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Novel approach to assessing residual biomass from pruning: A case study in Atlantic *Pinus pinaster* Ait. timber forests

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4 **Novel approach to assessing residual biomass from pruning: A case**
5 **study in Atlantic *Pinus pinaster* Ait. timber forests**

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26 **Abstract**

27 Forestry residual biomass from pruning operations is an important, though little
28 studied, potential resource. Residues normally remain in the stand, since tools
29 for their accurate quantification do not exist and it has no particular end use.
30 Traditional tree biomass estimation models consider the whole-tree, but
31 estimating pruned biomass requires the development of more specific
32 equations. This work provides a modelling approach for assessing biomass
33 along the stem and the corresponding residual biomass from forest pruning,
34 and quantitative results from different pruning intensities in *Pinus pinaster* Ait.
35 are presented. Two types of models were considered: allometric biomass
36 equations (whole-tree) and biomass ratio equations (tree by height along the
37 stem), and the 2-parameter Weibull distribution function resulted in the best
38 characterization. Diameter at breast height was the best explanatory variable in
39 all equations, and model accuracy increased when models were combined with
40 total tree height for the tree stem and thicker branches, or with crown ratio for
41 the remaining tree crown components. This study provides a powerful tool to
42 estimate residual pruned biomass, enabling its better management as a
43 valuable source of bioenergy, as well as the importance in nutrient balance and
44 fire risk which it plays in a sustainable forestry production.

45

46

47 **Keywords:** maritime pine, forest biomass waste, Weibull distribution function,
48 forestry modelling, silviculture.

49

50

51

52 **Highlights**

53

54 • Final models combine allometric equations and Weibull probability density

55 function.

56 • Biomass equations by height along the stem allow accurate estimation of

57 pruned biomass.

58 • Model can be adapted to ascertain residual biomass from different pruning

59 intensities.

60 • Work provides a valuable tool to manage processing of residual pruned

61 biomass.

62

63

64 1. Introduction

65 Maritime pine (*Pinus pinaster* Aiton) is one of the most important conifer
66 timber species in the Atlantic area and Southern Europe, as well as having
67 great potential as a source of residual forest biomass. However, there is a
68 distinct lack of information about the forest management of this species in the
69 Atlantic region, which affects the optimal utilization of both timber and residual
70 forest biomass. It is therefore of enormous value to expand the knowledge base
71 for the silvicultural management of this species and its associated residues in
72 order to improve and optimise the sustainability and profitability of *P. pinaster*
73 stands.

74 In timber forests, thinning and pruning are two of the key interventions to
75 consider due to their role in enhancing the quality of wood. Residual tree
76 biomass from thinning operations has been estimated for some of the main
77 forest species [1-3] but biomass extracted by pruning has not, however, been
78 quantified very frequently in forest species. Indeed, only a few recent studies in
79 urban forests [4-6] and agricultural systems [7] focusing on pruned biomass can
80 be found. Consequently, there is little information on the availability and
81 characteristics of the residual biomass resulting from forest pruning, which is
82 usually left in the forest stand without any further processing or proper
83 management.

84 The spatial distribution of biomass within crowns is generally ignored,
85 although more intensive silvicultural methods are now occasioning the need for
86 information on the vertical distribution of branch wood biomass in some regions
87 (e.g. [8]). Particularly, distinct crown components have been studied at
88 disparate levels of resolution in different fields, but recent work has been both

89 more attentive to developments in other disciplines and increasingly concerned
90 with the vertical structure of the crown. There remains, however, comparatively
91 little information concerning the magnitude of intrinsic variation in crown
92 architecture or on the effects of stand manipulations [9].

93 Biomass estimation of forests has been subject to research for over a century
94 (c.f. Ref. [10]) and the importance of monitoring and assessing forest biomass
95 for governments worldwide has gained increased attention in the last few
96 decades against the background of global climate change [11,12]. To quantify
97 tree and forest biomass, mathematical equations that transform tree or stand
98 variables into biomass estimates have been shown to be important and
99 powerful tools for forest management. Most tree biomass estimates rely on
100 allometric relationships developed using traditional forest measurements and
101 include the whole-tree aboveground biomass for each tree component.
102 However, forest pruning only removes part of the tree crown biomass, meaning
103 that new studies and models are needed to better understand and quantify the
104 biomass extracted by pruning to different heights along the stem. This data is
105 essential to both establish and quantify the role of these residues in forest
106 systems with respect to aspects such as their use as biofuel [13] and the
107 important role they play as regards nutrient stability, silviculture and ecology
108 [13,14] as well as fire hazard [15-18]. What is more, the use of forestry biomass
109 for bioenergy is one of the flagship initiatives within the Europe 2020 framework
110 to develop a low carbon economy by 2050 (COM(2011)112 final) [19].

111 Several previous studies of *Pinus pinaster* in Atlantic forests have developed
112 biomass equations [1,2,18,20]. However, most have been carried out in adult
113 stands and employ traditional allometric equations for the whole-tree. In

114 addition, these studies are limited by the lack of research on forest residual
115 biomass from silvicultural interventions [1,2], and those studies which do exist
116 mainly rely upon data from thinning treatments or final harvesting, rather than
117 pruning. Thus, it can be seen that research directed at filling these gaps in
118 information would be of great value when taking forestry management decisions
119 in timber forests.

