PRODUCTIVITY MODEL AND REFERENCE DIAGRAM FOR SHORT ROTATION BIOMASS CROPS OF POPLAR GROWN IN MEDITERRANEAN ENVIRONMENTS

N. Oliveira [a], H. Sixto [a], I. Cañellas [a], R. Rodríguez-Soalleiro [b], C. Pérez-Cruzado [c].

[a] Dpto. Selvicultura y Gestión de los Sistemas Forestales, INIA-CIFOR, Madrid E-28040, Spain

[b] Unidad de Gestión Forestal Sostenible, Universidad de Santiago de Compostela, Lugo E-27002, Spain

[c] Chair of Forest Inventory and Remote Sensing, Georg-August-Universität Göttingen, D-37077, Germany

Corresponding author:
Nerea Oliveira
tel. + 34 913 473579
fax + +34 913 572 293
e-mail: nerea.oliveira@inia.es

Abstract

A Reference Diagram (RD) was constructed for first rotations of the Euroamerican poplar 'I-214' grown as short rotation coppice (SRC). Data from 144 plots, established in eleven sites in Mediterranean environments, were used to develop the model. The density at establishment of the plantations ranged between 6 666 and 33 333 stools ha^{-1}, covering the usual densities ranges used in short rotation forestry (SRF). The RD was based on a density-independent mortality model that relates the density of living stools to the average height of dominant shoot and the initial plantation density, and it includes a system of two simultaneously fitted equations relating a) quadratic mean basal diameter of dominant shoots to the average height of dominant shoot and the final density, and b) total above-ground woody dry biomass to quadratic mean basal diameter and final density. The isolines in the RD represented mortality, quadratic mean basal diameter of dominant shoots and total above-ground woody dry biomass at the end of a first rotation of three years. The final yield in terms of biomass ranged from 1 to 85 Mg dm ha^{-1}. The RD enables rapid and straightforward comparison of different situations, both at planting and at harvesting, and is a useful tool, based on a wide range of empirical data, for management and decision making regarding short rotation poplar crops.

KEYWORDS: Poplar, Short rotation coppice (SRC), Density Management Diagrams, Reference Diagrams, Biomass.

1. Introduction

Woody biomass is a renewable resource that is suitable for getting different bioproducts, including bioenergy for different applications (heat, electricity or second generation biofuels)[1, 2]. Use of woody biomass for bioenergy purposes represents a promising opportunity to contribute to the mitigation of climate change, to the extent that the presence of this resource may become important in the overall energy mix. The production and management of woody biomass may provide a new opportunity for economic development of rural areas [3] involving many different productive sectors.

Forestry crops represent one source of supply of woody biomass, which is characterized by its spatiality and temporality [4]. Such crops can be established on both abandoned agricultural land and on marginal land. Short rotation woody crops under coppicing management (SRC), such as *Salicaceae* (*Populus* spp. or *Salix* spp.), are well represented in northern and central Europe and to a lesser extent in southern Europe [5-7]. Studies involving the production of these crops have revealed a wide range of biomass yield depending on different factors such as plant material, site characteristics, crop design (density and rotation), management regime, presence of pest and diseases, and survival after planting [8-10].

Plantation density is an important factor to be considered in SRC and has both production and economic implications. As tree density increases, the total yield rises initially in proportion to the number of plants per area if individual plants receive sufficient resources for growth. However, the specific density at which optimal production is attained has not yet been determined, although the range within which production remains constant is known [11]. Several experimental and commercial plantations have been established to test densities ranging from 1 000 to more than 40 000 plants ha^{-1} [12-14].

Density Management Diagrams (DMDs) are used to graphically illustrate the relationships between density, yield and density dependant mortality at all stages of stand development [15], including concepts such as competition, site occupancy and self-thinning. These biological models are mainly used for decision-making in density management, for example to determine the post-thinning density or even to display and evaluate alternative density regimes in forest management [16].There are many examples for different areas and species, such as *Pinus palustris* Mill. [16], *Quercus robur* L. [17] and *Pseudotsuga menziesii* (Mirb.) Franco [18]. However, as far we know, models relating the initial cutting density to yield, stool mortality or height and basal diameter growth for different developmental stages in SRC are scarce. Such models have been developed, e.g. for *Eucalyptus globulus* Labill. and *Eucalyptus nitens* (Deane and Maiden) Maiden, on the basis of plantations established at the usual range of initial forest densities used in southwestern Europe and managed in short rotations [19]. In SRC, density reduction is not a common management practice and because of the short rotation, these crops rarely reach self-thinning limits, so that the application of DMD will be severely limited. We have therefore applied the basic concepts used in the construction of DMDs to propose a Reference Diagram (RD) for SRC management. These models may play an important role in helping understand short rotation yield patterns in poplar plantations as adaptation of the models may assist in the assessment of energy yield potential, and optimum stand management in terms of density and rotations, as reported for eucalypts [19].

The SRC yield of poplar has been considered in many studies by the application of allometric equations that can estimate shoot biomass from basal diameter and shoot height, which must therefore be measured in sample plots [20-24]. As basal diameter growth is directly related to stool density, and height growth is more dependent on site properties and management [24], the development of whole crop yield models can provide estimation tools based on easily measured crop variables, particularly height and living stool density. However, as coppicing causes large changes in shoot density and growth rate, different sets of equations must be developed for the first and subsequent rotations. This is the most important factor limiting the application of process-based models to SRC [22]. Whole crop empirical statistical based models, which are powerful tools for estimating biomass, calculating economic gains and helping managers reach decisions about the timing of harvesting, are not yet available. A wide range of empirical data is required to enable development of such models [25].

The aim of the present study was to develop a whole crop model based on biomass, mean basal diameter and stool evolution as a function of mortality in a short rotation poplar crop, thus enabling subsequent development of a practical and dynamic adaptation of Density Management Diagram concept, that we call Reference Diagram. A further objective was to study the effect of initial density on biomass production at a rotation age of 3 years.

2. Materials and methods

2.1. Data

The study was carried out using data from a trial network of short rotation *Populus* plots established in 11 sites in Spain under Mediterranean conditions (Table 1). The clone selected for development of the DMD was 'I-214' (*Populus x canadensis* Moench), this clone is a hybrid between *Populus deltoides* Marsh and *Populus nigra* L. This is a well known clone widely planted in Mediterranean environments because of its high site plasticity and yield. This justifies use of 'I-214' as the reference clone in the trial plots for comparison of yield and other growth-related features. Data from 144 plots were available for fitting the base equations, these data were taken from three types of experimental plots in which the aim was to evaluate the clone effect, stocking rate and site by measuring variables related to production. Clone 'I-214' was used in all the experiments. As the trial design took competition effects into account, the plot size is large enough to ensure that the measured samples are not subjected to an edge effect. The trial plots include plantations ranging in surface area from 0.25 ha to 8 ha. Plots were established in early spring between 2005 and 2009, with 3 to 11 replications per site and plant densities. These densities ranged from 6 666 cuttings ha^{-1} to 33 333 cuttings ha^{-1}.

Plantations were established using hardwood cuttings of 20-30 cm in length, planted in single rows 3 m apart, either by hand or by use of adapted planting machines. Similar management was applied, including fertilization during soil tillage according to the specific soil characteristics, pre-emergence treatment with oxyfluorfen (4 l ha^{-1}) to control weeds, and drip or flooding irrigation (to field capacity) during the summer months [26]. A rotation length of three years was established in all plots. In some (32) plots, trees were cut back to a height of 0.1 m one year after planting, to stimulate sprouting [27, 28]. In these plots, root age was 4 and shoot age was 3 years (R4S3) at harvest time (Table 2). In the remaining plots (112), root age and shoot age were both 3 years (R3S3). In addition, 16 plots in the database had been already harvested once and were in a stage of development corresponding to R7S3; however, the data from these plots were only used to test the performance of the diagram for a second rotation and not for model development.

Measurements were made annually after planting. Diameter over bark at 10 cm (d10, mm) and at 130 cm (dbh, mm) were measured using a digital calliper, once leaves had fallen. This first diameter (d10) accounts for the size of the shoots at the usual harvesting height. Total height of the highest stool (H, cm) was also measured with the aid of a measuring pole. The number of shoots per stool and the density of living stools per plot were also recorded. The above-ground fresh biomass, excluding leaves, was evaluated in all plots by destructive analysis at the end of the third year. Total above-ground woody dry biomass (Ws, kg dm ha^{-1})

was calculated from the estimated dry weight of randomly selected whole plants from each of the plots after oven-drying a subsample of 1 kg for each clone to constant weight at 105ºC.

2.2. Model development

The following crop variables were used for each plot: crop age (t), number of stools per hectare (N), basal area of basal diameters (G_{b0}), basal quadratic mean diameter of dominant shoots (dg_{b0}), mean height of the dominant shoot of each stool (H_0), total above-ground woody dry biomass (Ws) and mortality. The number of stools per hectare (N) was calculated as the difference between the initial density (N_0) and the natural mortality. The basal area of basal diameters (G_{b0}) was calculated as the sum of the basal section of dominants shoots of all the stools in each plot. Basal quadratic mean diameter of dominant shoots (dg_{b0}) was calculated as the quadratic mean diameter of the dominant shoots of each stool (Table 3).

A static density-independent mortality equation was fitted with data from a total of 333 plot density measurements covering the 3 years rotation established for each plot. Reduction in stool number was fitted directly without prior consideration of the probability of mortality in the plots [29]. In this case, the age of the crop was not included in the model, as the height of the dominant shoot in the stool is the variable represented in the RD. Age was not included in the model because in short rotation crops, the relationships between age and height of the stools is highly dependent on the climatic conditions during the rotation, and therefore height is more representative (than age) of biomass yield. The equation used to predict the changes in stool density is exponential, which provides a constant rate of mortality independently of the initial density, as derived from the data:

$$N = N_0 \, \mathrm{e}^{K\,H_0} \quad (1)$$

where N is the density (stool ha^{-1}), N_0 is the initial density (stool ha^{-1}), H_0 is the average height of the dominant shoot of each stool (cm), and K is a constant parameter.

Structurally, DMDs consist of a number of functional and empirical quantitative relationships that collectively represent the cumulative effect of various underlying competition processes on tree and stand yield variables [30]. The RD developed in this study included a previously calculated density-independent mortality equation, and a system of two equations, the first of which is used to predict the quadratic basal mean diameter and the second of which is used to predict above-ground woody dry biomass:

$$dg_{b0} = a_1 H_0^{a_2} N^{a_3} \tag{2}$$

$$W_s = a_4 \, dg_{b0}^{a_5} N^{a_6} \tag{3}$$

where dg_{b0} is the quadratic mean diameter of dominant shoots (cm), H_0 is the average height of the dominant shoot of each stool (cm), N is the crop density (stools ha^{-1}), Ws is the above-ground woody dry biomass (kg dm ha^{-1}), and a_1, a_2, a_3, a_4, a_5 and a_6 are constant parameters.

The first equation is based on the relationship between average tree size, density and a productivity indicator [31-33]. The second equation relates stand productivity (expressed in terms of stand above-ground woody dry biomass) to basal quadratic mean diameter and number of stools per hectare.

Graphical representation of the model was carried out using the lattice function of the R statistical package [34, 35], which enables plotting of multivariate data. In this case, the xyplot function was used to produce a two-dimensional graphic. The RD was constructed by plotting mean height of dominant shoots (H_0, cm) on the X-axis and the number of stools per hectare (N, stools ha^{-1}) in logarithmic scale on the Y-axis. The basal quadratic mean diameter of the dominant shoot isolines were represented in the diagrams by using constant values for dg_{b0} and solving equation (2) for N. The mortality isolines were represented in the diagrams by using constant values for N_0 and solving equation (1) for N. The above-ground woody dry biomass isolines were represented in the diagrams, clearing the basal quadratic mean diameter of the dominant shoots for equation (2), using constant values for Ws and solving equation (3) for N.

Bioenergy and ash content application were also provided. The energy content in above-ground woody dry biomass was calculated on the basis of the lowest heating value (LHV) at 0% moisture content, which corresponds to 18.36 MJ kg^{-1} for three year old shoots of the 'I-214' poplar clone [36]. The ash content (%) was calculated on the basis of the percentage of ash considered by Klasnja et al. [37] for the 'I-214' clone (5.44% for bark and 0.78% for wood), and the percentage of bark as a function of diameter at breast height (dbh) measured by Guidi et al. [38]. For application of the latter percentage, an equation relating dbh to dg_{b0} was required:

$$dg_{b0}\ (mm) = 10.666 + 1.0649 * dbh \qquad (4)$$

Data from 144 plots were used to fit equation (4). The estimated single coefficient of the model is highly significant, and the model accounted more than 90% of the total variability of basal quadratic mean diameter of dominant shoots (dg_{b0}). This model was used to obtain the relationship between dg_{b0} and ash content (2.25 % for dg_{b0}=2.54 cm, 2 % for dg_{b0}=3.47 cm, 1.75 % for dg_{b0}=4.42 cm and 1.5 % for dg_{b0}=8.92 cm).

For graphical representation, the dominant height axis ranged from 100 to 1 200 cm, and densities ranged from 3 000 to 35 000 stools ha^{-1} on a logarithmic scale. The basal quadratic mean diameters values ranged from 1 to 10 cm and finally the above-ground woody dry biomass values ranged from 0 to 100 Mg dm ha^{-1}

2.3. Statistical analysis

Equation (1) was fitted with the nls procedure of the R software program [39]. Although this equation can also be considered as part of a simultaneous fitting system along with equations (2) and (3), separate fitting was preferred because of the different sample size and the interest in obtaining the most accurate estimate of living density of stools.

Equations (2) and (3) define a structurally simultaneous system, in which N and H_0 are exogenous variables whose values are determined independently of the system of equations, Ws is an endogenous variable, and dg_{b0} is an endogenous instrumental variable. The system of equations was fitted simultaneously using the SYSTEMFIT package [40] and the SUR (Seemingly unrelated regression) methodology in the R statistical package [39]. The adjusted coefficient of determination and the root mean square error were used to check the accuracy of the models.

Analysis of variance (ANOVA) was performed, using the R statistical package [39], to evaluate the effect of the stage of development in terms of height growth and Mean Annual Increment (MAI) in biomass, and as the samples sizes were different for different stages of development, the generalized linear model procedure (GLM) was used. Tukey's HSD test was used for comparison of means when significant differences of $p<0.05$ were observed.

