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Silvicultural manipulation and site effect on above and belowground biomass equations for young *Pinus radiata*

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ABSTRACT

There is little understanding of how silvicultural treatments, during the early stages of tree development, affect allometric relationships. We developed and compared stem, branch, foliage, coarse and fine root biomass, and leaf area estimation equations, for four-year-old genetically improved radiata pine trees grown on three contrasting soil-site conditions. At each site, selected trees were destructively sampled from a control (shovel planted, no weed control, fertilized with 2 g of boron), a shovel planted + weed control (2 first years) + complete fertilization (nitrogen + phosphorus + boron 2 first years + potassium 2nd year), and a soil tillage (subsoil at 60 cm) + weed control (first 2 years) + complete fertilization treatment. Tissues were separated into foliage, branch, stem, fine and coarse roots (>2 mm). Regression equations for each tree biomass tissue versus leaf area were fit for each site and compared among treatments and sites with the same genetic material. Our results indicated that individual tree biomasses for young plantations are affected by silvicultural treatment and site growing conditions. Higher variability in estimates was found for foliage and branches due to the ephemeral nature of these components. Stem biomass equations vary less, but differences in biomass equations were found among sites and treatments. Coarse root biomass estimates were variable but less than expected, considering the gradient among sites. Similar to stem biomass, a simple positive general linear relationship between root collar diameter, or diameter at breast height with coarse roots biomass was developed across sites and treatments.

1. Introduction

Radiata pine is one of the major commercial species in the world with approximately 4 million ha in plantations [1]. Considering the increasing interest to account for carbon credits [2–5] adequate biomass estimates are required to improve carbon estimates from forest plantations at different stages of development. Individual allometric relationships, based on tree diameter (DBH) and height (H), have been the major tool to obtain biomass estimates at the tree and stand level [6]. However, there is limited research indicating specifically how biomass allometric relationships are affected by silvicultural treatments, genetic material and/or site-specific limitations. Estimates of above and belowground biomass accumulation are also of critical importance to understand how site-specific resources (light, water,

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nutrients) may affect individual tree growth and stand productivity [7].

For radiata pine, most of the literature on biomass equations has been focused on developing relationships for different ages, planting densities, thinning and pruning regimes [4,8,9]. However, as shown by major recent reviews [4,9], there is limited availability of equations for young radiata pine. Given the large body of research quantifying how silvicultural treatments (soil preparation, weed control, fertilization) and genetic material affect tree growth and morphology (taper, specific density, leaf area), the lack of published allometric relationships for young radiata pine is surprising. The period of early tree growth and stand development before canopy closure represents one of the most critical stages in stand development [10]. This period has been described by growth response types based on how silvicultural manipulations affect site resources and the access to site resources by crop trees [11–13]. Planted tree crop interactions with weeds, site fertility and soil physical properties may affect patterns of biomass accumulation of radiata pine [14–19] and their effects may be long-term [20]. Therefore, changes in young tree allometrics may provide an understanding on how future biomass accumulation and partitioning will be affected [21]. Quantifying silvicultural effects on allometric relationships will be a further step in current efforts to model and forecast early plantation development [22–24]. Incorporation of this information into empirical, process based, or hybrid models, may allow for further improvements in decision-making processes [10,25].

The objective of this study was to develop and compare above and belowground biomass equations for young radiata pine from three sites with different silvicultural treatment intensities.

2. Materials and methods

2.1. Sites characteristics

Three sites with three to four year old plantations were selected to represent contrasting major soil types and climatic range in the central Valley of Chile (Table 1, Fig. 1). The sites considered andesitic-basaltic dry sands (Dry Sands), old volcanic ash red clay soils (Red Clay) and recent volcanic ash loamy soils (Recent Volcanic). During May or June 2000, a broadcast vegetation control treatment (Glyphosate 2 kg ha^{-1} + Atrazine 3 kg ha^{-1} + Galactic surfactant 1 ml L^{-1}) was applied prior to planting at each site to reduce pine volunteers and competing vegetation.

2.2. Experimental design

The experimental design was planned as a split-plot design with the main plots testing the effects of soil tillage (shovel vs. subsoil at 80 cm + mounding 20 cm). However, due to logistical issues related to timing of tillage operations, soil tillage treatments were applied prior to plot establishment. The tillage main plots were randomly applied at each site and no bias was observed in plots established in the different tilled areas allowing us to complete analyses as a split-plot design. Main tillage plots were arranged in four blocks testing a factorial combination of weed control (none vs. two years 2 m band Glyphosate 2 kg ha^{-1} + Atrazine 3 kg ha^{-1} + Galactic surfactant 1 cm^3 L^{-1}) and fertilization (1.5 g boron at establishment vs. complete fertilization with 59 g N + 65 g P + 4.5 g B + 25 g K total considering establishment and a 2nd year application) as subplots. Fertilizers were applied around each

Table 1 – Location, climate, soil-site characteristics and initial stand information for the sites examined in this study.

Site Name	Dry Sands	Red Clay	Recent Volcanic
Latitude and longitude	37° 10′ 40″ S 72° 15′ 47″ W	37° 50′ 43″ S 72° 20′ 5″ W	39° 4′ 40″ S 72° 24′ 23″ W
Mean annual temperature (°C)	13.7	13.3	10.7
Mean annual rainfall (mm)	1168	1117	2184
Geology	Volcanic sands	Old volcanic ash	Recent volcanic ash
Soil taxonomic name	Fragmental, Thermic Dystric Xerorthents	Very fine, Mixed, Thermic Typic Rhodoxeralfs	Medial, Mesic Typic Haploxerands
Drainage	Somewhat excessively well	Well	Well
Family Genotype[a]	IF24	MP31	MP31
Past land use	2nd Rotation	2nd Rotation	Ex-pasture
Site Index at 20 years (m)	14.9	24.4	NA
Previous Rotation MAI at 24 years (m^3 ha^{-1} yr^{-1})	7.8	15.5	NA
Spacing (trees ha^{-1})	1250	1000	1000
Stand DBH mean (cm)	3.7	5.7	10.7
range (cm)	0.2–9.4	0.9–14	1.0–19.7
Sampled trees DBH mean (cm)	5.1	7.0	12.2
range (cm)	0.6–8.1	2.1–11.4	6.3–16.6
Stand H mean (cm)	2.8	4.1	6.0
range (cm)	0.2–5.6	1.3–7.6	1.2–9.7
Sampled trees H mean (cm)	3.3	4.9	6.6
H range (cm)	1.3–5.2	2.0–6.9	4.6–7.7

NA: Not available; MAI: Mean annual increment; H: Height; DBH: Diameter at breast height.

[a] Company codes for each genotype.

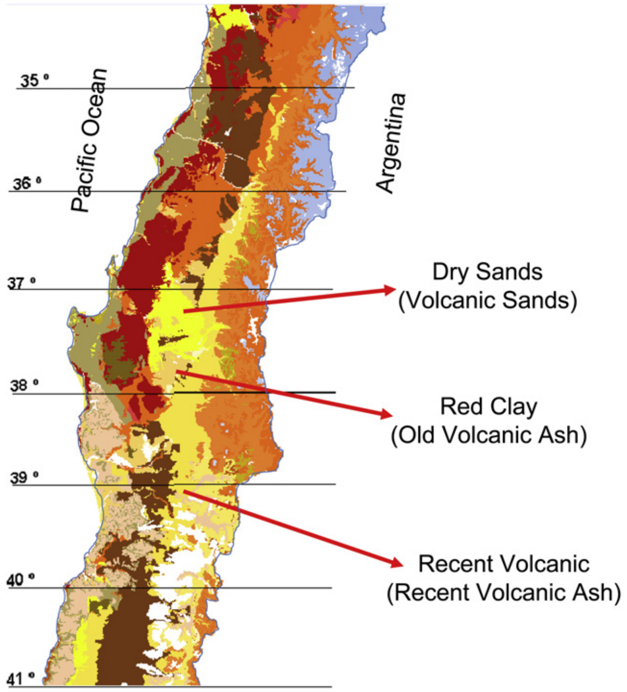

Fig. 1 – Location of the study sites in Chile.

plant at planting and along the band at year 2. Bareroot 1-0 radiata pine cuttings of the best genetic families were planted at each site during June and July 2000 at different spacing among sites (Table 1). Final treatment plots were 0.4 ha with an internal measurement plot ranging 0.09–0.12 ha for 100 measurement trees and a buffer area of 10 m on all sides.

