

**Representation of the carbon content and the structure of understorey vegetation in a temporal oak forest by allometric analyses**

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## Abstract

The concentration of carbon dioxide (CO<sub>2</sub>) has been increasing and caused environmental issues. Forests provide a large sink of carbon and mitigate the increase in CO<sub>2</sub>. It is essential to comprehend the partition of carbon pool at forest ecosystems to predict the carbon cycle and deal with the environmental problems. In contrast to relatively well described overstorey, understorey vegetation is poorly described in simulation models of the carbon cycle.

However, some research suggested that understorey vegetation stores 10 to 20 % of carbon contained in overstorey. The purpose of the current study is to improve the representation of understorey at British oak woodland. This project focused on hazel. The hypotheses that shoot biomass, shoot length, and shoot age were described as a function of shoot diameter were tested based on observation, and allometric relationships were established to assess carbon content and the structure of hazel. Measurement plots were set in Alice Holt research woodland located in southeast England. Firstly, the frequency distribution of shoot diameter was established. In next, ranging the whole distribution, shoots were selected and their dry mass, length and age were measured. A stool and coarse roots were measured as below-ground biomass, and the ratio to above-ground biomass was calculated. Carbon concentration in shoots, and stools and coarse roots were measured. Regression analyses showed that the hypotheses were correct. Using the established allometric functions and the ratio between above-ground and below-ground biomass, the amount of carbon contained in hazel was estimated. In conclusion, hazel at this site stored 0.77 kg Carbon per m<sup>2</sup>, and 11 year-old, approximately 70 % of which was derived from above-ground and 30 % from below-ground biomass. The amount of carbon storage may be affected by light conditions and thinning of overstorey vegetation.

## **Introduction**

Forests provide a large sink of carbon and play an important role in the carbon cycle on the earth (Dixon et al., 1994). The amount of carbon dioxide (CO<sub>2</sub>) in the atmosphere has been dramatically increasing mainly due to human activities since preindustrial times, and caused serious problems (Houghton and Intergovernmental Panel on Climate Change., 2001).

Accurate estimation of the amount of carbon forests can store is required in order to predict the carbon cycle and deal with the environmental problems due to the increase in CO<sub>2</sub>.

Therefore, it is necessary to comprehend the partition of carbon pool at forest ecosystems. In

Britain woodland plays an essential role which provides a large sink of carbon. Although it accounts for only 11 % of rural land area, it stores 80 % of the total amount of carbon

contained in British terrestrial vegetation (Barr et al., 1992, Milne and Brown, 1997,

CANNELL and MILNE, 1995). However, although temperate forests typically comprise

overstorey and understorey, those values were estimated from only dominant overstorey

species. There are a number of factors contributing to the carbon sink of forests. Among

others understorey vegetation is considerable. Pateau (2003) and Satchell (1969) found that

the carbon content of understorey vegetation was approximately 10 to 20 % of that of

overstorey. Biogeochemical processes involving the carbon dynamics around a canopy and

the atmosphere have been relatively well described by simulation models (Jarvis et al., 1985,

Running and Coughlan, 1988, Williams et al., 1996), whereas there is limited number of

research on understorey and its carbon content. Pateau et al (2003) carried out

comprehensive research on carbon content at forests including understorey vegetation;

however, shoots less than 0.07 m in diameter at breast height was not taken into consideration.

The purpose of the current study is to improve the representation of understorey at British

oak woodland in order to understand the carbon cycle comprehensively at forest ecosystems.

In this project the following hypotheses regarding to allometric relationships for hazel

obtained from fieldwork are tested by regression analyses, and thereby the carbon content and the structure of understorey vegetation are assessed. The hypotheses are shoot diameter at 1.3 m from the base is strongly related to basal shoot diameter, shoot dry mass, shoot length and shoot age, and fine roots biomass reduces according to its depth.

## **Materials and Methods**

### **Site**

This project was carried out at the Straits site within Alice Holt research wood land located in southeast England (51° N 0.5° W) from November 2010 to March 2011. It is a 90 ha block mainly composed of approximately 85 year-old mixed oak (*Quercus robur L.* and *Q. petraea Mattuschka Liebl.*) and partly Ash (*Fraxinus excelsior L.*), and has 495 trees per ha in density. The dominant species of understorey vegetation is hazel (*Corylus avellana L.*) followed by hawthorn (*Crataegus monogyna Jacq.*). The mean annual precipitation and temperature from 1971 to 2000 were 779 mm and 9.5 °C respectively. Thinning of oak trees was carried out in the eastern part of the site in 2008, resulting in damage to understorey vegetation. The soil is surface water gleysol (Wickham series) with a 3 cm-deep-O-layer and the 80 cm-deep cretaceous clay C horizon. The pH is 4.6 in the organic, and 4.8 in mineral horizons respectively.

### **Materials**

This study focused on the assessment of hazel. It is composed of above-ground and below-ground components. Above-ground component is mainly derived from foliage and shoots. Below-ground is from a stool, coarse roots and fine roots. This study assessed the biomass of shoots, stool and coarse roots. As a pilot study, fine roots depth was determined.

## **Mensuration plot**

Six 10 x 10 m<sup>2</sup> plots were selected in the western part of the straits: one of them was located where thinning of oak trees was carried out in 1996, and the others have not been disturbed over 20 years (Fig.1).

## **Above-ground carbon pool component**

### **Basal shoot diameter and diameter at 1.3 m**

On one hand, basal shoot diameter ( $d_b$ ) is used as shoot diameter in some studies (Pitman, 1999); on the other hand, diameter at 1.3 m along the shoot from the base ( $d_{1.3}$ ) was used in some other studies (Patenaude et al., 2003, Satchell, 1969). In order to make the results of this study applicable to other studies, whether if there was a strong, allometric relationship between those diameters were tested. In total 144 pairs of live shoot diameter were measured by a vernier calliper (dialMax-5921, Swiss Precision, Ashton, Switzerland). At least one small and one tall plant were selected from every plot to cover the whole range of shoot sizes. The geometric mean was computed for shoot diameter ( $d$ ) measured from two right-angled directions ( $d_1$  and  $d_2$ ) (Husch et al., 2003).

$$d = \sqrt{d_1 \times d_2} \quad (1)$$

The allometric relationship was computed as:

$$d_b = f(d_{1.3}) \quad (2)$$

### **Shoot dry mass and $d_{1.3}$**

$d_{1.3}$  was measured for every live shoot in all plots by a computerised caliper (Masser Racal series, Savcor Group Ltd., Finland) and the frequency distribution was established (Fig. 4-A).

Ranging the whole distribution, 20 shoots were selected, and then desiccated in an oven (PPP0550, Pickstone Oven, Pickstone Ltd, England) at 100 °C for approximately 1 week until the reduction of their mass stopped, and then their dry mass ( $DM_S$ ) was weighed on a scale (HL206-31 scale, Avery Berkel, USA). Shoot dry mass was computed as a function of diameter as:

$$DM_S = f(d_{1.3}) \quad (3)$$

Estimates of above-ground biomass ( $DM_{ag}$ ) for each plant were computed as:

$$DM_{ag} = \sum_{S=1}^n DM_S \quad (4)$$

where n is the number of shoots for each plant.

The carbon concentration in a shoot on a mass basis was determined for 5 shoots by a dynamic flush combustion method using an NC soil auto-analyzer (Flash EA 1112 Series, Carlo Ebra Strumentazione, Italy). The amount of above-ground carbon was computed by multiplying  $DM_{ag}$  by the carbon concentration in a shoot.

### **Shoot length and $d_{1.3}$**

Ranging the whole distribution of  $d_{1.3}$ , 21 shoots were selected, and then their lengths ( $L_S$ ) were measured with a meter tape (ITEM NO. 000007, DURATOOL, Taiwan). Shoot length was computed as a function of  $d_{1.3}$ ,

$$L_S = f(d_{1.3}) \quad (5)$$

### **Shoot age and $d_{1.3}$**

Ranging the whole distribution of  $d_{1.3}$ , 19 shoots were selected and the number of their annual rings were counted with a microscope (WILD M3Z, HEERBRUGG, Switzerland). Shoot age ( $A_S$ ) was computed as a function of  $d_{1.3}$  as:

$$A_S = f(d_{1.3}) \quad (6)$$

## **Below-ground carbon pool component**

### **Stool and coarse roots**

A coarse root is a root more than 2 mm in diameter. Stool and coarse roots biomass was measured for the 2 average-size plants. Cross section area of shoots was computed from  $d_{1.3}$  for every live shoot and aggregated for every plant, which was used as an index of a plant size (Fig. 4-B). The average of aggregated cross section area of shoots was computed and the 2 average-size plants were selected. Firstly, their shoots were taken out from their stools and  $d_{1.3}$  was recorded, and then their stools and coarse roots were excavated manually using a pickaxe, shovel and spade. The depth of the coarse roots and the length of the longest coarse root were measured with a meter tape (ITEM NO. 000007, DURATOOL, Taiwan). The adhered soil to the plants was removed using high-pressure water (K-6.91 Karcher, Germany). They were desiccated in the oven, and  $DM_{bg}$  were weighed in the same way as shoot dry mass. Shoot biomass was calculated from  $d_{1.3}$  using equation (3) for each plant, and then the ratio ( $r_R$ ) between  $DM_{ag}$  and  $DM_{bg}$  were calculated as:

$$r_R = \frac{DM_{bg}}{DM_{ag}} \quad (7)$$

$DM_{bg}$  for the other plants were estimated by multiplying  $DM_{ag}$  by  $r_R$ .

The carbon concentration contained in a stool and coarse roots was determined in the same way as shoots described above. The amount of below-ground carbon was given by  $DM_{bg}$  times the carbon concentration.