120 In the present study, the amount of biomass from young pruned trees was
121 estimated using dendrometric parameters obtained from field measurements
122 and data from destructive sampling in *P. pinaster* stands in Northwest Spain.
123 The objectives were: (i) to develop biomass prediction tools for tree fractions for
124 the whole-tree and at different heights along the stem and (ii) to assess the
125 residual biomass extracted under different intensities of pruning. This
126 constitutes a novel methodological approach which can be applied to a variety
127 of silvicultural interventions in timber forests where pruning is an essential
128 treatment.

129 **2. Material and methods**

130 **2.1. Study sites and tree data collection**

131 The present study took place in the north-western region of Asturias, Spain
132 (Fig. 1a), which has an Atlantic climate, with mild temperatures (annual average
133 12-14 °C) and abundant rainfall (930-1475 mm) spread throughout the year.
134 Mean elevation ranged between 101 and 296 m above sea level. Soils were
135 acid (pH from 3.75 to 4.33), and the average slope of the plots was between
136 15% and 31 %.

137 The biomass study was carried out in three temporary plots (trees being 7 to
138 11 years at the time of the study) across the area of distribution of *P. pinaster*.

139 They were previously unmanaged (i.e. were without silviculture interventions)
 140 and each was located close to one of a permanent network of silvicultural
 141 research sites (Figure 1c) established in the region [21].

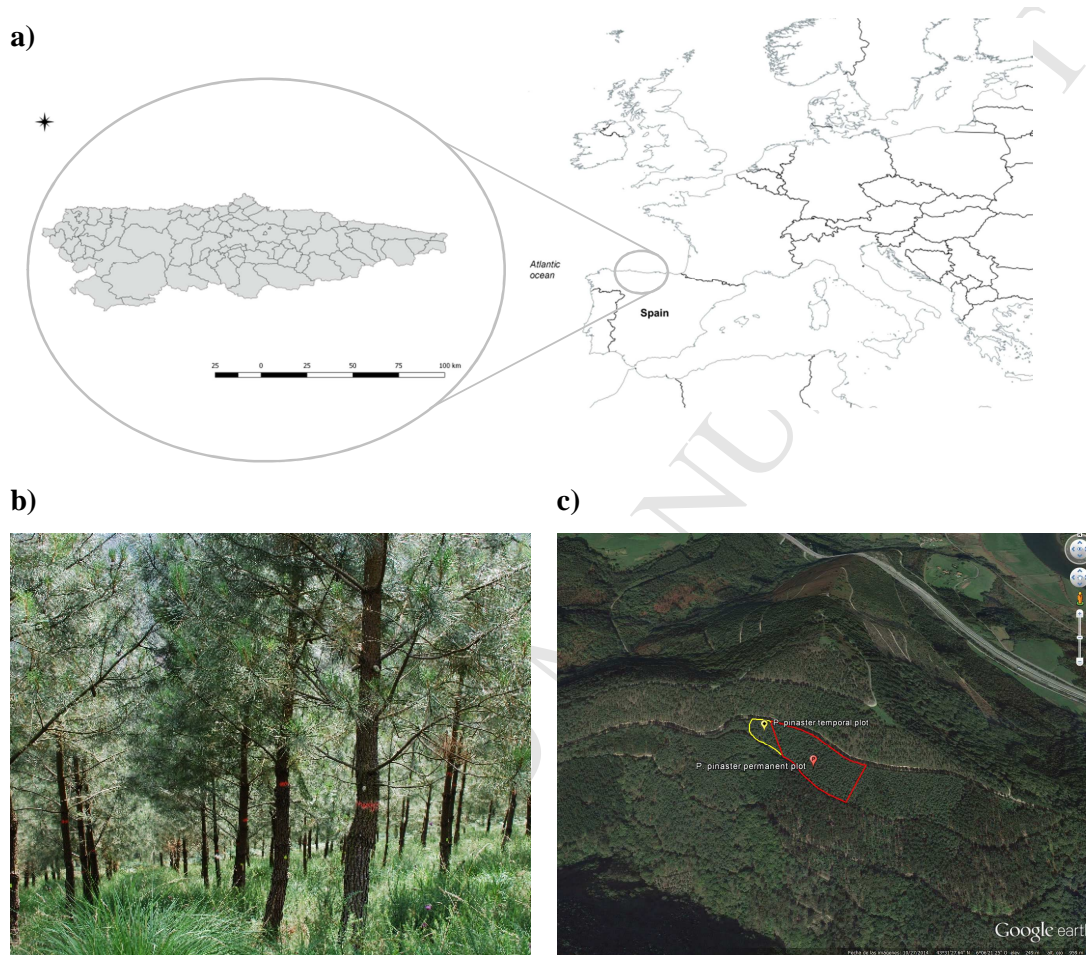


Fig. 1. (a) Location of the study area in Southern Europe (Northwestern Spain),
 (b) example of a trial from the permanent network of silvicultural research sites
 (light pruning intensity), and (c) example of location of one temporary (yellow)
 and one permanent (red) plot in *Pinus pinaster* stands.

