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# Allometric Models to Predict Aboveground Woody Biomass of Black Locust (*Robinia pseudoacacia* L.) in Short Rotation Coppice in Previous Mining and Agricultural Areas in Germany

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**Abstract:** Black locust is a drought-resistant tree species with high biomass productivity during juvenility; it is able to thrive on wastelands, such as former brown coal fields and dry agricultural areas. However, research conducted on this species in such areas is limited. This paper aims to provide a basis for predicting tree woody biomass for black locust based on tree, competition, and site variables at 14 sites in northeast Germany that were previously utilized for mining or agriculture. The study areas, which are located in an area covering 320 km × 280 km, are characterized by a variety of climatic and soil conditions. Influential variables, including tree parameters, competition, and climatic parameters were considered. Allometric biomass models were employed. The findings show that the most important parameters are tree and competition variables. Different former land utilizations, such as mining or agriculture, as well as growth by cores or stumps, significantly influenced aboveground woody biomass production. The new biomass models developed as part of this study can be applied to calculate woody biomass production and carbon sequestration of *Robinia pseudoacacia* L. in short rotation coppices in previous mining and agricultural areas.

**Keywords:** black locust; allometric models; short rotation coppice; mining; agriculture; carbon sequestration

## 1. Introduction

*Robinia pseudoacacia* L. was one of the first North American tree species to be introduced into Europe at the beginning of the 17th century [1,2]. It is also one of the most widely planted woody species in the world [3], and the third most important deciduous tree species, after *Populus* and *Eucalyptus*, for plantations, particularly short rotation coppices (SRCs). Fast growing trees are important worldwide. In Brazil, for example, *Eucalyptus* is crucial for pulp and paper production [4]. In Europe and particularly Germany, a change in energy policies towards reduction in use of fossil fuels and towards a stronger use of renewable energy, as outlined in the "Erneuerbare Energien Gesetz" (EEG 2004) [5], marked an increase in fast-growing tree production. Short rotation coppice can have a rotation cycle of 2–3 (short), 4–10 (medium), or 10–20 years (long), depending on management objectives [6,7]. To initiate SRCs, black locust seedlings are typically cultivated for one or two years in tree nurseries and thereafter grown in plantations (in the following referred to as core growth). After harvesting (first, second, etc., rotation) secondary stocks resprout from the stump (referred to as stump growth). Black locust is not only a fast-growing tree species, but like many pioneer trees, it is an undemanding species. It grows in areas with soil pH up to 8 [8], and since it belongs to the legume family it is capable of nitrogen fixation (N) [9]. Therefore, black locust also survived in areas with less nutrients and limited water supply, such as previous open-cast mining areas [10]. Other extremely dry and sometimes salty environments where it survives are urban environments [11]. Black locust is a tree with many benefits. However, there are also those who express concerns about its invasiveness [12–14].

Studies and feedback by practitioners have shown that the yields of SRC, as well as forest biomass production, are affected by a number of interrelated factors, such as plant species provenance [3], age, planting distance, stand density [15–17], soil conditions [18,19], previous land use [20], harvest frequency, and climatic conditions [11,21,22]. In central Europe, the ecology of black locust has been studied for over 100 years [2,3,23–25]. Overall, growth and biomass productivity is one of its most important features, particularly for commercial forestry [26–30]. Research analyzing the growth of juvenile *Robinia pseudoacacia* L. in Europe has been conducted in Hungary [31,32], Austria [33], Italy [34], Bulgaria [35], Poland [19,36], and Germany [20,37–42]. In Germany, the development of allometric models has so far focused on forestry stands [37,41], seedlings [42], and in one case, on a post-mining area [20]. To date, there is no allometric equation available for the calculation of woody biomass in SRC in previous mining and agricultural areas.

To fill this research gap, the objectives of this study were (1) to develop allometric biomass equations for *Robinia pseudoacacia* L. growing in SRC in Germany; (2) to assess whether the inclusion of competition- and climate variables improves predictions from allometric biomass equations; (3) to determine if different biomass equations are necessary for trees growing on former agricultural and mining sites, as well as core versus stump growth; and (4) to determine the absolute woody biomass production and carbon storage per hectare and per year in the analyzed study stands (SRC) for black locust in Germany.

## 2. Materials and Methods

### 2.1. Site Description

Trees were collected in northeastern Germany, in the federal states of Brandenburg, Saxony-Anhalt, and Mecklenburg-Western Pomerania (Table 1, Figure 1). The investigated stands represent 2.4% of the area afforested with black locust in Germany [43].

The 14 study sites differ considerably in regards to their climate and soil characteristics. The annual precipitation ranges between 500 mm and 621 mm and mean annual temperature (1965–2015) ranges between 8.4 °C and 9.3 °C [44]. Nine of the sites are former agricultural sites whereas the other five are former brown coal open-cast mining areas. These two site-types were chosen as their former land use clearly differs regarding their soil characteristics. Former mining soils are relatively acidic due to carboniferous and sulfur-containing substrates, as well as high iron and aluminum concentrations. These sites have low soil pH and low nutrient concentrations. In contrast, former agricultural soils have higher soil pH (>5.5) and nutrient availability caused by fertilization in the past [45]. Data regarding former utilizations, stand age, planting distance, harvest periods, and regional distinctions were provided by the owner or manager.

**Table 1.** Site description including federal states, location, longitude (long), latitude (lat), elevation above sea level (ASL), mean annual temperature (MAT), mean annual precipitation (MAP), former utilization, age, and rotation.

| Site | Federal States * | Location | long (°E) | lat (°N) | ASL (m) | MAT (°C) | MAP (mm) | Former Utilization | Age (years) | Rotation |
|---|---|---|---|---|---|---|---|---|---|---|
| BE | MV | Bennin | 10°51′49″ | 53°27′45″ | 35 | 8.9 | 589 | Agriculture | 8 | 0 |
| BG | BB | Blumberg | 14°10′24″ | 53°12′25″ | 22 | 8.8 | 528 | Agriculture | 3 | 2 |
| BH | MV | Buchholz | 12°38′9″ | 53°15′34″ | 64 | 8.6 | 632 | Agriculture | 2 | 1 |
| CA | BB | Cahnsdorf | 13°45′54″ | 51°52′18″ | 63 | 9.4 | 555 | Agriculture | 5 | 0 |
| DA | BB | Grunow-Dammendorf | 14°25′5″ | 52°8′26″ | 70 | 9.4 | 555 | Agriculture | 3 | 1 |
| GU | BB | Gumtow | 12°14′11″ | 52°59′46″ | 61 | 7.4 | 495 | Agriculture | 2 | 1 |
| HM | ST | Hohenmölsen | 12°6′1″ | 51°10′23″ | 149 | 9.4 | 525 | Mining | 2 | 0 |
| KL | BB | Klein Loitz | 14°30′57″ | 51°36′35″ | 140 | 9.4 | 555 | Agriculture | 2 | 3 |
| LH | BB | Lauchhammer | 13°50′57″ | 51°32′20″ | 111 | 9.4 | 555 | Mining | 8 | 0 |
| PA | BB | Paulinenaue | 12°43′52″ | 52°39′44″ | 31 | 7.4 | 495 | Agriculture | 3 | 1 |
| RA | BB | Ragow | 13°33′7″ | 52°18′8″ | 41 | 9.8 | 584 | Mining | 7 | 0 |
| RM | ST | Röblingen | 11°42′42″ | 51°25′57″ | 149 | 9.4 | 525 | Mining | 7 | 0 |
| WA | BB | Wainsdorf | 13°29′40″ | 51°24′50″ | 92 | 9.3 | 671 | Agriculture | 1 | 2 |
| WZ | BB | Welzow | 14°14′7″ | 51°33′32″ | 123 | 9.4 | 555 | Mining | 1 | 1 |

* BB: Brandenburg, ST: Saxony-Anhalt, MV: Mecklenburg-Western Pomerania.