### **Fine roots**

A fine root is a root less than 2 mm in diameter. To determine the depth of fine roots destructive soil coring was carried out at plot 1 and plot 2 with a roots corer. It was a cylindrical soil coring sampling tube 6 cm in diameter and 15 cm in length with a sharp edge to cut fine roots. The root corer was driven into the ground with a 2 kg hammer. The coring was conducted to a depth of 60 cm, and 4 columns of the soil were sampled at every 15 cm depth: 0-15, 15-30, 30-45, 45-60 cm. The collected soil samples were dried in an oven for 1 to 2 hours at 80 °C and broken up. Fine roots were extracted from them, washed with water to remove the adherent soil, desiccated in the oven for 1- 2 days at 80 °C, and then their dry masses were weighed on a scale (PR5003 scale, Mettler, Switzerland). Fine root dry mass per  $m^2$  ( $DM_f$ ) was computed as a function of depth (D) as:

$$DM_f = f(D) \quad (8)$$

### **Statistical analysis**

R version 2.12.2 was used to carry out statistical analyses and to make figures. Regression analyses were performed to test whether  $d_b$ ,  $DM_s$ ,  $L_s$  and  $A_s$  can be described as a function of  $d_{1.3}$  and  $DM_f$  as a function of D, and to predict models. A power and exponential models were performed by both a linear regression with logarithmic transform ( $\ln(y) = a + b \ln(x)$  or  $\ln(y) = a + bx$ ), and non-linear regression ( $y = ax^b$  or  $y = ae^{bx}$ ). Different models were assessed by F test when their degrees of freedom were different and response variables were the same. When their degrees of freedom were the same, they were assessed on the basis of



squared-r ( $r^2$ ), homogeneity of variance, and normality of the error distribution. Akaike's Information Criterion (AIC) and residual standard error (RMSE) were also taken into consideration when the models had the same response variables. Analysis of covariance (ANCOVA) was carried out to test whether the data on  $d_b$  and  $DM_S$  provided by Pitman in 1999 corresponded to those collected from the current project.

To describe plot characteristics, one-way analysis of variance (1-way ANOVA) with post-hoc Tukey's test was performed, and above-ground biomass per plant and the means of plant age among the plots were compared. The means of plant age for each plot were calculated from the means of shoot age per plant. Shoot age varied even in one plant. To determine the relative contribution of a plot, plant, and shoot to the variation in plant age, variance components were assessed. The experimental design was unbalanced, because each plant had different numbers of shoots. Therefore, a linear mixed effects model using lmer function in R was performed. The number of shoots per plant was assessed by analysis of deviance with a generalized linear model. The log link function was used to make all the fitted values positive. Dispersion parameters were assessed to determine the error distribution. A significant difference was shown by P-value less than 0.05.

## **Results**

### **Above-ground components**

#### **Basal shoot diameter and diameter at 1.3 m**

A second-degree polynomial regression showed that there was a strong, positive relationship between  $d_b$  and  $d_{1.3}$  (Fig.2-A). F test showed that it explained the relationship significantly better than a liner regression ( $P < 0.05$ ).  $r^2$  and RMSE were 0.9873 and 0.00305 (m), respectively, in the polynomial model, and 0.9868 and 0.00309 (m) in the liner model.

### **Shoot dry mass and $d_{1.3}$**

The relationship between  $d_{1.3}$  and  $DM_S$  was well described by a power model resulting from a linear regression with logarithmic transform ( $\ln(y) = a + b \ln(x)$ ), indicating that increasing shoot diameter at 1.3 m leads to exponential increases of shoot dry mass (Fig.2-B). The residual plots against the fitted values seemed to scatter randomly in the linear regression. In contrast, a non-linear regression ( $y = ax^b$ ) showed a wedged pattern of residuals which increased with the fitted values, indicating that the linear regression met the homogeneity of variance better. In the Normal Q-Q plot resulting from the non-linear regression showed an obvious S-shaped pattern, indicating that the errors were not normally distributed.  $r^2$  showed that the linear regression fitted the data better. For those reasons, the linear regression was selected (Appendix 1). Using this model dry mass for every shoots was estimated (Table.2). The carbon concentration contained in shoots was  $48.7 \pm 0.3 \%$  (1 SD,  $n = 5$ ) of shoot biomass in the average.

In 1990, Pitman found the allometric relationship between  $DM_S$  and  $d_b$  of hazel at the same site, measuring shoots ranging from 0.013 to 0.047 m in basal diameter. The data of  $d_b$  collected by her was transformed to  $d_{1.3}$  using the allometric relationship obtained from the regression above (Equation 2, Fig.2-A), and ANCOVA was carried out to test whether the relationship obtained from this study was different from Pitman's. It showed that in a logarithmic scale their slopes were not significantly different ( $P > 0.05$ ) but the intercept predicted from her data was significantly lower than that from this study ( $P < 0.01$ ). It indicated that although the predicted relationship between  $DM_S$  and  $d_{1.3}$  were not significantly different between these two studies, in Pitman's study  $DM_S$  given shoot diameter was significantly lower than that of this study (Appendix 2).

### **Shoot length and $d_{1.3}$**

The relationship between  $d_{1.3}$  and  $L_S$  was described by a power model (Fig.2-C). The exponent of the model was between 0 and 1, indicating that shoot length increases, whereas its increasing rate decreases with shoot diameter. The variation in  $L_S$  seemed to become larger with  $d_{1.3}$ . Three regression models were assessed to describe the relationship: linear ( $y = a + bx$ ), linear with logarithmic transform ( $\ln(y) = a + b \ln(x)$ ), and non-linear ( $y = ax^b$ ) model. The residual plot against the fitted values resulting from the second model showed the slightly less curved pattern than that resulting from the first model. In addition the Normal Q-Q plots showed that the errors from the second model distributed more normally than those from the first model. AIC, RSME and  $r^2$  resulting from the last model showed better values than those from the first model, indicating that the power model described the data better than the linear model. There did not seem to be obvious difference between the second and the last regression model in their residual and Normal Q-Q plots. However,  $r^2$  showed that the second model fitted the data better. Therefore, the linear regression with logarithmic transform was selected to describe the relationship (Appendix 3).

### **Shoot age and $d_{1.3}$**

There seemed to be a 2-parameter asymptotic exponential relationship between  $A_S$  and  $d_{1.3}$  (Fig.2-D). F test showed that a 3-parameter asymptotic exponential model did not explain the data significantly better than the 2-parameter model ( $P > 0.05$ ), justifying model simplification.  $r^2$ , RMSE and AIC resulting from a second-degree polynomial model showed better values than those from the asymptotic model. There was no clear difference between their residual plots (Appendix 4). Although those results supported the polynomial model, it is unlikely that shoot age have a maximum. Therefore, the asymptotic was applied.

### **Below-ground components**

### **Stool and course roots**

DM<sub>bg</sub> was smaller than DM<sub>ag</sub>.  $r_R$  was 0.30 in the mean (n = 2) (Table 2). The carbon concentration contained in stool and coarse roots was 47.5 % (n = 2) of DM<sub>bg</sub> in the average. The course root depth and the length of the longest course root were 0.30 (m) and 0.33 (m) respectively (n = 2).

### **Fine roots**

DM<sub>f</sub> declined with the soil depth (D) and became nearly 0 at a depth of 0.50 m along an exponential model (Fig.3). Since the exponent was negative, the decreasing rate of roots dry mass became lower according to a depth. Three regression models were assessed to describe the relationship: linear, linear with logarithmic transform ( $\ln(y) = a + bx$ ), and non-linear ( $y = ae^{bx}$ ) model. Although there was not clear difference in the residual plots against the fitted values and the Normal Q-Q plots among them, it seemed that the Normal Q-Q plot resulting from the second and last regression models behaved slightly better than that from the first model. AIC and RMSE also showed that the last model fitted the data better than the first, indicating that the exponential model was more appropriate than the linear model. There was no obvious difference between the second and last model.  $r^2$  obtained from the second was slightly higher than that from the last; therefore, the linear regression model with logarithmic transform was selected (Appendix 5).

### **Plot characteristics (Table 2)**

Dry mass and age for every live shoot in the experimental plots were estimated using the models predicted above (Equation. 3, 6, Fig. 2-B, D). There was no significant difference in DM<sub>ag</sub> per plant among the plots (Fig. 5-B). DM<sub>ag</sub> per plant in plot 6 had the larger mean and variance than the others. The mean of the number of shoots per plant in plot 6 was

significantly larger than the others ( $P < 0.05$ ) (Fig. 5- A, Appendix 6). There was a significant plot effect on the mean of shoot age ( $P < 0.001$ ). The number of plants in plot 6 was smaller than the others. The mean of shoot age per plant in plot 6 was significantly younger than plot 2 ( $P < 0.05$ ) and plot 4 ( $P < 0.001$ ), and that in plot 4 was significantly older than that in plot 1 ( $P < 0.001$ ). The linear mixed effects model showed that the variance in shoot age due to the difference among individual plants explained only approximately 10 % of the total variance, indicating that the variations of shoot age within an individual plant more importantly contributed to the total variation.

## **Discussion**

This study showed that diameter at 1.3 m were strongly related to basal shoot diameter, shoot dry mass, shoot length, and shoot age. Values of squared-R ( $r^2$ ) as an index of the degree of scatter were quite close to 1 in the regression analyses of  $d_b$ ,  $DM_S$ , and  $L_S$  as a function of  $d_{1.3}$  (Fig 2-A-D); therefore, the predicted models may be applicable to other research. However, extrapolation may not well behave especially for the regression model of  $L_S$  and  $d_{1.3}$ . Their relationship might be explained by an exponential model instead of a power model unlike this study. In that case predicted values beyond the range can be far different from the actual values. It may be more appropriate to employ a regression analysis again after collecting data which covers the whole required range.

$L_S$  seemed to more vary than  $DM_{ag}$  in larger shoot diameter. It may be because the structure of a large shoot varies more than that of a small one. Depending on their location, some shoots grow straight with fewer branches, while some are short with more branches.