3. Results

3.1. Model fitting

The results of fitting the three equations included in the model are shown in Table 4. The estimate of the single coefficient of the density-independent mortality model was highly significant ($p< 0.0001$) and the model accounted for more than 80% of the total variability in stool number. The equation obtained can be used to estimate the number of living stools from the mean height of the dominant shoots and planting density, and it produces a fixed mortality rate, which is consistent with the observations (Fig. 1).

For the simultaneous fit, all the coefficient estimates were highly significant ($p< 0.0001$), except for parameter a_4 of biomass equation (3). This has not serious implications, as this parameter does not have any biological meaning [41]. The models accounted for more than 85% of the total variability in both the quadratic mean basal diameter and the biomass yield, (equations 2 and 3). It is usually difficult to obtain accurate prediction of diameters because of the dependence on changes in density over time when longer rotations are considered.

3.2. Reference diagram

The range of values represented by the axes and the isolines in the RD (Fig. 2) were similar to the ranges included in the database used to construct the diagram (Table 3). The RD shows the isolines for basal quadratic mean diameter (dg_{b0}), above-ground woody dry biomass (Ws) and mortality, as well as the observed values of H_0 and N in the plots used for fitting (Fig. 2).

The isolines for stool density decrease gradually with increasing dominant height, derived from a continuous reduction in stool number of 1.67% for each metre of increment in H_0. The diagram can be used either by considering the initial density to predict the living stool density for a given dominant height or by directly using the actual stool density recorded in the plots. In both cases, the values of the final densities recorded in the plots ranged widely, from 3 735 to 33 333 stools ha^{-1}, and therefore the model can account for large differences in stool density. The dominant height ranged from 153 to 1 026 cm, and did not increase with initial density (Fig. 3).

The isolines for biomass yield are curves that tend to be vertical for low dominant heights, indicating a small effect of stool density at such stages of crop development. As dominant height increases, these isolines become more horizontal and less separated, showing strong differences depending on density and height growth (Fig. 2). The isolines represented a range from 5 to 100 Mg dm ha^{-1}, according to the values measured in the plots, shown in Table 3. The crops are most productive, as far as the first rotation is concerned, at densities higher than 15 000 stools ha^{-1}. These isolines can be used to define biomass thresholds for harvesting, which should be assessed in terms of stool density and dominant height, with the possibility of lengthening the rotation if necessary.

The isolines for basal quadratic mean diameter show a strong dependence on stool density, with very variable values (isolines considered from 2 to 10 cm, according to the observed values in the plots, Table 2). These isolines are rather uniformly separated and are representative of harvesting conditions and biomass quality (Fig. 2). The isolines tend to become more horizontal as dominant height increases. The basal area of basal diameters, a variable not included in the diagrams but used to obtain the basal quadratic mean diameter, ranged between 0.70 and 22.81 m^2 ha^{-1} yr^{-1} (Fig. 3) and tended to increase with density.

In the database, sixteen of the plots are at developmental stage corresponding to R7S3. This information was used to test the behaviour of the diagrams for a second rotation (Fig. 4) and it was noted that significant biases occur both in the case of diameter and biomass.

3.3. Example of RD use to determine energy production

As a practical example (Fig. 5), we simulated an initial planting density of 10 000 stools ha^{-1} and a final basal quadratic mean diameter of 8 cm (which allows efficient harvesting of the crop by a chip harvester). The total aboveground woody dry biomass yield was approximately 60 Mg dm ha^{-1}, the final density was less than 9 000 stools ha-1 and the dominant height obtained was about 11 m. As an additional guide to exploring the possible values of H_0 over time, the observed values of the quartiles for this variable are represented in Figure 6, along with the predicted quartiles for R4T4 and R5T4. Significant differences in height according to the stage of development ($p<0.0001$) were observed with increasing root age, although not in the case of shoot age. This was also found for Mean Annual Increment (MAI) in biomass ($p<0.0001$), except in the first year shoots, in which this variable did not vary significantly (Fig. 7). The rotation for calculating MAI is considered as being the period between planting and harvesting (root age), and the biomass produced is considered as the sum of the yield at harvest time and the small quantities obtained during the first coppicing at age 1 year (R1S1) in the corresponding cases. The total energy production for this simulation was 1 100 GJ ha^{-1} and the ash content approximately was 1.53 %. Therefore the energy production rate would be 366.6 GJ ha^{-1} yr^{-1}.

These values indicate that an area of 81.8 ha covered by poplar under SRC would be needed to supply a municipal power plant of 5 MW, with a performance of 1 500 hours per year and a thermal efficiency of 90% (typical dimension for several public buildings and a network of heat to various individual homes). This indicates the possibility of promoting SRC for thermal use in areas where the current biomass supply is low.

4. Discussion

4.1. Model utility and limitations

The system of related equations presented enables accurate estimation of crop yield in terms of oven dry biomass and total energy, while also providing the predicted changes in stool number, which is a useful tool for decision making. A density-independent mortality model was used rather than the density-dependant model usually used for DMDs because no different trends in mortality rate for different planting densities were observed. This may be because the development stage of the plantations under study may not have reached the self-thinning threshold, as indicated by the low mean mortality rate (< 15 %) across planting densities. The two main variables included in the diagram and used for decision-making were the initial cutting density and the rotation age, represented by the increase in mean height of the dominant shoots with age, depending on site properties and the crop management. The mean height of dominant shoots can be determined easily by measurement with telescopic rods in a sample plot or from LiDAR information.

The adjusted coefficient of determination in the case of the biomass model is, however, slightly lower than the values obtained by other authors for pine or oak stands [17, 33, 42]. This may be because in the present study, fitting was at the stool level, without inclusion of additional variables such as the shoot number per stool. The average shoot number per stool is often highly correlated with total biomass; however, for the information of first rotation managed in this study, the values obtained were low and did not improve the models. Nevertheless, this variable may have a major impact in models developed for subsequent rotations.

The variability in basal quadratic mean diameter explained by this model can be considered high relative to that reported by other authors [19], probably because in short rotations crops, basal diameter is more directly dependent on initial stool density. This variable may be important for considering the harvester limits and harvesting time. Chip harvesters specifically used for these types of crops may be limited by basal diameters greater than 15 cm, while multi-cutter harvesters may be more cost effective for basal diameters between 15 and 20 cm [43]. Tools such as that obtained in this study may provide a basis for comparing the management options for overcoming these limitations, not only by using appropriate densities but also choosing the best harvesting time. On the other hand, knowledge of the market value of the biomass as well as the costs associated with different management practices may also enable economic analysis to obtain the optimal planting density of poplar SRC. However, the models provided here are only valid for the first rotation. The predictable vigorous sprouting after the first coppice [44] would promote rapid canopy closure and full site occupancy, reducing the differences in biomass yield between initial density levels.

Comparing the results obtained for the second rotation to those predicted by this model, we confirmed the need to develop a different set of equations for the second rotation, as basal quadratic mean diameter is overestimated by the model and there is a strong tendency for biomass yield to be underestimated for high observed values of biomass, this was expected due to the higher growth of this type of crop in successive rotations [45-47]; the effect of an already well-formed root system, which is able to absorb more nutrients and water, and the ability of the stool to provide multiple shoots together favour higher production after coppicing, and therefore the prediction for the second rotation with an equation fitted with first rotation data causes significant bias. This emphasizes the importance of developing similar models to those proposed here for future rotations.

The basal area of basal diameters tended to increase with density. However, by decreasing the density, the diameter of trees increased due to the decreased competition for resources, which results in a large average tree size [48-51], thus improving the quality of the biomass arising from lower bark content, lower ash content and greater lower heating value [52].

High ash content of wood is less desirable for fuelwood as it is non-combustible and reduces the heat of combustion [37, 53]. As the share of bark depends on the age of wood [38], and the ash content in the whole tree is mainly related to the amount of bark [54, 55], the ash content will also depend on the age of wood. Bark percentage decreases rapidly with increasing dbh, although it is thought that at dbh> 5 cm, the percentage of dry bark stabilizes at around 7% of dry matter and the decrease in ash content thus slows down [38]. Previously reported values were used instead of an equation [38] to estimate the ash content because the basal quadratic mean diameter in the diagram ranged between 2-10. The ash values derived from the procedure described here were lower than the ash content observed for 'I-214' clone by Fernández et al. [36] at the end of a three year rotation (i.e. about 2.4 % on a dry weight basis).

4.2. Comparison with data from other studies

The values obtained in the present study in relation to the annual above-ground woody dry biomass for 'I-214' clone in function of their densities showed a similar yield range to those reported by other authors, such as Facciotto et al. [56] (15 and 35 Mg dm ha^{-1} yr^{-1}), Liberloo et al. [57] (20 and 25.8 Mg dm ha^{-1} yr^{-1}) and Paris et al. [58] (7.25 Mg dm ha^{-1} from a low soil quality site and 21.86 to 23.74 Mg dm ha^{-1} for medium and high soil quality sites). Under the Mediterranean conditions of the Iberian Peninsula, the observed range was between 19 and 8 Mg dm ha^{-1} yr^{-1} [59]. However, 'I-214' has been identified as stable in terms of yield for a given density [59, 60], i.e. without departing from the expected behaviour estimated from its average genotypic value.

Although the energy obtained from LHV is a theoretical value that can only be achieved at 0% moisture, the information derived from this product may also be useful for determining the energy value of the biomass produced in the different management scenarios. In fact, the following equations enable calculation of biomass, lower heating value and bulk density for chips with a moisture content (h %, wet basis), considering a wood and bark basic density of 0.35 Mg m^{-3} (data not show) and a ratio of 0.38 solid m^3/apparent m^3:

$$W_h = W_s \frac{100}{100-h} \quad (5)$$

$$LHV_h = LHV_0 \frac{100-h}{100} - 0.02443\, h \quad (6)$$

$$BD_h = 0.35\ 0.38 \frac{100}{100-h} \quad (7)$$

where W_h is the biomass weight at a humidity content (h %, wet basis), W_s is the above-ground woody dry biomass obtained from the diagrams, LHV_h is the low heating value (MJ kg^{-1}) and BD is the bulk density (Mg m^{-3}). The application of such equations for the usual humidity content at harvest time (55%) provides BD_{55}=296 Mg m^{-3}. Drying chips to h=30% would provide a biofuel classified as BD150 (BD_{30}=190 Mg m^{-3}), Q11 (LHV_{30}=12.1 MJ kg^{-1}), A3.0 (ash percentage always less than 3%) and thus class B for non industrial uses, according to the European standard EN14961-4.

The predicted values for the energy production at the end of the rotation ranged between 100-2 000 GJ ha^{-1}, which is higher than the values reported for poplar (173-259 GJ ha^{-1}; 10-15 Mg dm ha^{-1} yr^{-1}) grown as a short rotation woody crop [61]. Mean plot values ranged from 4.83 to 522.27 GJ ha^{-1} yr^{-1}, which includes the range of values obtained by other authors (165.51-311.78 GJ ha^{-1} yr^{-1} [36]) and even reached as high as the values for second rotations, which are expected to be higher (e.g. 351-537 GJ ha^{-1} yr^{-1} [62]).

4. Conclusions

Reference diagrams are useful because of their simplicity and the fact that the inputs required are easily obtainable. These features make this Reference Diagram an excellent tool for stand management, adapted to short rotation coppice of poplar. The extensive network of heterogeneous plots used to develop this RD confers the model a wide range of performance, whether for planning plantation, as a tool to examine the different options to achieve an end goal (i.e. to achieve a specific production to supply a plant or not to exceed certain stage of development that can be limiting at harvest time), and at the end life of the plantation, for calculating the optimal cutting time for a final goal. In both cases, this type of diagram proved to be a very useful tool for planning different management according to the constraints of the desired product and optimizing resources to maximize the performance.

Although the translation of dominant height data to age would depend on site conditions and management, the models developed are useful for estimating the amount of biomass accumulated at a certain stage of development and initial planting density and to determine the maximum developmental stage that allows the use of available machinery to harvest the crop. These models are also useful for economic optimization of the initial density of planting in relation to production, although this requires models that are sensitive to the possible effect of the crop origin in relation to the initial density of the following rotations. Future research in this field of work should consider all these aspects.

Acknowledgements

This work was financially supported by DECOCEL and RTA2011-00006-00-00 projects. We also thank María José Hernández for technical support and Christine Francis for checking the English version of this article.

References

[1] Kauter D, Lewandowski L, Claupein W. Quantity and quality of harvestable biomass from *Populus* short rotation coppice for solid fuel use - a review of the physiological basis and management influences. Biomass Bioenerg. 2003;24:411-27.

[2] White E. Woody Biomass for Bioenergy and Biofuels in the United States- A Briefing Paper. OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station ed. Portland: USDA General Technical Report PNW-GTR-825 2010.

[3] European Commission EU. The EU rural development Policy: facing the Challenges. European Communities. 2008.

[4] Sixto H, Hernández M, Barrio M, Carrasco J, Cañellas I. Plantaciones del género *Populus* para la producción de biomasa con fines energéticos: revisión. Forests System. 2007;16(3):277-94.

[5] Mareschi L, Paris P, Sabatti M, Nardin F, Giovanardi R, Manazzone S, et al. The new varieties of poplar biomass guarantee interesting yield. Informatore Agrario. 2005;6(18):49-53.

[6] Yemshanov D, McKenney D. Fast-growing poplar plantations as a bioenergy supply source for Canada. Biomass Bioenerg. 2008;32:185-97.

[7] Verwijst T, Lundkvist A, Edelfeldt S, Albertsson J. Development of Sustainable Willow Short Rotation Forestry in Northern Europe, Biomass Now -. Sustainable Growth and Use, Dr Miodrag Darko Matovic (Ed). 2013;19:481-502.

[8] Laureysens I, Deraedt W, Indeherberge T, Ceulemans R. Population dynamics in a 6-year old coppice culture of poplar. I. Clonal differences in stool mortality, shoot dynamics and shoot diameter distribution in relation to biomass production. Biomass Bioenerg. 2003;24(2):81-95.

[9] Pérez-Cruzado C, Sanchez-Ron D, Rodríguez-Soalleiro R, Hernández M, Sánchez-Martín M, Cañellas I, et al. Biomass production assessment from *Populus* spp. short-rotation irrigated crops in Spain. Glob Chage Biol Bioenerg. 2013.