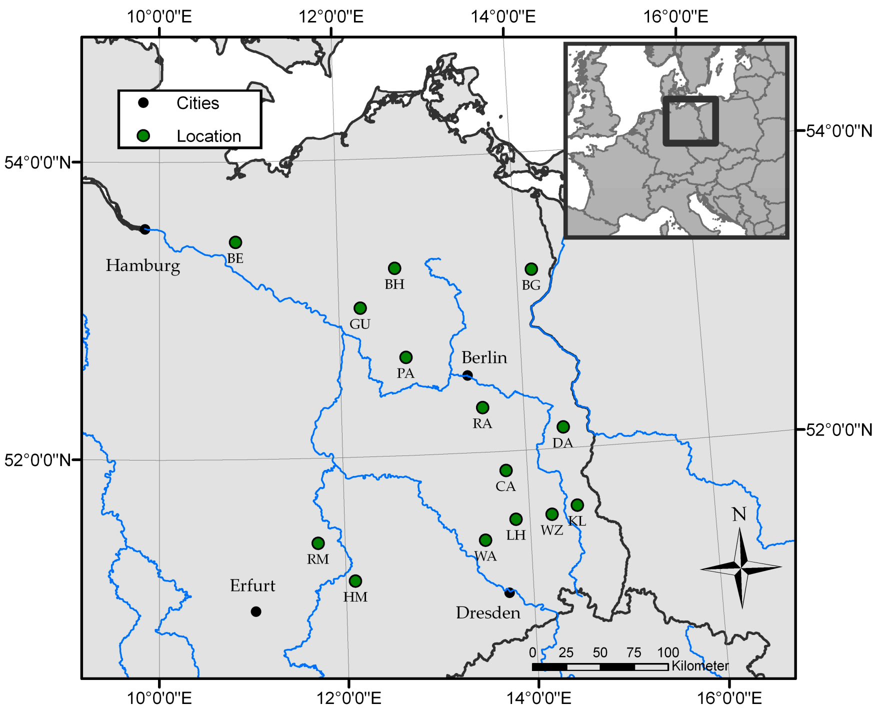


**Figure 1.** Map of the study area in Europe, indicating the 14 sampling sites (locations) in Germany of *Robinia pseudoacacia* L. [46]. For an overview of site abbreviations, see Table 1.

## 2.2. Field Data Collection and Calculation

Tree parameters were collected between November 2016 and January 2017, measuring leafless trees in 62 sample plots. In total, 9729 black locust trees were investigated. Of these, 6407 trees were surveyed in Brandenburg, 1876 trees in Saxony-Anhalt, and 1446 trees in Mecklenburg-Western Pomerania. To all investigated stands, the same procedures were applied by the same investigator to avoid site-specific biases. The calculation of the necessary sample size [47] ($p$-value < 0.05) of 427 trees per stand was achieved by taking a sample surface (600 diameter) of the plantations in Röblingen (Saxony-Anhalt). Furthermore, based on a calculated raster (uniform distribution on each site map) three plots per study area with more than 150 trees were measured. In two areas, the measurement of only one plot was feasible (size of the areas <0.6 ha). In the 14 study sites, the planting distance and plant loss were different. Therefore, the radius per plot varied in each stand; minimum 4 m till maximum 14 m.

The diameter at breast height (DBH) and root collar diameter (RCD) were measured at more than 150 trees per sample plot. Each sprout of the stump was measured as an individual tree. DBH was measured with a diameter measurement tape at a height of 1.3 m. To allow comparability with previous studies [20,41] and to account for the different conditions at the 62 sample plots (core and stump growth), RCD was consistently measured at a height of 0.1 m. The basal area (BA) per tree was calculated using RCD in the circular area formula. As an index of competition, the percentile of the BAs frequency distribution (PCT) [48,49] was used. The classification of individual trees was calculated by dividing the tree-specific RCD from the stand average of RCD (d/dg).

The local stand density index (SDI) by Reineke [50] was calculated to compare competition levels between the fourteen sample sites. SDI was calculated with the number of plants (NoP) in each study site. Furthermore, dg represents the average value of RCD in the 14 study sites. The value of the exponent, −1.605, was used according to the generic stand density rule by Reineke [16,17,50,51]. Reineke [50] analyzed the stand density index for evenly-aged forests with different stand densities (under- and over-stocked). For small trees like in this study, it was possible to calculate the SDI by using a numerator of 5 cm (mean tree diameter).

$$SDI = NoP\left(\frac{5}{dg}\right)^{-1.605} \quad (1)$$

After measurement of diameter (RCD, and DBH), trees were categorized. Hence, for 25 trees per plot, representative of the whole diameter spectrum (categories), the following parameters were additionally measured: tree height, height to crown base, fresh aboveground woody biomass after cutting 10 cm above soil surface (kg, overall total weight 4.5 tones), biomass aliquot (kg, overall total weight 614 kg), and biomass after dehydration (g). Tree height (H) and crown base height (CB) [distance from the lowest primary branch to the top of the crown] were tape measured after cutting the tree. Similar to d/dg, individual trees in the stand were classified, by dividing the tree-specific height from the average stand height (h/hg). The classification of the value of the average height of predominant trees ($h_{100}$) and age (Bon) was calculated by employing the yield table by Lockow and Lockow [37] used for *Robinia pseudoacacia* L. Lockow and Lockow [37] analyzed trees with a minimum age of five years; thus, the extrapolation for younger trees was necessary. To express tree slenderness, their height was divided by diameter (h/d). Biomass after cutting and biomass after dehydration were measured by using an electronic scale with a spring balance (precision ± 1 g). For each sample, a representative, plot-related aliquot of shredded tree biomass was dried for 48 h in the laboratory at 103.5 °C (DIN 52183 [52]) until a constant mass was reached [20,34–36,53,54]. This aliquot was used to estimate the total value of dry woody biomass for each sample.

*2.3. Climate Data*

Data of temperature, precipitation, and daylight hours (sun) were provided by the German weather service DWD [44] for the period of 1965 to 2015 (50 years) of eight weather stations (Angermünde, Berlin Tempelhof, Cottbus, Dresden-Klotsche, Leipzig-Halle, Marnitz, Neuruppin, Schwerin) in close proximity to the sampled stands. Based on these climate data, the De Martonne aridity index (DMI) [55] was calculated.

$$DMI = \frac{Precipitation}{Temperature + 10} \quad (2)$$

The aridity index of De Martonne is useful for assessing the relationships between water supply and tree growth [11,56]. Also, an important qualitative climatic variable for plants is the climatic water balance (CWB), described as the difference between precipitation and potential evapotranspiration [57].

*2.4. Statistical Analysis, Allometric Modelling and Total Biomass Production*

At first, a Pearson correlation matrix [58] was calculated to assess correlations between mean stand dry biomass and all acquired variables averaged per stand, such as RCD, DBH, BA, H, h/d, CB, Age, NoP, SDI, Bon, DMI, CWB, Prec, Temp, and Sun.

Linear regression models were calculated to test the structure of individual tree data. However, linear models do not represent the real nature of biomass production. The correlation between growth variables of single trees can be described with an allometric function, as given in Equation (3) [59]:

$$BM = ax^b \tag{3}$$

where $a$ and $b$ are scaling coefficients and $x$ is the independent and explanatory variable. All regressions were undertaken using natural logarithmic transformation (Equation (4)) of the tree dimensions, in line with previous work done by Pretzsch et al. [56], Böhm et al. [20], Annighöfer et al. [34,42], and Stankova et al. [35]:

$$\ln(y) = a + b * ln(x) \tag{4}$$

A nonlinear least square regression was employed to obtain estimates for the coefficients $a$ and $b$. Mixed models by Fisher [60] allow the use of different data frames within one model:

$$ln(y)_{ijk} = a_0 + a_1 ln(x)_{ijk} + b_i + b_{ij} + \varepsilon_{ijk} \tag{5}$$

Here, the three different subdivisions are location ($i$), circle of the samples ($j$), and the individual tree ($k$). $x$ represents tree features, competitive indices, and climate parameters (altogether 17 variables were tested). Additionally, competition variables like h/hg, d/dg, and PCT were integrated into the tree individual allometric models to predict biomass, as supplement to variables of the correlation matrix (tree- and climate parameter). Since it was not possible to obtain DBH for trees smaller than 1.3 m, RCD was fitted as the predictor variable. To quantify model performance and to compare among models, an analysis of variance (ANOVA) was performed. The standard error as the standard deviation of the sample distribution, $p$-value, as well as confidence intervals of every variable were derived. Conditional coefficient of determination ($R^2$) [61], variance of the residuals, the Akaike's Information Criterion (AIC) [62], and the Bayesian Information Criterion (BIC) [63] were used to select and rank among best fit models. For reasons of clarity, only the top four candidate models are presented.

Fixed effects were independent variables including tree diameter (RCD in cm) at 0.1 m, height (H in m), h/hg, and h/d. The following functional formulas were compared (Table 2, $M_{01}$–$M_{04}$).