The relationship between  $DM_S$  and  $d_{1.3}$  resulting from this study was the same as that from Pimans's study (1990). On the other hand, her data showed significantly smaller  $DM_S$  at

given  $d_{1.3}$ . There were mainly 3 possible explanations for this. Firstly, she used the arithmetic mean of shoot diameters measured from two different directions as shoot diameter unlike this study where the geometric mean was applied instead; the arithmetic mean is always equal to or above the geometric when all values are positive. Secondly, her data covered a much smaller range of  $d_{1.3}$ . Lastly,  $d_{1.3}$  was estimated from  $d_b$ , causing biases. It was less likely that the shoots collected in this study were not completely dry, because they were desiccated in the oven until the reduction of their masses stopped.

The ratio between  $DM_{ag}$  and  $DM_{bg}$  ( $r_R$ ) was 0.30. Since the samples size to measure  $DM_{bg}$  was 2, this value is not statistically reliable. However, in 1971, Satchell conclude that the ratio was 0.30 from 21 hazel plants. In addition, Patenaude (2003) applied 0.285 as the value of the ratio referred to from Cannell's (1982) report in order to calculate  $DM_{bg}$  from  $DM_{ag}$ . Therefore, the value obtained in this study seemed reasonable. A power calculation for two-sample t tests was performed to determine the sample size when the difference between  $DM_{ag}$  and  $DM_{bg}$  to be detected is 30 % as shown here with probability 0.8.  $DM_{ag}$  per plant was not distributed normally (Fig. 4-C), so that logarithmic transform was carried out and the expected standard deviation was calculated for the power calculation. It showed that the sample size for each component needs to be larger than 23.

According to Table.2, plot 6 appeared to have slightly special characteristic compared to the others. It showed fewer plants, younger shoot age, more shoots and  $DM_{ag}$  per plant with high variances. It might have been caused by thinning carried out in 1996. Although it was to thin out oak trees, equipment for that might have disturbed hazel resulting in fewer number of plants. On the other hand, thinning made gaps in the canopy, leading to better light conditions for undersorey vegetation. As a result, some plant might have developed huger shoots and more sprouts than plants in the other plots (Appendix 7).

The scatter plot and regression model of  $A_S$  and  $d_{1.3}$  indicated that although a shoot grows constantly until its  $d_{1.3}$  becomes around 0.05 m, the growing rates become more varying afterwards. Small shoots less than 0.05 m in  $d_{1.3}$  may grow constantly regardless of their conditions; however, for shoots larger than that there might be such factors as nutrition and light which regulate the growth rates. Among others light might considerably influences the growth rates. As indicated above, in plot 6 thinning might have led to canopy gaps, resulting in rapid growth of some shoots. When  $d_{1.3}$  becomes approximately 0.05 m, its growth rate may be promoted exponentially by light, whereas the growth rate may become lower under a canopy.

The carbon contained in hazel at this site was 7.7 t per ha. Satchell (1971) found that the carbon content of hazel was 16 t per ha at Mathop Woodland where dominant overstorey species were oak, ash, birch and sycamore, and understorey was hazel. Patenoude (2003) concluded that the carbon content of understorey was 18 t per ha at Monks Wood where dominant overstorey species were ash, oak, field maple and aspen, and understorey were hawthorn, hazel, dogwood and wild privet. Satchell basically covered the whole range of hazel size, whereas Patenoude defined that plants 7 to 18 cm in diameter at breast height were understorey. According to those studies and Cannel and Milne (1995), the estimate of the carbon content of overstorey at British woodland was approximately 100 to 120 t per ha. Although the estimated value in this study seems smaller than previous research, it is expected that hazel contributes to the carbon stock of oak woodland at a rate of 5 % of overstorey.

### **Further work**

There were not enough samples to differentiate  $DM_{ag}$  from  $DM_{bg}$ . To estimate below-ground biomass more accurately more than 23 plants are required. There were not enough samples to

estimate carbon content attributable to fine roots as well. Vanguelova (2002) concluded that at least 10 samples per 10 x 10 m<sup>2</sup> plot are statistically required to represent the carbon content of fine roots. In this study, fine roots species were not identified. To attribute below-ground biomass to above-ground biomass, identification of species of fine roots and individual estimates are required. By doing so, the contribution of each species to below-ground biomass can be understood. The current study did not take foliage into account. Since carbon storage varies depending on the season (Corcuera et al., 2005, Sun et al., 2001), such components as leaf area index (LAI) and litter fall need assessing in order to understand phenological variations. This project only focused on hazel; however, hawthorn is also an important component of understorey vegetation. It stored 4.6 % of carbon in British woodland (CANNELL and MILNE, 1995). Evaluation of carbon contained in hawthorn is required for comprehensive understanding of understorey ecosystems.

The current study suggested that thinning might have great impact on carbon contents of understorey vegetation even after about 15 years. To understand the variation of carbon storage of understorey vegetation, chronosequence analyses of the impact of thinning may be required by setting multiple measurement plots at places where thinning was carried out in different years.

## **Conclusion**

Hazel at this site stored 7.7 t Carbon per ha and is 11-year-old, approximately 70 % of which was derived from above-ground and 30 % from below-ground component. The amount of carbon storage may be affected by light conditions and thinning of overstorey vegetation.



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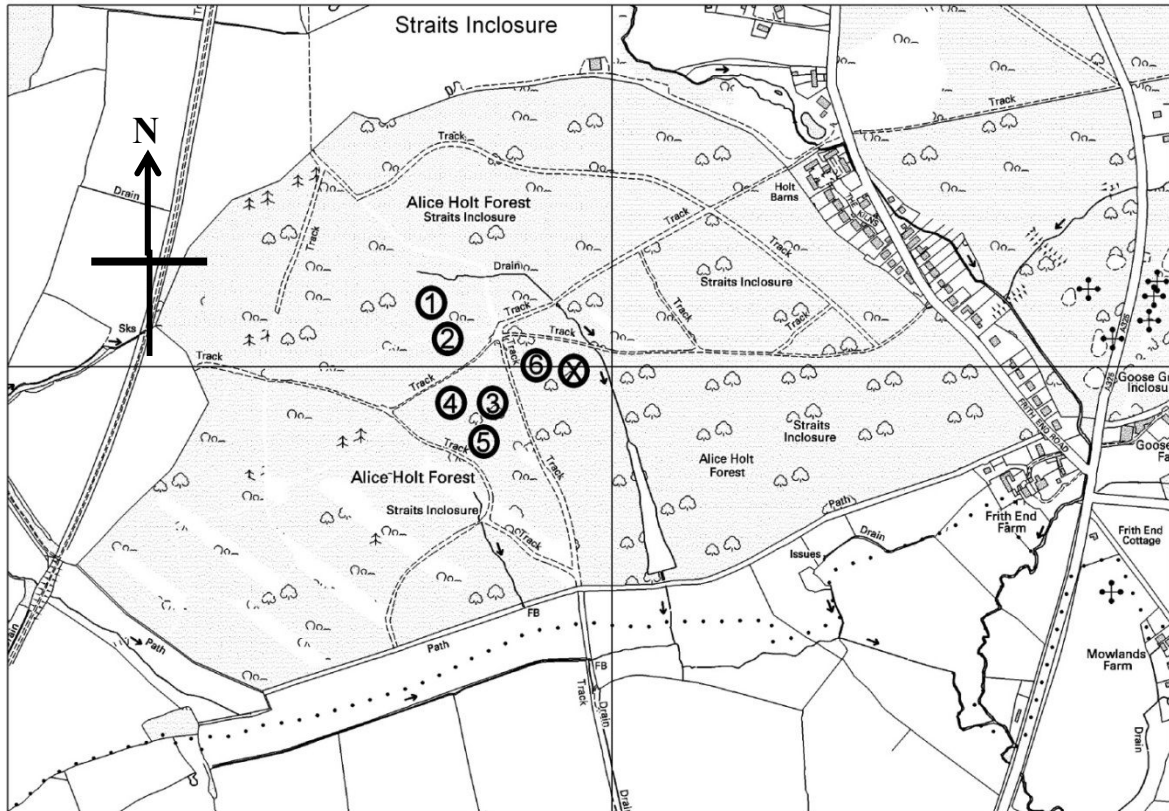


Figure 1. The map of the Straits site. Numbers depict the location of the mensuration plots. Plot 6 was located where thinning of oak trees was carried out in 1996. The cross shows the location of the Eddy Covariance flux tower.

