above ground biomass for coast redwood were conducted on a single plot with an area of 1.44 ha [17,18].

3.3. Scope and Limitations of Application

Since the study focused on developing a localized model, application outside the particular ecosystem should be done with caution [51]. The stands in this study can be characterized as even-aged, with multiple species and having a maritime influence. Furthermore, the samples collected in the study did not include trees in clumps. Therefore, this model would not be suitable for such conditions. Additionally, due to the huge size that certain redwood trees can reach, the use of these models should be restricted to the given dbh range. Application outside the range may produce biased estimates.

The possible model verification options were limited for this study due to the small sample size [48]. However, an in-model verification was done to check the behavior of the models by randomly sub-classifying the observations (K-fold cross validation) and results showed a significant difference ($p > 0.05$). Future studies for estimating total above ground biomass in coastal redwood may incorporate collecting more samples from a broader range of regions. It would also be advisable to include trees in different stand density and height classes [50,53]. Finally, the difference in total above ground biomass between trees regenerated from sprouts and seeds would be interesting.

4. Conclusions

Redwood is a major merchantable timber species in northwestern California. They also have a critical role in the ecosystem. Six models were developed in this study to predict biomass components, including TAGB, bole, bark, foliage, live and dead branches. Additionally, five allometric models were developed for structural tree dimensions including height to live crown, height of the tree, weight and volume of bole. The following highlights the main results from this study:

1. Compared to the results of this study, previous generic allometric models published [5,6,12,21–25] estimated different values for TAGB.
2. Biomass components and tree dimensions, in general, were closely related to the dbh and were able to account for around 90% of the variance.
3. The study site can be characterized as a second-growth even-aged stand and the dbh range for candidate trees used to estimate TAGB and foliage was 2.54–84.07 cm, while for all other tree components and dimensions the range was 8.25–84.07 cm.

Acknowledgments: This project was supported by the Agriculture and Food Research Initiative, Biomass Research and Development Initiative, Competitive Grant No. 2011-10006-30357 from the USDA National Institute of Food and Agriculture, USA. We would also like to express our gratitude to San-Kyun Han, Timothy Montgomery, and Joel Bisson, Humboldt State University, Arcata, CA, USA for assisting in data collection, R. Coltrin, for the roles he took during the initial part of the study, and to Martin Ritchie, Aaron Weiskittel, Jereme Frank, and John-Pascal Berrill, for their valuable suggestions during the manuscript preparation. Our appreciation goes to Michael Alcorn and Daniel Opalach (Green Diamond Resource Co.) for their cooperation on the operational aspect of the study.

Author Contributions: Han-Sup Han conceived, designed and performed the experiments; Anil Raj Kizha analyzed the data and wrote the article.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

dbh	diameter at breast height
H	Height
Ln	natural logarithm
log10	Log to the base of 10
ODKg	Oven dry kilogram
TAGB	Total Aboveground Biomass