[10] Benetka V, Novotná K, Štochlová P. Biomass production of *Populus nigra* L. clones grown in short rotation coppice systems in three different environments over four rotations. iForest-Biogeosciences and Forestry. 2014:232.

[11] Willebrand E, Ledin S, Verwijst T. Willow coppice system in short rotation forestry: effects of plant spacing rotation length and clonal composition on biomass production. Biomass Bioenerg. 1993;4(5):232-1.

[12] Fiala M, Bacenetti J, Scaravonati A, Bergonzi A. Short rotation coppice in northern Italy: Comprenhensive Sustainability. European Biomass Conference and Exhibition. 2010;18th:342-8.

[13] Cañellas I, Huelin P, Hernández M, Ciria P, Calvo R, Gea-Izquierdo G, et al. The effect of density on Short Rotation *Populus* spp. plantations in the Mediterranean area. Biomass Bioenerg. 2012;46:645-52.

[14] Klasnja B, Orlovic S, Drekic M, Markovic M. Energy production from short rotation poplar plantations. VIITH International symposium interdisciplinary regional research - ISIRR 2003;IV:161-6.

[15] Newton PF, Weetman GF. Stand density management diagram for managed black spruce stands. Forest Chron. 1994;70(1):65-74.
[16] Shaw JD, Long JN. A density management diagram for longleaf pine stands with application to red-cockaded woodpecker habitat. S J Appl Forestry. 2007;31(1):28-38.
[17] Barrio-Anta M, Álvarez-González JG. Development of a stand density management diagram for even-aged pedunculate oak stands and its use in designing thinning schedules. Forestry. 2005;78(3):209-16.
[18] López-Sánchez C, Rodríguez-Soalleiro R. A density management diagram including stand stability and crown fire risk for *Pseudotsuga Menziesii* (Mirb.) Franco in Spain. Mt Res Dev. 2009;29(2):169-76.
[19] Pérez-Cruzado C, Merino A, Rodríguez-Soalleiro R. A management tool for estimating bioenergy production and carbon sequestration in *Eucalyptus globulus* and *Eucalyptus nitens* grown as short rotation woody crops in north-west Spain. Biomass Bioenerg. 2011;35(7):2839-51.
[20] Pontailler JY, Ceulemans R, Guittet J, Mau F. Linear and non-linear functions of volume index to estimate woody biomass in high density young poplar stands. Ann Sci For. 1997;54(4):335-45.
[21] Verwijst T, Telenius B. Biomass estimation procedures in short rotation forestry. For Ecol Manage. 1999;121(1-2):137-46.
[22] Amichev BY, Johnston M, Van Rees KCJ. Hybrid poplar growth in bioenergy production systems: Biomass prediction with a simple process-based model (3PG). Biomass Bioenerg. 2010;34(5):687-702.
[23] Headlee WL, Zalesny Jr RS, Donner DM, Hall RB. Using a process-based model (3-PG) to predict and map hybrid poplar biomass productivity in Minnesota and Wisconsin, USA. BioEnergy Research. 2013;6(1):196-210.
[24] Mosseler A, Major J, Labrecque M, Larocque G. Allometric relationships in coppice biomass production for two North American willows (*Salix* spp.) across three different sites. For Ecol Manage. 2014:320.
[25] Dickmann D. Silviculture and biology of short-rotation woody crops in temperate regions: then and now. Biomass Bioenerg. 2006;30:696–705.
[26] Sixto H, Hernández MJ, de Miguel J, Cañellas I. Red de parcelas de cultivos leñosos en alta densidad y turno corto. Madrid2013.
[27] Willebrand E, Verwijst T. Population dynamics of willow coppice systems and their implications for management of short-rotation forests. Forest Chron. 1993;69(6):699-704.
[28] Kopp R, Abrahamson L, White E, Volk T, Nowak C, Fillhart R. Willow biomass production during ten successive annual harvests. Biomass Bioenerg. 2001;20(1):1-7.
[29] Dieguez-Aranda U, Castedo-Dorado F, Alvarez-Gonzalez JG, Rodriguez-Soalleiro R. Modelling mortality of Scots pine (*Pinus sylvestris* L.) plantations in the northwest of Spain. Eur J For Res. 2005;124(2):143-53.
[30] Newton PF, Lei Y, Zhang SY. Stand-level diameter distribution yield model for black spruce plantations. For Ecol Manage. 2005;209(3):181-92.
[31] Goulding CJ. Simulation techniques for a stochastic model of the growth of Douglas-fir. Vancouver, British Columbia: Thesis (Ph.D.) University of British Columbia; 1972.
[32] Long JN, Shaw JD. A density management diagram for even-aged ponderosa pine stands. West J Appl For. 2005;20(4):205-15.
[33] Castedo-Dorado F, Crecente-Campo F, Álvarez-Álvarez P, Barrio-Anta M. Development of a stand density management diagram for radiata pine stands including assessment of stand stability. Forestry. 2009;82(1):1-16.
[34] Sarkar D. Lattice: Multivariate Data Visulization with R. Springer, New York. 2008.

[35] Sarkar d, Andrews F. latticeExtra: Extra Graphical Utilities Based on Lattice. R package version 06-19. 2011.
[36] Fernández MJ, Ciria P, Barro R, Losada J, Pérez J, Sixto H, et al. Quality of the biomass produced in Short Rotation Coppices of poplar, willow, black locust and sycamore in two different spanish locations. 21 st European Biomass Conference and Exhibition. 2013.
[37] Klasnja B, Kopitovic S, Orlovic S. Wood and bark of some poplar and willow clones as fuelwood. Biomass Bioenerg. 2002;23(6):427-32.
[38] Guidi W, Piccioni E, Ginanni M, Bonari E. Bark content estimation in poplar (*Populus deltoides* L.) short-rotation coppice in Central Italy. Biomass Bioenerg. 2008;32(6):518-24.
[39] R Development Core Team. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing; 2013.
[40] Henningsen A, Hamann JD. systemfit: A Package for Estimating Systems of Simultaneous Equations in R. Journal of Statistical Software. 2007:23(4).
[41] Antonio N, Tome M, Tome J, Soares P, Fontes L. Effect of tree, stand, and site variables on the allometry of *Eucalyptus globulus* tree biomass. Can J For Res-Rev Can Rech For. 2007;37(5):895-906.
[42] Barrio-Anta M, Balboa-Murias MA, Castedo-Dorado F, Diéguez-Aranda U, Álvarez-González JG. An ecoregional model for estimating volume, biomass and carbon pools in maritime pine stands in Galicia (northwestern Spain). For Ecol Manage. 2006;223(1-3).
[43] Berhongaray G, El Kasmioui O, Ceulemans R. Comparative analysis of harvesting machines on an operational high-density short rotation woody crop (SRWC) culture: One-process versus two-process harvest operation. Biomass Bioenerg. 2013;58:333-42.
[44] Stanturf JA, Oosten Cv, Isebrands J, Richardson J. Operational Poplar and Willow culture. In: Isebrands J, Richardson J, editors. Poplars and Willows: Trees for society and the environment 2014. p. 200.
[45] Dillen SY, Djomo SN, Al Afas N, Vanbeveren S, Ceulemans R. Biomass yield and energy balance of a short-rotation poplar coppice with multiple clones on degraded land during 16 years. Biomass Bioenerg. 2013;56:157-65.
[46] Di Matteo G, Sperandio G, Verani S. Field performance of poplar for bioenergy in southern Europe after two coppicing rotations: effects of clone and planting density. Iforest-Biogeosciences and Forestry. 2012;5:224-9.
[47] Sennerby-Forsse L, Ferm A, Fauppi A. Coppicing ability and sustainability. In: Mitchell C, Ford-Robertson J, Hinckley T, Sennerby-Forsse L, editors. Ecophysiology of Short Rotation forest Crops. London: Elselvier; 1992. p. 146-73.
[48] Hamilton G. The dependence of volume increment of individual trees on dominance, crown dimensions, and competition. Forestry. 1969;42(2):133-44.
[49] Assmann E. The principles of forest yield study: studies in the organic production, structure, increment, and yield of forest stands. Oxford: Pergamon Press; 1970.
[50] Curtis RO. Stand density measures an interpretation. For Sci. 1970;16(4):403.
[51] Dean TJ, Long JN. Influence of leaf-area and canopy structure on size-density relations in even-aged lodgepole pine stands. For Ecol Manage. 1992;49(1-2):109-17.
[52] Bergante S, Facciotto G, Minotta G. Identification of the main site factors and management intensity affecting the establishment of Short-Rotation-Coppices (SRC) in Northern Italy through stepwise regression analysis. Cent Eu J Biol. 2010;5(4):522-30.
[53] Goel VL, Behl HM. Fuelwood quality of promising tree species for alkaline soil sites in relation to tree age. Biomass Bioenerg. 1996;10(1):57-61.
[54] Steenari BM, Lindqvist O. Stabilisation of biofuel ashes for recycling to forest soil. Biomass Bioenerg. 1997;13(1-2):39-50.
[55] Tharakan PJ, Volk TA, Abrahamson LP, White EH. Energy feedstock characteristics of willow and hybrid poplar clones at harvest age. Biomass Bioenerg. 2003;25(6):571-80.

[56] Facciotto G, Bergante S, Lioia C, Rosso L, Mughini G, Zenone T, et al. Produttività di cloni di pioppo e salice in piantagioni a turno breve. Forest@-Journal of Silviculture and Forest Ecology. 2006;3(2):238.
[57] Liberloo M, Calfapietra C, Lukac M, Godbold D, LUO ZB, Polle A, et al. Woody biomass production during the second rotation of a bio-energy Populus plantation increases in a future high CO2 world. Global Change Biology. 2006;12(6):1094-106.
[58] Paris P, Mareschi L, Sabatti M, Pisanelli A, Ecosse A, Nardin F, et al. Comparing hybrid Populus clones for SRF across northern Italy after two biennial rotations: Survival, growth and yield. Biomass Bioenerg. 2011;35(4):1524-32.
[59] Sixto H, Gil P, Ciria P, Camps F, Sánchez M, Cañellas I, et al. Performance of hybrid poplar clones in short rotation coppice in Mediterranean environments: analysis of genotypic stability. Glob Chage Biol Bioenerg. 2013.
[60] Cruset JE, Voltas J. Adaptation of poplar clones in the Ebro valley: a retrospective analysis of the experimental network established in the 80s by mixed models (in Spanish). In: S.E.C.F. JCyL, editor. 5º Congreso Forestal Español Ávila 2009.
[61] McKendry P. Energy production from biomass (part 1): overview of biomass. Bioresour Technol. 2002;83(1):37-46.
[62] Luo ZB, Polle A. Wood composition and energy content in a poplar short rotation plantation on fertilized agricultural land in a future CO_2 atmosphere. Global Change Biology. 2009;15(1):38-47.

*Manuscript
Click here to view linked References

PRODUCTIVITY MODEL AND REFERENCE DIAGRAM FOR SHORT ROTATION BIOMASS CROPS OF POPLAR GROWN IN MEDITERRANEAN ENVIRONMENTS

N. Oliveira [a], H. Sixto [a], I. Cañellas [a], R. Rodríguez-Soalleiro [b], C. Pérez-Cruzado [c].

[a] Dpto. Selvicultura y Gestión de los Sistemas Forestales, INIA-CIFOR, Madrid E-28040, Spain

[b] Unidad de Gestión Forestal Sostenible, Universidad de Santiago de Compostela, Lugo E-27002, Spain

[c] Chair of Forest Inventory and Remote Sensing, Georg-August-Universität Göttingen, D-37077, Germany

Corresponding author:

Nerea Oliveira

tel. + 34 913 473579

fax + +34 913 572 293

e-mail: nerea.oliveira@inia.es

Abstract

A Reference Diagram (RD) was constructed for first rotations of the Euroamerican poplar 'I-214' grown as short rotation coppice (SRC). Data from 144 plots, established in eleven sites in Mediterranean environments, were used to develop the model. The density at establishment of the plantations ranged between 6 666 and 33 333 stools ha^{-1}, covering the usual densities ranges used in short rotation forestry (SRF). The RD was based on a density-independent mortality model that relates the density of living stools to the average height of dominant shoot and the initial plantation density, and it includes a system of two simultaneously fitted equations relating a) quadratic mean basal diameter of dominant shoots to the average height of dominant shoot and the final density, and b) total above-ground woody dry biomass to quadratic mean basal diameter and final density. The isolines in the RD represented mortality, quadratic mean basal diameter of dominant shoots and total above-ground woody dry biomass at the end of a first rotation of three years. The final yield in terms of biomass ranged from 1 to 85 Mg dm ha^{-1}. The RD enables rapid and straightforward comparison of different situations, both at planting and at harvesting, and is a useful tool, based on a wide range of empirical data, for management and decision making regarding short rotation poplar crops.

KEYWORDS: Poplar, Short rotation coppice (SRC), Density Management Diagrams, Reference Diagrams, Biomass.

1. Introduction

Woody biomass is a renewable resource that is suitable for getting different bioproducts, including bioenergy for different applications (heat, electricity or second generation biofuels)[1, 2]. Use of woody biomass for bioenergy purposes represents a promising opportunity to contribute to the mitigation of climate change, to the extent that the presence of this resource may become important in the overall energy mix. The production and management of woody biomass may provide a new opportunity for economic development of rural areas [3] involving many different productive sectors.

Forestry crops represent one source of supply of woody biomass, which is characterized by its spatiality and temporality [4]. Such crops can be established on both abandoned agricultural land and on marginal land. Short rotation woody crops under coppicing management (SRC), such as *Salicaceae* (*Populus* spp. or *Salix* spp.), are well represented in northern and central Europe and to a lesser extent in southern Europe [5-7]. Studies involving the production of these crops have revealed a wide range of biomass yield depending on different factors such as plant material, site characteristics, crop design (density and rotation), management regime, presence of pest and diseases, and survival after planting [8-10].

Plantation density is an important factor to be considered in SRC and has both production and economic implications. As tree density increases, the total yield rises initially in proportion to the number of plants per area if individual plants receive sufficient resources for growth. However, the specific density at which optimal production is attained has not yet been determined, although the range within which production remains constant is known [11]. Several experimental and commercial plantations have been established to test densities ranging from 1 000 to more than 40 000 plants ha^{-1} [12-14].