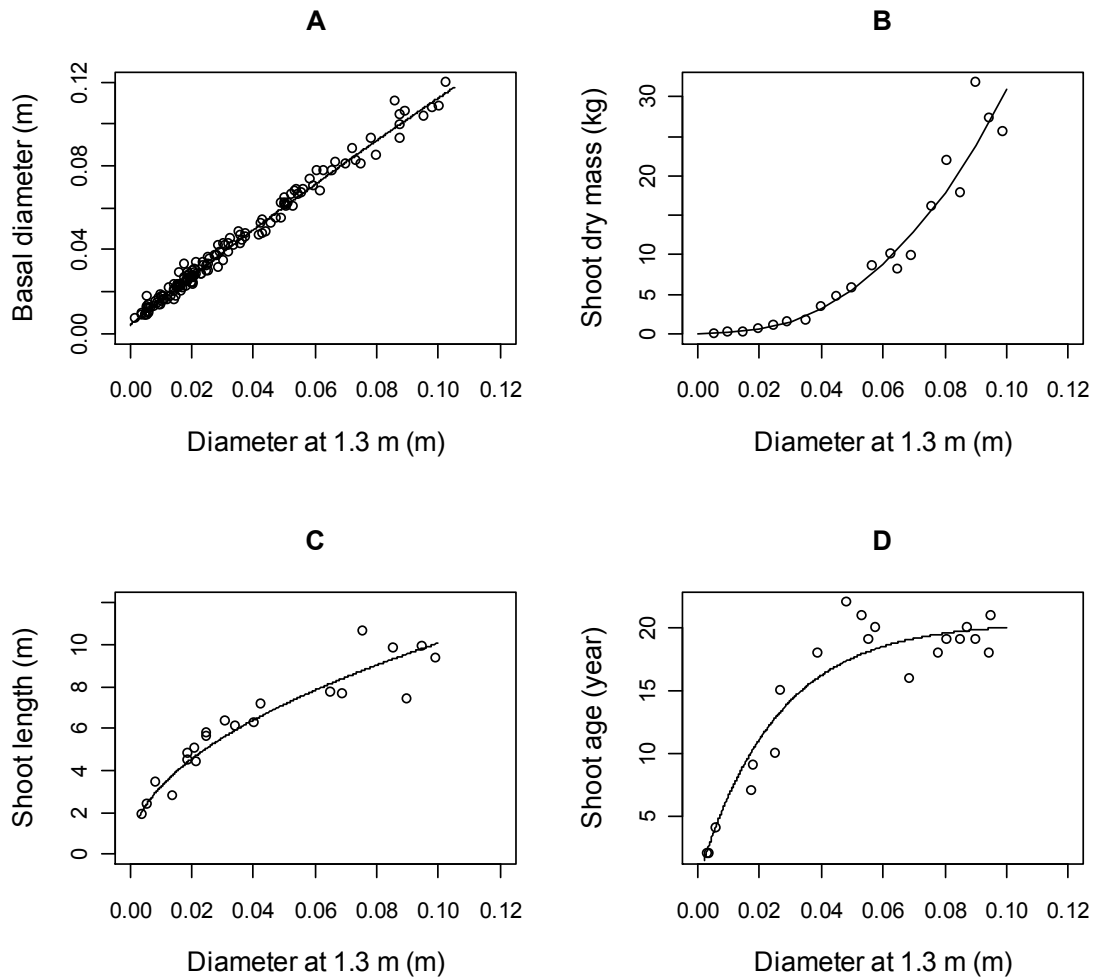


Figure 2. (A) The relationship between  $d_b$  and  $d_{1.3}$ . A regression analysis was carried out with a second-degree polynomial model. The model  $y = a + bx + cx^2$  had  $a = 0.004 \pm 0.001$ ,  $b = 1.172 \pm 0.074$ , and  $c = -0.874 \pm 0.777$  (95 % CI,  $n = 144$ ,  $P < 0.001$ ,  $r^2 = 0.99$ , RMSE = 0.003 (m)). (B) The relationship between  $DM_S$  and  $d_{1.3}$ . A linear regression analysis with logarithmically transformed data was carried out. The power model  $y = ax^b$ , had  $a = 9248$  (6736 – 12697), and  $b = 2.475 \pm 0.968$  (95 % CI,  $n = 20$ ,  $P < 0.001$ ,  $r^2 = 0.99$ , RMSE = 0.162 (log (kg))). (C) The relationship between  $L_S$  and  $d_{1.3}$ . A linear regression analysis was carried out with logarithmically transformed data. The power model  $y = ax^b$  had  $a = 31.62$  (24.92 - 41.12) and  $b = 0.496 \pm 0.066$  (95 % CI,  $n = 21$ ,  $P < 0.001$ ,  $r^2 = 0.93$ , RMSE = 0.130 (log

(m)). (D) The relationship between  $A_S$  and  $d_{1.3}$ . A non-linear regression analysis was performed with a 2-parameter asymptotic exponential model. The model  $y = a(1 - e^{-bx})$  had  $a = 20.44 \pm 2.13$  and  $b = 39.47 \pm 14.10$  (95 % CI,  $n=20$ ,  $r^2 = 0.91$ , RMSE = 2.103 (year)).

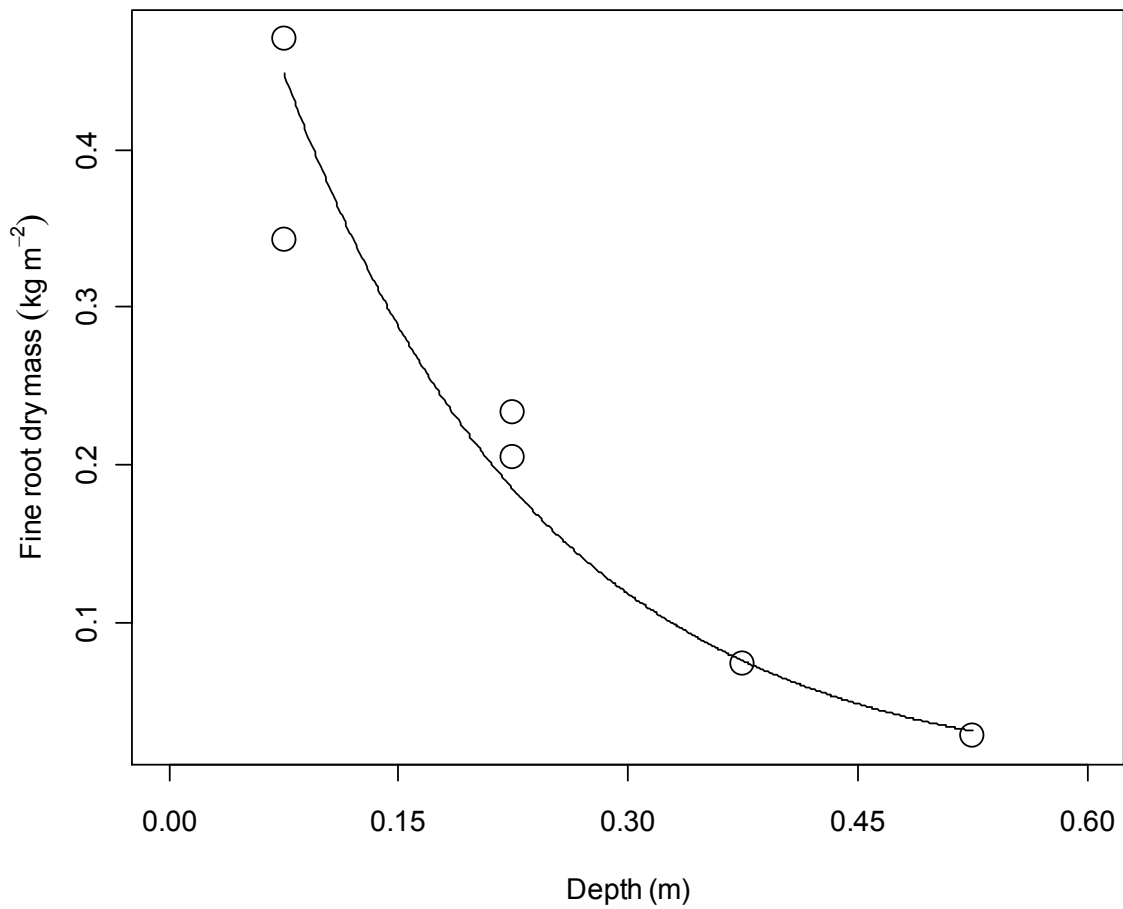


Figure 3. The relation between fine roots dry mass and soil depth ( $n = 6$ ). A linear regression analysis was performed with logarithmically transformed fine root dry mass. The model  $y = ae^{bx}$  had  $a = 0.699$  (0.467 - 1.051) and  $b = - 5.920 \pm 1.375$  (95 % CI,  $n = 6$ ,  $P < 0.001$ ,  $r^2 = 0.97$ , RMSE = 0.194)