2.3. *Aboveground and belowground biomass assessments*

The biomass study was undertaken during the 3rd and 4th year after establishment. Height (H), root collar diameter (RCD), and diameter at breast height (DBH) after the third year, were measured for each tree (Table 1). Based on volume growth results and potential effects of tillage on belowground biomass allocation, assessments were conducted on contrasting silvicultural treatments considering: a) a low intensity treatment (Low), including shovel planting, fertilization with only boron, and no weed control; b) a medium intensity treatment (Medium, M), including shovel planting, complete fertilization, and weed control; and c) a high intensity treatment (High, H), including subsoiling, complete fertilization, and weed control. These treatments allowed comparison of silvicultural intensity (Low, Medium, High) and site (DS, RC, RV) effects on equations to estimate individual tree biomass.

2.3.1. *Aboveground biomass*

From August to September 2004 (dormant season), biomass samples were obtained for aboveground and belowground biomass components for the range of tree sizes found at each site on the selected treatments (Table 1). Aboveground biomass sampling at Recent Volcanic included 5 trees each for the Low and High treatments. For Dry Sands and Red Clay sites, 5, 5, and 2 trees were sampled on Low, Medium and High treatments, respectively. Trees were felled at the ground line and divided into stem sections (wood + bark) and branches. Stem sample discs were obtained along the bole every 1 m for Dry Sands and Red Clay sites, and every 2 m for Recent Volcanic site, starting at 10 cm above ground level. Foliage and branchwood material were subsampled from branches from across the range of branch diameters (BD) and relative distance from the top of the tree (RDFT) found on the felled trees (6–28 branches per tree). Foliage and branch tissues were separated in the field for each sampled branch. In addition, foliage was separated by year of development and branch class (1st, 2nd, and 3rd order branch) based on cohort development and foliage size and color. Green weights of sample discs and stem sections were recorded in the field. Stem discs, branch, and foliage tissues were oven dried at 70 °C to a constant weight for moisture content determination. Field green weights of stem sections were then adjusted to dry weight. Tree stem biomass was calculated multiplying field green weights of stem sections by average dry weights of the corresponding top and bottom sample disc of each section. Branch and foliage biomass was estimated using a two-stage approach. First, foliage and branch biomass of individual branches were estimated using RDFT and BD based equations using data collected for all living branches on each felled tree (Equations (1), (2) and (3)). Second, branch estimates were then summed to provide total tree estimates of branch and foliage biomass.

2.3.2. *Belowground biomass*

Estimates of coarse (>2 mm diameter) and fine root (<2 mm diameter) biomass were obtained from 1 m × 1 m × 1 m excavated soil pits centered on the trees that were sampled for aboveground biomass. For each Low, Medium and High intensity treatments, 3 trees were sampled at Dry Sands, 2 trees were sampled at Red Clay, and 1 tree was sampled at Recent Volcanic site except for the High intensity treatment where only an average diameter tree (not sampled for aboveground analyses) was selected. Pits were excavated in 0.2 m increment soil layers to a depth of 1 m. Prior to removal of each layer, fine roots estimates were obtained by hammering six randomly distributed cores (5 cm diameter × 7.5 cm height) into the top of each layer. Live radiata pine coarse roots were visually separated by sieving each soil layer through a 5 mm mesh screen. Roots were kept cool and transported to the lab until further processing. Coarse roots were washed to remove soil particles. Fine roots were separated carefully from the soil using a combination of sieving and washing procedures based on soil-root adherence related with silt and clay content of the sample. Finally, coarse and fine roots samples were oven-dried at 70 °C to a constant weight.

2.3.3. *Leaf area*

Prior to oven-drying to a constant weight, foliage from each cohort year and branch class (1st, 2nd, and 3rd order branch) was subsampled for specific leaf area (SLA) determinations. Fifteen to 20 fascicles were randomly sampled for each branch, and projected leaf area was estimated using an optical projection system (AT Delta-T Devices Ltd.). Samples were then oven-dried, weighed, and specific leaf area (SLA) estimates were obtained. Leaf area estimates at the branch level were obtained by multiplying SLA by foliage dry weight for each foliage year-class for each sampled tree.

2.4. *Data analyses*

2.4.1. *Equations to estimate individual branch biomass*

Three components of branch biomass (foliage mass, leaf area, and branch mass) were regressed on the logarithm of branch diameter (BD) and the relative distance from the top of the tree (RDFT). Block and whole plots effects were included in the models. The response variables were transformed to logarithms or square roots based on graphical examination of the data. Logarithmic transformations of the type ln(1000*Y_i+1) for foliage biomass, ln(1000*Y_i) for branch biomass, and ln (Y_i+1) for leaf area, were used to avoid working with values close to zero. A stepwise procedure using BD and RDFT was used to select the best equation (Equations (1), (2) and (3)) for each transformed biomass component:

$$\ln(1000 * Y_i + 1) = a + b * \ln(BD_i + 1) + c * (RDFT_i^2 + 1) + \epsilon_i \qquad (1)$$

$$\ln(1000 * Yi) = a + b * \ln(BD_i + 1) + c * (\ln(BD_i + 1))^2 + d * (\ln(RDFT_i + 1)) + \epsilon_i \qquad (2)$$

$$\ln(Y_i + 1) = a + b * \ln(BD_i + 1) + c * (\ln(BD_i + 1))^2 + d * (\ln(RDFT_i + 1)) + \epsilon_i, \qquad (3)$$

where Y_i is the biomass (g, mg) or leaf area (cm^2) at the *i*th branch, BD is branch diameter in cm at the *i*th branch, RDFT is the relative distance of insertion of the branch from the top of the tree (0.0–1.0) at the *i*th branch, and ϵ_i is the error associated with the *i*th branch. Final equations were selected based on best fit, R^2 values, residuals analyses, variance inflation factors, and Mallow's Cp statistic.

Equations to estimate branch biomass were tested for site and treatment effects in the slope and intercept parameters. Because only two trees were sampled at High treatments for Dry Sands and Red Clay sites, Medium and High treatments trees were pooled together and called M&H to test for effects against the Low intensity silvicultural treatments at each site. Site and treatment specific individual branch regression equations were tested using regression analysis with indicator variables for each site and treatment combination (Equations (4), (5) and (6)):

$$\begin{aligned}\ln(1000 * Y_{ijklm} + 1) = {} & a + b * T_{k(i)} + c * R_l + d * (RW)_{lm} + p_i * Z_i \\ & + e * \ln(BD_{ijklm} + 1) + f * \ln\left(RDFT^2_{ijklm} + 1\right) \\ & + q_i * Z_i * \ln(BD_{ijklm} + 1) + r_i * Z_i \\ & * \ln\left(RDFT^2_{ijklm} + 1\right) + \epsilon_{ijklm}\end{aligned} \qquad (4)$$

$$\begin{aligned}\ln(1000 * Y_{ijklm}) = {} & a + b * T_{k(i)} + c * R_l + d * (RW)_{lm} + p_i * Z_i \\ & + e * \ln(BD_{ijklm} + 1) + f * (\ln(BD_{ijklm} + 1))^2 \\ & + g * \ln(RDFT_{ijklm} + 1) + q_i * Z_i * \ln(BD_{ijklm} + 1) \\ & + r_i * Z_i * (\ln(BD_{ijklm} + 1))^2 + s_i * Z_i \\ & * \ln(RDFT_{ijklm} + 1) + \epsilon_{ijklm}\end{aligned} \qquad (5)$$

$$\begin{aligned}\ln(Y_{ijklm} + 1) = {} & a + b * T_{k(i)} + c * R_l + d * (RW)_{lm} + p_i * Z_i \\ & + e * \ln(BD_{ijklm} + 1) + f * (\ln(BD_{ijklm} + 1))^2 \\ & + g * \ln(RDFT_{ijklm} + 1) + q_i * Z_i * \ln(BD_{ijklm} + 1) \\ & + r_i * Z_i * (\ln(BD_{ijklm} + 1))^2 + s_i \\ & * Z_i * \ln(RDFT_{ijklm} + 1) + \epsilon_{ijklm},\end{aligned} \qquad (6)$$

where Y_{ijklm} is the biomass (g, mg) or leaf area (cm^2), $T_{k(i)}$ is the random tree effect, R_l is the random effect associated with the *l*th block, $(RW)_{lm}$ is the whole plot random error associated with the *l*th block × *m*th soil tillage treatment, BD_{ijklm} is branch diameter in cm, $RDFT_{ijklm}$ is the relative distance of insertion of the branch from the top of the tree (0.0–1.0), Z_i is the indicator variable for site-treatment effects (Dry Sands-Low, Dry Sand-M&H, Red Clay-Low, Red Clay-M&H, Recent Volcanic-Low, Recent Volcanic-M), *a*, *b*, *c*, *d*, *e*, *f*, *g*, p_i, q_i, r_i and s_i are the coefficients of the model, ϵ_{ijklm} is the error of the model, $i = 1$ to 6 site-treatment combination, $j = 1,\ldots,n_{ik}$ branches in the *k*th tree at the *i*th site-treatment combination, $k = 1,\ldots,r_i$ tree at the *i*th site-treatment combination, $l = 1$ to 4 blocks and $m = 0$ or 1 site preparation treatment. For each equation, if interaction terms p_i, q_i, r_i, or s_i were not significant, the terms were dropped from the models and reduced models were tested for intercept differences between regressions for each component (Equations (7), (8) and (9)):