Density Management Diagrams (DMDs) are used to graphically illustrate the relationships between density, yield and density dependant mortality at all stages of stand development [15], including concepts such as competition, site occupancy and self-thinning. These biological models are mainly used for decision-making in density management, for example to determine the post-thinning density or even to display and evaluate alternative density regimes in forest management [16].There are many examples for different areas and species, such as *Pinus palustris* Mill. [16], *Quercus robur* L. [17] and *Pseudotsuga menziesii* (Mirb.) Franco [18]. However, as far we know, models relating the initial cutting density to yield, stool mortality or height and basal diameter growth for different developmental stages in SRC are scarce. Such models have been developed, e.g. for *Eucalyptus globulus* Labill. and *Eucalyptus nitens* (Deane and Maiden) Maiden, on the basis of plantations established at the usual range of initial forest densities used in southwestern Europe and managed in short rotations [19]. In SRC, density reduction is not a common management practice and because of the short rotation, these crops rarely reach self-thinning limits, so that the application of DMD will be severely limited. We have therefore applied the basic concepts used in the construction of DMDs to propose a Reference Diagram (RD) for SRC management. These models may play an important role in helping understand short rotation yield patterns in poplar plantations as adaptation of the models may assist in the assessment of energy yield potential, and optimum stand management in terms of density and rotations, as reported for eucalypts [19].

The SRC yield of poplar has been considered in many studies by the application of allometric equations that can estimate shoot biomass from basal diameter and shoot height, which must therefore be measured in sample plots [20-24]. As basal diameter growth is directly related to stool density, and height growth is more dependent on site properties and management [24], the development of whole crop yield models can provide estimation tools based on easily measured crop variables, particularly height and living stool density. However, as coppicing causes large changes in shoot density and growth rate, different sets of equations must be developed for the first and subsequent rotations. This is the most important factor limiting the application of process-based models to SRC [22]. Whole crop empirical statistical based models, which are powerful tools for estimating biomass, calculating economic gains and helping managers reach decisions about the timing of harvesting, are not yet available. A wide range of empirical data is required to enable development of such models [25].

The aim of the present study was to develop a whole crop model based on biomass, mean basal diameter and stool evolution as a function of mortality in a short rotation poplar crop, thus enabling subsequent development of a practical and dynamic adaptation of Density Management Diagram concept, that we call Reference Diagram. A further objective was to study the effect of initial density on biomass production at a rotation age of 3 years.

2. Materials and methods

2.1. Data

The study was carried out using data from a trial network of short rotation *Populus* plots established in 11 sites in Spain under Mediterranean conditions (Table 1). The clone selected for development of the DMD was ‘I-214’ (*Populus x canadensis* Moench), this clone is a hybrid between *Populus deltoides* Marsh and *Populus nigra* L. This is a well known clone widely planted in Mediterranean environments because of its high site plasticity and yield. This justifies use of ‘I-214’ as the reference clone in the trial plots for comparison of yield and other growth-related features. Data from 144 plots were available for fitting the base equations, these data were taken from three types of experimental plots in which the aim was to evaluate the clone effect, stocking rate and site by measuring variables related to production. Clone ‘I-214’ was used in all the experiments. As the trial design took competition effects into account, the plot size is large enough to ensure that the measured samples are not subjected to an edge effect. The trial plots include plantations ranging in surface area from 0.25 ha to 8 ha. Plots were established in early spring between 2005 and 2009, with 3 to 11 replications per site and plant densities. These densities ranged from 6 666 cuttings ha^{-1} to 33 333 cuttings ha^{-1}.

Plantations were established using hardwood cuttings of 20-30 cm in length, planted in single rows 3 m apart, either by hand or by use of adapted planting machines. Similar management was applied, including fertilization during soil tillage according to the specific soil characteristics, pre-emergence treatment with oxyfluorfen (4 l ha^{-1}) to control weeds, and drip or flooding irrigation (to field capacity) during the summer months [26]. A rotation length of three years was established in all plots. In some (32) plots, trees were cut back to a height of 0.1 m one year after planting, to stimulate sprouting [27, 28]. In these plots, root age was 4 and shoot age was 3 years (R4S3) at harvest time (Table 2). In the remaining plots (112), root age and shoot age were both 3 years (R3S3). In addition, 16 plots in the database had been already harvested once and were in a stage of development corresponding to R7S3; however, the data from these plots were only used to test the performance of the diagram for a second rotation and not for model development.

Measurements were made annually after planting. Diameter over bark at 10 cm (d10, mm) and at 130 cm (dbh, mm) were measured using a digital calliper, once leaves had fallen. This first diameter (d10) accounts for the size of the shoots at the usual harvesting height. Total height of the highest stool (H, cm) was also measured with the aid of a measuring pole. The number of shoots per stool and the density of living stools per plot were also recorded. The above-ground fresh biomass, excluding leaves, was evaluated in all plots by destructive analysis at the end of the third year. Total above-ground woody dry biomass (Ws, kg dm ha^{-1})

was calculated from the estimated dry weight of randomly selected whole plants from each of the plots after oven-drying a subsample of 1 kg for each clone to constant weight at 105ºC.

2.2. Model development

The following crop variables were used for each plot: crop age (t), number of stools per hectare (N), basal area of basal diameters (G_{b0}), basal quadratic mean diameter of dominant shoots (dg_{b0}), mean height of the dominant shoot of each stool (H_0), total above-ground woody dry biomass (Ws) and mortality. The number of stools per hectare (N) was calculated as the difference between the initial density (N_0) and the natural mortality. The basal area of basal diameters (G_{b0}) was calculated as the sum of the basal section of dominants shoots of all the stools in each plot. Basal quadratic mean diameter of dominant shoots (dg_{b0}) was calculated as the quadratic mean diameter of the dominant shoots of each stool (Table 3).

A static density-independent mortality equation was fitted with data from a total of 333 plot density measurements covering the 3 years rotation established for each plot. Reduction in stool number was fitted directly without prior consideration of the probability of mortality in the plots [29]. In this case, the age of the crop was not included in the model, as the height of the dominant shoot in the stool is the variable represented in the RD. Age was not included in the model because in short rotation crops, the relationships between age and height of the stools is highly dependent on the climatic conditions during the rotation, and therefore height is more representative (than age) of biomass yield. The equation used to predict the changes in stool density is exponential, which provides a constant rate of mortality independently of the initial density, as derived from the data:

$$N = N_0 \, e^{K H_0} \qquad (1)$$

where N is the density (stool ha^{-1}), N_0 is the initial density (stool ha^{-1}), H_0 is the average height of the dominant shoot of each stool (cm), and K is a constant parameter.

Structurally, DMDs consist of a number of functional and empirical quantitative relationships that collectively represent the cumulative effect of various underlying competition processes on tree and stand yield variables [30]. The RD developed in this study included a previously calculated density-independent mortality equation, and a system of two equations, the first of which is used to predict the quadratic basal mean diameter and the second of which is used to predict above-ground woody dry biomass:

$$dg_{b0} = a_1 {H_0}^{a_2} N^{a_3} \tag{2}$$

$$W_s = a_4 \, {dg_{b0}}^{a_5} N^{a_6} \tag{3}$$

where dg_{b0} is the quadratic mean diameter of dominant shoots (cm), H_0 is the average height of the dominant shoot of each stool (cm), N is the crop density (stools ha^{-1}), Ws is the above-ground woody dry biomass (kg dm ha^{-1}), and a_1, a_2, a_3, a_4, a_5 and a_6 are constant parameters.

The first equation is based on the relationship between average tree size, density and a productivity indicator [31-33]. The second equation relates stand productivity (expressed in terms of stand above-ground woody dry biomass) to basal quadratic mean diameter and number of stools per hectare.

Graphical representation of the model was carried out using the lattice function of the R statistical package [34, 35], which enables plotting of multivariate data. In this case, the xyplot function was used to produce a two-dimensional graphic. The RD was constructed by plotting mean height of dominant shoots (H_0, cm) on the X-axis and the number of stools per hectare (N, stools ha^{-1}) in logarithmic scale on the Y-axis. The basal quadratic mean diameter of the dominant shoot isolines were represented in the diagrams by using constant values for dg_{b0} and solving equation (2) for N. The mortality isolines were represented in the diagrams by using constant values for N_0 and solving equation (1) for N. The above-ground woody dry biomass isolines were represented in the diagrams, clearing the basal quadratic mean diameter of the dominant shoots for equation (2), using constant values for Ws and solving equation (3) for N.

Bioenergy and ash content application were also provided. The energy content in above-ground woody dry biomass was calculated on the basis of the lowest heating value (LHV) at 0% moisture content, which corresponds to 18.36 MJ kg^{-1} for three year old shoots of the ‘I-214’ poplar clone [36]. The ash content (%) was calculated on the basis of the percentage of ash considered by Klasnja et al. [37] for the ‘I-214’ clone (5.44% for bark and 0.78% for wood), and the percentage of bark as a function of diameter at breast height (dbh) measured by Guidi et al. [38]. For application of the latter percentage, an equation relating dbh to dg_{b0} was required:

$$dg_{b0}\ (mm) = 10.666 + 1.0649 * dbh \qquad (4)$$

Data from 144 plots were used to fit equation (4). The estimated single coefficient of the model is highly significant, and the model accounted more than 90% of the total variability of basal quadratic mean diameter of dominant shoots (dg_{b0}). This model was used to obtain the relationship between dg_{b0} and ash content (2.25 % for dg_{b0}=2.54 cm, 2 % for dg_{b0}=3.47 cm, 1.75 % for dg_{b0}=4.42 cm and 1.5 % for dg_{b0}=8.92 cm).

For graphical representation, the dominant height axis ranged from 100 to 1 200 cm, and densities ranged from 3 000 to 35 000 stools ha^{-1} on a logarithmic scale. The basal quadratic mean diameters values ranged from 1 to 10 cm and finally the above-ground woody dry biomass values ranged from 0 to 100 Mg dm ha^{-1}

2.3. Statistical analysis

Equation (1) was fitted with the nls procedure of the R software program [39]. Although this equation can also be considered as part of a simultaneous fitting system along with equations (2) and (3), separate fitting was preferred because of the different sample size and the interest in obtaining the most accurate estimate of living density of stools.

Equations (2) and (3) define a structurally simultaneous system, in which N and H_0 are exogenous variables whose values are determined independently of the system of equations, Ws is an endogenous variable, and dg_{b0} is an endogenous instrumental variable. The system of equations was fitted simultaneously using the SYSTEMFIT package [40] and the SUR (Seemingly unrelated regression) methodology in the R statistical package [39]. The adjusted coefficient of determination and the root mean square error were used to check the accuracy of the models.

Analysis of variance (ANOVA) was performed, using the R statistical package [39], to evaluate the effect of the stage of development in terms of height growth and Mean Annual Increment (MAI) in biomass, and as the samples sizes were different for different stages of development, the generalized linear model procedure (GLM) was used. Tukey's HSD test was used for comparison of means when significant differences of $p<0.05$ were observed.

3. Results

3.1. Model fitting

The results of fitting the three equations included in the model are shown in Table 4. The estimate of the single coefficient of the density-independent mortality model was highly significant ($p< 0.0001$) and the model accounted for more than 80% of the total variability in stool number. The equation obtained can be used to estimate the number of living stools from the mean height of the dominant shoots and planting density, and it produces a fixed mortality rate, which is consistent with the observations (Fig. 1).

For the simultaneous fit, all the coefficient estimates were highly significant ($p< 0.0001$), except for parameter a_4 of biomass equation (3). This has not serious implications, as this parameter does not have any biological meaning [41]. The models accounted for more than 85% of the total variability in both the quadratic mean basal diameter and the biomass yield, (equations 2 and 3). It is usually difficult to obtain accurate prediction of diameters because of the dependence on changes in density over time when longer rotations are considered.

3.2. Reference diagram

The range of values represented by the axes and the isolines in the RD (Fig. 2) were similar to the ranges included in the database used to construct the diagram (Table 3). The RD shows the isolines for basal quadratic mean diameter (dg_{b0}), above-ground woody dry biomass (Ws) and mortality, as well as the observed values of H_0 and N in the plots used for fitting (Fig. 2).

The isolines for stool density decrease gradually with increasing dominant height, derived from a continuous reduction in stool number of 1.67% for each metre of increment in H_0. The diagram can be used either by considering the initial density to predict the living stool density for a given dominant height or by directly using the actual stool density recorded in the plots. In both cases, the values of the final densities recorded in the plots ranged widely, from 3 735 to 33 333 stools ha^{-1}, and therefore the model can account for large differences in stool density. The dominant height ranged from 153 to 1 026 cm, and did not increase with initial density (Fig. 3).

The isolines for biomass yield are curves that tend to be vertical for low dominant heights, indicating a small effect of stool density at such stages of crop development. As dominant height increases, these isolines become more horizontal and less separated, showing strong differences depending on density and height growth (Fig. 2). The isolines represented a range from 5 to 100 Mg dm ha^{-1}, according to the values measured in the plots, shown in Table 3. The crops are most productive, as far as the first rotation is concerned, at densities higher than 15 000 stools ha^{-1}. These isolines can be used to define biomass thresholds for harvesting, which should be assessed in terms of stool density and dominant height, with the possibility of lengthening the rotation if necessary.

The isolines for basal quadratic mean diameter show a strong dependence on stool density, with very variable values (isolines considered from 2 to 10 cm, according to the observed values in the plots, Table 2). These isolines are rather uniformly separated and are representative of harvesting conditions and biomass quality (Fig. 2). The isolines tend to become more horizontal as dominant height increases. The basal area of basal diameters, a variable not included in the diagrams but used to obtain the basal quadratic mean diameter, ranged between 0.70 and 22.81 m^2 ha^{-1} yr^{-1} (Fig. 3) and tended to increase with density.

In the database, sixteen of the plots are at developmental stage corresponding to R7S3. This information was used to test the behaviour of the diagrams for a second rotation (Fig. 4) and it was noted that significant biases occur both in the case of diameter and biomass.