142

143 A total of 28 non-pruned trees (from the three temporary plots) were
 144 exhaustively characterized and destructively sampled. First, the following
 145 dendrometric variables were collected from the trees while they were still
 146 standing: diameter at breast height (d), total tree height (h), crown base height

147 (h_{base}), defined as the height from ground to the point on the stem of the lowest
 148 branch (live or dead), height to live crown base (h_{base_v}), defined as the height
 149 from ground to the point on the stem of the lowest live branch and crown
 150 diameter (d_{crown}). Next, certain of these measurements were used to calculate
 151 the following tree variables: crown length, cl (total and live crown) and crown
 152 ratio, CR , defined as the ratio between crown length and total tree height (cl/h).
 153 In addition, age of the stand (t), number of trees per hectare (N), stand basal
 154 area (G), quadratic mean diameter (D_g), mean diameter (D_m), mean height (H_m),
 155 dominant diameter (D_o) and dominant height (H_o), defined as the mean
 156 diameter and mean height of the 100 thickest trees per hectare, respectively,
 157 were estimated in each plot. Tables 1 and 2 show the main tree and stand
 158 variables. Additional information about the study sites can be found in Hevia
 159 [21].

160 **Table 1** Details of the temporary plots at the time of the destructive sampling
 161 (winter 2008-2009).

162

Experiment site	t	N	G	D_g	D_m	D_o	H_m	H_o
Valsera	11	1352	15.31	12.02	11.53	18.44	7.89	9.68
Monteagudo	11	1670	17.88	11.68	11.38	16.51	6.49	7.67
Loris	14	1450	25.77	15.05	14.55	19.42	12.75	14.95

163 t : age of the stand (years); N : number of trees per hectare (stems ha^{-1}); G : stand basal
 164 area ($m^2 ha^{-1}$); D_g : quadratic mean diameter (cm); D_m : mean diameter (cm); D_o :
 165 dominant diameter (cm); H_m : mean height (m); H_o : dominant height (m).

166

167 **2.2. Aboveground tree biomass sampling**

168 After felling the 28 selected trees, destructive sampling was undertaken, and
 169 the tree variables d , h , h_{base} and h_{base_v} were verified. Conventional

170 methodologies for estimating forest biomass do not take into account the
171 vertical distribution of the different elements of the crown and are thus limited in
172 their ability to quantify biomass removed by forest pruning. In this work,
173 therefore, a more detailed destructive sampling of tree crown biomass was
174 made (see Fig. 2) whereby data such as the location within the tree of the
175 various biomass components (i.e., log, whorl) were noted.

176 Aboveground tree biomass was separated into two main tree components:
177 stem and crown (Fig. 2). The tree stem was further divided into stem wood and
178 stem bark (W_{sw} and W_{sb}), while tree crown (which is of interest as these are the
179 components affected by pruning) was separated into the fine biomass
180 components of needles (W_n) and twigs (up to 0.6 cm butt diameter, W_{b06}), as
181 well as thin branches (butt diameter of 0.6 to 2 cm, W_{b2}) and thick branches
182 (butt diameter of 2 to 7 cm, W_{b7}). In addition, in the field, the position of every
183 branch along the length of the stem was noted, allowing the characterization of
184 the vertical distribution of each crown component along the tree stem.

185 For each stump following felling, diameter at the bottom and top (cm), length
186 (cm) and bark thickness at the top (mm) were measured. The stem was then
187 cut into logs of 1 m, to a thin-end diameter of 7 cm, and data of diameter at
188 bottom and top (cm), length (m), and bark thickness at bottom and top of each
189 log (mm) collected. Each whorl on each log was also characterized by
190 measuring whorl diameter (cm) and distance between whorls (cm). For each
191 branch, which was cut individually with pruning shears, diameter at insertion
192 (cm), length (cm), weight (g), physiological status (live or dead) and position on
193 the tree (specific log and whorl) were defined. Each pruned branch was
194 defoliated and weighed in the field. The fresh weight of each tree component

195 was measured using portable balances: the thicker fractions were weighed to
196 the nearest 50 g and the fine tree crown fractions to the nearest 0.01 g.

197 After field measurements, a subsample of each tree component was selected
198 and characterized in the laboratory. The stem subsample was composed of five
199 transversal discs cut from different stem heights (stump, diameter at breast
200 height, beginning of the crown, maximum crown diameter and a random point
201 within the crown). The crown components subsample comprised the first live
202 (and dead if there were any) branch from each log, which were also separated
203 into needles, twigs, thin branches and thick branches. The processing of these
204 subsamples was as follows: stem discs were separated into stem wood and
205 stem bark, and all tree fractions (stem and crown) were oven-dried (at 65°C to a
206 constant weight) to determine field moisture content and to convert fresh weight
207 to dry weight and then establish the total aboveground biomass of each tree.
208 Table 2 lists the descriptive statistics of the destructively sampled trees.