**Table 2.** Allometric models to predict aboveground woody biomass, model number $M_{01}$–$M_{04}$, BM (Biomass dry), RCD (root collar diameter), H (height), h/hg (height divided by the mean BAs tree of height), and h/d (height divided by diameter). The letters a–e represent the parameters.

| Name | Model |
|---|---|
| $M_{01}$ | $ln(BM) = a + b\ ln(RCD) + \varepsilon$ |
| $M_{02}$ | $ln(BM) = a + bln(RCD) + c\ ln(H) + \varepsilon$ |
| $M_{03}$ | $ln(BM) = a + bln(RCD) + c\ ln(H) + d(\mathrm{h/hg}) + \varepsilon$ |
| $M_{04}$ | $ln(BM) = a + bln(RCD) + c\ ln(H) + d(\mathrm{h/hg}) + e(h/d) + \varepsilon$ |

To compare and cross-check the influence of different site conditions, dummy variables ($a_3$ and $a_4$) were used. Two different options for different growth exist in the data frame. These are related to former utilization (mining vs. agriculture) and type of growth (core vs. stump). The conditions are described by:

$$\ln(BM) = a_1 + a_2 \ln(RCD) + a_3 x + a_4 \ln(RCD) x \tag{6}$$

To compare results for previous land use, zero (=0) was used for mining and one (=1) was used for agricultural site. In regards to growth, zero (=0) was used for core and one (=1) for stump growth. The percentage error (Equation (7)) was calculated by using $M_{01}$ (Table 2) and $M_{01}t$ (theoretical value using a special formula for core, stump, previous mining, and agricultural area) [59].

$$\%\text{Error} = \frac{(M_{01} - M_{01}t)}{M_{01}t} * 100 \tag{7}$$

The analysis of total biomass production of the stands was calculated in tons per hectare and year [to $ha^{-1}$ $a^{-1}$] for each stand individually with the measured data (allometric models are not included). The actual NoP and the area of each sample plot were used. Furthermore, the biomass of all trees in the sample plot was added up and extrapolated from plot size to one hectare [64]. NoP is not directly included in the allometric model. However, the NoP has a strong influence on the current total biomass production per hectare. To calculate aboveground woody biomass per year, the total biomass production at the time of measurements was divided by the stand individual age in years. To estimate the carbon stock, dry woody biomass estimates were multiplied by 0.5 following IPCC [65–67].

All analyses were performed in R [68], version R 3.3.2 GUI 1.68 (R Core Team, 2016), especially with the packages "stats" [69], "ape" [70], and "ggplot2" [71].

## 3. Results

### 3.1. Yield Data

Table 3 provides an overview on all obtained variables (RCD, DBH, tree height, crown base, wet tree biomass, and dry tree biomass) separated by former land use. Both land-use types expressed a minimum RCD and DBH of 0.1 cm, while the maximum RCD was at 20.2 cm and the maximum DBH was at 14.4 cm. The tree height ranged from 0.7 m to 9.9 m, wet tree biomass ranged from 0.01 kg to 51.81 kg, and dry tree biomass from 0.01 kg to 32.15 kg.

**Table 3.** Measured and calculated tree variables for each sampled site: growth *, root collar diameter (RCD), diameter at breast height (DBH), tree height, wet tree biomass, and dry tree biomass of *Robinia pseudoacacia* L., categorized by former utilization (# $n_1$ = 9729, ~ $n_2$ = 1550).

| Site | Plots | # $n_1$ | ~ $n_2$ | G * | # RCD [cm] | # DBH [cm] | ~ Tree Height [m] | ~ Wet Tree Biomass [kg] | ~ Dry Tree Biomass [kg] |
|---|---|---|---|---|---|---|---|---|---|
| Mining | | 4311 | 700 | | 4.2 (0.1–20.2) | 3.1 (0.1–13.0) | 4.4 (0.9–9.4) | 3.6 (0.02–34.00) | 2.36 (0.01–22.70) |
| HM | 4 | 586 | 100 | C | 2.8 (0.4–7.8) | 2.1 (0.2–4.3) | 3.9 (1.6–6.5) | 1.4 (0.07–4.98) | 0.86 (0.04–2.87) |
| LH | 6 | 952 | 150 | C | 5.4 (0.6–18.4) | 4.2 (0.5–12.0) | 5.3 (1.4–9.4) | 4.8 (0.19–32.11) | 3.17 (0.13–21.09) |
| RA | 1 | 152 | 25 | C | 6.4 (1.3–15.1) | 4.7 (0.8–9.3) | 6.1 (4.7–7.2) | 9.3 (2.57–23.40) | 6.10 (1.71–15.74) |
| RM | 9 | 1290 | 225 | C | 6.6 (0.5–20.2) | 4.6 (0.4–13.0) | 5.6 (1.5–9.0) | 6.2 (0.10–34.00) | 4.00 (0.06–22.70) |
| WZ | 8 | 1331 | 200 | S | 1.4 (0.1–3.7) | 1.1 (0.1–3.2) | 2.6 (0.9–4.9) | 3.6 (0.02–2.07) | 0.19 (0.01–1.27) |
| Agriculture | | 5418 | 850 | | 2.8 (0.1–16.7) | 2.4 (0.1–14.4) | 3.8 (0.7–9.9) | 2.31 (0.01–51.81) | 1.43 (0.01–32.15) |
| BE | 3 | 446 | 75 | C | 7.3 (2.3–16.7) | 5.7 (1.2–14.4) | 6.4 (3.0–9.9) | 8.68 (0.56–51.81) | 5.29 (0.34–32.15) |
| BG | 3 | 441 | 75 | S | 3.9 (1.2–9.7) | 3.4 (1.0–7.8) | 5.6 (2.0–7.9) | 3.77 (0.24–21.79) | 2.33 (0.14–13.62) |
| BH | 6 | 1000 | 150 | S | 1.3 (0.1–4.0) | 0.9 (0.1–2.8) | 2.3 (0.8–4.0) | 0.30 (0.01–1.77) | 0.18 (0.01–1.10) |
| CA | 3 | 470 | 75 | C | 4.7 (1.3–12.5) | 3.4 (0.4–7.7) | 5.2 (2.3–7.8) | 3.60 (0.40–17.3) | 2.28 (0.01–10.86) |
| DA | 3 | 422 | 75 | S | 4.9 (1.0–11.3) | 3.7 (0.9–8.6) | 5.6 (2.0–9.4) | 4.05 (0.08–19.59) | 2.52 (0.04–12.06) |
| GU | 8 | 1314 | 200 | S | 1.2 (0.1–4.4) | 0.9 (0.1–3.1) | 2.2 (0.7–4.3) | 0.36 (0.01–2.35) | 0.22 (0.01–1.41) |
| KL | 3 | 478 | 75 | S | 3.4 (0.7–12.8) | 2.7 (0.6–7.4) | 5.6 (3.0–9.0) | 3.03 (0.26–14.47) | 1.90 (0.17–8.90) |
| PA | 1 | 167 | 25 | S | 2.2 (0.3–6.5) | 1.7 (0.6–4.5) | 2.9 (0.7–5.0) | 1.59 (0.16–3.79) | 1.00 (0.10–2.39) |
| WA | 4 | 680 | 100 | S | 1.6 (0.3–3.8) | 1.0 (0.1–3.4) | 2.5 (1.0–4.1) | 0.69 (0.02–31.00) | 0.44 (0.02–20.15) |

* G: Growth; S: stump shoots; C: core growth; mean (minimum and maximum).

### 3.2. Correlation of Tree, Stand, and Climate Parameters

The correlation matrix (Table 4) indicated a strong correlation between dry biomass (BMD) with the DBH, RCD, H, and the age of the tree. The variables NoP and h/d showed a strong negative correlation with the BMD. All other variables expressed a weaker correlation with the BMD. The weakest observed correlation with the BMD was with precipitation, daylight hours (sun), the De

Martonne Index, and the climatic water balance. All tree individual variables correlate well with each other (BMD, RCD, DBH, H, and CB). Age correlates well with BMD, RCD, DBH, and height-diameter association (h_d) (>0.8). The SDI has the strongest association with CB (0.75). The correlation matrix illustrates a strong correlation (0.93) between NoP and h_d (tree slenderness), as well as NoP and the diameters RCD, and DBH. All climatic parameters show a weak correlation to all tree, stand, and climatic variables. Noticeable is the temperature, with a correlation (>0.4) to BMD, RCD, DBH, H, CB, SDI, Bon, and Prec. For the allometric modelling, the RCD (DBH × 1.42) was only used as it is particularly applicable for young, small trees (<1.3 m tree height) and it is beneficial in cases, if forks are between 0.1 m and 1.3 m tree height.