3.3. Example of RD use to determine energy production

As a practical example (Fig. 5), we simulated an initial planting density of 10 000 stools ha^{-1} and a final basal quadratic mean diameter of 8 cm (which allows efficient harvesting of the crop by a chip harvester). The total aboveground woody dry biomass yield was approximately 60 Mg dm ha^{-1}, the final density was less than 9 000 stools ha-1 and the dominant height obtained was about 11 m. As an additional guide to exploring the possible values of H_0 over time, the observed values of the quartiles for this variable are represented in Figure 6, along with the predicted quartiles for R4T4 and R5T4. Significant differences in height according to the stage of development ($p<0.0001$) were observed with increasing root age, although not in the case of shoot age. This was also found for Mean Annual Increment (MAI) in biomass ($p<0.0001$), except in the first year shoots, in which this variable did not vary significantly (Fig. 7). The rotation for calculating MAI is considered as being the period between planting and harvesting (root age), and the biomass produced is considered as the sum of the yield at harvest time and the small quantities obtained during the first coppicing at age 1 year (R1S1) in the corresponding cases. The total energy production for this simulation was 1 100 GJ ha^{-1} and the ash content approximately was 1.53 %. Therefore the energy production rate would be 366.6 GJ ha^{-1} yr^{-1}.

These values indicate that an area of 81.8 ha covered by poplar under SRC would be needed to supply a municipal power plant of 5 MW, with a performance of 1 500 hours per year and a thermal efficiency of 90% (typical dimension for several public buildings and a network of heat to various individual homes). This indicates the possibility of promoting SRC for thermal use in areas where the current biomass supply is low.

4. Discussion

4.1. Model utility and limitations

The system of related equations presented enables accurate estimation of crop yield in terms of oven dry biomass and total energy, while also providing the predicted changes in stool number, which is a useful tool for decision making. A density-independent mortality model was used rather than the density-dependant model usually used for DMDs because no different trends in mortality rate for different planting densities were observed. This may be because the development stage of the plantations under study may not have reached the self-thinning threshold, as indicated by the low mean mortality rate (< 15 %) across planting densities. The two main variables included in the diagram and used for decision-making were the initial cutting density and the rotation age, represented by the increase in mean height of the dominant shoots with age, depending on site properties and the crop management. The mean height of dominant shoots can be determined easily by measurement with telescopic rods in a sample plot or from LiDAR information.

The adjusted coefficient of determination in the case of the biomass model is, however, slightly lower than the values obtained by other authors for pine or oak stands [17, 33, 42]. This may be because in the present study, fitting was at the stool level, without inclusion of additional variables such as the shoot number per stool. The average shoot number per stool is often highly correlated with total biomass; however, for the information of first rotation managed in this study, the values obtained were low and did not improve the models. Nevertheless, this variable may have a major impact in models developed for subsequent rotations.

The variability in basal quadratic mean diameter explained by this model can be considered high relative to that reported by other authors [19], probably because in short rotations crops, basal diameter is more directly dependent on initial stool density. This variable may be important for considering the harvester limits and harvesting time. Chip harvesters specifically used for these types of crops may be limited by basal diameters greater than 15 cm, while multi-cutter harvesters may be more cost effective for basal diameters between 15 and 20 cm [43]. Tools such as that obtained in this study may provide a basis for comparing the management options for overcoming these limitations, not only by using appropriate densities but also choosing the best harvesting time. On the other hand, knowledge of the market value of the biomass as well as the costs associated with different management practices may also enable economic analysis to obtain the optimal planting density of poplar SRC. However, the models provided here are only valid for the first rotation. The predictable vigorous sprouting after the first coppice [44] would promote rapid canopy closure and full site occupancy, reducing the differences in biomass yield between initial density levels.

Comparing the results obtained for the second rotation to those predicted by this model, we confirmed the need to develop a different set of equations for the second rotation, as basal quadratic mean diameter is overestimated by the model and there is a strong tendency for biomass yield to be underestimated for high observed values of biomass, this was expected due to the higher growth of this type of crop in successive rotations [45-47]; the effect of an already well-formed root system, which is able to absorb more nutrients and water, and the ability of the stool to provide multiple shoots together favour higher production after coppicing, and therefore the prediction for the second rotation with an equation fitted with first rotation data causes significant bias. This emphasizes the importance of developing similar models to those proposed here for future rotations.

The basal area of basal diameters tended to increase with density. However, by decreasing the density, the diameter of trees increased due to the decreased competition for resources, which results in a large average tree size [48-51], thus improving the quality of the biomass arising from lower bark content, lower ash content and greater lower heating value [52].

High ash content of wood is less desirable for fuelwood as it is non-combustible and reduces the heat of combustion [37, 53]. As the share of bark depends on the age of wood [38], and the ash content in the whole tree is mainly related to the amount of bark [54, 55], the ash content will also depend on the age of wood. Bark percentage decreases rapidly with increasing dbh, although it is thought that at dbh> 5 cm, the percentage of dry bark stabilizes at around 7% of dry matter and the decrease in ash content thus slows down [38]. Previously reported values were used instead of an equation [38] to estimate the ash content because the basal quadratic mean diameter in the diagram ranged between 2-10. The ash values derived from the procedure described here were lower than the ash content observed for 'I-214' clone by Fernández et al. [36] at the end of a three year rotation (i.e. about 2.4 % on a dry weight basis).

4.2. Comparison with data from other studies

The values obtained in the present study in relation to the annual above-ground woody dry biomass for 'I-214' clone in function of their densities showed a similar yield range to those reported by other authors, such as Facciotto et al. [56] (15 and 35 Mg dm ha^{-1} yr^{-1}), Liberloo et al. [57] (20 and 25.8 Mg dm ha^{-1} yr^{-1}) and Paris et al. [58] (7.25 Mg dm ha^{-1} from a low soil quality site and 21.86 to 23.74 Mg dm ha^{-1} for medium and high soil quality sites). Under the Mediterranean conditions of the Iberian Peninsula, the observed range was between 19 and 8 Mg dm ha^{-1} yr^{-1} [59]. However, 'I-214' has been identified as stable in terms of yield for a given density [59, 60], i.e. without departing from the expected behaviour estimated from its average genotypic value.

Although the energy obtained from LHV is a theoretical value that can only be achieved at 0% moisture, the information derived from this product may also be useful for determining the energy value of the biomass produced in the different management scenarios. In fact, the following equations enable calculation of biomass, lower heating value and bulk density for chips with a moisture content (h %, wet basis), considering a wood and bark basic density of 0.35 Mg m^{-3} (data not show) and a ratio of 0.38 solid m^{3}/apparent m^{3}:

$$W_h = W_s \frac{100}{100 - h} \quad (5)$$

$$LHV_h = LHV_0 \frac{100 - h}{100} - 0.02443\, h \quad (6)$$

$$BD_h = 0.35\ 0.38 \frac{100}{100 - h} \quad (7)$$

where W_h is the biomass weight at a humidity content (h %, wet basis), W_s is the above-ground woody dry biomass obtained from the diagrams, LHV_h is the low heating value (MJ kg^{-1}) and BD is the bulk density (Mg m^{-3}). The application of such equations for the usual humidity content at harvest time (55%) provides BD_{55}=296 Mg m^{-3}. Drying chips to h=30% would provide a biofuel classified as BD150 (BD_{30}=190 Mg m^{-3}), Q11 (LHV_{30}=12.1 MJ kg^{-1}), A3.0 (ash percentage always less than 3%) and thus class B for non industrial uses, according to the European standard EN14961-4.

The predicted values for the energy production at the end of the rotation ranged between 100-2 000 GJ ha^{-1}, which is higher than the values reported for poplar (173-259 GJ ha^{-1}; 10-15 Mg dm ha^{-1} yr^{-1}) grown as a short rotation woody crop [61]. Mean plot values ranged from 4.83 to 522.27 GJ ha^{-1} yr^{-1}, which includes the range of values obtained by other authors (165.51-311.78 GJ ha^{-1} yr^{-1} [36]) and even reached as high as the values for second rotations, which are expected to be higher (e.g. 351-537 GJ ha^{-1} yr^{-1} [62]).

4. Conclusions

Reference diagrams are useful because of their simplicity and the fact that the inputs required are easily obtainable. These features make this Reference Diagram an excellent tool for stand management, adapted to short rotation coppice of poplar. The extensive network of heterogeneous plots used to develop this RD confers the model a wide range of performance, whether for planning plantation, as a tool to examine the different options to achieve an end goal (i.e. to achieve a specific production to supply a plant or not to exceed certain stage of development that can be limiting at harvest time), and at the end life of the plantation, for calculating the optimal cutting time for a final goal. In both cases, this type of diagram proved to be a very useful tool for planning different management according to the constraints of the desired product and optimizing resources to maximize the performance.

Although the translation of dominant height data to age would depend on site conditions and management, the models developed are useful for estimating the amount of biomass accumulated at a certain stage of development and initial planting density and to determine the maximum developmental stage that allows the use of available machinery to harvest the crop. These models are also useful for economic optimization of the initial density of planting in relation to production, although this requires models that are sensitive to the possible effect of the crop origin in relation to the initial density of the following rotations. Future research in this field of work should consider all these aspects.

Acknowledgements

This work was financially supported by DECOCEL and RTA2011-00006-00-00 projects. We also thank María José Hernández for technical support and Christine Francis for checking the English version of this article.

References

[1] Kauter D, Lewandowski L, Claupein W. Quantity and quality of harvestable biomass from *Populus* short rotation coppice for solid fuel use - a review of the physiological basis and management influences. Biomass Bioenerg. 2003;24:411-27.
[2] White E. Woody Biomass for Bioenergy and Biofuels in the United States- A Briefing Paper. OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station ed. Portland: USDA General Technical Report PNW-GTR-825 2010.
[3] European Commission EU. The EU rural development Policy: facing the Challenges. European Communities. 2008.
[4] Sixto H, Hernández M, Barrio M, Carrasco J, Cañellas I. Plantaciones del género *Populus* para la producción de biomasa con fines energéticos: revisión. Forests System. 2007;16(3):277-94.
[5] Mareschi L, Paris P, Sabatti M, Nardin F, Giovanardi R, Manazzone S, et al. The new varieties of poplar biomass guarantee interesting yield. Informatore Agrario. 2005;6(18):49-53.
[6] Yemshanov D, McKenney D. Fast-growing poplar plantations as a bioenergy supply source for Canada. Biomass Bioenerg. 2008;32:185-97.
[7] Verwijst T, Lundkvist A, Edelfeldt S, Albertsson J. Development of Sustainable Willow Short Rotation Forestry in Northern Europe, Biomass Now -. Sustainable Growth and Use, Dr Miodrag Darko Matovic (Ed). 2013;19:481-502.
[8] Laureysens I, Deraedt W, Indeherberge T, Ceulemans R. Population dynamics in a 6-year old coppice culture of poplar. I. Clonal differences in stool mortality, shoot dynamics and shoot diameter distribution in relation to biomass production. Biomass Bioenerg. 2003;24(2):81-95.
[9] Pérez-Cruzado C, Sanchez-Ron D, Rodríguez-Soalleiro R, Hernández M, Sánchez-Martín M, Cañellas I, et al. Biomass production assessment from *Populus* spp. short-rotation irrigated crops in Spain. Glob Chage Biol Bioenerg. 2013.
[10] Benetka V, Novotná K, Štochlová P. Biomass production of *Populus nigra* L. clones grown in short rotation coppice systems in three different environments over four rotations. iForest-Biogeosciences and Forestry. 2014:232.
[11] Willebrand E, Ledin S, Verwijst T. Willow coppice system in short rotation forestry: effects of plant spacing rotation length and clonal composition on biomass production. Biomass Bioenerg. 1993;4(5):232-1.
[12] Fiala M, Bacenetti J, Scaravonati A, Bergonzi A. Short rotation coppice in northern Italy: Comprenhensive Sustainability. European Biomass Conference and Exhibition. 2010;18th:342-8.
[13] Cañellas I, Huelin P, Hernández M, Ciria P, Calvo R, Gea-Izquierdo G, et al. The effect of density on Short Rotation *Populus* spp. plantations in the Mediterranean area. Biomass Bioenerg. 2012;46:645-52.
[14] Klasnja B, Orlovic S, Drekic M, Markovic M. Energy production from short rotation poplar plantations. VIITH International symposium interdisciplinary regional research - ISIRR 2003;IV:161-6.

[15] Newton PF, Weetman GF. Stand density management diagram for managed black spruce stands. Forest Chron. 1994;70(1):65-74.

[16] Shaw JD, Long JN. A density management diagram for longleaf pine stands with application to red-cockaded woodpecker habitat. S J Appl Forestry. 2007;31(1):28-38.

[17] Barrio-Anta M, Álvarez-González JG. Development of a stand density management diagram for even-aged pedunculate oak stands and its use in designing thinning schedules. Forestry. 2005;78(3):209-16.

[18] López-Sánchez C, Rodríguez-Soalleiro R. A density management diagram including stand stability and crown fire risk for *Pseudotsuga Menziesii* (Mirb.) Franco in Spain. Mt Res Dev. 2009;29(2):169-76.

[19] Pérez-Cruzado C, Merino A, Rodríguez-Soalleiro R. A management tool for estimating bioenergy production and carbon sequestration in *Eucalyptus globulus* and *Eucalyptus nitens* grown as short rotation woody crops in north-west Spain. Biomass Bioenerg. 2011;35(7):2839-51.

[20] Pontailler JY, Ceulemans R, Guittet J, Mau F. Linear and non-linear functions of volume index to estimate woody biomass in high density young poplar stands. Ann Sci For. 1997;54(4):335-45.

[21] Verwijst T, Telenius B. Biomass estimation procedures in short rotation forestry. For Ecol Manage. 1999;121(1-2):137-46.

[22] Amichev BY, Johnston M, Van Rees KCJ. Hybrid poplar growth in bioenergy production systems: Biomass prediction with a simple process-based model (3PG). Biomass Bioenerg. 2010;34(5):687-702.

[23] Headlee WL, Zalesny Jr RS, Donner DM, Hall RB. Using a process-based model (3-PG) to predict and map hybrid poplar biomass productivity in Minnesota and Wisconsin, USA. BioEnergy Research. 2013;6(1):196-210.

[24] Mosseler A, Major J, Labrecque M, Larocque G. Allometric relationships in coppice biomass production for two North American willows (*Salix* spp.) across three different sites. For Ecol Manage. 2014:320.

[25] Dickmann D. Silviculture and biology of short-rotation woody crops in temperate regions: then and now. Biomass Bioenerg. 2006;30:696–705.

[26] Sixto H, Hernández MJ, de Miguel J, Cañellas I. Red de parcelas de cultivos leñosos en alta densidad y turno corto. Madrid2013.

[27] Willebrand E, Verwijst T. Population dynamics of willow coppice systems and their implications for management of short-rotation forests. Forest Chron. 1993;69(6):699-704.