209 **Table 2** Summary statistics of the 28 destructively sampled trees.

Statistics	d	h	CR	W_{sw}	W_{sb}	W_{b7}	W_{b2}	W_{b06}	W_n	W_{cb}	W_{fc}
Mean	9.18	7.57	0.81	12.09	2.95	0.46	1.82	0.70	3.19	2.28	3.89
Min.	4.15	3.06	0.46	1.05	0.39	0.00	0.38	0.10	0.41	0.38	0.62
Max.	15.20	11.53	0.96	37.13	8.00	5.23	4.75	1.83	13.25	9.98	13.67
SD	3.00	2.51	0.11	9.24	1.92	1.05	1.02	0.49	2.66	1.93	2.86

210 d : diameter at breast height, 1.30 m aboveground (cm); h : total tree height (m); CR ,
211 crown ratio, estimated as c/h ; c : crown length (m); W_i : total dry weight (kg) for each
212 tree component (W_{sw} = stem wood, W_{sb} =stem bark, W_{b7} = thick branches, W_{b2} = thin
213 branches, W_{b06} = twigs, W_n = needles) or group of components (W_{cb} = crown branches,
214 W_{fc} = fine crown biomass); SD: standard deviation for each variable (d , h , CR , etc.).

215

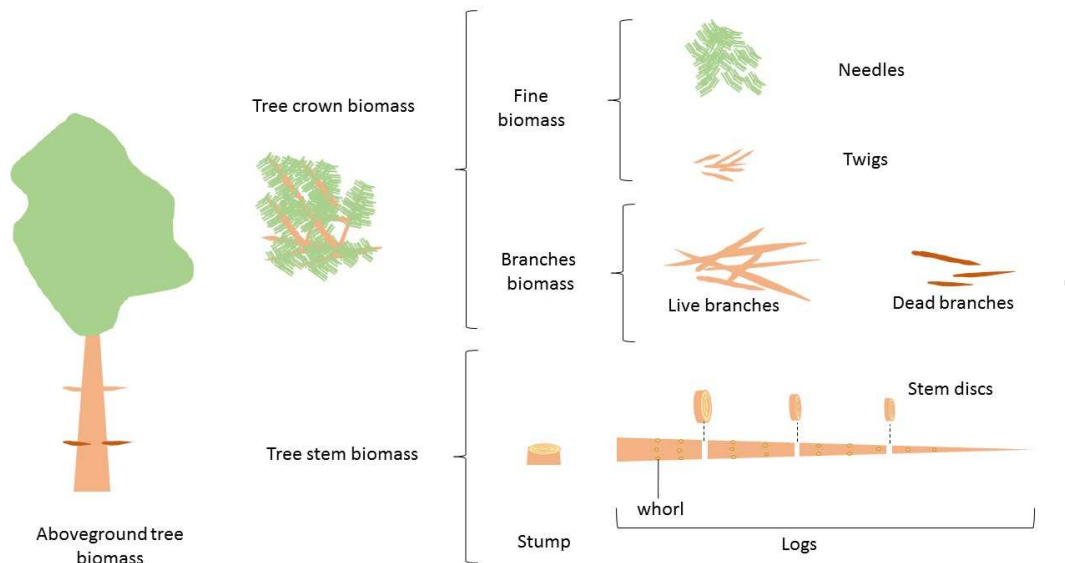


Fig. 2. Schematic figure representing tree biomass components defined in the present study.

216

217 **2.3. Aboveground tree biomass modelling**

218 All statistical analyses were performed with SAS 9.1 [22,23]. Biomass
 219 modelling in this study related the dry weight of each tree component (needles,
 220 twigs, thin branches, thick branches, stem wood and stem bark) at two levels:
 221 (1) the whole-tree and (2) tree by height along the stem. The level of
 222 significance chosen was 0.05 ($\alpha = 5\%$). The White test [24] was used for
 223 heteroscedasticity and functions were weighted when necessary.

224 **2.3.1. Biomass equations for the whole tree**

225 The analysis of the whole-tree biomass was carried out by fitting allometric
 226 equations (Equation 1) for the different tree components using the following
 227 function:

$$W_i = \beta_0 \cdot X^{\beta_1} + e_i \quad (1)$$

228 where W_i is the biomass of each tree component (i = needles, twigs, thin
 229 branches, thick branches, stem wood, stem bark) for the whole-tree (kg); X ,
 230 the dependent tree variables; β_0 and β_1 , the model parameters; and e_i , the
 231 model error.

232 Equation 1 was linearized previously using natural logarithms and then the
 233 best set of dendrometric variables to include in the model was selected by the
 234 stepwise procedure using proc REG of SAS/STAT® [23]. Once the independent
 235 variables were selected, the allometric models were individually fitted using proc
 236 MODEL of SAS/ETS® [22].