**Table 4.** Correlation among mean tree and stand variables for *Robinia pseudoacacia* L.

| | BMD | RCD | DBH | H | CB | Age | h_d | SDI | Bon | NoP | Prec | Temp | Sun | DMI | CWB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **BMD** | 1 | 0.95 | 0.95 | 0.87 | 0.72 | 0.89 | −0.82 | 0.32 | −0.19 | −0.79 | 0.03 | 0.43 | −0.01 | −0.18 | 0.28 |
| **RCD** | | 1 | 0.99 | 0.92 | 0.82 | 0.91 | −0.84 | 0.47 | −0.07 | −0.84 | −0.04 | 0.47 | 0.08 | −0.28 | 0.18 |
| **DBH** | | | 1 | 0.94 | 0.85 | 0.90 | −0.82 | 0.49 | −0.03 | −0.84 | −0.07 | 0.45 | 0.11 | −0.30 | 0.15 |
| **H** | | | | 1 | 0.91 | 0.75 | −0.71 | 0.68 | 0.23 | −0.80 | −0.10 | 0.54 | 0.31 | −0.37 | 0.10 |
| **CB** | | | | | 1 | 0.69 | −0.59 | 0.75 | 0.22 | −0.67 | −0.30 | 0.45 | 0.32 | −0.55 | 0.08 |
| **Age** | | | | | | 1 | −0.86 | 0.29 | −0.39 | −0.77 | −0.06 | 0.30 | −0.03 | −0.21 | 0.11 |
| **h_d** | | | | | | | 1 | −0.20 | 0.34 | 0.93 | 0.12 | −0.19 | 0.10 | 0.23 | −0.29 |
| **SDI** | | | | | | | | 1 | 0.58 | −0.29 | −0.07 | 0.64 | 0.64 | −0.38 | 0.02 |
| **Bon** | | | | | | | | | 1 | 0.08 | 0.09 | 0.48 | 0.59 | −0.14 | −0.18 |
| **NoP** | | | | | | | | | | 1 | 0.29 | −0.20 | −0.08 | 0.42 | −0.16 |
| **Prec** | | | | | | | | | | | 1 | 0.42 | −0.12 | 0.90 | −0.06 |
| **Temp** | | | | | | | | | | | | 1 | 0.53 | −0.02 | 0.11 |
| **Sun** | | | | | | | | | | | | | 1 | −0.39 | −0.46 |
| **DMI** | | | | | | | | | | | | | | 1 | −0.12 |
| **CWB** | | | | | | | | | | | | | | | 1 |

BMD: dry biomass, RCD: root collar diameter, DBH: diameter at breast height, H: height, CB: crown base, Age: tree age, h_d: height–diameter association, SDI: stand density index, Bon: classification, NoP: number of plants, Prec: Precipitation, Temp: temperature, Sun: sun duration, DMI: De Martonne Index, and CWB: climatic water balance.

### 3.3. Allometric Models

RCD had the strongest association on BMD ($M_{01}$). Model $M_{02}$ showed the best conditional coefficient of determination ($_{c}R^2 = 0.953$) of all models and is a combination of RCD and tree height. Furthermore, $M_{04}$ was the minimum adequate model based on AIC, BIC, and variance. That is, a combination of RCD, H, h/hg, and h/d (Table 5). According to the models, the influence of environmental variables on the BMD was negligible. The temperature influenced the model, but did not create a better model fit. The confidence interval of biomass estimates of Model $M_{01}$ is presented in the Appendix A (Figure A1). The axes (*x*- and *y*-axis) of the confidence interval are log-transformed. Consequently, increasing RCD (or tree height) implies increasing the confidence interval and inaccuracy of the estimated values (Model $M_{01}$–$M_{04}$).

Site conditions (former mining sites versus agricultural sites) and growth type (core versus stump) influenced biomass prediction from the allometric equation. The analysis by using dummy variables (Equation (10)) showed significant differences between different land use and growth types (Tables 6 and 7, Figure 2). Overall, significance was obtained in the analysis of the BM versus RCD, comparing former mining areas with former agricultural areas ($p$-value < 0.05). Significant differences were also shown with the dummy variables in the comparison of BM with H ($p$-value < 0.001). The results also showed significant differences in woody biomass production between the growth types (core versus stump) in the categories BM and RCD, as well as BM and H ($p$-value < 0.001).

Figure 2 presents the nonlinear least square relationship and allometric relationship of double-logarithmic representation between RCD (cm) and aboveground woody biomass (kg), tree height (m) and aboveground woody biomass [kg] separated by previous land utilization (agriculture and mining) and growth (core and stump). In all categories, the equations and biomass estimates are very similar if the trees are small (RCD, and tree height). Larger trees show different aboveground woody biomass accumulation between agriculture and mining, core and stump. In previous agricultural areas, trees produce at the equal RCD more aboveground woody biomass than in previous mining areas. At the same tree height, the accumulated biomass is higher in mining areas. Moreover, by comparing the equations of core and stump, stumps accumulated more biomass at the equal RCD and core at the identical tree height.

**Table 5.** Comparison among the top four candidate models.

| Model | Variable | Coefficient | Estimate | SE | *p*-Value | $_cR^2$ | AIC | Variance | Confidence Interval | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | 2.5% | 97.5% |
| $M_{01}$ | Intercept | a | −2.65499 | 0.0436 | <0.001 | 0.9353 | 1890 | 0.2061 | −2.7404 | −2.5696 |
| | RCD | b | 2.29325 | 0.0239 | <0.001 | | | | 2.2464 | 2.3401 |
| $M_{02}$ | Intercept | a | −3.50576 | 0.0649 | <0.001 | 0.9532 | 1466 | 0.1572 | −3.6331 | −3.3784 |
| | RCD | b | 1.52190 | 0.0403 | <0.001 | | | | 1.4429 | 1.6008 |
| | H | c | 1.20956 | 0.0541 | <0.001 | | | | 1.1035 | 1.3156 |
| $M_{03}$ | Intercept | a | −3.40775 | 0.0794 | <0.001 | 0.9492 | 1437 | 0.1567 | −3.5634 | −3.2521 |
| | RCD | b | 1.50926 | 0.0399 | <0.001 | | | | 1.4309 | 1.5876 |
| | H | c | 0.58536 | 0.1183 | <0.001 | | | | 0.3532 | 0.8175 |
| | h/hg | d | 0.63665 | 0.1063 | <0.001 | | | | 0.4280 | 0.8452 |
| $M_{04}$ | Intercept | a | −3.69133 | 0.0930 | <0.001 | 0.9510 | 1419 | 0.1528 | −3.8736 | −3.5090 |
| | RCD | b | 1.94216 | 0.0961 | <0.001 | | | | 1.7536 | 2.1307 |
| | H | c | 0.27772 | 0.1340 | 0.0383 | | | | 0.0149 | 0.5405 |
| | h/hg | d | 0.53084 | 0.1056 | <0.001 | | | | 0.3236 | 0.7380 |
| | h/d | e | 0.26262 | 0.0535 | <0.001 | | | | 0.1576 | 0.3676 |

RCD: root collar diameter, H: height, h/hg: stand normalized height, h/d: slenderness, SE: standard error of the estimate, *p*-value, $_cR^2$: conditional coefficient of determination, AIC: Akaike's Information Criterion, variance, and confidence interval.

**Table 6.** Comparing different sites and growth conditions by using dummy variables of power regression in the mixed models, with woody biomass (BM) as the response variable and the tree variables root collar diameter and height as predictor variables, for mining, agriculture, core, and stump (Equation (10)). The table below shows the parameter ($a_1$, $a_2$, $a_3$, $a_4$), estimates, standard error (SE), and *p*-value ($n$ = 1550).

| Model | Variables | Parameter | Estimate | SE | *p*-Value |
|---|---|---|---|---|---|
| Mining vs. Agriculture | BM and RCD | $a_1$ | −2.73527 | 0.0849 | <0.001 |
| | | $a_2$ | 2.36960 | 0.0377 | <0.001 |
| | | $a_3$ | 0.14295 | 0.1054 | 0.2 |
| | | $a_4$ | −0.13925 | 0.0494 | <0.05 |
| Mining vs. Agriculture | BM and H | $a_1$ | −4.90281 | 0.0696 | <0.001 |
| | | $a_2$ | 3.35715 | 0.0478 | <0.001 |
| | | $a_3$ | 0.42611 | 0.0846 | <0.001 |
| | | $a_4$ | −0.37694 | 0.0602 | <0.001 |
| Core vs. stump | BM and RCD | $a_1$ | −2.94658 | 0.0862 | <0.001 |
| | | $a_2$ | 2.47837 | 0.0405 | <0.001 |
| | | $a_3$ | 0.41101 | 0.1012 | <0.001 |
| | | $a_4$ | −0.30298 | 0.0513 | <0.001 |
| Core vs. stump | BM and H | $a_1$ | −4.12556 | 0.0970 | <0.001 |
| | | $a_2$ | 2.91852 | 0.0590 | <0.001 |
| | | $a_3$ | −0.42888 | 0.1070 | <0.001 |
| | | $a_4$ | 0.02504 | 0.0711 | 0.725 |