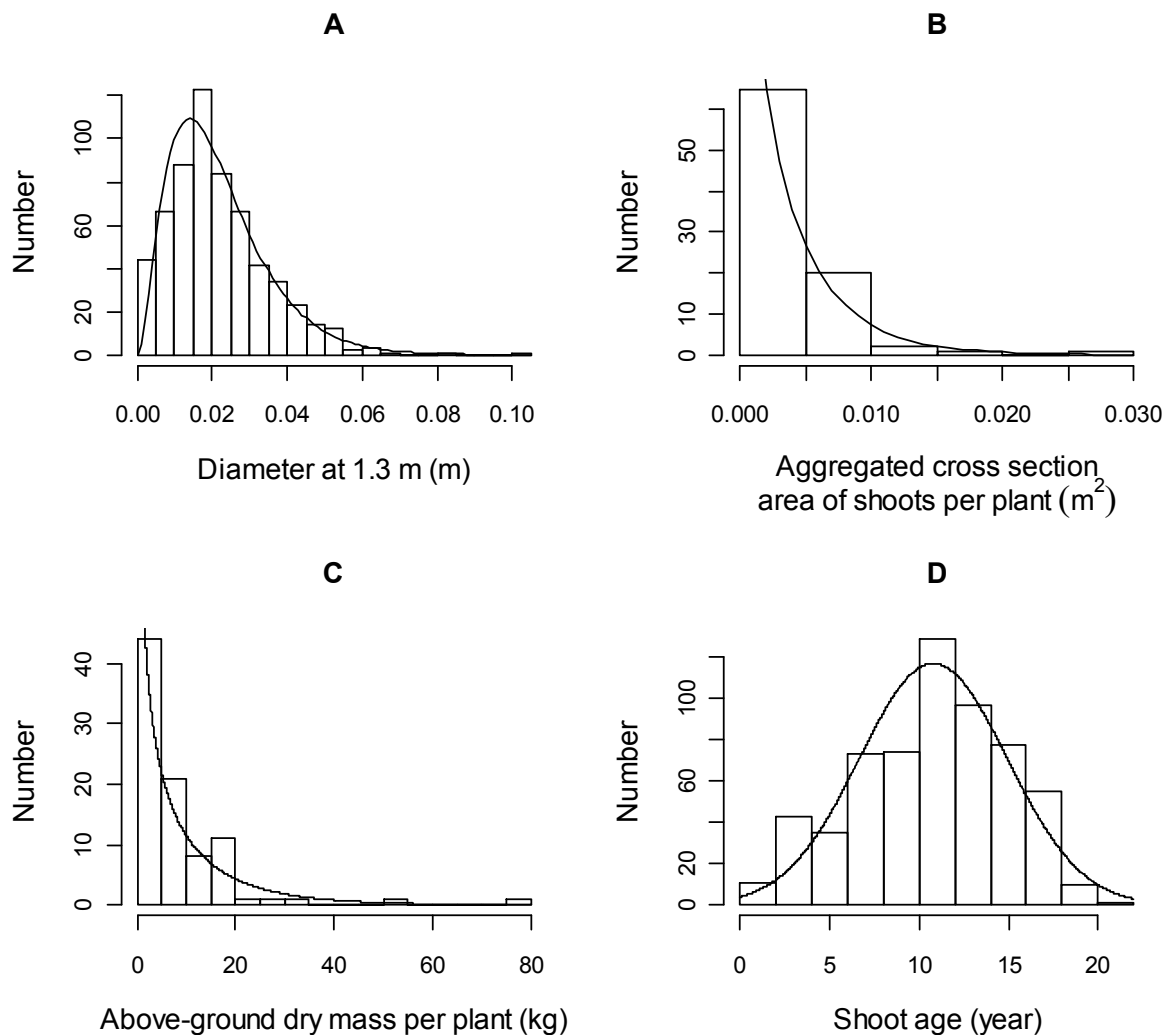


Figure 4. The frequency distributions. (A) Shoot diameter at 1.3 m ( $d_{1.3}$ ) ( $n = 603$ ) was the gamma distribution whose shape and rate parameters were 2.784 and 127.3 respectively (solid line). According to the gamma distribution, 95 % of the values fallen between 0.004 and 0.054 m.  $d_{1.3}$  was 0.023 m in the mean, and ranged from 0.001 to 0.104 m. (B) Aggregated cross section area of shoots per plant ( $n = 89$ ) was the gamma distribution whose shape and rate parameters were 0.79201 and 229.1 respectively (solid line). According to the distribution, 95 % of the values fallen between 0.00004 to 0.01411 m<sup>2</sup>. The mean of aggregated cross section of shoots per plant was 0.00346 m<sup>2</sup>. It ranges from 0.00003 to 0.00267 m<sup>2</sup>. (C) Above-ground dry mass per plant ( $n = 89$ ) was the gamma distribution

whose shape and rate parameters were 0.5637 and 0.06771 respectively (solid line). According to the distribution, 95 % of the values fallen between 0.02 and 39.60 kg per plant.  $DM_{ag}$  per plant was 8.32 kg in the mean, and ranged between 0.03 and 77.80 kg. (D) Shoot age ( $n = 603$ ) was not significantly different from the normal distribution. Shoot age was estimated using the model in Fig. 2-D from  $d_{1,3}$ . Student's t-test showed that neither the values of skewness nor kurtosis were significantly different from zero ( $P > 0.05$ ). According to the Normal distribution (solid line), 95 % of the values fallen between 3 and 19. The mean of shoot age was 11. It ranged from 1 to 20.



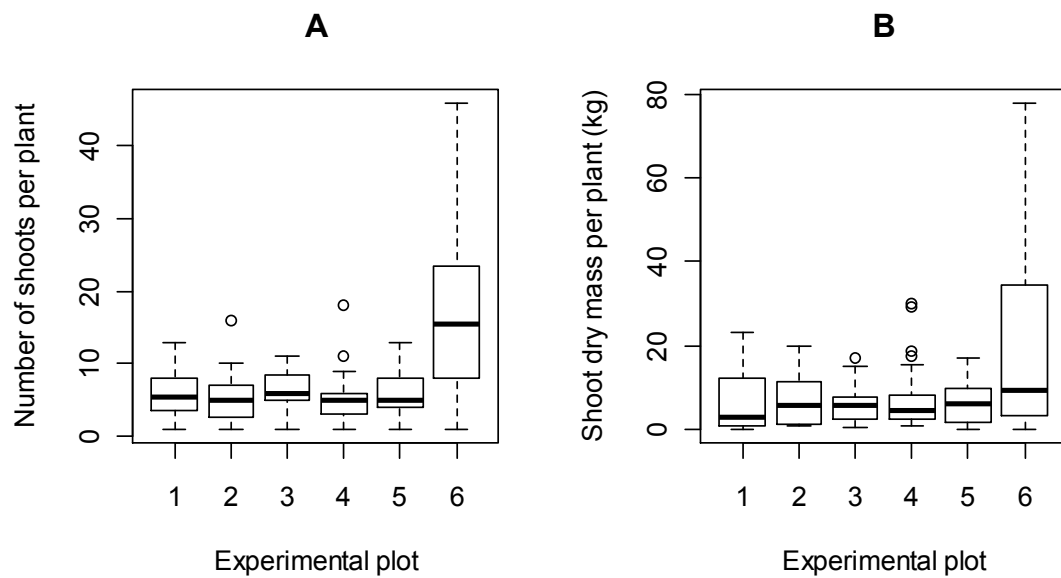


Figure 5. (A) The number of shoots per plant in a plot was compared by an analysis of deviance where overdispersion was assumed. It showed that the number of shoots per plant in plot 6 was significantly larger than the others ( $P < 0.001$ ). The number of shoots per plant in plot 6 varied more greatly than the others. (B) Shoot dry mass ( $DM_S$ ) per plant.  $DM_S$  was compared by one-way ANOVA among plots. The variance of plot 6 appears to be larger than the others. In order to make the variances of  $DM_S$  constant among the plots, logarithmic transform of the values of  $DM_S$  was conducted before the ANOVA test was carried out. It showed the difference in mean shoot mass is not significantly different ( $P > 0.05$ ).

Table 1. Abbreviations

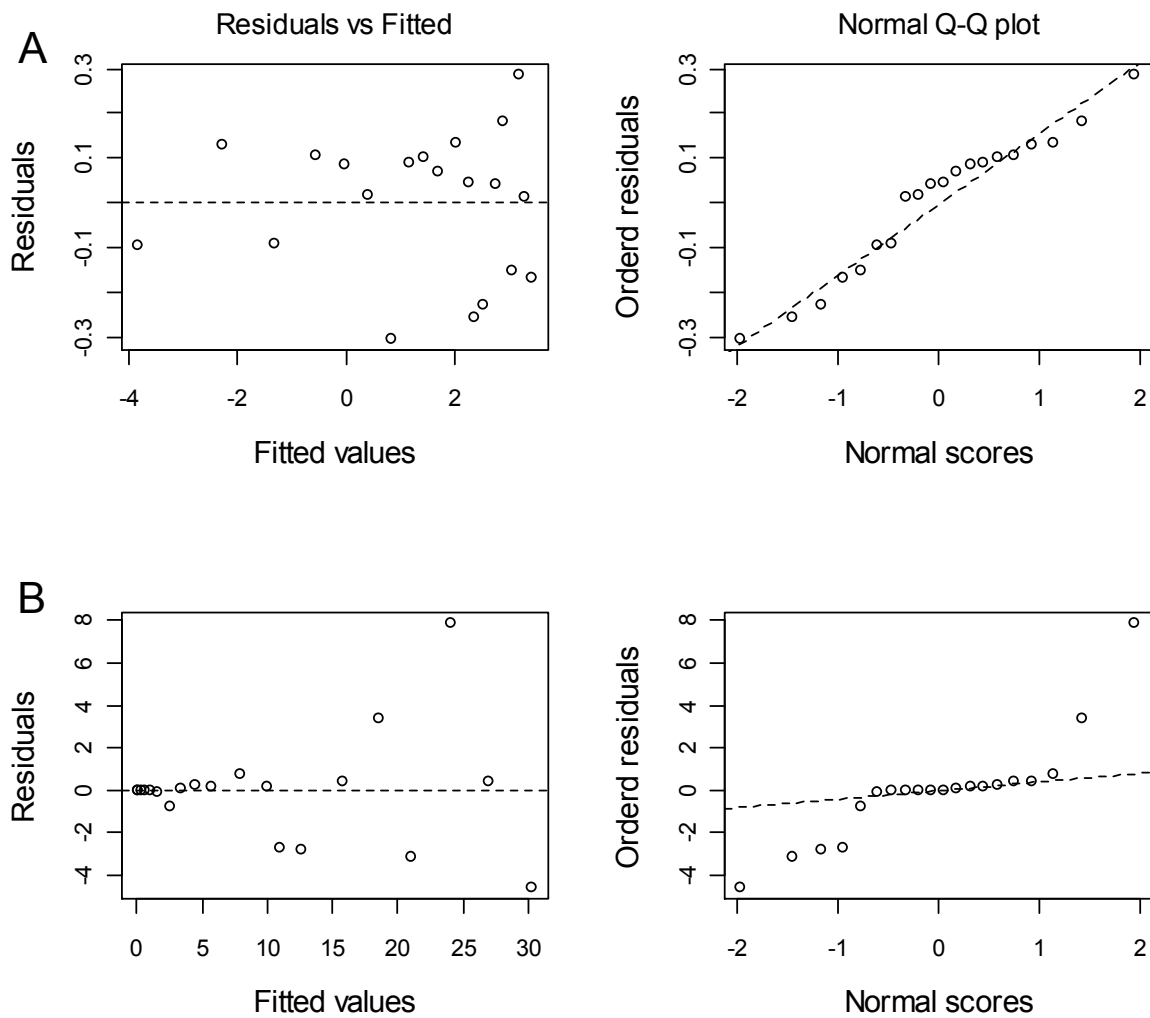
Abbreviation	Definition
$d_b$	basal shoot diameter
$d_{1.3}$	shoot diameter at 1.3 m along the shoot from the base
$DM_S$	shoot dry mass
$L_S$	shoot length
$DM_{ag}$	above-ground dry mass
$A_S$	shoot age
$DM_{bg}$	dry mass of a stool and coarse roots
$DM_f$	fine roots dry mass