237 **2.3.2. Biomass equations by height along the stem**

238 The initial analysis indicated that the 2-parameter Weibull distribution function
 239 was the best equation to describe biomass by height along the stem in *P.*
 240 *pinaster* young stands. In this work, this function was used such that the
 241 cumulative distribution for each biomass component took the following form:

$$\frac{W_{hi}}{W_i} = 1 - e^{-(h_i'/b)^c}, \text{ where } h_i' = (h_i - h_{base})/cl \quad (2)$$

242 where W_{hi} is the cumulative tree biomass component (kg) at a specific position
 243 within the crown; W_i , the whole-tree biomass component (kg); h_i' , the relative
 244 height from the top of the tree (value of 1) with respect to the base of the crown
 245 (value of 0); h_{base} , the height from the ground to the base of the crown; cl , the
 246 crown length; h_i , the specific height within the crown (m). b and c , the scale and
 247 shape parameters of the Weibull distribution function which together describe
 248 the amount (or density) and distribution of the tree crown biomass.

249 The 2-parameter Weibull distribution function was restricted to estimate the
 250 biomass of each tree component from the bottom to the top (as illustrated in
 251 Fig. 3) as follows:

$$\begin{cases} W_{hi} = 0 \text{ if } h_i \leq h_{base} \\ W_{hi} = W_i \cdot \left(1 - e^{-\left(\frac{h_i}{b}\right)^c} \right) \text{ if } h_i > h_{base} \\ W_{hi} = W_i \text{ if } h_i = h \end{cases} \quad (3)$$

252 All terms are explained in Equation 2.

253 The system of equations constituted by the allometric models for the whole-tree
 254 (Equation 1) and the biomass distribution models by height along the stem
 255 (Equation 3) for each tree component was fitted simultaneously using the
 256 MODEL procedure of SAS/ETS® [22]. Because simultaneous fitting requires the
 257 same number of observations for all the variables, for each biomass value along
 258 the stem, we included the whole-tree biomass of each component. Then, the
 259 whole-tree equations were weighted by the inverse of the number of
 260 observations of biomass by height along the stem for each tree. Figure 3 shows
 261 the criteria considered for the definition of Equation (3).

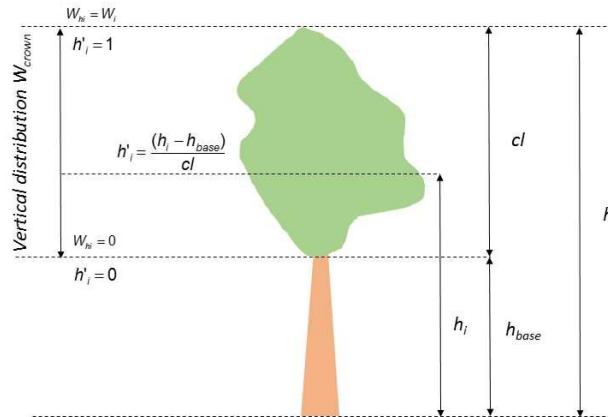


Fig. 3. Criteria for tree biomass equations by height along the stem.

262 2.3.3. Evaluation of models

263 Biomass models were evaluated by graphical analysis of residuals and by
 264 applying the two goodness-of-fit statistics, root mean square error (*RMSE*) and
 265 adjusted coefficient of determination (R^2_{adj}).

266 2.4. Assessment of performance of biomass equations for forest pruning

267 Crown components are usually left in forest stands, and no data on pruning
 268 extraction and best pruning intensity in timber forests exists, to our knowledge.
 269 The biomass equations estimated in this work were used to assess the tree-
 270 and stand- biomass removed through pruning interventions in *P. pinaster*
 271 stands. Data from a previously established network of permanent research plots
 272 of *P. pinaster* of similar characteristics (age, number of trees per hectare, etc.)
 273 (cf. Hevia [21] and Hevia et al. [25]; Fig. 1b) were used to simulate six different
 274 intensities of pruning (from 0% to 60% of crown length removed).

275 Residual biomass for each tree crown component and pruning intensity were
 276 estimated. Values at tree- and stand- level used in this study assume that both
 277 sampled tree and plot are representative of the current young timber stands of
 278 this species in the Atlantic region.

279 3. Results and discussion

280 3.1. Aboveground tree biomass modelling

281 The final equations of each biomass component (stem wood, stem bark,
282 needles, twigs, thin branches and thick branches), and the value of $RMSE$ and
283 R^2_{adj} for each equation, are given in Table 3. All the parameters were found to
284 be significant at the 5% level.

285 Diameter at breast height (d) was found to be the best tree-level predictor
286 variable. The strong relationship between d and various of the different tree
287 fractions studied, together with the practicability and low cost of its
288 measurement in the field ensure that d is one of the most widely used variables
289 in biomass functions [e.g. 2,18, 26-30]. Some authors, however, assume that d
290 is not sufficient for accurate predictions of tree biomass [31] and as a result d
291 has often been combined with other tree variables which are considered more
292 accurate in biomass equations. In the present study, total tree height (h) was
293 the variable selected together with d for the stem fractions (W_{sw} , W_{sb}), and thick
294 branches (W_{b7}) models. This concurs with other studies [e.g. 32-33] which also
295 found a significant improvement of biomass equations when h was used. In
296 contrast, crown ratio (CR) was the variable selected for the rest of the crown
297 biomass models (crown components of W_n , W_{b06} , W_{b2}), results in line with other
298 different works [e.g. 15,18,29-31,34-36] which obtained the most accurate
299 estimations of crown biomass components when crown variables were
300 included. Moreover, the use of CR as an independent variable in the model
301 ensures it is sensitive to changes in the crown parameters when silviculture
302 techniques such as pruning are applied. The CR is also important in explaining

303 the variability of crown biomass fractions, which has also been observed for
304 needles of *P. pinaster* [37] and other conifers such as *Pinus taeda* L. [38].