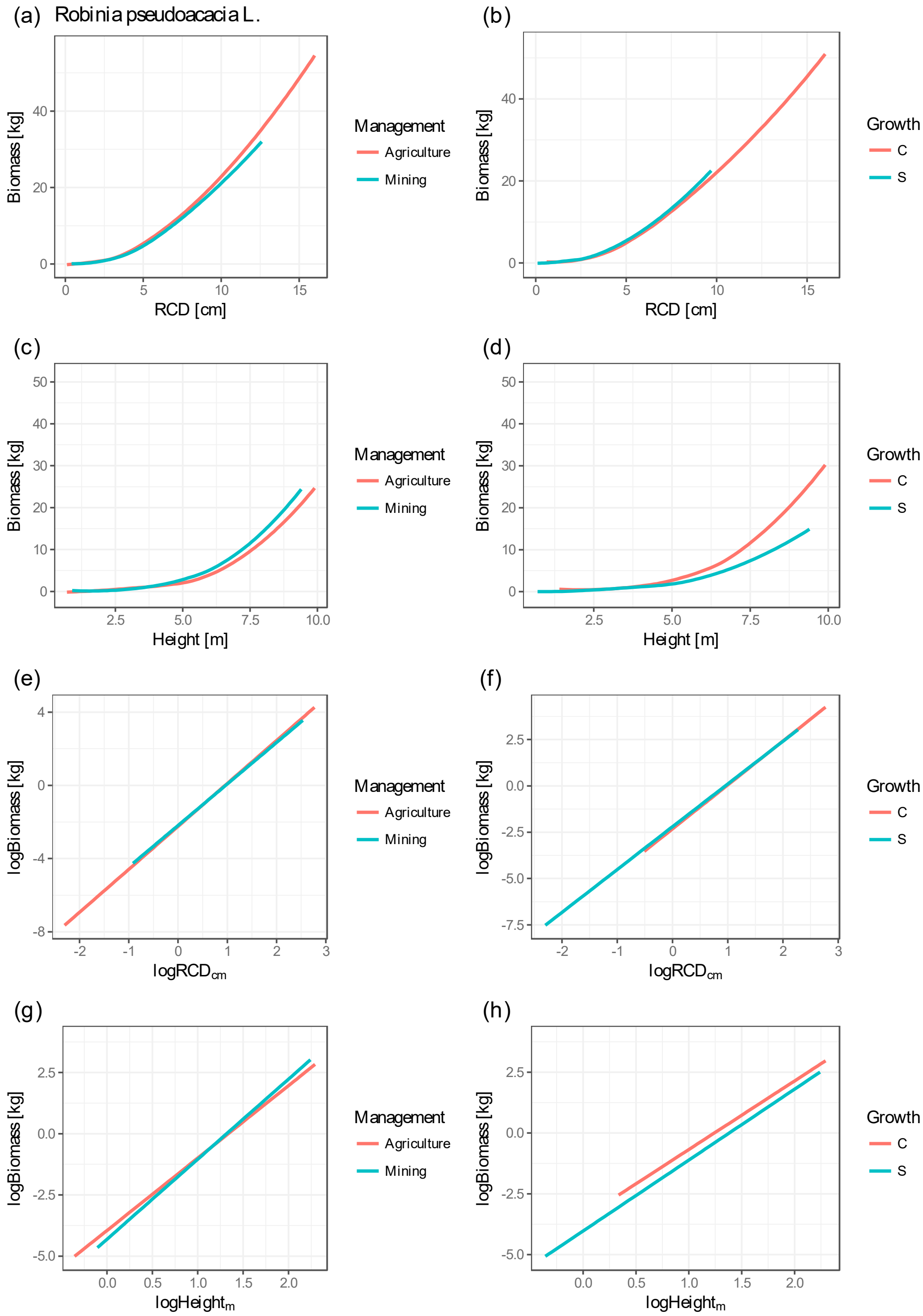


**Figure 2.** Allometric nonlinear least square relationship (**a**–**d**) and allometric relationship of double-logarithmic (**e**–**h**) representation between RCD (cm) and aboveground woody biomass (kg) (**a**,**b**,**e**,**f**), tree height (m) and aboveground woody biomass (kg) (**c**,**d**,**g**,**h**) separated by previous land utilization (Agriculture and Mining) and growth (C = Core and S = Stump). The statistical characteristics of the regression lines are presented in Tables 6 and 7.

**Table 7.** Comparison of different former utilization and growth type models, by using the value of 4.7 cm and 9.0 cm for RCD and 5.2 m and 7.3 m for H, Min = Mining, Agr = Agriculture, C = Core, and S = Stump.

| Figure 3 | Explanatory Variable | Value | Min (kg) | Agr (kg) | Min–Agr (kg) | Hectare (to) | C (kg) | S (kg) | C–S (kg) | Hectare (to) |
|---|---|---|---|---|---|---|---|---|---|---|
| (a), (b) | RCD (cm) | 4.7 | 2.449 | 2.362 | 0.087 | 0.722 # | 2.478 | 2.247 | 0.231 | 1.923 # |
| | | 9.0 | 11.713 | 10.054 | 1.659 | 3.318 * | 12.292 | 9.164 | 3.128 | 6.256 * |
| (c), (d) | H (m) | 5.2 | 1.648 | 1.677 | 0.029 | 0.244 # | 1.991 | 1.573 | 0.418 | 3.480 # |
| | | 7.3 | 4.305 | 4.663 | 0.358 | 0.717 * | 5.185 | 4.425 | 0.760 | 1.520 * |

# 8333 NoP, * 2000 NoP (assumed values).

In Table 7, two selected values, arithmetic mean and 75% quartile (upper quartile, 25% of the largest values in the data set) of all stands, represent the differences for an individual tree (Min–Agr, C–S) and a one-hectare plantation of black locust woody biomass (Hectare). By using biomass equations with a RCD of 4.7 cm (mean value of all stands), the difference between mining and agriculture was at 0.09 kg per tree and between Core and Stump 0.23 kg per tree. Calculations with a RCD of 9.0 cm (75% quantile of all stands) showed a difference of 1.66 kg per tree (mining vs. agriculture) and 3.13 kg per tree (core vs. stump). Consequently, this is a difference of 3.3 tons per hectare (mining vs. agriculture) and 6.3 tons per hectare (core vs. stump) when assuming 2000 trees per hectare. Regarding the comparison of height (mining vs. agriculture, core vs. stump), the maximum difference with a height of 7.3 m is 0.76 kg per tree (Table 7). The percentage error for an RCD of 5 cm, when applied to $M_{01}$, is −2.4% for $C_{01}$ (core), 9.7% for $S_{01}$ (stump), 3.9% for $Agr_{01}$ (agriculture), and −0.9% for $Min_{01}$ (mining). Further details on all allometric models—mining, agriculture, core, and stump—are concluded in the Appendix A (Table A1).

### *3.4. Absolute Wood bioMass Productivity*

The absolute stand biomass productivity per hectare of juvenile black locust trees in the analyzed study stands is presented in Table 8. The minimum dry biomass productivity was found to be 1.0 to $ha^{-1}$ $a^{-1}$ and the maximum was at 13.8 to $ha^{-1}$ $a^{-1}$. Differences in wet biomass ranged from a minimum of 1.6 to $ha^{-1}$ $a^{-1}$ to a maximum of 22.1 to $ha^{-1}$ $a^{-1}$. Carbon sequestration per hectare and year ranged from 0.5 tons to 6.9 tons. The mean annual carbon storage per hectare and year is 2.9 tons.

**Table 8.** Ranking of the study sites based on aboveground woody biomass productivity (to $ha^{-1}$ $a^{-1}$).

| Rank | Site | Former Utilization | *n* | Age | Biomass Wet | | Biomass Dry | | Carbon Sequestration |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | (to $ha^{-1}$) | (to $ha^{-1}$ $a^{-1}$) | (to $ha^{-1}$) | (to $ha^{-1}$ $a^{-1}$) | (to $ha^{-1}$ $a^{-1}$) |
| 1 | KL | Agriculture | 75 | 2 | 44.2 | 22.1 | 27.6 | 13.8 | 6.9 |
| 2 | BG | Agriculture | 75 | 3 | 48.6 | 16.2 | 30.0 | 10.0 | 5.0 |
| 3 | DA | Agriculture | 75 | 3 | 44.7 | 14.9 | 27.9 | 9.3 | 4.7 |
| 4 | HM | Mining | 100 | 2 | 23.8 | 11.9 | 14.4 | 7.2 | 3.6 |
| 5 | CA | Agriculture | 75 | 5 | 55.5 | 11.1 | 35.5 | 7.1 | 3.6 |
| 6 | WZ | Mining | 200 | 1 | 9.8 | 9.8 | 6.0 | 6.0 | 3.0 |
| 7 | WA | Agriculture | 100 | 1 | 9.5 | 9.5 | 5.9 | 5.9 | 3.0 |
| 8 | RM | Mining | 225 | 7 | 55.3 | 7.9 | 37.1 | 5.3 | 2.7 |
| 9 | LH | Mining | 150 | 8 | 43.2 | 5.4 | 28.0 | 3.5 | 1.8 |
| 10 | RA | Mining | 25 | 7 | 34.3 | 4.9 | 22.4 | 3.2 | 1.6 |
| 11 | BE | Agriculture | 75 | 8 | 39.2 | 4.9 | 24.0 | 3.0 | 1.5 |
| 12 | BH | Agriculture | 150 | 2 | 7.6 | 3.8 | 4.6 | 2.3 | 1.2 |
| 13 | GU | Agriculture | 200 | 2 | 7.2 | 3.6 | 4.2 | 2.1 | 1.1 |
| 14 | PA | Agriculture | 25 | 3 | 4.8 | 1.6 | 3.0 | 1.0 | 0.5 |

## 4. Discussion

### *4.1. Correlation of Stand Parameter and Allometric Biomass Models*

Although numerous studies exist dealing with the biomass productivity of black locust [19,20,31,34,35,37,38,64,72,73], the existing tools are very limited for quantifying the behavior of black locust in SRC in previous brown coal mining and agricultural areas. However, the benefit of *Robinia pseudoacacia* L. in SRC for our society, ecology, and economy lies in biomass and energy production, as well as carbon sequestration. By comparing stand parameters on the basis of a correlation matrix, we found that most important factors to explain the variability of dry biomass were RCD, DBH, age, height, and h/d association. Dahlhausen et al. [17] reported a significant correlation between SDI and biomass production in young oak stands (*Quercus robur*). Stand density index in this study did not show this influence because it is a collective SDI and not an individual tree SDI.