Table 2. Plot characteristics.  $n_s$  was assessed among the plots by analysis of deviance where overdispersion was assumed ( $P < 0.05$ ) (Fig. 5-A, Appendix 6). The differences of the mean of shoot age per plant and logarithmically transformed above-ground dry mass per plant among were evaluated by 1-way ANOVA among the plots with Post-hoc Tukey's test. Significantly different results are indicated by different letters beside each value ( $P < 0.05$ ). (mean  $\pm$  1 SD)

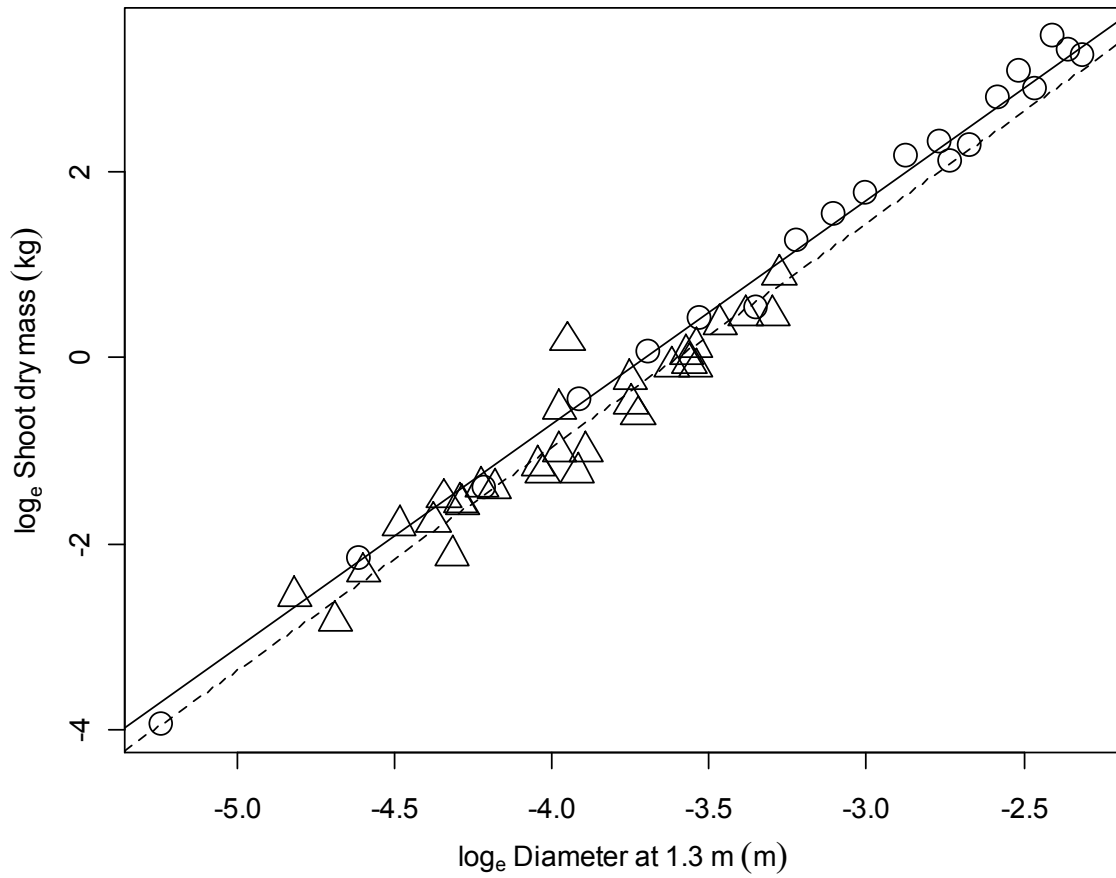
Plot	$n_p$	$n_s$ (plant <sup>-1</sup> )	Age (plant <sup>-1</sup> )	Above-ground			Below-ground			$C_{total}$ (kg m <sup>-2</sup> )
				DM		C	DM		C	
				(kg plant <sup>-1</sup> )	(kg m <sup>-2</sup> )	(kg m <sup>-2</sup> )	(kg plant <sup>-1</sup> )	(kg m <sup>-2</sup> )	(kg m <sup>-2</sup> )	
1	16	6 $\pm$ 3 <sup>a</sup>	9 $\pm$ 3 <sup>ab</sup>	6.32 $\pm$ 7.50 <sup>a</sup>	1.01	0.49	1.87 $\pm$ 2.22	0.30	0.14	0.63
2	16	6 $\pm$ 4 <sup>a</sup>	12 $\pm$ 2 <sup>bc</sup>	7.18 $\pm$ 6.43 <sup>a</sup>	1.15	0.56	2.12 $\pm$ 1.90	0.34	0.16	0.72
3	12	6 $\pm$ 3 <sup>a</sup>	11 $\pm$ 2 <sup>abc</sup>	6.10 $\pm$ 5.28 <sup>a</sup>	0.73	0.36	1.8 $\pm$ 1.56	0.22	0.10	0.46
4	25	5 $\pm$ 4 <sup>a</sup>	12 $\pm$ 2 <sup>c</sup>	8.16 $\pm$ 8.29 <sup>a</sup>	2.04	0.99	2.41 $\pm$ 2.45	0.60	0.29	1.28
5	12	6 $\pm$ 3 <sup>a</sup>	11 $\pm$ 3 <sup>abc</sup>	6.37 $\pm$ 5.59 <sup>a</sup>	0.76	0.37	1.88 $\pm$ 1.65	0.23	0.11	0.48
6	8	18 $\pm$ 14 <sup>b</sup>	9 $\pm$ 1 <sup>a</sup>	21.49 $\pm$ 28.02 <sup>a</sup>	1.72	0.84	6.35 $\pm$ 8.27	0.51	0.24	1.08
Mean	15 $\pm$ 6	8 $\pm$ 5	11 $\pm$ 1	9.27 $\pm$ 6.03	1.24 $\pm$ 0.53	0.60 $\pm$ 0.26	2.74 $\pm$ 1.78	0.36 $\pm$ 0.16	0.17 $\pm$ 0.07	0.77 $\pm$ 0.33

DM and C indicate dry mass and carbon mass, respectively.  $n_p$  and  $n_s$  are the number of plants and the mean of the number of shoots per plant, respectively.