References

1. Picard, N.; Saint-André, L.; Henry, M. Manual for building tree volume and biomass allometric equations from field measurement to prediction. In *Food and Agriculture Organization of the United Nations and Centrede Coopération*; Internationale en Recherche Agronomique pour le Développement (CIRAD): Rome, Italy, 2012; p. 215.
2. Niklas, K.J. *Plant Allometry: The Scaling of Form and Process*; University of Chicago Press: Chicago, IL, USA, 1994.
3. Wang, C. Biomass allometric equations for 10 co-occurring tree species in Chinese temperate forests. *For. Ecol. Manag.* **2006**, *222*, 19–16. [CrossRef]
4. Basuki, T.M.; van Laake, P.E.; Skidmore, A.K.; Hussin, Y.A. Allometric equations for estimating the above-ground biomass in tropical lowland Dipterocarp forests. *For. Ecol. Manag.* **2009**, *257*, 1684–1694. [CrossRef]
5. Jenkins, J.C.; Chojnacky, D.C.; Heath, L.S.; Birdsey, R.A. National-scale biomass estimators for United States tree species. *For. Sci.* **2003**, *49*, 12–35.
6. Chojnacky, D.C.; Jenkins, J.C.; Heath, L.S. Updated generalized biomass equations for North American tree species. *Forestry* **2014**, *87*, 129–151. [CrossRef]
7. Koukoulomatis, K.; Mitsopoulos, J.D. Crown fuel weight estimation of Black pine (*Pinus nigra*) plantations in southern Bulgaria. *Silva Balc.* **2007**, *8*, 57–65.
8. Cobb, R.C.; Chan, M.N.; Meentemeyer, R.K.; Rizzo, D.M. Common factors drive disease and coarse woody debris dynamics in forests impacted by Sudden Oak death. *Ecosystems* **2012**, *15*, 242–255. [CrossRef]
9. Huang, S.; Crabtree, R.L.; Potter, C.; Gross, P. Estimating the quantity and quality of coarse woody debris in Yellowstone post-fire forest ecosystem from fusion of SAR and optical data. *Remote Sens. Environ.* **2009**, *113*, 1926–1938. [CrossRef]
10. Vitorelo, B.D.; Han, H.-S.; Elliot, W. Cost and productivity of two mechanical fire hazard reduction methods: Mastication and thinning. *For. Prod. J.* **2011**, *61*, 664–674.
11. Kizha, A.R.; Han, H.-S. Forest residues recovered from whole-tree timber harvesting operations. *Eur. J. For. Eng.* **2015**, *1*, 46–55.
12. Jenkins, J.C.; Chojnacky, D.C.; Heath, L.S.; Birdsey, R.A. *Comprehensive Database of Diameter-Based Biomass Regressions for North American Tree Species*; USDA Forest Service General Technical Report NE-319; Northern Research Station: Burlington, VT, USA, 2004; p. 48.
13. Woodall, C.W.; Heath, L.S.; Domke, G.M.; Nichols, M.C. *Methods and Equations for Estimating Aboveground Volume, Biomass, and Carbon for Trees in the U.S. Forest Inventory 2010*; USDA Forest Service General Technical Report NRS-88; Northern Research Station: Newtown Square, PA, USA, 2011; p. 34.
14. Woudenberg, S.W.; Conkling, B.L.; O'Connell, B.M.; LaPoint, E.B.; Turner, J.A.; Waddell, K.L. *The Forest Inventory and Analysis Database: Database Description and Users Manual Version 4.0 for Phase 2*; USDA Forest Service General Technical Report RMRS-GTR-245; Rocky Mountain Research Station: Fort Collins, CO, USA, 2010; p. 344.
15. Stewart, W. *The New Economies of the Redwood Region in the 21st Century*; USDA Forest Service General Technical Report PSW-GTR-194; Pacific Southwest Research Station: Albany, CA, USA, 2007; pp. 393–401.
16. Standiford, R.B. Trends in harvest levels and stumpage prices in coastal California. In *Forest Research and Outreach*; Cooperative Extension Forestry; University of California: Berkeley, CA, USA, 2012.
17. Fujimori, T. *Ecological and Silvicultural Strategies for Sustainable Forest Management*; Elsevier Science: Amsterdam, Netherland, 2001.