$$\begin{aligned}\ln(1000 * Y_{ijklm} + 1) = {} & a + b * T_{k(i)} + c * R_l + d * (RW)_{lm} + p_i * Z_i + c \\ & * \ln(BD_{ijklm} + 1) + e * \ln\left(RDFT^2_{ijklm} + 1\right) \\ & + \epsilon_{ijklm}\end{aligned} \qquad (7)$$

$$\begin{aligned}\ln(1000 * Y_{ijklm}) = {} & a + b * T_{k(i)} + c * R_l + d * (RW)_{lm} + p_i * Z_i \\ & + e * \ln(BD_{ijklm} + 1) + f * (\ln(BD_{ijklm} + 1))^2 \\ & + g * \ln(RDFT_{ijklm} + 1) + \epsilon_{ijklm}\end{aligned} \qquad (8)$$

$$\begin{aligned}\ln(Y_{ijklm} + 1) = {} & a + b * T_{k(i)} + c * R_l + d * (RW)_{lm} + p_i * Z_i + e \\ & * \ln(BD_{ijklm} + 1) + f * (\ln(BD_{ijklm} + 1))^2 + g \\ & * \ln(RDFT_{ijklm} + 1) + \epsilon_{ijklm}.\end{aligned} \qquad (9)$$

If slopes or intercepts were different for site-treatment effects ($p < 0.05$), separate regression equations were generated for sites and/or treatments using equations of the form

$$\begin{aligned}\ln(1000 * Y_{ijklm} + 1) = {} & a + b * T_{k(i)} + c * R_l + d * (RW)_{lm} + e \\ & * \ln(BD_{ijklm} + 1) + \epsilon_{ijklm}\end{aligned} \qquad (10)$$

$$\begin{aligned}\ln(1000 * Y_{ijklm}) = {} & a + b * T_{k(i)} + c * R_l + d * (RW)_{lm} + e * \ln(BD_{ijklm} \\ & + 1) + f * \left(RDFT^2_{ijklm} + 1\right) + \epsilon_{ijklm}\end{aligned} \qquad (11)$$

$$\begin{aligned}\ln(Y_{ijklm} + 1) = {} & a + b * T_{k(i)} + c * R_l + d * (RW)_{lm} + e * \ln(BD_{ijklm} \\ & + 1) + f * (\ln(BD_{ijklm} + 1))^2 + g * \ln(RDFT_{ijklm} + 1) \\ & + \epsilon_{ijklm},\end{aligned} \qquad (12)$$

where Y_{ijklm} is the biomass (g, mg) or leaf area (cm^2), $T_{k(i)}$ is the random tree effect, R_l is the random effect associated with the *l*th block, $(RW)_{lm}$ is the whole plot random error associated with the *l*th block × *m*th soil tillage treatment, BD_{ijklm} is branch diameter in cm, $RDFT_{ijklm}$ is the relative distance of insertion of the branch from the top of the tree (0.0–1.0), *a*, *b*, *c*, *d*, *e* and *f* coefficients of the model, ϵ_{ijklm} is the error of the model, $i = 1$ to

6 site-treatment combination, $j = 1,\ldots,n_{ki}$ branches in the kth tree at the ith site-treatment combination, $k = 1,\ldots,r_i$ tree at the ith site-treatment combination, $l = 1$ to 4 blocks and $m = 0$ or 1 site preparation treatment. Equations (10), (11), (12) were transformed back to the original scale to provide estimates of leaf area, foliage, and branch biomass using the correction factor for bias from back transformation from logarithmic scale suggested by Baskerville [26] with the form CF = exp (Mean Square Error/2).

2.4.2. *Individual tree foliage, branch, stem, leaf area, coarse and fine roots biomass equations*

Estimations of whole tree foliage, branch biomass, and leaf area were calculated by adding estimates generated by individual branch diameter regression equations. Individual tree biomass equations for stem, branch, foliage, coarse roots, fine roots, and leaf area were regressed on either logarithm of root collar diameter (RCD), logarithm of diameter at breast height (DBH) or logarithm DBH squared multiplied by tree height (DBH^2H). Individual tree biomass regression equations were tested for site and treatment effects for slope and intercept. Regression analyses used full models to test for differences in slope between sites or treatments of the form

$$\ln(Y_{ijlm}) = a + b * R_l + c * (RW)_{lm} + p_i * Z_i + d * \ln(X_{ijlm}) + q_i * Z_i * \ln(X_{ijlm}) + \epsilon_{ijlm}, \quad (13)$$

where Y_{ijlm} is biomass component (foliage, branch, stem) in grams, or leaf area in cm^2, X_{ijlm} is RCD, DBH, or DBH^2H, Z_i is the indicator variable for site-treatment effects, a, b, c, d, p_i, q_i are the coefficients of the model, ϵ_{ijlm} is the error of the model, $i = 1$ to 6 site-treatment combination, $j = 1,\ldots,n_i$ plot in the ith site-treatment combination, $l = 1$ to 4 blocks, $m = 0$ or 1 site preparation treatment. Given the smaller number of sampled trees for belowground assessments, coarse roots indicator variable Z_i considered Recent Volcanic Medium and High treatments together (Recent Volcanic-M&H), with $i = 1$ to 5 site-treatment combinations, and for fine roots Z_i considered only site effects for Dry Sand and Red Clay (Dry Sands-Low&M&H vs Red Clay Low&M&H) with $i = 1,2$. If no differences in slopes were found, the interaction term q_i was dropped and a reduced model was used to test for intercept differences between regressions (Equation 14). If slopes or intercepts were different ($p < 0.05$), separate regression equations were generated for sites and/or treatments using a simple model (Equation 15).

$$\ln(Y_{ijlm}) = a + b * R_l + c * (RW)_{lm} + p_i * Z_i + d * \ln(X_{ijlm}) + \epsilon_{ijlm}. \quad (14)$$

$$\ln(Y_{ijlm}) = a + b * R_l + c * (RW)_{lm} + d * \ln(X_{ijlm}) + \epsilon_{ijlm}. \quad (15)$$

Statistical analyses were performed using SAS software version 9.1 PROC GLM and PROC MIXED. Exploratory graphical analyses were performed using the software JMP version 5.1.2. A logarithmic transformation was applied to reduce data heterodasticity when needed [27].

2.4.3. *Comparison with published equations*

Published equations for above ground biomass for radiata pine stands of similar age and size were compiled, and graphically compared with our equations. Comparison of estimates from our models and published equations were performed using the range of height and diameter inventory data collected at the study sites.

3. Results

3.1. *Individual branch biomass equations*

Individual branch biomass estimates of foliage, branch mass, and leaf area were significantly related to BD and RDFT ($p < 0.01$). The equation form, intercept and slope coefficients, varied among sites and among treatments within site (Data not shown). For foliage and leaf area (LA) at Dry Sands one equation fit all intensity treatments. However, for branch biomass different intercepts and slope coefficients were obtained for Low vs. M&H at Dry Sands. At Red Clay, two separate equations were obtained, one for Low and other for the M&H treatments. Similar to Dry Sands, Recent Volcanic showed homogeneity of equations and coefficients for foliage and LA for all treatments but different intercept and slope coefficients were obtained for branch biomass on the Low and Medium treatments (Data not shown).

3.2. *Individual tree foliage, branch, stem, and leaf area biomass-equations*

Foliage biomass equations regressed with DBH or DBH^2H as independent variables differed only in intercept between Dry Sands-Low and Dry Sands-M&H. No differences in intercept or slope were observed for root collar diameter (Table 2). Branch biomass equations differed in slope between Red Clay-Low and Red Clay-M&H. Branch equation intercepts differed between Dry Sands and Red Clay sites for all independent variables and between Dry Sands-Low and Dry Sands-M&H for root collar diameter. For stem biomass, diameter at breast height based equations, showed differences in slopes and intercepts between Dry Sand-Low and Dry Sand-M&H, and root collar diameter based equations showed differences in intercepts for Red Clay-Low and Red Clay-M&H. For leaf area, all independent variables showed differences in slope between Red Clay-Low and Red Clay-M&H. Leaf area equation intercepts differed between Dry Sands and Red Clay sites for all independent variables and between Dry Sands-Low and Dry Sands-M&H for root collar diameter. Differences in slopes and intercepts resulted in single or multiple aboveground biomass equations across sites and treatments for each independent variable (Table 3, Fig. 2a,b).