[28] Kopp R, Abrahamson L, White E, Volk T, Nowak C, Fillhart R. Willow biomass production during ten successive annual harvests. Biomass Bioenerg. 2001;20(1):1-7.

[29] Dieguez-Aranda U, Castedo-Dorado F, Alvarez-Gonzalez JG, Rodriguez-Soalleiro R. Modelling mortality of Scots pine (*Pinus sylvestris* L.) plantations in the northwest of Spain. Eur J For Res. 2005;124(2):143-53.

[30] Newton PF, Lei Y, Zhang SY. Stand-level diameter distribution yield model for black spruce plantations. For Ecol Manage. 2005;209(3):181-92.

[31] Goulding CJ. Simulation techniques for a stochastic model of the growth of Douglas-fir. Vancouver, British Columbia: Thesis (Ph.D.) University of British Columbia; 1972.

[32] Long JN, Shaw JD. A density management diagram for even-aged ponderosa pine stands. West J Appl For. 2005;20(4):205-15.

[33] Castedo-Dorado F, Crecente-Campo F, Álvarez-Álvarez P, Barrio-Anta M. Development of a stand density management diagram for radiata pine stands including assessment of stand stability. Forestry. 2009;82(1):1-16.

[34] Sarkar D. Lattice: Multivariate Data Visulization with R. Springer, New York. 2008.

[35] Sarkar d, Andrews F. latticeExtra: Extra Graphical Utilities Based on Lattice. R package version 06-19. 2011.
[36] Fernández MJ, Ciria P, Barro R, Losada J, Pérez J, Sixto H, et al. Quality of the biomass produced in Short Rotation Coppices of poplar, willow, black locust and sycamore in two different spanish locations. 21 st European Biomass Conference and Exhibition. 2013.
[37] Klasnja B, Kopitovic S, Orlovic S. Wood and bark of some poplar and willow clones as fuelwood. Biomass Bioenerg. 2002;23(6):427-32.
[38] Guidi W, Piccioni E, Ginanni M, Bonari E. Bark content estimation in poplar (*Populus deltoides* L.) short-rotation coppice in Central Italy. Biomass Bioenerg. 2008;32(6):518-24.
[39] R Development Core Team. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing; 2013.
[40] Henningsen A, Hamann JD. systemfit: A Package for Estimating Systems of Simultaneous Equations in R. Journal of Statistical Software. 2007:23(4).
[41] Antonio N, Tome M, Tome J, Soares P, Fontes L. Effect of tree, stand, and site variables on the allometry of *Eucalyptus globulus* tree biomass. Can J For Res-Rev Can Rech For. 2007;37(5):895-906.
[42] Barrio-Anta M, Balboa-Murias MA, Castedo-Dorado F, Diéguez-Aranda U, Álvarez-González JG. An ecoregional model for estimating volume, biomass and carbon pools in maritime pine stands in Galicia (northwestern Spain). For Ecol Manage. 2006;223(1-3).
[43] Berhongaray G, El Kasmioui O, Ceulemans R. Comparative analysis of harvesting machines on an operational high-density short rotation woody crop (SRWC) culture: One-process versus two-process harvest operation. Biomass Bioenerg. 2013;58:333-42.
[44] Stanturf JA, Oosten Cv, Isebrands J, Richardson J. Operational Poplar and Willow culture. In: Isebrands J, Richardson J, editors. Poplars and Willows: Trees for society and the environment 2014. p. 200.
[45] Dillen SY, Djomo SN, Al Afas N, Vanbeveren S, Ceulemans R. Biomass yield and energy balance of a short-rotation poplar coppice with multiple clones on degraded land during 16 years. Biomass Bioenerg. 2013;56:157-65.
[46] Di Matteo G, Sperandio G, Verani S. Field performance of poplar for bioenergy in southern Europe after two coppicing rotations: effects of clone and planting density. Iforest-Biogeosciences and Forestry. 2012;5:224-9.
[47] Sennerby-Forsse L, Ferm A, Fauppi A. Coppicing ability and sustainability. In: Mitchell C, Ford-Robertson J, Hinckley T, Sennerby-Forsse L, editors. Ecophysiology of Short Rotation forest Crops. London: Elselvier; 1992. p. 146-73.
[48] Hamilton G. The dependence of volume increment of individual trees on dominance, crown dimensions, and competition. Forestry. 1969;42(2):133-44.
[49] Assmann E. The principles of forest yield study: studies in the organic production, structure, increment, and yield of forest stands. Oxford: Pergamon Press; 1970.
[50] Curtis RO. Stand density measures an interpretation. For Sci. 1970;16(4):403.
[51] Dean TJ, Long JN. Influence of leaf-area and canopy structure on size-density relations in even-aged lodgepole pine stands. For Ecol Manage. 1992;49(1-2):109-17.
[52] Bergante S, Facciotto G, Minotta G. Identification of the main site factors and management intensity affecting the establishment of Short-Rotation-Coppices (SRC) in Northern Italy through stepwise regression analysis. Cent Eu J Biol. 2010;5(4):522-30.
[53] Goel VL, Behl HM. Fuelwood quality of promising tree species for alkaline soil sites in relation to tree age. Biomass Bioenerg. 1996;10(1):57-61.
[54] Steenari BM, Lindqvist O. Stabilisation of biofuel ashes for recycling to forest soil. Biomass Bioenerg. 1997;13(1-2):39-50.
[55] Tharakan PJ, Volk TA, Abrahamson LP, White EH. Energy feedstock characteristics of willow and hybrid poplar clones at harvest age. Biomass Bioenerg. 2003;25(6):571-80.

[56] Facciotto G, Bergante S, Lioia C, Rosso L, Mughini G, Zenone T, et al. Produttività di cloni di pioppo e salice in piantagioni a turno breve. Forest@-Journal of Silviculture and Forest Ecology. 2006;3(2):238.
[57] Liberloo M, Calfapietra C, Lukac M, Godbold D, LUO ZB, Polle A, et al. Woody biomass production during the second rotation of a bio-energy Populus plantation increases in a future high CO2 world. Global Change Biology. 2006;12(6):1094-106.
[58] Paris P, Mareschi L, Sabatti M, Pisanelli A, Ecosse A, Nardin F, et al. Comparing hybrid Populus clones for SRF across northern Italy after two biennial rotations: Survival, growth and yield. Biomass Bioenerg. 2011;35(4):1524-32.
[59] Sixto H, Gil P, Ciria P, Camps F, Sánchez M, Cañellas I, et al. Performance of hybrid poplar clones in short rotation coppice in Mediterranean environments: analysis of genotypic stability. Glob Chage Biol Bioenerg. 2013.
[60] Cruset JE, Voltas J. Adaptation of poplar clones in the Ebro valley: a retrospective analysis of the experimental network established in the 80s by mixed models (in Spanish). In: S.E.C.F. JCyL, editor. 5º Congreso Forestal Español Ávila 2009.
[61] McKendry P. Energy production from biomass (part 1): overview of biomass. Bioresour Technol. 2002;83(1):37-46.
[62] Luo ZB, Polle A. Wood composition and energy content in a poplar short rotation plantation on fertilized agricultural land in a future CO_2 atmosphere. Global Change Biology. 2009;15(1):38-47.

Tables

Table 1. Locations and UTM coordinates of the experimental SRC poplar plots located in Spain.

Site		UTM coordinates [a] X	Y	Elevation m asl	T [b] (ºC)	P [c] (mm)	pH	SOM [d] (%)	Sand (%)	Silt (%)	Clay (%)
Almazán	1	537782	4591237	827	11.19	447	8.42	2.08	18.2	34.44	47.35
Lubia	2	541547	4605407	1 090	10.19	614	6.39	0.57	85.14	5.52	9.33
Magaz de Arriba	3	691550	4720450	560	12.80	747	6.01	1.02	53.43	23.22	23.34
Cababañas Raras	4	692850	4721700	560	12.69	476	6.21	0.84	55.36	23.88	20.76
Valtierra	5	610103	4670081	263	14.10	405	8.52	1.24	38.3	37.01	24.70
Granada	6	431869	4116815	738	15.3	355	8.45	1.42	40.04	35.28	24.77
Gerona	7	506101	4656270	20	15.69	658	8.61	0.36	74.09	11.53	14.38
Barcelona	8	472777	4615983	52	16.10	677	6.31	0.29	82.59	6.03	11.36
Iscar	9	371577	4575970	756	12.30	440	9.04	0.89	80.1	11.28	8.62
Zuera	10	683168	4647632	279	14.50	408	8.26	1.14	54.90	23.64	20.70
Faramontanos	11	258370	4635706	705	12.10	484	5.41	1.51	57.66	21.56	20.77

[a] The UTM coordinates refer to grid 30; [b] T: average annual temperature; [c] P: annual accumulated rainfall; [d] SOM: soil organic matter in the A horizon.

Table 2. Information on the plot characteristics and the average values of the main variables evaluated

Site	Age	Initial Density	Number of Evaluated Plots	Replicate	Average H_0 [a] (cm)	Average Ws [b] (Mg dm ha^{-1})	Average G_{b0} [c] /ha (m^2 ha^{-1})	Average dg_{b0} [d] (cm)
1	R4T3	15 000	3	16	430.27	22.58	22.01	4.32
1	R4T3	25 000	3	16	391.17	22.95	27.42	3.73
1	R4T3	33 333	3	16	338.11	24.30	30.30	3.39
2	R4T3	17 316	3	16	617.96	66.04	48.37	5.95
2	R4T3	20 000	4	16	568.06	50.23	45.96	5.27
3	R3T3	13 333	4	25	524.41	17.50	17.82	4.06
3	R4T3	20 000	4	16	786.92	51.43	49.15	5.58
3	R4T3	20 000	3	16	774.06	51.73	42.15	5.17
3	R4T3	15 000	3	16	823.83	55.17	40.34	5.84
3	R4T3	25 000	3	16	797.27	70.17	57.08	5.38
3	R4T3	33 333	3	16	671.35	56.54	51.30	4.42
4	R3T3	13 333	4	16	481.13	13.96	16.67	3.96
6	R3T3	13 333	4	16	933.67	58.21	46.10	6.63
6	R3T3	13 333	4	25	747.65	32.83	31.98	5.51
6	R3T3	10 000	3	16	949.06	58.22	42.39	7.34
6	R3T3	15 000	3	16	909.79	62.97	49.29	6.45
6	R3T3	20 000	3	16	863.44	68.96	56.19	5.98
7	R3T3	13 333	4	16	501.18	25.27	23.36	4.70
7	R3T3	6 666	3	25	775.47	26.65	30.15	7.58
7	R3T3	13 333	3	25	686.39	27.72	34.62	5.74
7	R3T3	6 666	3	16	431.13	5.93	9.97	4.31
7	R3T3	10 000	3	16	470.45	9.22	16.77	4.54
7	R3T3	15 000	3	16	387.34	7.41	14.80	3.53
7	R3T3	20 000	3	16	423.66	14.79	22.94	3.76
8	R3T3	6 666	3	25	408.41	9.61	11.17	4.58
8	R3T3	13 333	3	25	472.83	16.73	23.37	4.71
9	R3T3	13 333	3	15	287.58	3.56	6.97	2.55
9	R3T3	13 333	4	25	170.76	1.11	3.09	1.68
9	R3T3	10 000	3	17	365.15	8.74	9.87	3.54
9	R3T3	15 000	3	16	322.97	8.77	14.53	3.50
9	R3T3	20 000	3	15	292.61	7.65	13.01	2.87
10	R3T3	13 333	3	16	634.67	27.98	27.21	5.09
10	R3T3	13 333	6	25	656.35	33.28	28.04	5.09
10	R3T3	10 000	3	17	731.86	33.13	28.85	6.05
10	R3T3	15 000	3	16	666.07	33.26	28.54	4.92
10	R3T3	20 000	3	16	737.68	49.70	40.88	5.08
11	R3T3	13 333	4	16	314.58	15.67	17.94	4.00
11	R3T3	6 666	4	25	488.52	16.20	12.33	4.81
11	R3T3	13 333	7	16	441.87	24.72	22.66	4.62
11	R3T3	10 000	3	16	500.02	21.71	20.63	5.08
11	R3T3	15 000	3	16	455.02	34.58	27.79	4.83
11	R3T3	20 000	3	16	378.76	20.66	20.59	3.61

[a] H_0: height of dominant shoots; [b] Ws: total above-ground woody dry biomass; [c] G_{b0}: basal area of basal diameters; [d] dg_{b0}: basal quadratic mean diameter of dominant shoots.