18. Busing, R.T.; Fujimori, T. Biomass, production and woody detritus in an old coast redwood (*Sequoia sempervirens*) forest. *Plant Ecol.* **2005**, *177*, 177–188. [CrossRef]
19. Fujimori, T. Stem biomass and structure of a mature *Sequoia sempervirens* stand on the Pacific Coast of northern California. *J. Jpn. For. Soc.* **1977**, *59*, 435–441.
20. Lindquist, J.L.; Palley, M.N. *Empiricial Yield Tables for Young-Growth Redwood*; California Agricultural Experiment Station; University of California: Berkeley, CA, USA, 1963.
21. Wensel, L.C.; Krumland, B. *Volume and Taper Relationships for Redwood, Douglas Fir Other Conifers in California's North Coast*; Division of Agricultural Sciences; University of California: Berkeley, CA, USA, 1983.
22. Wensel, L.C.; Olson, C.M. Tree taper models for major commercial California conifers. *Hilgardia* **1995**, *62*, 1–18.
23. Wensel, L.C.; Krumland, B.E.; Meerschaert, W.J. *CRYPTOS User's Guide: Cooperative Redwood Yield Project Timber Output Simulator*; Bulletin 1924, Agricultural Experiment Station; University of California: Berkeley, CA, USA, 1987; p. 89.
24. Krumland, B.E.; Wensel, L.C. *Preliminary Young Growth Volume Tables for Coastal California Counties*; Res. Note No. 1; Cooperative Redwood Yield Research Project; University of California: Berkeley, CA, USA, 1975; p. 18.
25. Forest Inventory and Analysis (FIA). National Core Field Guide: Field Data Collection Procedures for Phase 2 Plots Version 6.0. Available online: http://www.nrs.fs.fed.us/fia/data-collection/field-guides/p2/NRS_FG_6.0-Apri_2014-Complete_Document_NRSP2plus.pdf (accessed on 22 April 2016).
26. California Department of Park and Recreation (CaDPR). About Coast Redwoods. Available online: http://www.parks.ca.gov/?page_id=24200 (accessed on 23 October 2014).
27. Griffith, R.S. Sequoia sempervirens. In *Fire Effects Information System*; USDA Forest Service; Available online: http://www.fs.fed.us/database/feis/ (accessed on 1 September 1992).
28. Busing, R.T.; Fujimori, T. NPP Temperate Forest: Humboldt Redwoods State Park, California, U.S.A., 1972–2001. Available online: http://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=803 (accessed on 22 April 2016).
29. Munz, P.A. *A Flora of Southern California*; University of California Press: Berkeley, CA, USA, 1974.
30. Olson, D.F.; Roy, D.F.; Walters, G.A. *Sequoia Sempiervirens* (D. Don) Endl. In *Silvics of North America. Conifers*; Burns, R.M., Honkala, B.H., Eds.; USDA Forest Service: Washington, DC, USA, 1990; pp. 541–552.
31. Preston, R.J. *North American Trees*; the Iowa State College Press: Ames, IA, USA, 1948.
32. Western Regional Climate Center (WRCC). Willow Creek 1 NW, California-Climate Summary. Available online: http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?cawilc+nca (accessed on 29 May 2015).
33. WWF Global. Pacific Temperate Rainforests. Available online: http://wwf.panda.org/about_our_earth/ecoregions/pacific_temperate_rainforests.cfm (accessed on 20 October 2014).
34. Stuart, J.D. Fire history of an old-growth forest of *Sequoia sempervirens* (Taxodiaceae) forest in Humboldt Redwoods State Park, California. *Madrono* **1987**, *4*, 128–141.
35. Stone, E.C.; Vasey, R.B. Preservation of coast redwoods on alluvial flats. *Science* **1968**, *15*, 157–161. [CrossRef] [PubMed]
36. Veirs, S.D. Coast redwood forest: Stand dynamics, successional status, and the role of fire. In *Forest Succession and Stand Development Research in the Pacific Northwest*; Means, J.E., Ed.; Oregon State University Forest Research Lab: Corvallis, OR, USA, 1982; pp. 119–141.
37. Monserud, R.A.; Marshall, J.D. Allometric crown relations in three northern Idaho conifer species. *Can. J. For. Res.* **1999**, *29*, 521–535. [CrossRef]
38. Snell, J.A.K.; Little, S.N. *Predicting Crown Weight and Bole Volume of Five Western Hardwoods*; USDA Forest Service General Technical Report PNW-151; Pacific Northwest forest and range experiment station: Portland, OR, USA, 1983; p. 37.
39. European Committee for Standardization. *Solid Biofuels-Determination of Moisture Content-Oven Dry Method-Part 1: Total Moisture-Reference Method*; FprEN 14774-1; Management Centre: Brussels, Belgium, 2009; p. 8.
40. Parresol, B.R. Assessing tree and stand biomass: A review with examples and critical comparisons. *For. Sci.* **1999**, *45*, 573–593.
41. Sokal, R.R.; Rohlf, F.J. *Biometry: The Principles and Practice of Statistics in Biological Research*; W.H. Freeman and Co.: New York, NY, USA, 1995.