Individual tree foliage, branch, stem biomass, and leaf area relationships with root collar diameter, diameter at breast height, or height were strong (Table 3, Fig. 2a,b). Coefficients of determination (R^2) ranged 0.76–0.91 for foliage, 0.80–0.97 for branches, 0.96–0.99 for stem, and 0.61–0.96 for LA. In general, lower values were associated with estimations for leaf area and foliage and higher values were associated with branch and stem biomass.

Table 2 – Statistical significance (p-value $> F$) indicating differences in slopes or intercepts for biomass equations for individual tree foliage, branch mass, stem, leaf area (m^2 tree^{-1}), coarse roots and fine roots using X_{ijlm} (RCD, DBH, DBH^2H) as independent variables. Site and treatment effects on slope and intercepts were tested using models (13) and (14).

Tests for differences in slopes (Full Model)	Foliage			Branch			Stem			Leaf Area			Coarse Roots		
	RCD	DBH	DBH^2H	RCD	DBH	DBH^2H	RCD	DBH	DBH^2H	RCD	DBH	DBH^2H	RCD	DBH	DBH^2H
DS-Low vs. M&H	0.418	0.601	0.369	0.550	0.761	0.487	0.075	**0.046**	0.226	0.365	0.615	0.377	**0.027**	0.484	0.347
RC-Low vs. M&H	0.124	0.059	0.065	**0.015**	**0.012**	**0.020**	0.524	0.646	0.378	0.052	**0.025**	**0.029**	0.375	0.558	0.471
RV-Low vs. M&H	0.941	0.421	0.829	0.372	0.149	0.500	0.675	0.263	0.554	0.806	0.340	0.649	NA	NA	NA
DS-M&H vs. RC-Low	0.329	0.514	0.492	**0.045**	0.116	0.144	0.812	0.483	0.666	0.318	0.509	0.485	**0.006**	0.831	0.835
RC-M&H vs. RV-Low	0.907	0.514	0.342	0.681	0.375	0.253	0.107	0.700	0.826	0.253	0.537	0.807	NA	NA	NA
Test for differences in intercepts (Reduced Model)															
DS-Low vs. M&H	0.360	**0.017**	**0.025**	**< 0.001**	0.271	0.273	0.383	**0.040**	**0.016**	0.083	**0.002**	**0.003**	0.688	0.485	0.347
RC-Low vs. M&H	0.302	0.244	0.169	0.109	0.157	0.292	**0.018**	**0.042**	0.160	0.930	0.812	0.597	0.545	0.558	0.471
RV-Low vs. M&H	0.088	0.995	0.926	0.733	0.053	0.080	0.166	0.177	0.284	0.513	0.310	0.388	NA	NA	NA
DS-M&H vs. RC-Low	0.059	0.153	0.148	**0.008**	**0.025**	**0.026**	0.216	0.275	0.254	**< 0.001**	**< 0.001**	**< 0.001**	0.168	0.414	0.835
RC-M&H vs. RV-Low	0.503	0.475	0.592	0.055	0.175	0.153	0.580	0.356	0.437	0.420	0.379	0.493	NA	NA	NA

Sites coded as DS = Dry Sand, RC = Red Clay, RV = Recent Volcanic Ash.

Silvicultural intensity treatments coded as Low = Low intensity, M&H = Medium and High Intensity.

X_{ijlm} is RCD, DBH or DBH^2H.

Z_i indicator variable with values 1 = DS-Low, 2 = DS-M&H, 3 = RC-Low, 4 = RC- M&H, 5 = RV-Low, 6 = RV-M&H.

$i = 1$ to 6 site-treatment combination.

$j = 1,\ldots n_i$ plot in the ith site-treatment combination.

$l = 1$ to 4 blocks.

$m = 0$ or 1 site preparation treatment.

RCD: Root collar diameter at 5 cm above ground level.

DBH: Diameter at breast height (cm).

H: Height of the tree (m).

NA: Not available.

Values in bold are significant at $p < 0.05$.

Table 3 – Individual tree biomass (kg tree^{-1}) and leaf area (m^2 tree^{-1}) regression equations for all sites and treatments. Model (15) transformed back[a] to the original scale to provide direct estimates of foliage, branch and stem is $Y = (\mathrm{EXP}(a + b{*}\ln(X)){*}\mathrm{CF}){*}10^{-3}$, and for leaf area is $Y = (\mathrm{EXP}(a + b{*}\ln(X)){*}\mathrm{CF}){*}10^{-4}$.

	RCD				DBH				DBH^{2}H			
Treatments[b]	a	b	CF	R^2-adj	a	b	CF	R^2-adj	a	b	CF	R^2-adj
	Foliage											
DS-Low	3.762**	1.855**	1.061	0.82	5.873**	1.552**	1.067	0.91	2.687**	0.630**	1.060	0.91
DS-M&H	3.762**	1.855**	1.061	0.82	5.428**	1.372**	1.063	0.88	2.321**	0.565**	1.063	0.86
RC-Low	3.762**	1.855**	1.061	0.82	5.428**	1.372**	1.063	0.88	2.321**	0.565**	1.063	0.86
RC-M&H	3.762**	1.855**	1.061	0.82	5.428**	1.372**	1.063	0.88	2.321**	0.565**	1.063	0.86
RV-Low	3.762**	1.855**	1.061	0.82	5.428**	1.372**	1.063	0.88	2.321**	0.565**	1.063	0.86
RV-M	3.762**	1.855**	1.061	0.82	5.428**	1.372**	1.063	0.88	2.321**	0.565**	1.063	0.86
	Branch											
DS-Low	2.281**	2.363**	1.016	0.94	5.072**	1.590**	1.037	0.96	1.902**	0.629**	1.038	0.96
DS-M&H	3.304*	2.103**	1.055	0.92	5.072**	1.590**	1.037	0.96	1.902**	0.629**	1.038	0.96
RC-Low	4.488**	1.267*	1.017	0.94	5.719**	0.903**	1.015	0.80	4.116**	0.333**	1.014	0.80
RC-M&H	2.129**	2.603**	1.015	0.94	3.400**	2.417**	1.033	0.78	−1.305^{ns}	0.934**	1.043	0.77
RV-Low	2.129**	2.603**	1.015	0.94	3.400**	2.417**	1.033	0.78	−1.305^{ns}	0.934**	1.043	0.77
RV-M	2.129**	2.603**	1.015	0.94	3.400**	2.417**	1.033	0.78	−1.305^{ns}	0.934**	1.043	0.77
	Stem											
DS-Low	2.447**	2.535**	1.021	0.97	5.447**	1.519**	1.025	0.97	2.355**	0.613**	1.023	0.97
DS-M&H	2.447**	2.535**	1.021	0.97	4.771**	1.877**	1.011	0.98	1.135**	0.728**	1.009	0.98
RC-Low	2.447**	2.535**	1.021	0.97	4.771**	1.877**	1.011	0.98	1.135**	0.728**	1.009	0.98
RC-M&H	3.775**	2.081**	1.008	0.95	4.623**	2.002**	1.004	0.98	1.135**	0.728**	1.009	0.98
RV-Low	3.775**	2.081**	1.008	0.95	4.623**	2.002**	1.004	0.98	1.135**	0.728**	1.009	0.98
RV-M	3.775**	2.081**	1.008	0.95	4.623**	2.002**	1.004	0.98	1.135**	0.728**	1.009	0.98
	Leaf Area											
DS-Low	7.666**	2.195**	1.042	0.79	10.302**	1.531**	1.006	0.96	7.156**	0.622**	1.055	0.96
DS-M&H	7.666**	2.195**	1.042	0.79	9.909**	1.401**	1.016	0.96	7.367**	0.526**	1.023	0.96
RC-Low	6.945**	2.054**	1.030	0.93	9.350**	1.151*	1.059	0.61	7.344**	0.420**	1.061	0.60
RC-M&H	6.945**	2.054**	1.030	0.93	7.812**	1.976**	1.027	0.90	3.935*	0.765**	1.032	0.88
RV-Low	6.945**	2.054**	1.030	0.93	7.812**	1.976**	1.027	0.90	3.935*	0.765**	1.032	0.88
RV-M	6.945**	2.054**	1.030	0.93	7.812**	1.976**	1.027	0.90	3.935*	0.765**	1.032	0.88
	Coarse Roots											
DS-Low	2.809*	2.548**	1.140	0.90	6.034*	1.310**	1.215	0.78	3.610**	0.495**	1.215	0.78
DS-M&H	2.809*	2.548**	1.140	0.90	6.034*	1.310**	1.215	0.78	3.610**	0.495**	1.215	0.78
RC-Low	4.488**	1.754**	1.048	0.93	6.034*	1.310**	1.215	0.78	3.610**	0.495**	1.215	0.78
RC-M&H	4.488**	1.754**	1.048	0.93	6.034*	1.310**	1.215	0.78	3.610**	0.495**	1.215	0.78
RV-Low&M	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Fine Roots											
DS-Low& M&H	1.699*	1.994**	1.045	0.90	4.017**	1.166*	1.063	0.96	2.884*	0.356**	1.059	0.96
RC-Low,RC-M&H	−1.848*	3.248**	1.010	0.92	0.7873^{ns}	2.529**	1.027	0.86	−1.375^{ns}	0.733**	1.018	0.88
RV-Low&M	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

X: is RCD, DBH, or DBH^{2}H.