305 Most of the models obtained in the present work showed accurate predictions
306 of tree biomass, particularly the equations by height along the stem, which
307 comparatively fitted at least slightly better than the whole-tree models for the
308 same biomass component, except for thick branches (Table 3). Specifically,
309 models for the whole-tree explained between 96% and 97% of the observed
310 variability for stem wood, stem bark and thick branches, and 74% to 76% for
311 needles and thin branches, respectively, with lower accurate predictions for
312 twigs (40%). On the another hand, equations by height along the stem
313 explained 96% to 99% of variability for stem wood, stem bark and thick
314 branches, and much higher variability for needles and thin branches (both 93%)
315 as well as twigs (95%). The goodness-of-fit data obtained in our study were
316 generally similar to those given in most biomass studies for the whole-tree
317 which use allometric equations for the same species [e.g. 18,37,39,40].
318 Moreover, similar goodness-of-fit statistics have been obtained in other studies
319 in which the Weibull distribution equation was used, e.g., for crown fuel biomass
320 of *P. pinaster* trees [18] and *P. ponderosa* trees [41] and branches and needles
321 of *P. taeda* [42]. In line with this, the 2-parameter Weibull distribution function
322 has also been used to adequately describe the foliage distribution of different
323 pine species [43-45].

324 In general, the models obtained for stem components fitted better than those
325 for crown fractions (Table 3). Specifically, and with respect to all components,
326 stem wood was the most accurate and twigs was the least, and this effect was
327 greater for the whole-tree equation. This result is to be expected due to the

328 difficulties of estimating the thinner fractions in relation to the whole-tree. Our
329 results confirm previous studies with *P. pinaster* [46], *Pinus radiata* D. Don [47]
330 and comparing both conifers [2], where crown biomass models were less
331 accurate than those pertaining to stem components. These differences may be
332 related to factors such as the random method of selecting crown components
333 during the sampling, or differences in tree age, tree species or tree distribution
334 in the stand [2]. It has been stated that the crowns of conifers may be highly
335 variable for the same tree as well as for different trees, particularly with respect
336 to foliar biomass and surface area [48]. Moreover, the prediction of crown
337 biomass is more difficult compared to that of stem biomass, mainly because of
338 the lack of homogeneity of the components and the complexity of crown
339 composition [6,38].

340 In accordance with the literature, the inclusion of other independent variables
341 (i.e. with respect to age, silviculture, provenance, site quality, etc.) in future
342 works could substantially improve the precision of the models, particularly age,
343 which has been shown to be the variable most strongly associated with biomass
344 in *P. pinaster* (e.g. for site-specific studies [2,18,49], and more generalized
345 studies across contrasting environments [40]). The inclusion of age, as well as
346 employing long-term studies, will also provide more dynamic equations, to
347 better describe the effect of silviculture on biomass allocation.

348 **Table 3** Biomass equations and goodness-of-fit statistics for the whole-tree and the tree by height along the stem models for *P.*
 349 *pinaster* obtained by simultaneous fitting.

Tree Level	Tree fraction	Tree component	Biomass Equation	RMSE (kg)	R^2_{adj}
Whole-tree	Stem	Wood	$W_{sw} = 0.024 \cdot d^{2.360} \cdot h^{0.381}$	1.6873	0.9681
		Bark	$W_{sb} = 0.019 \cdot d^{1.557} \cdot h^{0.729}$	0.3812	0.9615
	Crown	Needles	$W_n = 0.015 \cdot d^{2.574} \cdot CR^{2.617}$	1.3864	0.7439
		Twigs (up to 0.6 cm)	$W_{b06} = 0.031 \cdot d^{1.226} \cdot CR^{-1.482}$	0.3759	0.3953
		Thin branches (0.6 to 2.0 cm)	$W_{b2} = 0.062 \cdot d^{1.601} \cdot CR^{1.017}$	0.5039	0.7555
		Thick branches (2.0 cm to 7 cm)	$W_{b7} = 3.47 \cdot 10^{-6} \cdot d^{10.572} \cdot h^{-6.441}$	0.2042	0.9746
Tree by height along the stem	Stem	Wood	$W_{h_sw} = W_{sw} \cdot \left(1 - \exp \left(- \left(\frac{h_i'}{0.275} \right)^{1.181} \right) \right)$	1.0822	0.9823
		Bark	$W_{h_sb} = W_{sb} \cdot \left(1 - \exp \left(- \left(\frac{h_i'}{0.210} \right)^{0.977} \right) \right)$	0.2070	0.9865