The most frequently used independent variables for tree biomass equations are RCD, DBH, H, and age (tree stem parameter), particularly for black locust [19,20,31,34–38]. Modelling by employing mixed models, as used by Forrester et al. [74], Grote et al. [75], and Pretzsch et al. [76] has the advantage of being applicable at different geographical and differently structured sites. In this study, RCD had the strongest correlation with BMD ($M_{01}$). Model $M_{02}$ (being based on RCD and H) was the top equation with respect to the coefficient of determination ($R^2$). Furthermore, in regards to AIC [77] and variance, model $M_{04}$ (being based on RCD, height, h/hg, and h/d) performed best. Given the rather similar model performance, practical users can choose between $M_{02}$ and $M_{04}$. Both models provide similar estimates. It is recommended to use the simpler over the more complex model, but for the sake of completeness, it was decided to present both models here. The average temperature was the climatic parameter with the strongest influence among climatic parameters. However, it did not improve model fit significantly. The confidence intervals of biomass estimates show for all models that the results are as accurate as possible, if the variables RCD and tree height are as small as possible. The inaccuracy increases with increasing explanatory variables (RCD, tree height).

A comparison with three other biomass equations from the literature revealed that the allometric model $M_{01}$ had the comparably lowest slope (Figure 3). This is probably related to the differing representations of the studies considered. That is, Lange et al. [41] calculated a biomass equation for young black locust trees in an ecosystem forest which featured a lower number of planted trees per hectare (2000–3000) compared with typical SRCs (8000–10,000 [7]). Compared to our equation, the differences at RCD 10 cm were 15.0 kg per tree which probably reflects the different stature of trees under differing stand densities. The study by Annighöfer et al. [42] analyzed seedlings of 19 tree species, including *Robinia pseudoacacia* L. ($n$ = 238). Compared to our study, there is a difference of 1.3 kg per tree for a RCD of 3.0 cm. The maximum RCD reported by Annighöfer et al. [43] was at 3.9 cm, but in our study the maximum RCD was at 20.2 cm, which was a large deviation in the analyzed RCD spectrum. The equation presented by Böhm et al. [20] expressed the highest similarity to our model. That is, up to the RCD of 7 cm, the curves were equal. However, at RCD of 13.0 cm, biomass prediction from Böhm et al. [20] was 10.0 kg per tree higher compared to our model. The relatively high similarity is probably due to the fact that Böhm et al. [20] analyzed black locust on reclaimed soil in a former open-cast mining area in the Welzow energy forest (EEW), which is also one of the sites investigated in this study. The similarity is influenced by the subsample effect.

Land management in the past significantly influenced biomass production in the presence. The allometric models $M_{01}$–$M_{04}$ are based on the complete data set. Therefore, to obtain more precise results, the integration of the former land utilization (mining or agriculture) and growth by core or stump will improve model predictions. In terms of energy production in the past and present, Germany exhibits several former open cast lignite mines. Just recently, these disturbed landscapes are being restored and recultivated [78]. Within this context, black locust was planted as leguminous and modest tree species [9]. In this study, it was possible to compare previous mining with previous agricultural areas. In agricultural areas, the results showed that aboveground woody biomass is higher at the same RCD, so presumably the plants concentrate on vertical growth and biomass allocation. An assumption of this fact is that biomass accumulation at the equal RCD is higher if the tree height growth is superior. A reason for those results could be that tree height growth is strongly influenced by soil and site conditions. In this study, it seems that trees in former agricultural sites have better height growth than trees in nutrient poor former mining sites. In former mining areas, the biomass at the same tree height is higher than in agricultural areas. Probably, the tree growth in former mining areas is reinforced on radial growth and biomass allocation. Diameter growth is more influenced by competition for light, water, and nutrients in even-aged stands. The connection between diameter growth and competition is also indicated by the strong correlations between numbers of plants and RCD (DBH) in Table 4. Practitioners can apply the global models, but with increasing RCD and tree height the differences are not negligible. For example, the calculation of biomass with allometric models for mining and agriculture (Appendix A, Table A1) showed a difference at an RCD of 9.0 cm of 3.3 tons per hectare (NoP 2000). In detail, the reasons for this different behavior are not yet clear and consequently more research is needed on the ecological reactions of black locust to different environmental conditions. However, it seems possible that a higher nutrient load in former agricultural sites may affect the relatively stronger vertical growth.

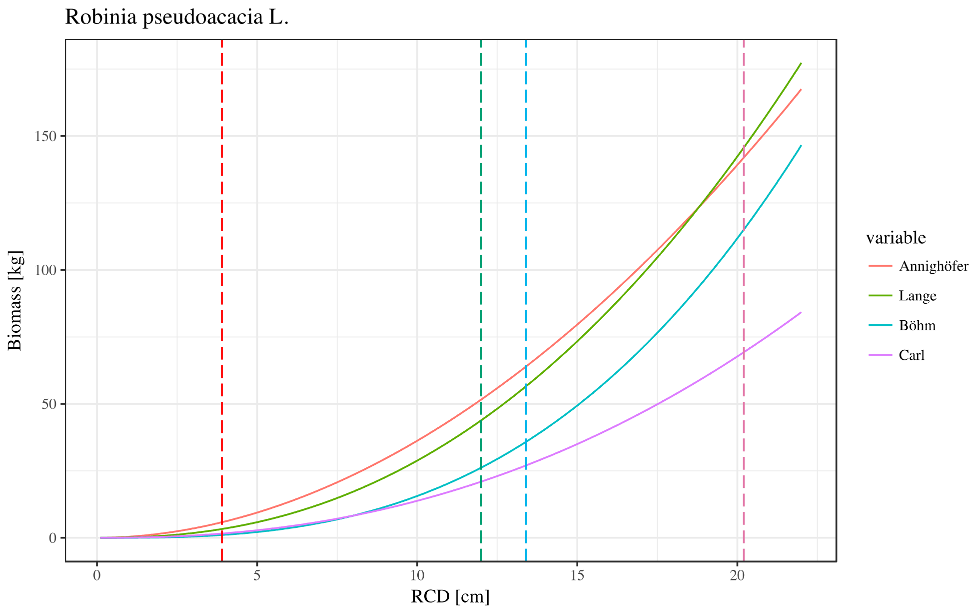


**Figure 3.** Biomass equations comparing *Robinia pseudoacacia* L. biomass to RCD of different investigations, including the current study $M_{01}$, Lange et al. [41], Annighöfer et al. [42], and Böhm et al. [20]. The dashed line illustrates the maximum RCD, which was incorporated into the biomass equations.

In Germany, it is common to plant SRC in short-, medium-, or long-term rotation systems [6,7] independent of the planned harvesting periods from the local manager. After harvesting (first, second, etc., rotation), *Robinia pseudoacacia* L. resprouts from the stumps with a varying multiple number of sprouts. These sprouts of one stump compete with each other for resources, especially light. All in all, significant differences were observed between the growth types core (planted trees before harvesting, zero rotation) and stump (after harvesting, first, second, etc., rotation). Stumps have a higher slope in regression of RCD to biomass. Therefore, at the same RCD, sprouts have a higher aboveground woody biomass accumulation in the analyzed areas. Multiple sprouts on the same stump are in closer proximity to each other than sprouts from different stumps. Hence, the assumption is that competition for light among sprouts on the same stump is more intense than among sprouts from different stumps and trees growing by the core. Competition for light usually results in taller, more slender stems because height growth is less negatively influenced than radial growth. The multiple sprouts per stump share a common root system. Therefore, they may have different abilities to compete for the shared water and nutrient supply. In general, taller and faster growing sprouts likely get more of the resources than shorter, shaded, and slower growing sprouts. All in all, in consideration of certain parts of the shoot and certain parts of the root system, more vigorous sprouts likely provide more carbohydrates to the roots that provide them water and nutrients, creating a positive feedback that allows the larger sprouts to obtain a larger part of the shared soil resources. Cores have a higher slope in regression of height to biomass. Therefore, at the same height, cores have a higher aboveground woody biomass accumulation in the analyzed areas. Probably, cores focus on radial growth and biomass allocation. Within-stump competition is not present in trees growing by core. Core trees have only a single stem per root system. However, cores must allocate a higher proportion of their fixed carbon to building their root system compared to sprouts which already have an existing root system. This would certainly influence allocation to above-ground biomass production. The difference between core and stump is even more concise than in areas affected by former mining and agriculture usage. Here, at RCD 9.0 cm, the aboveground woody biomass differs by 6.3 tons per hectare (NoP 2000). These differences are probably related to different levels of competition between core stands and stump stands, but further research is needed to get a better understanding of the details of this behavior.