RCD: Root collar diameter at 5 cm above ground level.

DBH: Diameter at breast height (cm).

H: Height of the tree (m).

NA: Not available.

CF: Correction factor for back transformation from log scale suggested by Baskerville (13).

**significant at $p < 0.01$, *significant at $p < 0.1$, ^{ns}not significant.

[a] Estimates from back-transformations were divided by 10^{-4} for leaf area estimates to convert cm^2 to m^2 per tree, and divided for 10^{-3} for foliage, branches, stem, coarse and fine roots to convert from grams to kg per tree.

[b] Sites coded as DS = Dry Sand, RC = Red Clay, RV = Recent Volcanic Ash; Selected treatments coded as Low = Low intensity treatment and M&H = Medium and high intensity treatments.

3.3. *Individual tree coarse and fine roots biomass equations*

Analyses for coarse roots biomass equations for DBH and DBH^{2}H independent variables differed in slope between Dry Sand-Low and Dry Sand-M&H, and between Dry Sands and Red Clay sites for root collar diameter (Fig. 2c). No differences in slopes or intercepts were found for DBH or DBH^{2}H across treatments or sites, allowing development of a strong simple linear relationship (Fig. 2d). For fine roots, considering all independent variables, only differences in intercepts were found between Dry Sands and Red Clay equations (p-values: 0.0003 for RCD, 0.0024 for DBH and 0.0043 for DBH^{2}H), with no treatment effects. Differences in slopes and intercepts resulted in single or multiple aboveground biomass equations across sites and treatments for each independent variable

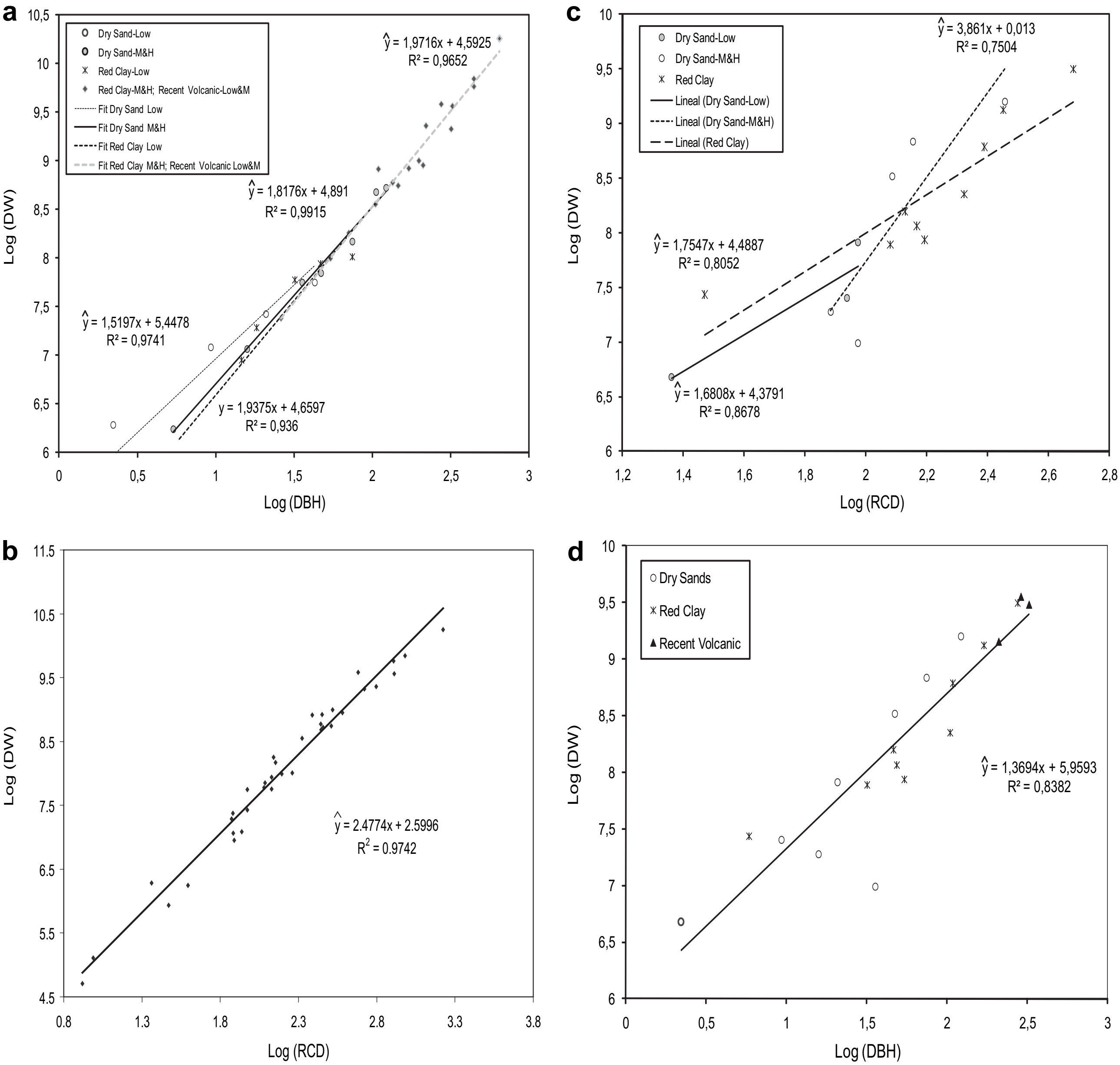

Fig. 2 – Stem biomass and coarse roots regression equations showing differences in slopes and intercepts among sites and treatments a) Equations between stem Log(DW) and Log(DHB), b) Equations between stem Log(DW) and Log(RCD), c) Relationship of coarse roots with RCD by treatment and site, d) Relationship of coarse roots with DBH, a similar relationship was observed with DBH^{2}H.

(Table 3). Final equations R^2 ranged from 0.60 to 0.96 for coarse roots, and 0.86 to 0.96 for fine roots. In general, stronger linear relationships were found for coarse roots and no significantly different from zero intercepts were observed in coarse roots vs. root collar diameter equations.

3.4. *Comparison with published equations*

Our relationships were compared with published equations from the literature for the same range of tree sizes and independent variables. A small number of published equations for young radiata pine plantations were found (Table 4). Several equations were discarded as they used diameter at the base of the live crown [9] or basal area [28,29] as independent variables.

4. Discussion

4.1. *Individual branch biomass Equations*

Relationships between foliage biomass and LA with all independent variables were weaker than the comparable branch biomass relationships (Table 3). One possible reason is that

Table 4 – Summary of biomass equations for young radiata pine trees published in the literature. Equations used to estimate biomass components are: A) $y = \exp(a)*(x)^b$, B) $y = \exp(a)*(x1)^b*((x1)^c)^2$, C) $y = \exp(a)*(x1)^b*((x2)^c)^2$, D) $y = \exp(a)*((x1)^b)^2$ and E) $y = \exp(a)*(x1*x2)^b$. Where y represents each biomass component dry weight, x1 and x2 independent variables, and *a*, *b* and *c* coefficients of each model.