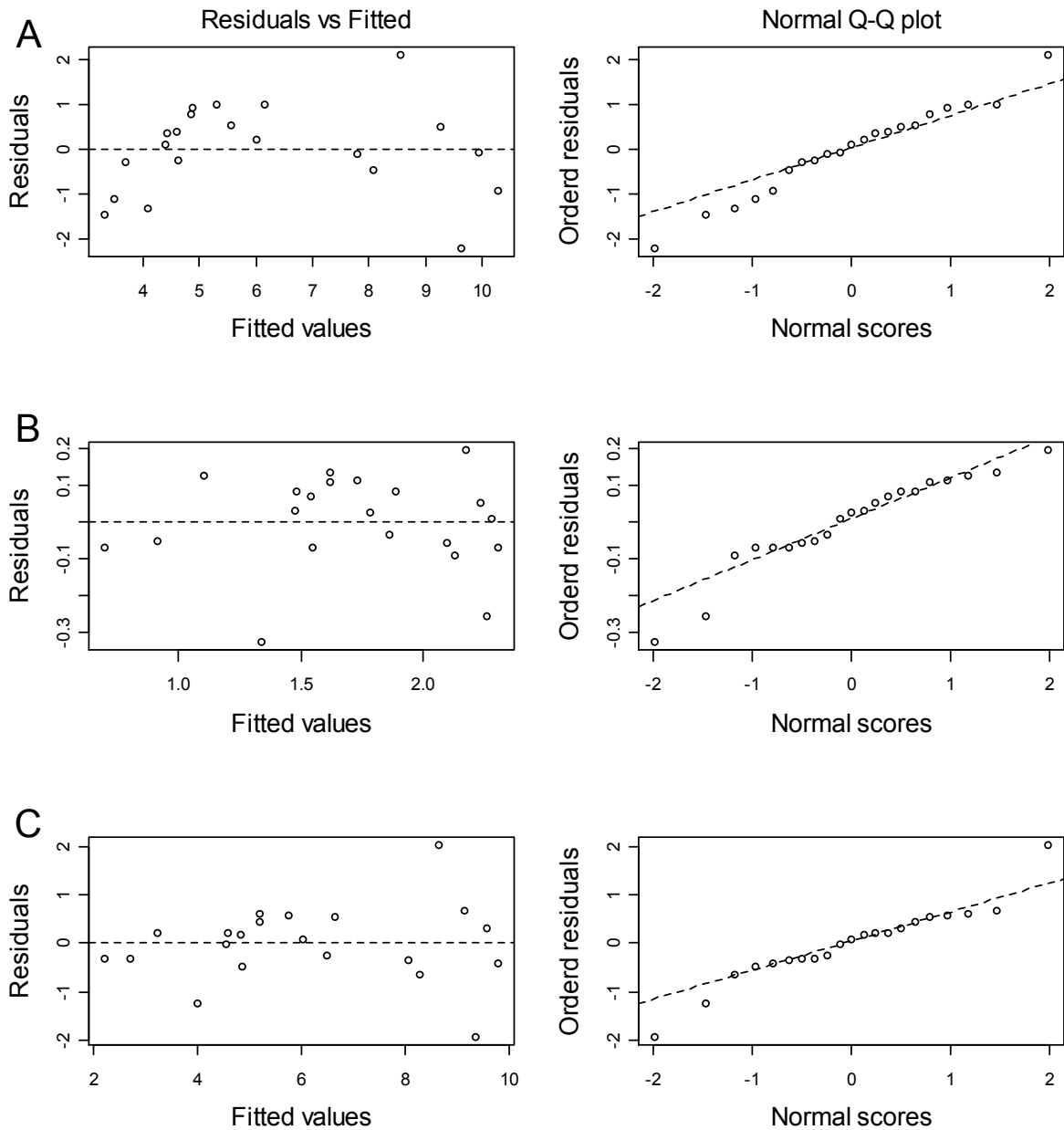
## Appendix



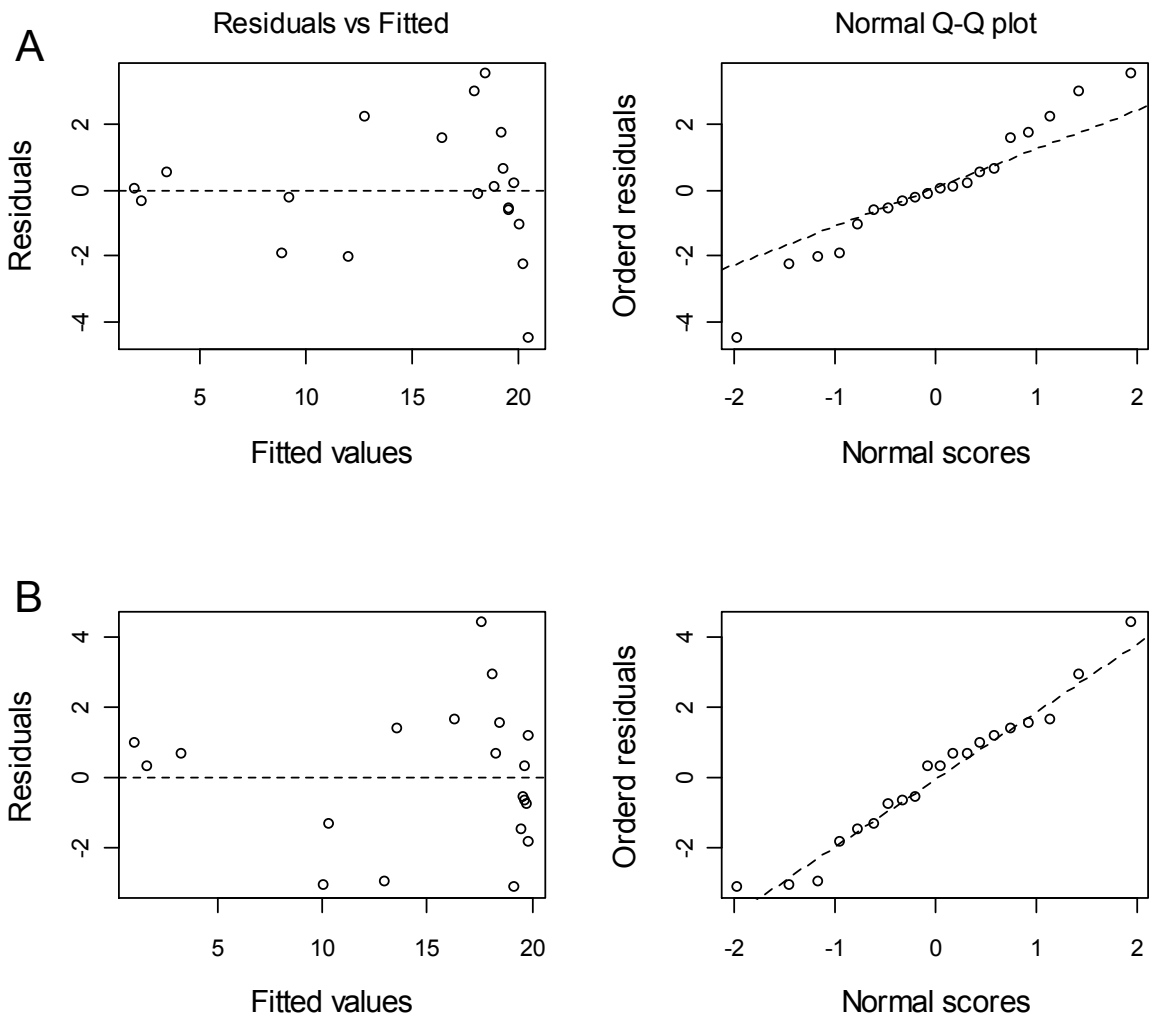
Appendix 1. Residual plot against fitted values (left) and normal Q-Q plot (right) resulting from a linear with logarithmic transform (A) ( $r^2 = 0.99$ ,  $RSME = 0.162$  (log (kg))), and non-linear regression (B) ( $r^2 = 0.94$ ,  $RSME = 2.598$  (kg)) for the relationship between  $DM_S$  and  $d_{1.3}$ .



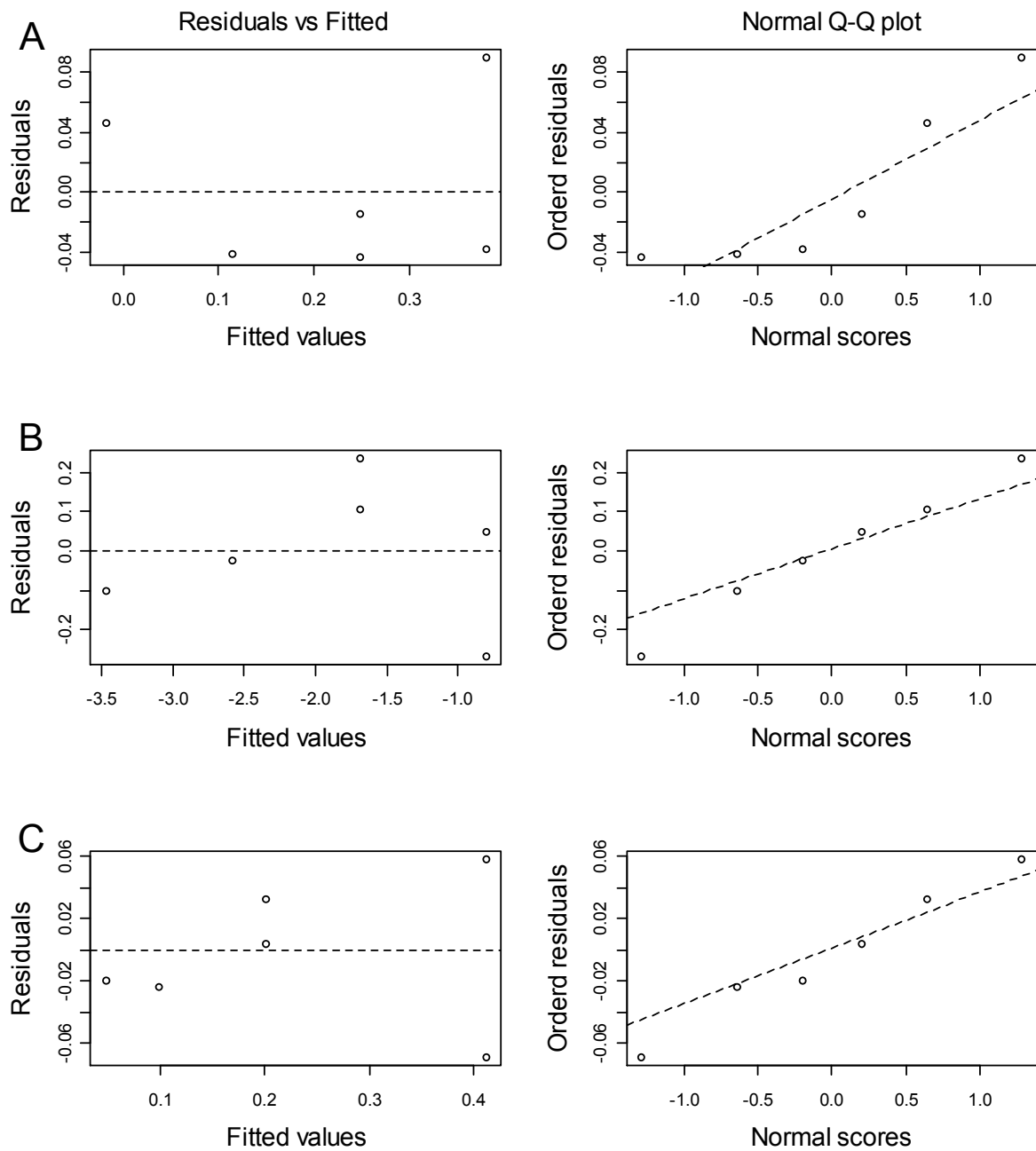
Appendix 2. The relationship between  $DM_S$  and  $d_{1.3}$  in a logarithmic scale given by ANCOVA. Circles and a solid line,  $y = a + bx$ , were the data from this study. Triangles and dotted line,  $y = c + bx$ , were from Pitmans's data (1999).  $a = 8.901 \pm 0.174$ ,  $b = 2.403 \pm 0.121$ ,  $c = 8.652 \pm 0.487$  (95 % CI,  $n = 50$ ,  $P < 0.001$ ,  $r^2 = 0.98$ ,  $RMSE = 0.252$ ).



Appendix 3. Residual plot against fitted values (left) and normal Q-Q plot (right) resulting from a linear (A) ( $r^2 = 0.84$ , RSME = 1.026 (m), AIC = 64.58), linear with logarithmic transform (B) ( $r^2 = 0.93$ , RSME = 0.130 (log (m)), AIC = -22.20), and non-linear regression (C) ( $r^2 = 0.90$ , RSME = 0.811 (m), AIC = 54.74), for the relationship between  $L_S$  and  $d_{1.3}$ .