Growth differences exist between growth in previous mining and agricultural areas, core and stump growth. The reason for these growth differences should be analyzed in further studies dealing with the ecological effects of the different initial conditions (previous utilization and growth) to black locust. The global equations ($M_{01}$–$M_{04}$) are applicable, but if the previous utilization and growth conditions are known, specific models can be used (agriculture, mining, core, and stump). Overall, the woody biomass mixed models offer the possibility to calculate the biomass of black locust in SRC for practitioner, foresters, researcher, students, and other interested stakeholders. A biomass calculator as a tool for *Populus* in SRC exists [53,54,79]. This study represents a scientifically grounded application for the tree species *Robinia pseudoacacia* L. in SRC.

### 4.2. Total Woody Biomass Productivity

Dry woody biomass production of the analyzed stands varied between 1.0 to $ha^{-1}$ $a^{-1}$ and 13.8 to $ha^{-1}$ $a^{-1}$. This fits well in the range of values reported elsewhere in literature. In Europe and North America, the biomass production of black locust ranges between 1.6–19.0 to $ha^{-1}$ $a^{-1}$. The values of biomass per hectare and year of the described studies did not show changes in storage. The total biomass at the time of measurements was divided by the stand's individual age in years. Therefore, the calculated biomass storage per year is a mean annual biomass increment of the whole growing time. Grünewald et al. [64] reported that four former German mining areas expressed 3.0–10.0 to $ha^{-1}$ $a^{-1}$ of core and stump growth, at a tree age of 3–14 years (stand age in this study ranged from 1–8 years). Their study found that the biomass production of black locust is higher than that of *Populus* and *Salix* in the same former mining areas [64]. Mirck et al. [38] estimated 6.9 to $ha^{-1}$ $a^{-1}$ of black locust in a five-year-old agroforestry system. In Hungary, Redei et al. [32] calculated 3.0–6.0 to $ha^{-1}$ $a^{-1}$ at five-year-old stems. In this study, the analyzed area in Cahnsdorf is the same age (five-years-old) and the production is 7.1 to $ha^{-1}$ $a^{-1}$. Werner et al. [40] reported 19.0 to $ha^{-1}$ $a^{-1}$ for trees of similar age, growing as stump stocks in agricultural landscapes. Peters et al. [39] found 5.0–6.0 to $ha^{-1}$ $a^{-1}$ harvested in a six-year-old area in Germany. These values are comparable with the estimates of 5.3 to $ha^{-1}$ $a^{-1}$ at the study site in Röblingen analyzed in this study. In Austria, Müller et al. [33] reported 7.0–10.0 to $ha^{-1}$ $a^{-1}$. In this study, three-year-old stands (Grunow-Dammendorf, Blumberg) show similar productivity (9.3–10.0 to $ha^{-1}$ $a^{-1}$) to Müller's study. Stolarski et al. [19] found 1.6–5.4 to $ha^{-1}$ $a^{-1}$ for four-year-old black locust stands in Poland. In the United States of America, Geyer et al. [26] described 11.7 to $ha^{-1}$ $a^{-1}$ for two-year-old trees and 8.0 to $ha^{-1}$ $a^{-1}$ for four-year-old black locust. The highest productivity in this study was measured in a two-year-old stand in Klein

Loitz with 13.8 to $ha^{-1}$ $a^{-1}$. A negative influence on biomass production in some of the study´s sites could have been Fusarium fungi [80], and for other sites, it may have been grazing in the year of planting [81]. Positive influences on the tree growth could be a thorough soil surface preparation, plant care, and fostering [81]. The study sites of this study stored on average 2.9 tons of carbon per hectare and per year. Consequently, over the whole study area, black locust captured 974 tons of carbon per hectare and per year.

## 5. Conclusions

This study highlights the aboveground woody biomass production of *Robinia pseudoacacia* L. in SRC in northeast Germany. Overall, 17 variables (related to tree features, competition, and climate) were tested to calculate an individual tree's biomass. In this study, root collar diameter (RCD) had the strongest impact on dry biomass ($M_{01}$) and a model combining RCD with tree height ($M_{02}$) was the best model in regards to the coefficient of determination. Moreover, a significant influence of former land utilization (open cast mining areas versus agricultural fields) as well as the type of growth (core versus stump) was found. Up to now, only limited data are available for black locust growth in previous agricultural and mining areas in central Europe; more research dealing with allometry, functions, and ecology of black locust is required.

Furthermore, this study showed that dry woody biomass production ranged between 1.0 and 13.8 to $ha^{-1}$ $a^{-1}$, and the mean carbon storage was 2.9 tons of carbon per hectare and year. The models presented in this study provide local managers, foresters, and scientists with the opportunity to estimate productivity (biomass yield, energy potential) and consequently carbon sequestration of black locust in the field based on a low number of parameters. Allometric models, and biomass analysis fill the knowledge gap of yield production dealing with black locust in previous agricultural and mining areas.

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**Author Contributions:** Dirk Landgraf, Hans Pretzsch and Christin Carl initiated and planed the project; Christin Carl performed the experiments, analyzed the data together with Peter Biber and Allan Buras, and wrote the manuscript. Dirk Landgraf, Hans Pretzsch, Peter Biber and Allan Buras contributed by revising the manuscript.

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

## Abbreviations

| | |
|---|---|
| AIC | Akaike Information Criterion |
| ANCOVA | Analyses of Covariance |
| ANOVA | Analyses of Variance |
| BA | Basal area |
| BIC | Bayesian Information Criterion |
| BM | Biomass (dry) |
| C | Core growth |
| CB | Crown base |
| CWB | Climatic water balance |
| DBH | Diameter at breast height |
| DMI | De Martonne Index |
| EEG | Erneuerbare-Energien-Gesetz (Renewable Energy law) |
| H | Height |

| | |
|---|---|
| NoP | Number of plants |
| PCA | Principle Component Analyses |
| PCT | Percentile of the basal area |
| RCD | Root collar diameter |
| S | Stump growth |
| SDI | Stand Density Index |
| SE | Standard error |
| SRC | Short rotation coppice |
| ${}_cR^2$ | Conditional coefficient of determination |

## Appendix A

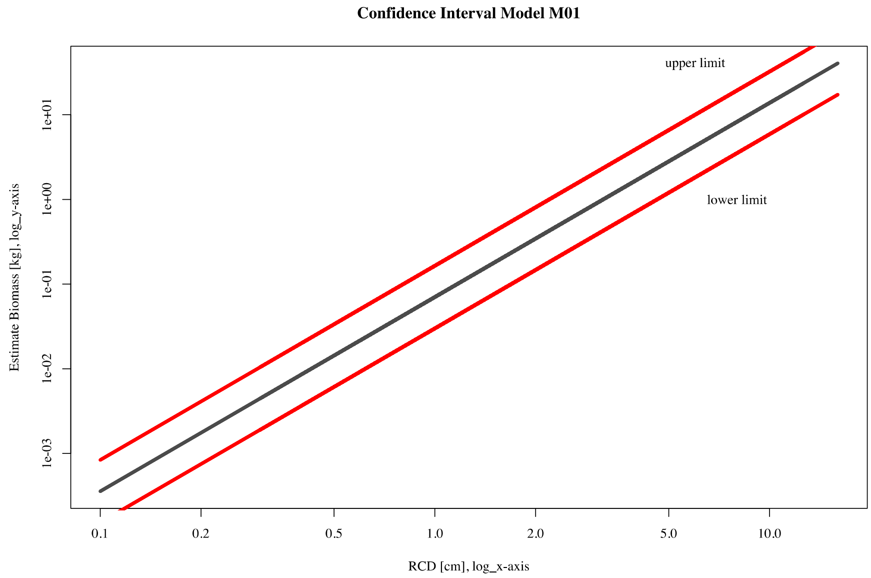


**Figure A1.** Confidence interval of Model $M_{01}$; upper and lower limit. The $x$-axis and $y$-axis are log transformed.