Crown	Needles	$W_{h_n} = W_n \cdot \left(1 - \exp \left(- \left(\frac{h_i'}{0.638} \right)^{3.398} \right) \right)$	0.5627	0.9295
	Twigs (up to 0.6 cm)	$W_{h_b06} = W_{b06} \cdot \left(1 - \exp \left(- \left(\frac{h_i'}{0.552} \right)^{2.573} \right) \right)$	0.0963	0.9457
	Thin branches (0.6 to 2.0 cm)	$W_{h_b2} = W_{b2} \cdot \left(1 - \exp \left(- \left(\frac{h_i'}{0.521} \right)^{2.343} \right) \right)$	0.2476	0.9318
	Thick branches (2.0 cm to 7 cm)	$W_{h_b7} = W_{b7} \cdot \left(1 - \exp \left(- \left(\frac{h_i'}{0.530} \right)^{3.753} \right) \right)$	0.1819	0.9639

350 W_i : biomass (kg) of the tree component i (W_{sw} = stem wood, W_{sb} =stem bark, W_{b7} = thick branches, W_{b2} = thin branches, W_{b06} = twigs, W_n =
351 needles); d : diameter at breast height (cm); h : total tree height (m); CR : crown ratio; $RMSE$: root mean square error; R^2_{adj} : the adjusted
352 coefficient of determination of the model. All coefficients were significant at $p < 0.05$.

353

354 **3.2. Assessment of performance of biomass equations for forest pruning**

355 The aboveground biomass removed by simulated pruning for each tree
 356 crown component in a representative tree and stand of *Pinus pinaster* in the
 357 Atlantic region are presented in Table 4. Quantification of this residual biomass
 358 gave a mean quantity of dry total crown biomass per tree of around 0 - 5 kg,
 359 which represents approximately 0 – 4 t per hectare of dry tree residues in the
 360 average stand (Table 4). This low value at stand level can be explained by the
 361 low weight of the (principally fine) tree crown components extracted in a forest
 362 pruning intervention.

363 **Table 4** Biomass extracted at tree- (kg) and stand- (t ha⁻¹) levels, in each
 364 simulated pruning intensity (from 10% to 60% of crown length), for an average
 365 *Pinus pinaster* tree and stand, based on data from Hevia [21].

Simulated pruning	W_n	W_{b06}	W_{b2}	W_{b7}	W_{fc}	W_{cb}	W_{c_tot}
At tree level							
10%	0.008	0.008	0.048	0.001	0.016	0.049	0.065
20%	0.085	0.048	0.233	0.008	0.133	0.241	0.374
30%	0.326	0.129	0.555	0.037	0.454	0.592	1.047
40%	0.814	0.242	0.964	0.097	1.055	1.061	2.116
50%	1.556	0.369	1.381	0.183	1.925	1.564	3.489
60%	2.444	0.486	1.740	0.264	2.929	2.003	4.933
At stand level							
10%	0.0002	0.0003	0.0029	0.0000	0.0005	0.0029	0.0034
20%	0.0195	0.0137	0.0801	0.0046	0.0332	0.0847	0.1179
30%	0.1318	0.0596	0.2953	0.0368	0.1914	0.3320	0.5234
40%	0.4292	0.1412	0.6263	0.1302	0.5703	0.7565	1.3268
50%	0.9611	0.2454	1.0042	0.2935	1.2065	1.2976	2.5042
60%	1.6722	0.3498	1.3499	0.4749	2.0220	1.8247	3.8467

366 W_n : needle biomass (kg); W_{b06} : twig biomass (kg); W_{b2} : thin branches biomass (kg);
 367 W_{b7} : thick branches biomass (kg); W_{fc} : fine crown biomass (kg); W_{cb} : crown branches
 368 biomass (kg); W_{c_tot} : total crown biomass (kg).
 369

370 Our simulations showed that pruning in a representative tree removes more
 371 than 50% of twigs and crown branches (thin and thick) when pruning involves
 372 removal of 50% of crown length. Needles, on the other hand, need heavier
 373 pruning intensities to be implemented in order for half of this tree fraction to be
 374 extracted (as illustrated in Fig. 4). These values are consistent with those
 375 obtained in previous studies on pine and other conifer species which found
 376 maximum foliage density to be located in the upper half of the tree [39,42,50-
 377 52].