Reference	Months (m) or years (y)	a	b	c	Ind.var.[a] x1,x2	Equation used	Units	Biomass Component
Stem								
O'Brien[b] [30]	10 m	2.822	2.086		RCD	A	g	Stemwood
O'Brien[b] [30]	16 m	2.681	2.072	0.159	RCD	B	g	Stemwood
O'Brien[b] [30]	22 m	2.360	2.550		RCD	A	g	Stemwood
O'Brien[b] [30]	28 m	5.210	0.850	0.290	DBH	B	g	Stemwood
O'Brien[b] [30]	34 m	5.330	0.850	0.290	DBH	B	g	Stemwood
Snowdon [46]	3–4 y	0.003	1.451	0.659	RCD, H	C	g	Stemwood + bark
Forrest [31]	5 y	−1.923	1.589		DBH	A	kg	Stemwood
Forrest [31]	7 y	−3.026	2.311		DBH	A	kg	Stemwood
Forrest [31]	9 y	−1.921	2.008		DBH	A	kg	Stemwood
Madgwick [9]	1–42 y	−3.097	0.849		DBH^2H	E	kg	Stemwood + bark
Bark								
O'Brien[b] [30]	10 m	2.215	1.640		RCD	A	g	NA
O'Brien[b] [30]	16 m	1.904	1.640	0.092	RCD	B	g	NA
O'Brien[b] [30]	22 m	1.820	1.930		RCD	A	g	NA
O'Brien[b] [30]	28 m	3.843	0.510	0.320	DBH	B	g	NA
O'Brien[b] [30]	34 m	4.013	0.510	0.320	DBH	B	g	NA
Forrest [31]	5 y	−3.541	1.384		DBH	A	kg	NA
Forrest [31]	7 y	−4.519	2.092		DBH	A	kg	NA
Forrest [31]	9 y	−3.153	1.667		DBH	A	kg	NA
Foliage								
O'Brien[b] [30]	10 m	3.673	1.600		RCD	A	g	NA
O'Brien[b] [30]	16 m	3.706	1.573	0.209	RCD	B	g	NA
O'Brien[b] [30]	22 m	3.110	2.191		RCD	A	g	NA
O'Brien[b] [30]	28 m	6.110	1.050		DBH	A	g	NA
O'Brien[b] [30]	34 m	6.140	1.050		DBH	A	g	NA
Forrest [31]	5 y	−2.014	1.652		DBH	A	kg	NA
Forrest [31]	7 y	−3.920	2.428		DBH	A	kg	NA
Forrest [31]	9 y	−1.315	1.155		DBH	A	kg	NA
Baker a [32]	4-49 y	−3.779	2.192		DBH	A	kg	NA
Baker b [32]	4-49 y	−3.365	1.893		DBH	A	kg	NA
Branches								
O'Brien[b] [30]	10 m	2.030	1.840		RCD	A	g	live
O'Brien[b] [30]	16 m	2.092	1.784	0.396	RCD	B	g	live
O'Brien[b] [30]	22 m	3.350	0.955		RCD	D	g	live
O'Brien[b] [30]	28 m	4.780	0.784		DBH	D	g	live
O'Brien[b] [30]	34 m	4.500	0.784		DBH	D	g	live
Forrest [31]	5 y	−3.881	2.506		DBH	A	kg	live
Forrest [31]	7 y	−6.804	3.669		DBH	A	kg	live
Forrest [31]	9 y	−3.313	1.939		DBH	A	kg	live
Baker a [32]	4–49 y	−4.332	2.413		DBH	A	kg	total
Baker b [32]	4–49 y	−4.727	2.459		DBH	A	kg	live

NA: Not applicable.

[a] RCD, DBH and H in cm, except for Madgwick [9] (H in m).

[b] Included additional equation for tip biomass estimates. See Snowdon [2] for details.

RDFT was the branch insertion location in the stem rather than the real position of foliage in the crown [33] and branch length was not included in the models [6]. Foliage is also a more ephemeral tissue component than branches and varies based on seasonal and site abiotic and biotic factors [33–37]. Longer soil-site resource availability effects on branch biomass were evident from differences in slope and intercepts of our final individual tree branch biomass equations for each site and treatment combination.

From all sites relationships, only the Red Clay site did not include RDFT as a regressor, suggesting that BD is more important than branch position in the crown for predicting foliage mass. Whitehead et al. [38] found a strong linear relationship between individual branch basal area and branch foliar area for a wide spacing trial. Major differences in foliage mass, related with its position in the crown, may be related to light availability (shading), foliage age class proportions on the branch, and specific leaf area [39–41]. For Recent Volcanic sites canopy closure may have imposed light limitations for lower branches affecting biomass estimates compared to other sites. Therefore, the similarity of equations between Red Clay and Dry Sands sites may also be explained by similarity in foliage senescence patterns [42,43].

Branch biomass equations were affected by intensity of silvicultural treatment but not by genetics when comparing Dry Sands versus RedClay equations. Results from growth analyses suggested that weed control effects affected branch production by increasing site fertility and other authors have observed similar effects by increased or reduced water availability [19,42,44–46].

4.2. *Individual tree foliage, branch, stem, and leaf area biomass equations*

Differences in slopes and intercepts suggest that single biomass equations for more ephemeral biomass components (e.g. foliage) at early stages of tree development are not valid across sites and silvicultural treatments. However, stem biomass equations were less site specific than other biomass components [47]. Similar findings have been reported by Naidu et al. [48] for loblolly pine. Snowdon [49], testing the homogeneity of biomass equations for young radiata families under fertilization, indicated that larger differences in biomass equations may be obtained among genetic materials than for nutrient additions. Our results suggest that effects of silvicultural treatments on biomass equations may be larger than genetic material when comparing Dry Sands M&H and Red Clays Low silvicultural intensity treatment. This difference in results may be related to the higher fertility of the site evaluated by Snowdon [44,50].

Lower intercepts and slopes in foliar equations may be reflecting larger differences in site resource availability [7,34]. Larger specific leaf areas were observed at Recent Volcanic sites compared to other sites [43]. For radiata pine, specific leaf area and total tree leaf area (foliage mass) increase by increased nutrition [34,51–54]. Variability in leaf age longevity was also observed among sites and treatments [43]. Delayed or early needlefall of older foliage has been also observed in response to reduced or increased water stress in radiata pine [34] and also other pine fast growing species [55,56]. For water limited environments, early needlefall has been commonly indicated as a major mechanism to reduce water loss [39,46,51]. However, delayed needlefall and longer foliage retention seems to be a non-well understood mechanism possible related to nutrient retention at water limited environments [19,34,43].

Large increases in total foliage mass and leaf area are dependent on both water and nutrient (mainly N) availability [34]. However, in well watered environments, nutrient availability, in particular nitrogen, may be the critical factor for foliage mass production [54]. This may explain the lack of differences in foliage biomass equation at Recent Volcanic site, which had higher fertility and water availability compared to Dry Sands, and the Red Clay site.

Differences in branch biomass equations may be attributed to crown size development. Undoubtedly, large foliage mass is closely related to larger branch development, particularly at earlier ages of stand development [53]. Genetic differences among sites were expected to have also caused differences in branch biomass equations [57–60]. However, except for Red Clay-Low, higher slopes observed for high intensity treatments (M&H) suggest that under increased site fertility, increases in branch biomass may be expected for a given tree diameter. Larger nutrient resource availability allowed more foliage production and larger branch development to support increases in foliage biomass.

Differences in stem biomass equations were small. Similar results have been found by Burdon [57] and Snowdon and Benson [46] suggesting that a single equation may be used across sites for stem biomass. Differences in stem biomass equations mainly for root collar diameter may be related to tree form (taper) or wood density [61,62].

4.3. *Individual tree coarse and fine roots biomass equations*

Positive linear relationships among coarse root biomass and diameter at breast height have been established before for radiata pine and other conifer and hardwood species [63,64]. The fact that similar coarse root models worked across sites and treatments for diameter at breast height and DBH^{2}H was surprising, considering the range of soil types and environmental conditions. Surprisingly, the two sites with the most contrasting soil textures, Dry Sands and Red Clay, shared the same coarse root biomass equations coefficients at the tree level. However, It might be expected that root collar diameter would be the independent variable more closely related to coarse root biomass, as it is physically closer to the root system. Differences in slope for each site and treatment found for RCD suggest large soil and treatment effects (Fig. 3a). Despite we were not able to obtain enough samples for the treatments at the Recent Volcanic site (only one tree per treatment), estimates for these trees fitted the same general model adjusted for Red Clay and Dry Sands (Fig. 3d).

Our positive linear relationships between fine roots and tree size for Dry Sands and Red Clay differed from Rodriguez [65] who found no relationship between fine roots pool and tree size. Differences in methods of determination have been suggested for lack agreement among belowground studies [66,67]. However, large differences exist in silvicultural treatments applied, age of the stand, and competition from weeds between studies. In addition, genetic differences may account for differences in carbon balance between sites and treatments [68].

4.4. *Comparison with published equations*

Our equations for diameter at breast height, and DBH^{2}H were in the range of estimation obtained from previous published biomass equations (Fig. 3a–d). As expected, the largest variability was found for branch and foliage equations. Unfortunately, we did not find equations to compare with larger RCD trees (>10 cm). When diameter at breast height was used as an independent variable for branch equations, a good agreement was found with published equations (Fig. 3a–d). Despite smaller differences were observed for stem biomass regressions, considerable variation still existed (Fig. 3). This suggests that using the same stem mass equation for contrasting sites may generate large biases in biomass estimates.