42. Spruge, D.G. Correcting for bais in Log transformed allometric equations. *Ecology* **1983**, *64*, 209–210. [CrossRef]
43. SAS Institute Inc. *SAS 9.1.3 Help and Documentation*; SAS Institute Inc.: Cary, NC, USA, 2004.
44. Baskerville, G.L. Use of Logarithmic regression in the estimation of plant biomass. *Can. J. For. Res.* **1972**, *2*, 49–53. [CrossRef]
45. Cole, T.G.; Ewel, J.J. Allometric equations for four valuable tropical tree species. *For. Ecol. Manag.* **2006**, *229*, 351–360. [CrossRef]
46. Enquist, B.J. Universal scaling in tree and vascular plant allometry: Toward a general quantitative theory linking plant form and function from cells to ecosystems. *Tree Physiol.* **2002**, *22*, 1045–1064. [CrossRef] [PubMed]
47. Gould, S.J. Allometry and size in ontogeny and phylogeny. *Biol. Rev.* **1966**, *41*, 587–640. [CrossRef] [PubMed]
48. Sileshi, G.W. A critical review of forest biomass estimation models, common mistakes and corrective measures. *For. Ecol. Manag.* **2014**, *329*, 237–254. [CrossRef]
49. Fehrmann, L.; Kleinn, C. General considerations about the use of allometric equations for biomass estimation on the example of Norway spruce in central Europe. *For. Ecol. Manag.* **2006**, *236*, 412–421. [CrossRef]
50. Coons, K.L. *Douglas–fir (Psuedotsuga menziesii) Biomass and Nutrient Removal under Varying Harvest Scenarios Involving Co-Production of Timber and Feedstock for Liquid Biofuels*; Master of Science; Oregon State University: Corvallis, OR, USA; 19; December; 2014.
51. Fried, J.S.; Zhou, X. *Forest Inventory-Based Estimation of Carbon Stocks and Flux in California Forests in 1990*; USDA Forest Service General Technical Report PNW-GTR-750; Pacific northwest forest and range experiment station: Portland, OR, USA, 2008; p. 32.
52. Case, B.S.; Hall, R.J. Assessing prediction errors of generalized tree biomass and volume equation for the boreal forest region of west-central Canada. *Can. J. For. Res.* **2008**, *38*, 878–889. [CrossRef]
53. Berrill, J.-P.; Jeffress, J.L.; Engle, J.M. Coast redwood live crown and sapwood dynamics. In *Proceedings of Coast Redwood Forests in a Changing California: A Symposium for Scientists and Managers*; Standiford, R.B., Weller, T.J., Piirto, D.D., Stuart, J.D., Eds.; USDA Forest Service General Technical Report PSW-GTR-238; Pacific Southwest Research Station: Albany, CA, USA, 2012; pp. 473–484.
54. Segura, M.; Kanninen, M. Allometric models for tree volume and total aboveground biomass in a tropical humid forest in Costa Rica. *Biotropica* **2005**, *37*, 2–8. [CrossRef]
55. Litton, C.M.; Kauffman, J.B. Allometric models for predicting aboveground biomass in two widespread woody plants in Hawaii. *Biotropica* **2008**, *4*, 313–320. [CrossRef]