Table 3. Statistics for the main variables measured in the plots:

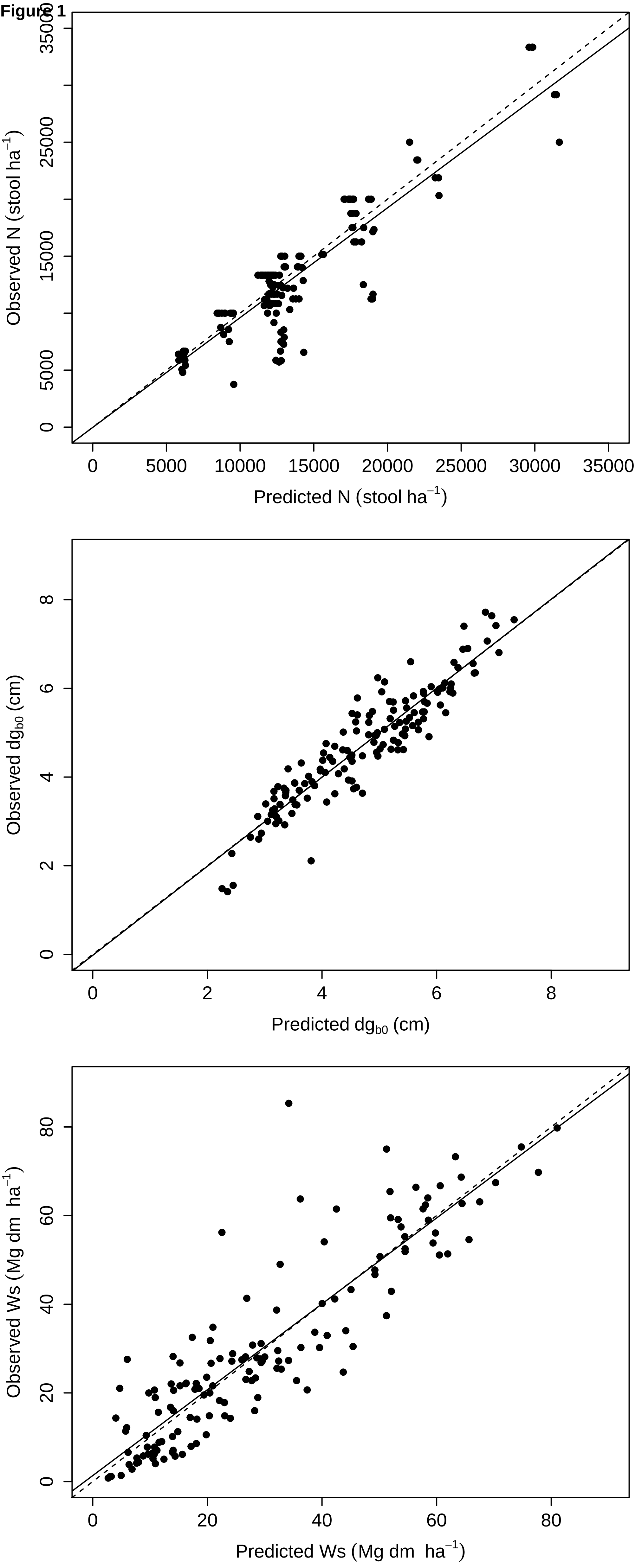
	Max [a]	Min [b]	Mean	Devest [c]
H_0 (cm)	1 025.6	153.1	557.9	214.3
dg_{bo} (cm)	7.72	1.41	4.74	1.28
N (stool ha^{-1})	33 333	3750	13 328.9	5 680.0
N_0 (stool ha^{-1})	33 333	6 666	15 378.4	6 085.2
Ws (Mg dm ha^{-1})	85.3394	0.7901	29.7845	20.9524

[a] Max: maximum; [b] Min: minimum; [c] Devest: mean deviation

Table 4. Non-linear regression coefficients and statistics obtained from the mortality equation and simultaneous fitting of the system of 2 equations predicting basal quadratic mean diameter and total above-ground woody dry biomass.

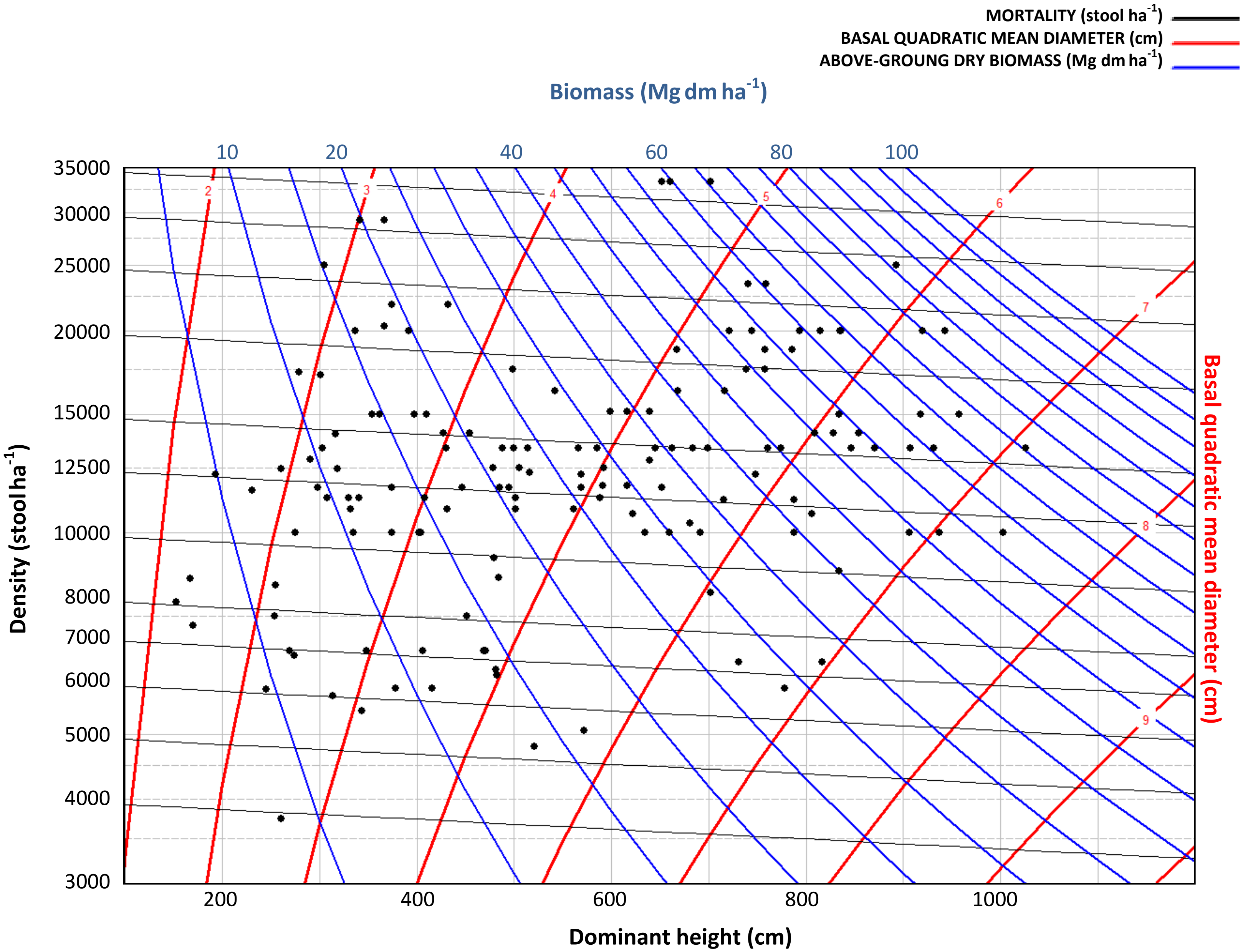
Equation	Parameter estimates			Adjusted R^2	RMSE	N data	DF Error
(1)	K	-0.0001689	<0.0001	0.8059	2 566	350	349
	a_1	0.41903566	<0.0001				
(2)	a_2	0.65089060	<0.0001	0.8553	0.488	144	139
	a_3	-0.17734437	<0.0001				
	a_4	0.05115256	0.1250824				
(3)	a_5	2.39193578	<0.0001	0.8569	7 927	144	139
	a_6	0.99484093	<0.0001				

Figure 1



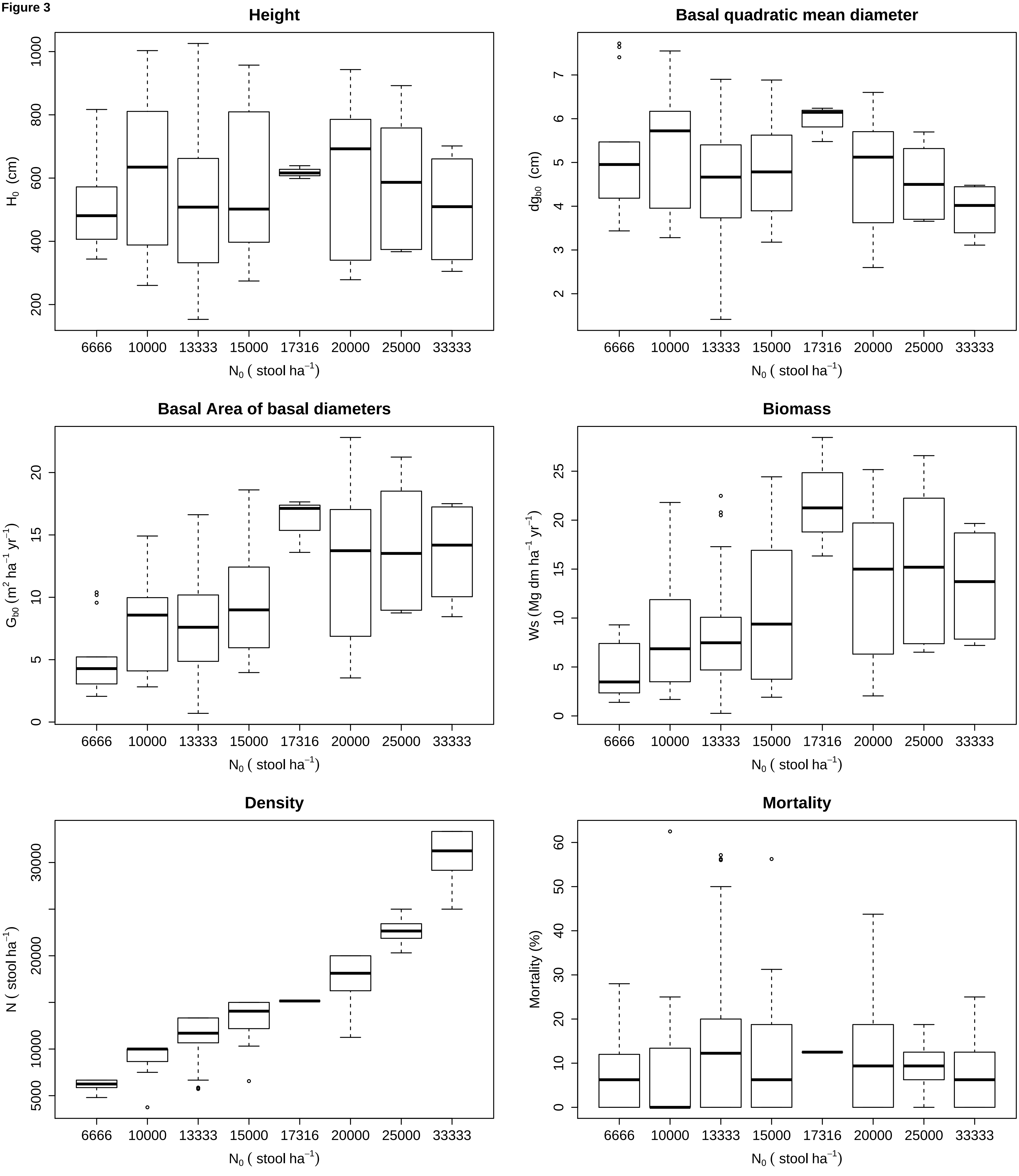
Observed N (stool ha^{-1})
Predicted N (stool ha^{-1})
0
5000
10000
15000
20000
25000
30000
35000
Observed dg$_{b0}$ (cm)
Predicted dg$_{b0}$ (cm)
0
2
4
6
8
Observed Ws (Mg dm ha^{-1})
Predicted Ws (Mg dm ha^{-1})
0
20
40
60
80

Figure 2



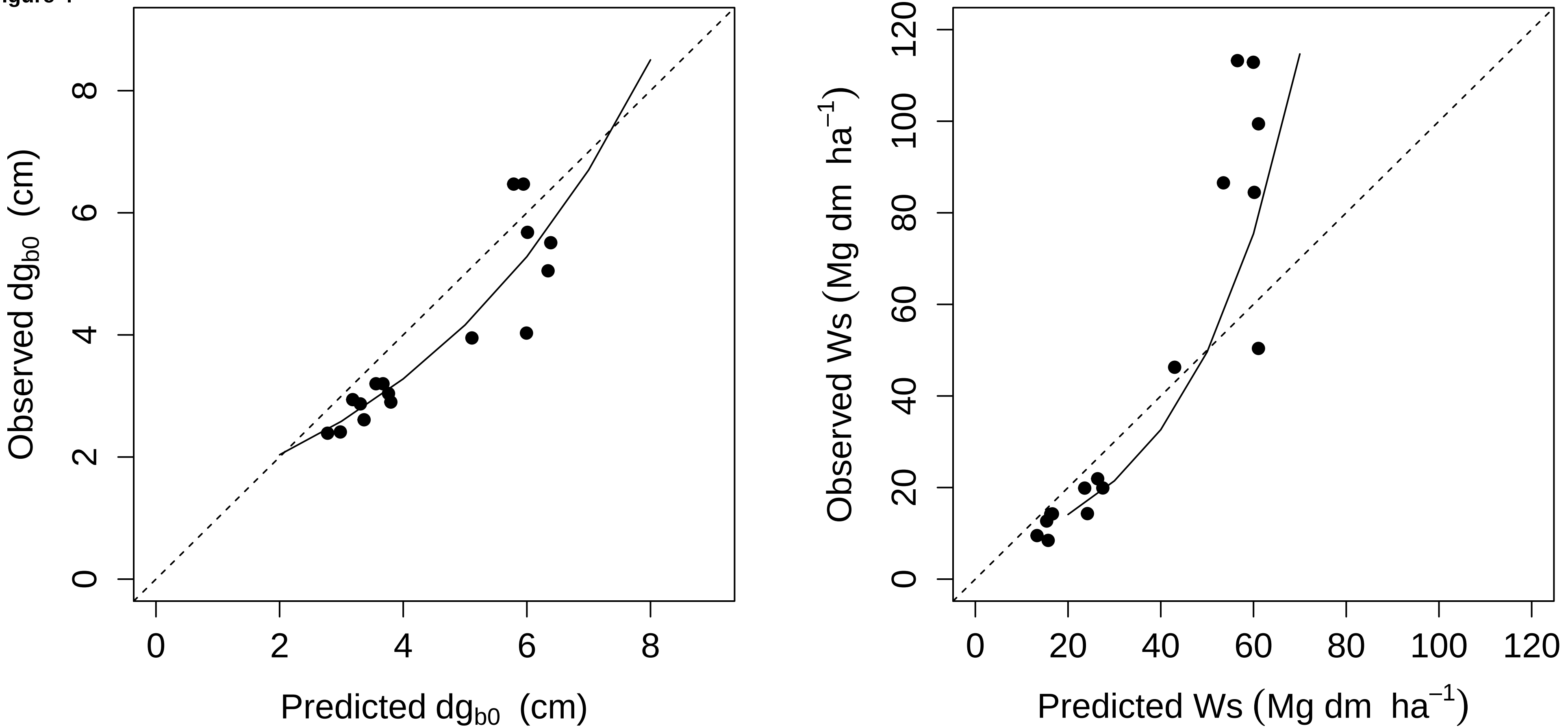
MORTALITY (stool ha-1)
BASAL QUADRATIC MEAN DIAMETER (cm)
ABOVE-GROUNG DRY BIOMASS (Mg dm ha-1)
Biomass (Mg dm ha-1)
10
20
40
60
80
100
35000
30000
25000
20000
15000
12500
10000
8000
7000
6000
5000
4000
3000
Density (stool ha-1)
2
3
4
5
6
7
8
9
Basal quadratic mean diameter (cm)
200
400
600
800
1000
Dominant height (cm)