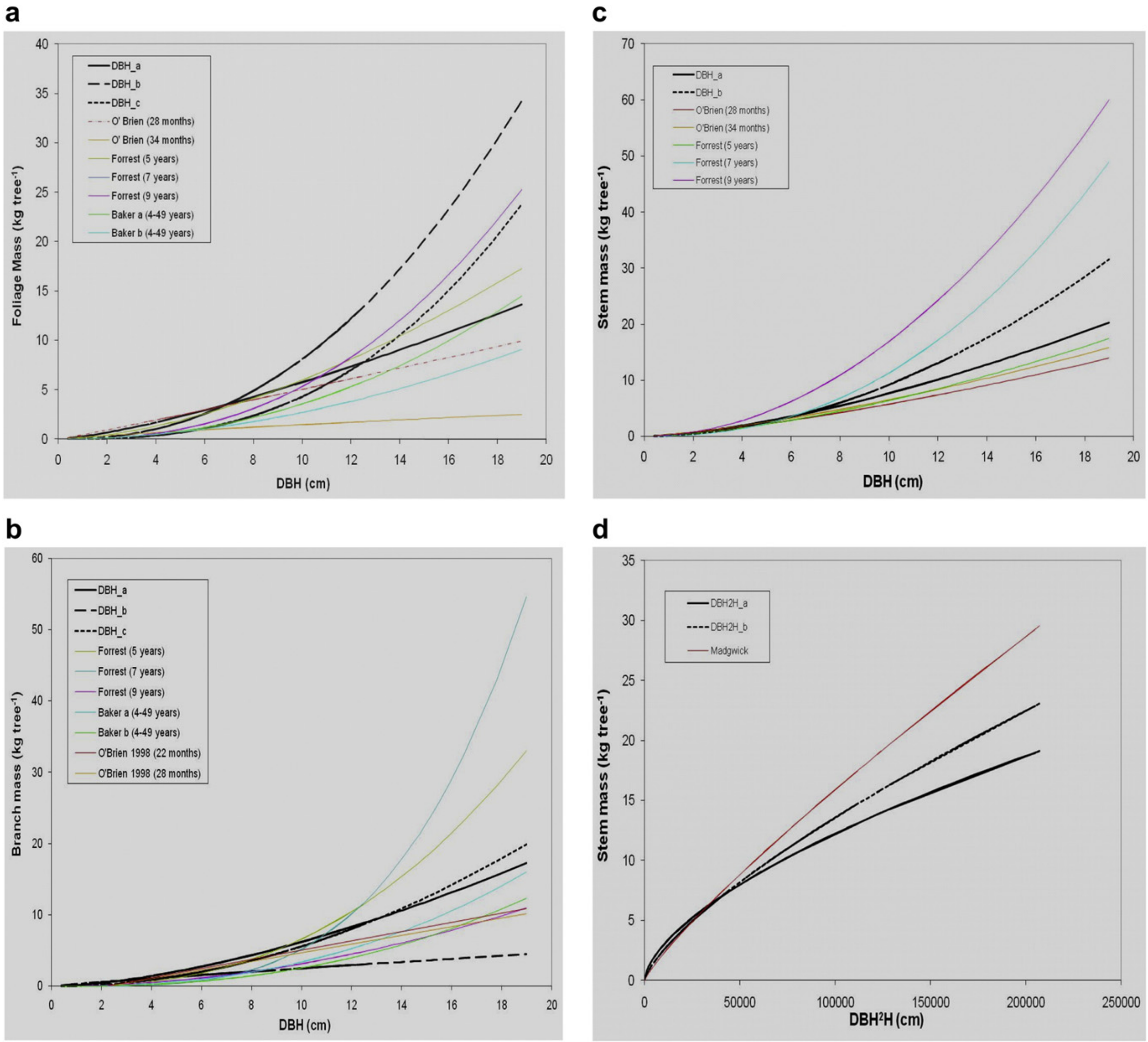

Fig. 3 – Comparison of developed equations with previous equations reported in the literature for: a) foliage and b) branches considering Dry Sands-Low, M&H and Red Clay-Low shown as equation DBH_a, Red Clay-M&H shown as equation DBH_b; Recent Volcanic-Low&M shown as equation DBH_c. Equations for stem c) and d) are compared considering Dry Sands-Low shown as equations DBH_a and DBH^{2}H_a; DS-M&H, RC-Low,M&H, and RV-Low&M shown as equations DBH_b and DBH^{2}H_b. All equations are compared against equations previously published in the literature for the same independent variables. For published equations details see Madgwick [9], Snowdon [47], O'Brien [67], Forrester [68], Baker et al. [32]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

5. Conclusions

Individual tree biomass equations for young radiata pine are site and treatment specific. Larger variation was found for foliage and branch regressions due the ephemeral nature of these biomass components. Stem biomass equations varied less but important differences in equations may be found among sites and treatments at younger ages. Coarse root biomass estimates were variable but less than expected considering the large soil and climatic gradient among our sites. A positive general linear relationship with RCD or DBH across sites and treatments for coarse roots suggested an allometric relationship comparable to stem mass.

REFERENCES

[1] CINTRAFOR. Radiata pine: a competitive force in asian markets. Center for International Trade in Forest Products, http://www.cintrafor.org/publications/factsheets/FS07.pdf; 1993. CINTRAFOR Fact Shet #7.

[2] Snowdon P, Eamus D, Gibbons P, Khanna P, Keith H, Raison J, et al. Synthesis of allometrics, review of root biomass and

design of future woody biomass sampling strategies. In: National carbon accounting system. Canberra: Australian Greenhouse Office; 2000. p. 136.

[3] Mosnaim A. Estimating CO_2 abatement and sequestration potentials for Chile. Energy Policy 2001;29(8):631–40.

[4] Keith H, Barret D, Keenan R. Review of allometric relationships for estimating woody biomass for New South Wales, the Australian Capital Terrritory, Victoria, Tasmania, and South Australia. In: National carbon accounting system. Canberra: Australian Greenhouse Office; 2002. p. 121.

[5] Espinosa M, Acuña E, Cancino J, Muñoz F, Perry D. Carbon sink potential of radiata pine plantations in Chile. Forestry 2005;78(1):11–9.

[6] Satoo T, Madgwick H. Methods of estimating forest biomass. In: Forest biomass. 1st ed. Masachussetts: Martinus Nijhoff Publishers; 1982. p. 15–46.

[7] Albaugh TJ, Allen HL, Dougherty PM, Kress LW, King JS. Leaf area and above- and belowground growth responses of loblolly pine to nutrient and water additions. For Sci 1998;44 (2):317–28.

[8] Beets PN, Pollock DS. Accumulation and partitioning of dry matter in Pinus radiata as related to stand age and thinning. NZJ For Sci 1987;17:246–71.

[9] Madgwick HA. Pinus radiata – biomass, form and growth. 1st ed. Rotorua: Madgwick; 1994.

[10] Watt MS, Kimberley MO, Richardson B, Whitehead D, Mason EG. Testing a juvenile tree growth model sensitive to competition from weeds, using Pinus radiata at two contrasting sites in New Zealand. Can J For Res 2004;34(10):1985–92.

[11] Snowdon P, Waring HD, Grey DC, Schonau AP, Schutz CJ. Long-term nature of growth responses obtained to fertilizer and weed control applied at planting and their consequences for forest management. In: Grey DC, APG Schonau, CJ Schutz, editors. Site and productivity of fast growing plantations. Proceedings IUFRO symp. Forestry Research Institute, Department of Environment Affairs. Pretoria: IUFRO; 1984. p. 701–11.

[12] Morris LA, Lowery RF. Influence of site preparation on soil conditions affecting stand establishment and tree growth. South J Appl For 1988;12:170–8.

[13] Allen HL. In: Evans J, editor. Silvicultural treatments to enhance productivity. The forest handbook, vol. II. Oxford: Blackwell Science Ltd; 2001. p. 437–53.

[14] Nambiar EK, Sands R. Effects of compaction and simulated root channels in the subsoil on root development, water-uptake and growth of radiata pine. Tree Physiol 1992;10(3):297–306.

[15] Sheriff DW, Nambiar EK. Effect of subsoil compaction and three densities of simulated root channels in the subsoil on growth, carbon gain and water uptake of Pinus radiata. Aust J Plant Physiol 1995;22(6):1001–13.

[16] Zou C, Sands R, Sun O. Physiological responses of radiata pine roots to soil strength and soil water deficit. Tree Physiol 2000;20(17):1205–7.

[17] Zou C, Penfold C, Sands R, Misra R, Hudson I. Effects of soil air-filled porosity, soil matric potential and soil strength on primary root growth of radiata pine seedlings. Plant Soil 2001;236(1):105–15.

[18] Constantini A, Doley D. Management of compaction during harvest of Pinus plantations in Queensland: II preliminary evaluation of compaction effects on productivity. Aust For 2001;64(3):186–92.

[19] Kirongo BB, Mason EG, Nugroho PA. Interference mechanisms of pasture on the growth and fascicle dynamics of 3-year-old radiata pine clones. For Ecol Manag 2002;159(3):159–72.

[20] Zerihun A, Montagu KD. Belowground to aboveground biomass ratio and vertical root distribution responses of mature Pinus radiata stands to phosphorus fertilization at planting. Can J For Res 2004;34(9):1883–94.

[21] Albaugh TJ, Allen HL, Kress LW. Biomass-D2h relationships for young loblolly-pine as affected by ozone. Biomass Bioenergy 1991;1(3):143–8.