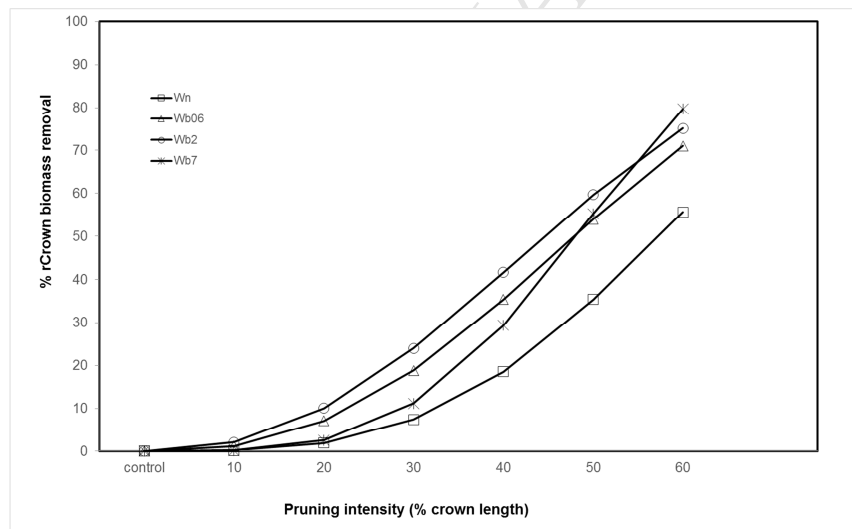


Fig. 4. Relative removal of crown biomass components (W_n = needles; W_{b06} = twigs; W_{b2} = thin branches, W_{b7} = thick branches) in relation to the total quantity of each crown fraction in a representative tree of 10.5 cm of diameter at breast height for different pruning intensity scenarios (0% (control) to 60% of pruned crown length).

378

379 Regarding the total crown biomass (W_{c_tot}), the heaviest pruning simulated
 380 removed around 20% of the total crown biomass (Fig. 5). Our results show that

381 fine crown biomass (W_{fc}) is more affected by pruning than crown branches (both
382 thin and thick branches) when removing over 40% of crown length.

383 The profitability of exploiting these resources is dependent upon the amount
384 of biomass that exists [5] and the intensity of the silvicultural treatment (see
385 Figs. 4 and 5; Table 4). For example, higher intensity pruning and larger trees
386 would provide a higher quantity of crown biomass [21].

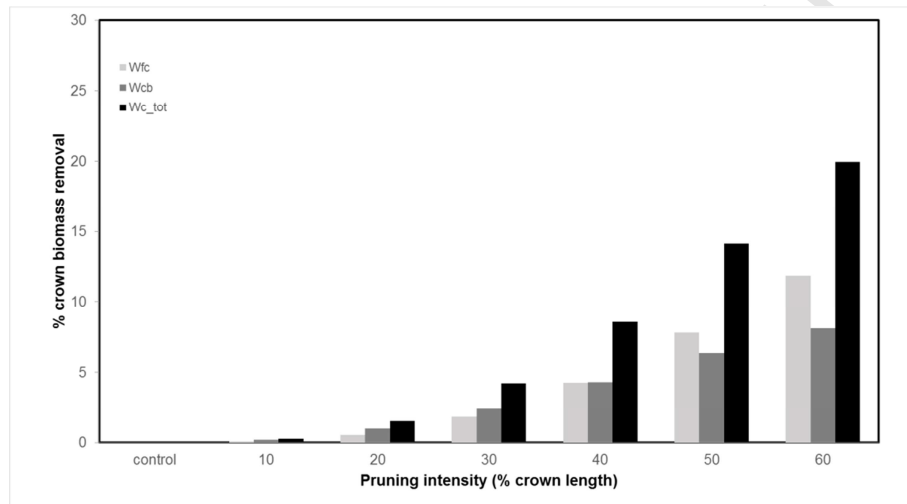


Fig. 5. Proportion of crown biomass —fine crown biomass (W_{fc} , pale grey bars), crown branches (W_{cb} , dark grey) and total crown biomass (W_{c_tot} , black)— removed in each simulated pruning intensity —0% (control) to 60% of crown length— in relation to the total tree biomass in an average *Pinus pinaster* tree with a 10.5 cm diameter at breast height.

387

388 The results obtained cannot be compared directly with other studies, since,
389 as far as we are aware, no data on residual biomass obtained from forest
390 pruning of Atlantic timber conifers has been published. Thus, the orientative
391 values illustrated here, together with the equations developed in the present
392 study, can be considered as a valuable precedent for future research in timber
393 forest species. Furthermore, and in accordance with previous studies in urban

394 forests [e.g. 4,6] the quantification of pruning residual biomass is of
395 considerable importance for the best planning for and management of these
396 biomass residues to achieve energy (biofuel) and environmental targets.

397 **4. Conclusions**

398 The development of biomass equations which allow the estimation of the
399 residual biomass resulting from forest pruning is crucial for timber species.
400 Moreover, the results obtained in this work extend the basic information
401 available to date for assessing forestry biomass in Atlantic managed *P. pinaster*
402 forests. This research has demonstrated that the residual pruned biomass of *P.*
403 *pinaster* can be determined with high precision from dendrometric variables and
404 biomass equations by height along the stem. In fact, the 2-parameter Weibull
405 distribution function selected showed comparatively better predictive reliability
406 than the classic allometric functions developed for the whole-tree. As such, the
407 equations developed here allow both total biomass and pruned biomass
408 residues to be determined from data contained in classic forest inventories.
409 Thus the equations and methodology presented here constitute a novel tool to
410 improve and optimise the management of timber forests which takes into
411 consideration the residues extracted by pruning operations, as well as the best
412 option for their further processing or proper management.

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