Figure 3



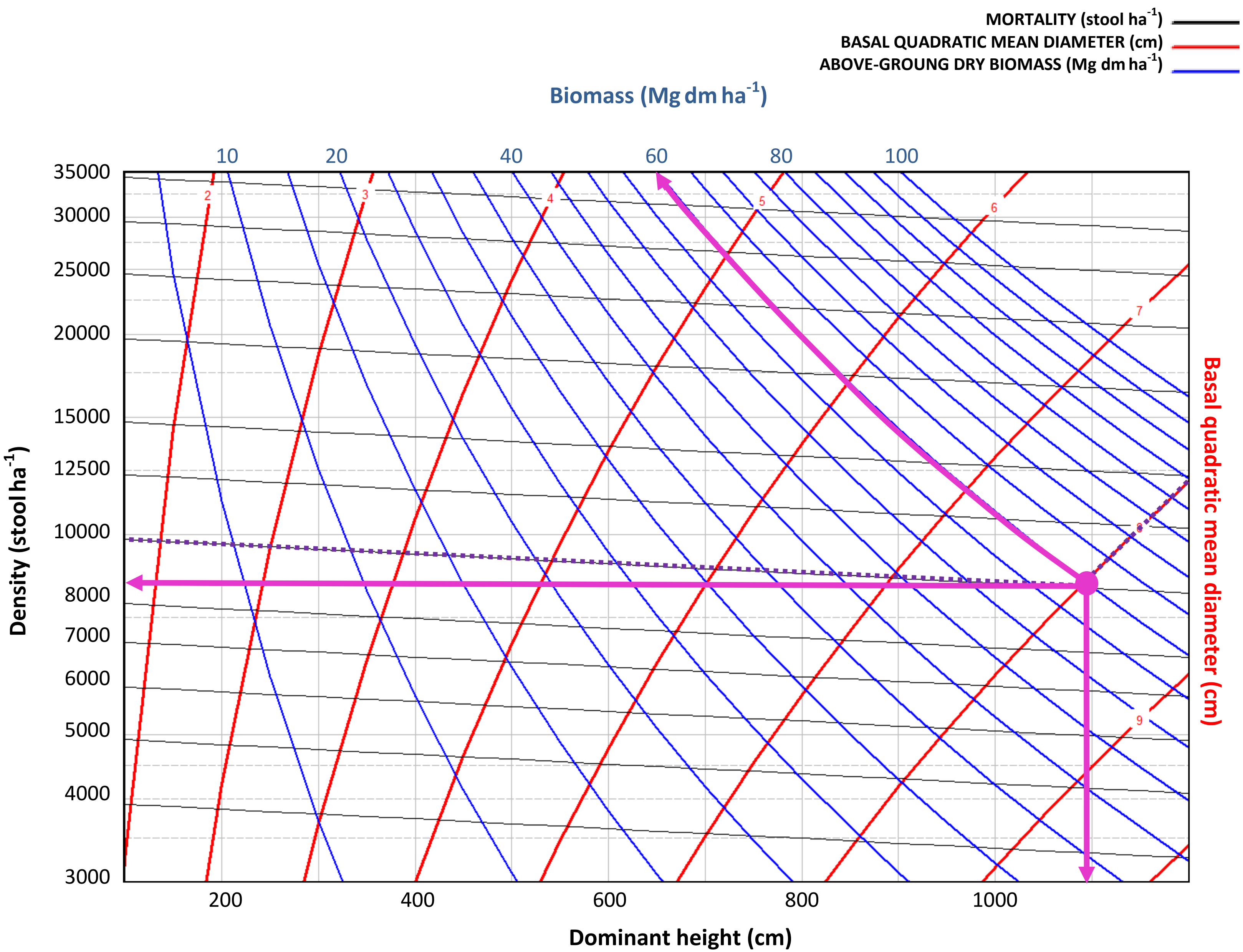
Height
H_0 (cm)
Basal quadratic mean diameter
dg_{b0} (cm)
Basal Area of basal diameters
G_{b0} (m^2 ha^{-1} yr^{-1})
Biomass
Ws (Mg dm ha^{-1} yr^{-1})
Density
N (stool ha^{-1})
Mortality
Mortality (%)
6666 10000 13333 15000 17316 20000 25000 33333
N_0 (stool ha^{-1})

Figure 4



Observed dgb0 (cm)
Predicted dgb0 (cm)
0
2
4
6
8
Observed Ws (Mg dm ha−1)
Predicted Ws (Mg dm ha−1)
0
20
40
60
80
100
120

Figure 5



MORTALITY (stool ha-1)
BASAL QUADRATIC MEAN DIAMETER (cm)
ABOVE-GROUNG DRY BIOMASS (Mg dm ha-1)
Biomass (Mg dm ha-1)
10
20
40
60
80
100
35000
30000
25000
20000
15000
12500
10000
8000
7000
6000
5000
4000
3000
Density (stool ha-1)
200
400
600
800
1000
Dominant height (cm)
Basal quadratic mean diameter (cm)
2
3
4
5
6
7
8
9

Figure 6

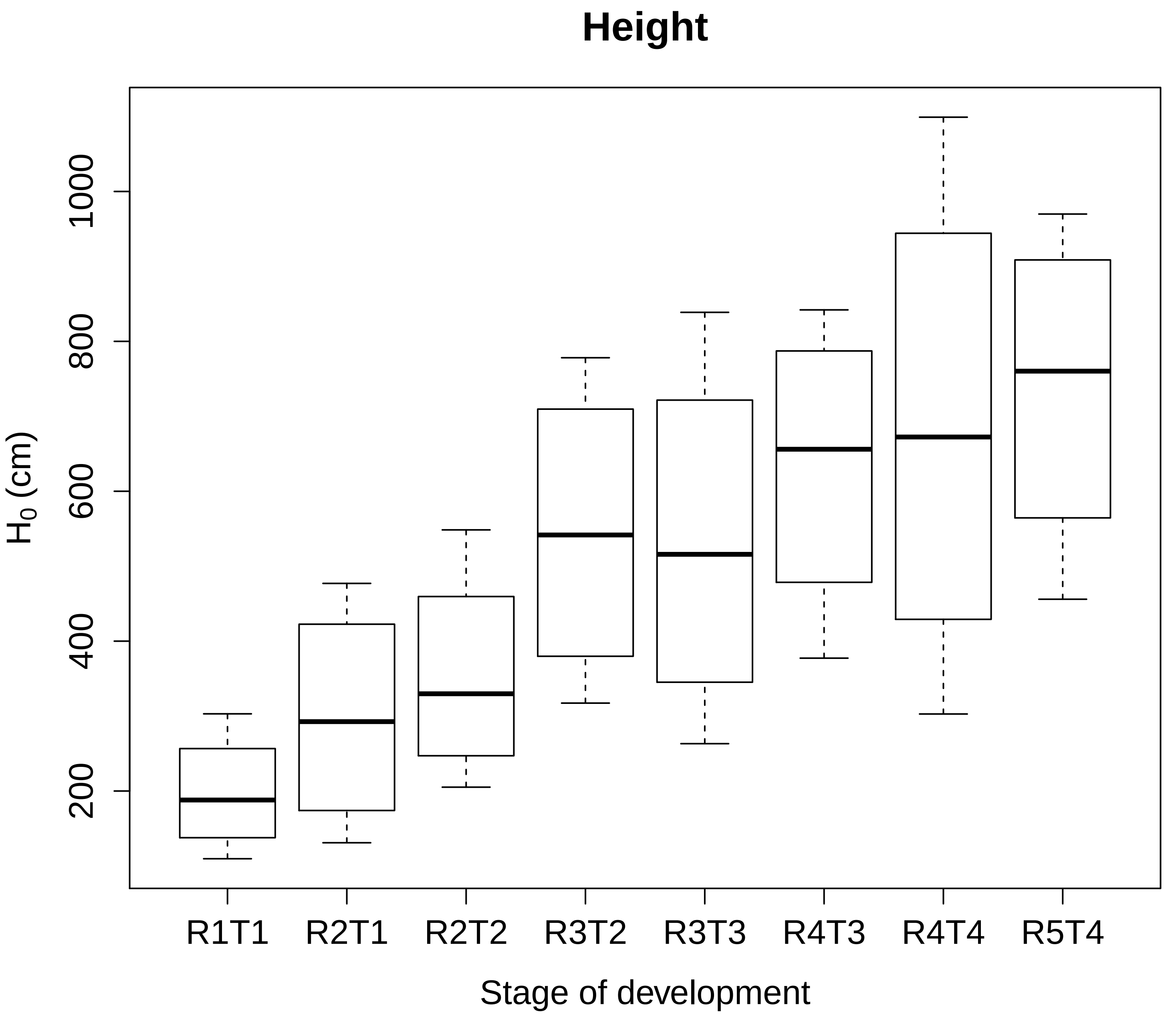
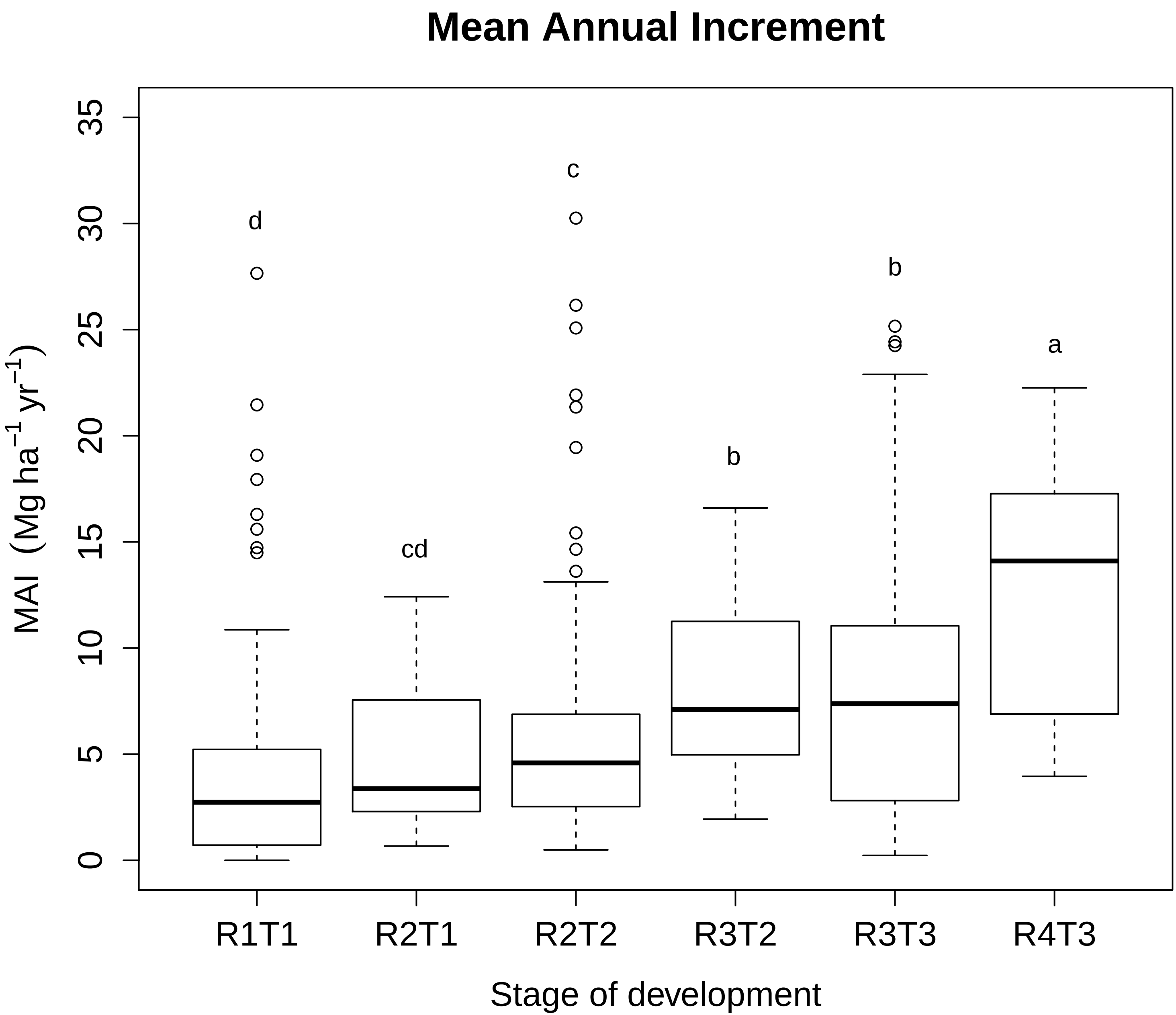

Height
H_0 (cm)
200
400
600
800
1000
R1T1
R2T1
R2T2
R3T2
R3T3
R4T3
R4T4
R5T4
Stage of development

Figure 7



Mean Annual Increment
MAI (Mg ha^{-1} yr^{-1})
0
5
10
15
20
25
30
35
d
cd
c
b
b
a
R1T1
R2T1
R2T2
R3T2
R3T3
R4T3
Stage of development

Figures Captions

Figure 1. Relationship between observed-predicted density values (stools ha^{-1}) in the mortality equations, basal quadratic mean diameters values (cm) and dry biomass values (Mg dm ha^{-1}) in the stool system of equations.

Figure 2. Reference diagram for ‘I-214’ poplar clone with isolines for mortality (stool ha^{-1}), basal quadratic mean diameter (cm), aboveground dry biomass (Mg ha^{-1}) and sample plots.

Figure 3. Boxplot of the variables height, basal quadratic mean diameter, basal area of basal diameters (all referring to dominant shoot per stool), and biomass, density and mortality as a function of the initial density (stool ha^{-1}).

Figure 4. Relationship between observed-predicted dry biomass values (Mg dm ha^{-1}) and basal quadratic mean diameters values (cm) for the second rotation, in the stool system of equations for first rotation used in the diagrams.

Figure 5. Practical example of the use of the reference diagram.

Figure 6. Quartiles height as a function of the stage of development.

Figure 7. Mean annual increment in biomass as a function of the stage of development. The rotation considered is the root age and the biomass is the total yield in the rotation. The letters represent the results of Tukey’s HSD post-hoc comparisons of group means ($p<0.05$).