**Table A1.** Variables, parameters, estimate, standard error (SE), $p$-value, conditional $R^2$ (${}_cR^2$), AIC, variance, and confidence interval (95%) for (ln) relationship of double-logarithmic of the mixed biomass equations $M_{01}$H, Mining (Min) $M_{01}$ till $M_{04}$, Agriculture (Agr) $M_{01}$ till $M_{04}$, Core (C) $M_{01}$ till $M_{04}$, and Stump (S) $M_{01}$ till $M_{04}$.

| Model | Variable | Coefficient | Estimate | SE | $p$-Value | ${}_cR^2$ | AIC | Variance | CI | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | 2.5% | 97.5% |
| $M_{01}$H | Intercept | a | −4.2976 | 0.1141 | <0.001 | 0.9025 | 2458 | 0.3566 | −4.5215 | −4.0737 |
| | H | b | 2.9365 | 0.0405 | <0.001 | | | | 2.8570 | 3.0161 |
| $Agr_{01}$ | Intercept | a | −2.5903 | 0.0710 | <0.001 | 0.9143 | 1249 | 0.2602 | −2.7298 | −2.4508 |
| | RCD | b | 2.2293 | 0.0357 | <0.001 | | | | 2.1591 | 2.2995 |
| $Agr_{01H}$ | Intercept | a | −4.4541 | 0.1454 | <0.001 | 0.9001 | 1507 | 0.3784 | −4.7396 | −4.1687 |
| | H | b | 3.0152 | 0.0606 | <0.001 | | | | 2.8962 | 3.1341 |
| $Agr_{02}$ | Intercept | a | −3.4829 | 0.1006 | <0.001 | 0.9368 | 1089 | 0.2145 | −3.6805 | −3.2853 |
| | RCD | b | 1.4897 | 0.0633 | <0.001 | | | | 1.3653 | 1.6141 |
| | H | c | 1.2090 | 0.0895 | <0.001 | | | | 1.0334 | 1.3846 |
| $Agr_{03}$ | Intercept | a | −3.4077 | 0.07935 | <0.001 | 0.9533 | 1468 | 0.2139 | −3.5634 | −3.2520 |
| | RCD | b | 1.5092 | 0.0399 | <0.001 | | | | 1.4309 | 1.5876 |
| | H | c | 0.5853 | 0.1183 | <0.001 | | | | 0.3532 | 0.8175 |
| | h/hg | d | 0.6366 | 0.1063 | <0.001 | | | | 0.4280 | 0.8452 |

**Table A1.** *Cont.*

| Model | Variable | Coefficient | Estimate | SE | *p*-Value | ${}_cR^2$ | AIC | Variance | CI | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | 2.5% | 97.5% |
| $Agr_{04}$ | Intercept | a | −3.6913 | 0.0929 | <0.001 | 0.9510 | 1419 | 0.2056 | −3.8737 | −3.5090 |
| | RCD | b | 1.9421 | 0.0961 | <0.001 | | | | 1.7536 | 2.1307 |
| | H | c | 0.2777 | 0.1339 | 0.0383 | | | | 0.0149 | 0.5405 |
| | h/hg | d | 0.5308 | 0.1056 | <0.001 | | | | 0.3236 | 0.7380 |
| | h/d | e | 0.2626 | 0.0535 | <0.001 | | | | 0.1576 | 0.3676 |
| $Min_{01}$ | Intercept | a | −2.8322 | 0.0726 | <0.001 | 0.9626 | 468 | 0.1353 | −2.9749 | −2.6894 |
| | RCD | b | 2.4089 | 0.0330 | <0.001 | | | | 2.3441 | 2.4737 |
| $Min_{01H}$ | Intercept | a | −4.1685 | 0.2906 | <0.001 | 0.9132 | 765 | 0.3150 | −4.7393 | −3.5976 |
| | H | b | 2.8313 | 0.0547 | <0.001 | | | | 2.7238 | 2.9389 |
| $Min_{02}$ | Intercept | a | −3.5994 | 0.0482 | <0.001 | 0.9761 | 175 | 0.0768 | −3.6942 | −3.5046 |
| | RCD | b | 1.5952 | 0.0407 | <0.001 | | | | 1.5152 | 1.6754 |
| | H | c | 1.1811 | 0.0583 | <0.001 | | | | 1.0665 | 1.2957 |
| $Min_{03}$ | Intercept | a | −3.4077 | 0.0793 | <0.001 | 0.9492 | 1436 | 0.0757 | −3.5634 | −3.2521 |
| | RCD | b | 1.5092 | 0.0399 | <0.001 | | | | 1.4309 | 1.5876 |
| | H | c | 0.5853 | 0.1183 | <0.001 | | | | 0.3532 | 0.8175 |
| | h/hg | d | 0.6366 | 0.1063 | <0.001 | | | | 0.4280 | 0.8452 |
| $Min_{04}$ | Intercept | a | −3.6913 | 0.0929 | <0.001 | 0.9510 | 1419 | 0.0757 | −3.8737 | −3.5089 |
| | RCD | b | 1.9421 | 0.0961 | <0.001 | | | | 1.7536 | 2.1307 |
| | H | c | 0.2777 | 0.1339 | 0.0383 | | | | 0.0149 | 0.5405 |
| | h/hg | d | 0.5308 | 0.1056 | <0.001 | | | | 0.3236 | 0.7380 |
| | h/d | e | 0.2626 | 0.0535 | <0.001 | | | | 0.1576 | 0.3676 |
| $C_{01}$ | Intercept | a | −2.9081 | 0.0672 | <0.001 | 0.8759 | 832 | 0.2073 | −3.0400 | −2.7760 |
| | RCD | b | 2.4654 | 0.0404 | <0.001 | | | | 2.3859 | 2.5448 |
| $C_{01H}$ | Intercept | a | −3.9640 | 0.1332 | <0.001 | 0.8111 | 1077 | 0.3223 | −4.2256 | −3.7024 |
| | H | b | 2.8220 | 0.0596 | <0.001 | | | | 2.7048 | 2.9391 |
| $C_{02}$ | Intercept | a | −3.6598 | 0.0769 | <0.001 | 0.9092 | 625 | 0.1497 | −3.8108 | −3.5088 |
| | RCD | b | 1.6378 | 0.0628 | <0.001 | | | | 1.5144 | 1.7612 |
| | H | c | 1.1972 | 0.0755 | <0.001 | | | | 1.0490 | 1.3455 |
| $C_{03}$ | Intercept | a | −3.4077 | 0.0793 | <0.001 | 0.9492 | 1436 | 0.1473 | −3.5634 | −3.2521 |
| | RCD | b | 1.5092 | 0.0399 | <0.001 | | | | 1.4309 | 1.5876 |
| | H | c | 0.5853 | 0.1183 | <0.001 | | | | 0.3532 | 0.8175 |
| | h/hg | d | 0.6366 | 0.1063 | <0.001 | | | | 0.4280 | 0.8452 |
| $C_{04}$ | Intercept | a | −3.6913 | 0.0929 | <0.001 | 0.9510 | 1419 | 0.1473 | −3.8737 | −3.5089 |
| | RCD | b | 1.9421 | 0.0961 | <0.001 | | | | 1.7536 | 2.1307 |
| | H | c | 0.2777 | 0.1339 | 0.0383 | | | | 0.0149 | 0.5405 |
| | h/hg | d | 0.5308 | 0.1056 | <0.001 | | | | 0.3236 | 0.7380 |
| | h/d | e | 0.2626 | 0.0535 | <0.001 | | | | 0.1576 | 0.3676 |
| $S_{01}$ | Intercept | a | −2.5393 | 0.0863 | <0.001 | 0.9168 | 1035 | 0.2040 | −2.7086 | −2.3700 |
| | RCD | b | 2.1639 | 0.0308 | <0.001 | | | | 2.1033 | 2.2244 |
| $S_{01H}$ | Intercept | a | −4.5737 | 0.1627 | <0.001 | 0.9015 | 1383 | 0.3352 | −4.8930 | −4.2544 |
| | H | b | 3.0490 | 0.0560 | <0.001 | | | | 2.9390 | 3.1591 |
| $S_{02}$ | Intercept | a | −3.4286 | 0.1025 | <0.001 | 0.9405 | 845 | 0.1610 | −3.6298 | −3.2274 |
| | RCD | b | 1.4806 | 0.0538 | <0.001 | | | | 1.3750 | 1.5860 |
| | H | c | 1.1707 | 0.0793 | <0.001 | | | | 1.0151 | 1.3262 |
| $S_{03}$ | Intercept | a | −3.4077 | 0.0793 | <0.001 | 0.9492 | 1436 | 0.1610 | −3.5634 | −3.2520 |
| | RCD | b | 1.5092 | 0.0399 | <0.001 | | | | 1.4308 | 1.5876 |
| | H | c | 0.5853 | 0.1183 | <0.001 | | | | 0.3532 | 0.8175 |
| | h/hg | d | 0.6366 | 0.1063 | <0.001 | | | | 0.4280 | 0.8452 |
| $S_{04}$ | Intercept | a | −3.6913 | 0.0929 | <0.001 | 0.9510 | 1419 | 0.1528 | −3.8737 | −3.5089 |
| | RCD | b | 1.9421 | 0.0961 | <0.001 | | | | 1.7535 | 2.1307 |
| | H | c | 0.2777 | 0.1339 | 0.0383 | | | | 0.0149 | 0.5405 |
| | h/hg | d | 0.5308 | 0.1056 | <0.001 | | | | 0.3236 | 0.7380 |
| | h/d | e | 0.2626 | 0.0535 | <0.001 | | | | 0.1576 | 0.3676 |

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