[22] Mason EG, Whyte AG, Wollons RC, Richardson BA. Model of the growth of juvenile radiata pine in the Central North Island of New Zealand: links with older models and rotation-length analyses of the effects of site preparation. For Ecol Manag 1997;97(2):187–95.

[23] Mason EG, Milne PG. Effects of weed control, fertilization, and soil cultivation on the growth of Pinus radiata at midrotation in Canterbury, New Zealand. Can J For Res 1999; 29(7):1985–92.

[24] Mason EG. A model of the juvenile growth and survival of Pinus radiata D. Don – adding the effects of initial seedling diameter and plant handling. New Forests 2001;22(1–2): 133–58.

[25] Landsberg JJ, Waring RH, Coops NC. Performance of the forest productivity model 3-PG applied to a wide range of forest types. For Ecol Manag 2003;172(2–3):199–214.

[26] Baskerville GL. Use of logarithmic regression in the estimation of plant biomass. Can J For Res 1972;2:49–53.

[27] Steel RG, Torrie JH. Principles and procedures of statistics: a biometrical approach. 2nd. ed. New York: McGraw and Hill; 1980.

[28] Snowdon P. Predicting foliar biomass of pinus-radiata from basal area increment. Aust For Res 1987;17(3):277–81.

[29] Madgwick HA. Seasonal changes in the biomass of a young pinus radiata stand. NZJ For Sci 1983;13(1):25–36.

[30] O'Brien ND. Nutritional physiology of Eucalyptus grandis and Pinus radiata irrigated with municipal effluent. PhD Thesis University of Melbourne, Australia; 1998.

[31] Forrest WG. Variation in the accumulation, distribution and movement of mineral nutrients in radiata pine plantations. PhD Thesis Australian National University, Canberra. Australia; 1969.

[32] Baker TG, Attiwill PM, Stewart HT. Biomass equations for pinus radiata in Gippsland, Vic. NZJ For Sci 1984;14:89–96.

[33] Rubilar RA, Allen HL, Kelting DL. Comparison of biomass and nutrient content equations for successive rotations of loblolly pine plantations on an Upper Coastal Plain Site. Biomass Bioenergy 2005;28(6):548–64.

[34] Raison RJ, Myers BJ, Benson ML. Dynamics of pinus-radiata foliage in relation to water and nitrogen stress 1. Needle production and properties. For Ecol Manag 1992;52(1–4): 139–58.

[35] Dougherty P, Whitehead D, Vose J. Environmental influences on the phenology of pine. Ecol Bull 1994;43:64–75.

[36] Zhang SS, Allen HL. Foliar nutrient dynamics of 11-year-old loblolly pine (Pinus taeda) following nitrogen fertilization. Can J For Res 1996;26(8):1426–39.

[37] Zhang SS, Allen HL, Dougherty PM. Shoot and foliage growth phenology of loblolly pine trees as affected by nitrogen fertilization. Can J For Res 1997;27(9):1420–6.

[38] Whitehead D, Grace JC, Godfrey MJ. Architectural distribution of foliage in individual pinus-radiata D Don crowns and the effects of clumping on radiation interception. Tree Physiol 1990;7(1–4):135–55.

[39] Reich PB, Walters MB, Ellsworth DS. Leaf life-span in relation to leaf, plant, and stand characteristics among diverse ecosystems. Ecol Monogr 1992;62(3):365–92.

[40] Beets PN, Lane PM. Specific leaf are of pinus radiata as influenced by stand age, leaf age, and thinning. NZJ For Sci 1987;17(2/3):283–91.

[41] Wang YP, Jarvis PG, Benson ML. Two-dimensional needle area density distribution within the crowns of Pinus radiata. For Ecol Manag 1990;32:217–37.

[42] Kirongo BB, Mason EG. Decline in relative growth rate of 3 juvenile radiate pine clones subjected to varying competition

levels in Canterbury, New Zealand. Ann For Sci 2003;60(7): 585–91.
[43] Rubilar RA. Environmental constraints on growth phenology, leaf area display, and above and belowground biomass accumulation of Pinus radiata (D. Don) in Chile. Ph.D. Dissertation. Dept. of Forestry, North Carolina State Univ., Raleigh, NC; 2005.
[44] Albaugh TJ, Rubilar RA, Alvarez JS, Allen HL. Radiata pine response to tillage, fertilization and weed control in Chile. Bosque 2004;25(2):5–15.
[45] Brix H. Effects of thinning and nitrogen-fertilization on branch and foliage production in Douglas-Fir. Can J For Res 1981;11(3):502–11.
[46] Snowdon P, Benson M. Effects of combinations of irrigation and fertilization on the growth and aboveground biomass production of pinus-radiata. For Ecol Manag 1992;52(1–4): 87–116.
[47] King JS, Albaugh TJ, Allen HL, Kress LW. Stand-level allometry in Pinus taeda as affected by irrigation and fertilization. Tree Physiol 1999;19(12):769–78.
[48] Naidu SL, DeLucia EH, Thomas RB. Contrasting patterns of biomass allocation in dominant and suppressed loblolly pine. Can J For Res 1998;28(8):1116–24.
[49] Snowdon P. Effects of fertilizer and family on the homogeneity of biomass regressions for young pinus-radiata. Aust For Res 1985;15(2):135–40.
[50] Flores FJ, Allen HL. Efectos del clima y capacidad de almacenamiento de agua del suelo en la productividad de rodales de pino radiata en Chile: Un analisis utilizando el modelo 3-PG. Bosque 2004;25(3):11–24.
[51] Sheriff DW, Nambiar EK, Fife DN. Relationships between nutrient status, carbon assimilation and water use efficiency in Pinus radiata needles. Tree Physiol 1986;2: 73–88.
[52] Nambiar E, Sands R. Competition for water and nutrients in forests. Can J For Res 1993;23(10):1955–68.
[53] Fife DN, Nambiar EK. Changes in the canopy and growth of Pinus radiata in response to nitrogen supply. For Ecol Manag 1997;93(1–2):137–52.
[54] Cromer R, Tompkins D, Barr N. Irrigation of pinus radiata with wastewater: tree growth in response to treatment. Aust For Res 1983;13:57–65.
[55] Vose JM, Allen HL. Quantity and timing of needlefall in N and P fertilized loblolly-pine stands. For Ecol Manag 1991;41(3–4): 205–19.
[56] Dougherty PM, Hennessey TC, Zarnoch SJ, Stenberg PT, Holeman RT, Wittwer RF. Effects of stand development and weather on monthly leaf biomass dynamics of a loblolly-pine (Pinus-Taeda L) stand. For Ecol Manag 1995;72(2–3):213–27.
[57] Burdon RD. Clonal repeatabilities and clone-site interactions in pinus radiata. Silvae Genet 1971;20:33–9.
[58] Madgwick HA. Differences in growth and weight of genotypes of pine with special reference to clones of pinus radiata. NZJ For Sci 1983;13(2):115–24.
[59] Snowdon P, Waring HD. Responses of some genotypes of Pinus radiata to clover and fertilization. Aust For Res 1985;15:125–34.
[60] Birk EM. Nitrogen availability in radiata pine plantations on former pasture sites in southern New-South-Wales. Plant Soil 1992;143(1):115–25.
[61] Snowdon P, Waring H. Effects of factorial combinations of urea, dicalcium phosphate, gypsum and KCl on growth and foliage composition of closely spaced pinus-radiata. Aust For Res 1985;15(3):333–52.
[62] Beets P, Gilchrist K, Jeffreys M. Wood density of radiata pine: effect of nitrogen supply. For Ecol Manag 2001;145(3):173–80.
[63] Vanlear DH, Kapeluck PR. Above and below-stump biomass and nutrient content of a mature loblolly-pine plantation. Can J For Res 1995;25(2):361–7.
[64] Drexhage M, Colin F. Estimating root system biomass from breast-height diameters. Forestry 2001;74(5):491–7.
[65] Rodriguez R, Hofmann G, Espinosa M, Rios D. Biomass partitioning and leaf area of Pinus radiata trees subjected to silvopastoral and conventional forestry in the VI region, Chile. Rev Chil Hist Nat 2003;76(3):437–49.
[66] Vogt KA, Vogt DA, Palmiotto PA, Boon P, O'Hara JA. Review of root dynamics in forest ecosystems grouped by climate, climatic forest type and species. Plant Soil 1996;187(2):159–219.
[67] King JS, Albaugh TJ, Allen HL, Buford MA, Strain BR, Dougherty PM. Below-ground carbon input to soil is controlled by nutrient availability and fine root dynamics in loblolly pine. New Phytol 2002;154(2):389–98.
[68] Li BL, Allen HL, Mckeand SE. Nitrogen and family effects on biomass allocation of loblolly-pine seedlings. For Sci 1991;37 (1):271–83.