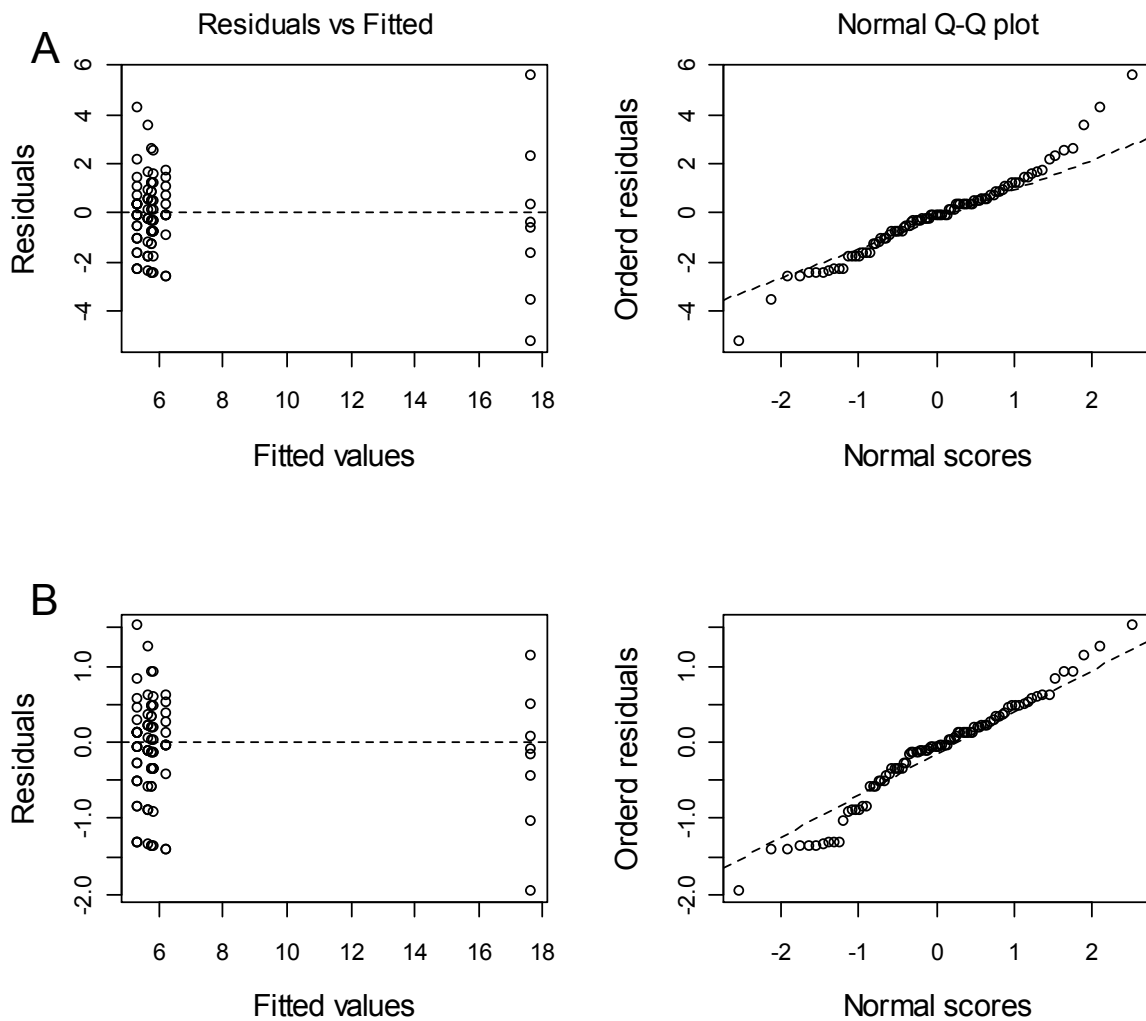


Appendix 4. Residuals plot against fitted values (left) and normal Q-Q plot resulting from a second-degree polynomial model (A) ( $r^2 = 0.92$ , RMSE = 1.995 (year), AIC = 89.14), and 3-parameter asymptotic exponential model (B) ( $r^2 = 0.91$ , RMSE = 2.095 (year), AIC = 91.08) for the relationship between  $A_S$  and  $d_{1,3}$ .

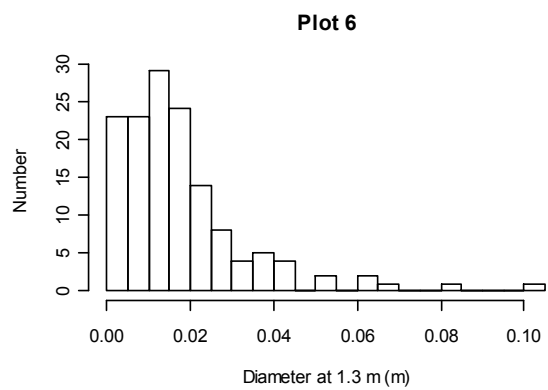
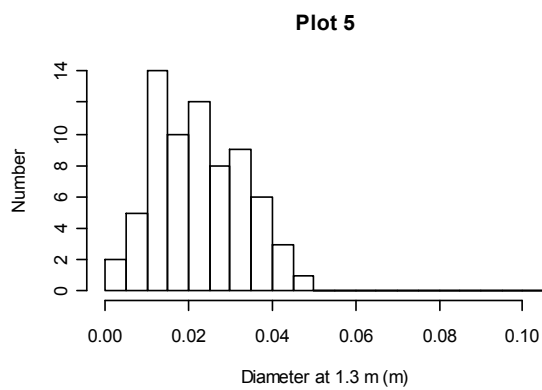
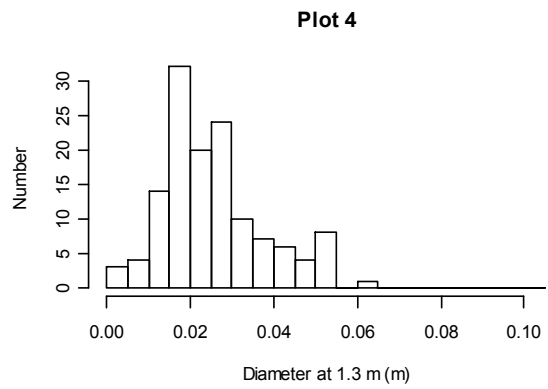
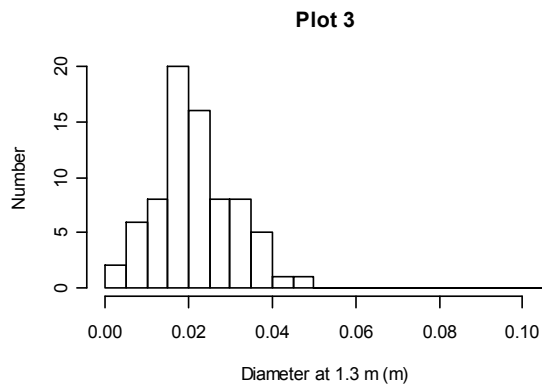
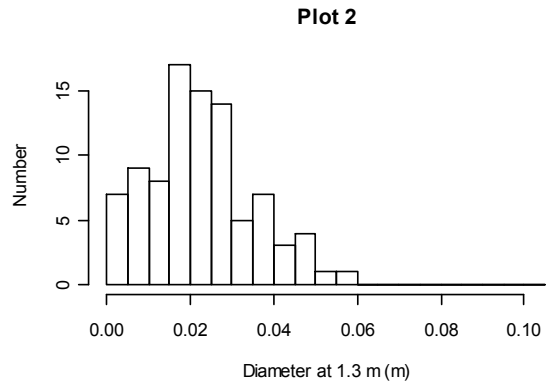
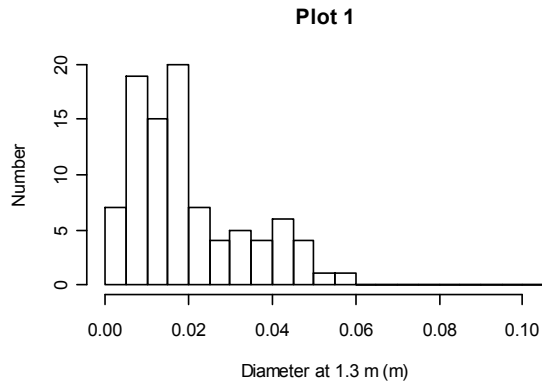


Appendix 5. Residuals plot against fitted values (left) and normal Q-Q plot (right) resulting from a linear (A) ( $r^2 = 0.89$ ,  $RMSE = 0.0618$  ( $\text{kg m}^{-2}$ ),  $AIC = -12.81$ ), linear with logarithmic transform of fine root biomass(B) ( $r^2 = 0.97$ ,  $RMSE = 0.194$  ( $\log(\text{kg m}^{-2})$ ),  $AIC = 0.93$ ), and non-linear regression ( $r^2 = 0.93$ ,  $RMSE = 0.504$  ( $\text{kg m}^{-2}$ ),  $AIC = -15.25$ ) for the relationship between  $DM_f$  and depth (D).





Appendix 6. Residuals plot against fitted values (left) and normal Q-Q plot (right) resulting from the generalized linear model of the number of shoots per plant and plots, assuming overdispersion (A) (the estimate of Dispersion Parameter was 2.915, and the actual value was 2.888), and overdispersion with the variance increasing with the square of the mean (B) (the estimate was 2.915, and the actual value was 0.4911). In the model assuming Poisson errors, the actual Dispersion Parameter was 2.888, which was bigger than the assumed value of 1, indicating that the number of shoots per plant was overdispersion. In the overdispersion model, the S-shaped pattern in the Normal Q-Q plot was slightly improved when it was assumed that the variance increased with the square of the mean.



Appendix 7. The frequency distributions of shoot diameter at 1.3 m ( $d_{1.3}$ ) for each plot.