Nutrient concentration and allometric models for hybrid eucalyptus planted in France

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ORIGINAL PAPER

Nutrient concentration and allometric models for hybrid eucalyptus planted in France

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Abstract
• ***Context*** Short rotation coppice (SRC) of hybrid *Eucalyptus* has been developed in France for almost 30 years for the production of pulp and paper and, since a few years, for energy purposes. In the traditional pulp production, only the stems are harvested, whereas the whole biomass may be harvested for energy purposes. Thus, a range of different harvest scenarios need to be considered with higher plantation densities or younger age of harvest for example.
• ***Aims*** The objective of this study was to build models to estimate biomass and nutrient content of eucalyptus at different ages and so to estimate the production and the nutrient exportation of a SRC, depending on the different harvest scenarios.
• ***Methods*** Over 250 trees were sampled in 16 stands at ages from 1 to 15 years. For each tree, biomass of different compartments and nutrient contents were recorded.
• ***Results*** A complete set of equations for the four compartments (wood, bark, branches, and leaves) of aboveground biomass and for nutrient concentration was set up.
• ***Conclusion*** Biomass and its allocation to different compartments and nutrient concentrations depended on the dimension and/or the age of the tree. In particular, nutrient concentration decreased with increasing tree diameter.

Keyword *Eucalyptus* · Biomass · Nutrient concentration · Allometry

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Contribution of the co-authors Alain Bouvet: data analysis and writing the paper.
Nicolas Nguyen-The: coordination of the research project and writing the paper.
Francis Melun: field and biomass measurements.

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1 Introduction

Eucalyptus is one of the most widely planted genera all over the world. Plantations have been made with different purposes but, in the past, mainly for pulp production (Iglesias-Trabado and Wisterman 2008). Nowadays, the interest for renewable energy sources leads to the search for different biomass feedstocks. Among others, short rotation coppice (SRC) may be developed in order to satisfy future needs of woody biomass and limit probable pressure on forest. Among different species adapted to this cropping system, eucalyptus is a good candidate due to its high growth potential and relative hardiness, not to mention the historical experience gathered on its cultivation.

In France, eucalyptus has been developed for pulp in the southwest part of the country for almost 30 years. Some 2,000 ha can be found today and some hundreds of hectares are still planted every year. The specie used is a hybrid of *Eucalyptus gunnii* Hook.f. and *Eucalyptus dalrympleana* Maiden (Melun and Nguyen-The 2006), with different clones obtained by the breeding program of FCBA (Potts and Potts 1986; Melun and Nguyen-The 2012).

The typical plantation scheme is based on a 10-year rotation with a stand density of 1,250 trees/ha (4×2 m). Three harvests in 30 years are expected, with an average productivity of 10 oven-dried tonnes/ha/year (Cauvin and Melun 1994).

For a few years, eucalyptus has also been planted in France for energy purposes. Indeed, the traditional pulp and paper SRC scheme can be directly transposed for biomass production with biofuel, heat, or power production objectives. And following the example of poplar or willow, shorter rotation systems are tested. SRC can be shortened to 7-year cycles as far as stand density is raised to 2,000–2,500 stems/ha. In the same way, the so-called very short rotation coppice is being tested and developed with the objective of a 3-year harvesting cycle. This requires far higher plantation densities that can reach 10,000 stems/ha. In these cases, smaller and more juvenile but more numerous stems are harvested.

While the technical and economical aspects of these systems are investigated (De Morogues et al. 2011), data and information should be provided on their sustainability. Several questions are raised. In the traditional pulp scheme, only stems without bark and above 7 cm diameter are exported, while the whole biomass (leaves and branches including) is harvested for energy purposes. Furthermore, shorter rotations with higher stem densities and more important biomass extraction are expected to lead to higher mineral export (Nguyen-The et al. 2010). This not only has an agronomical impact in terms of higher needs for fertilization but also an environmental impact as higher levels of fertilization lead to higher greenhouse gas emissions.

Biomass equations that identify the contribution of the different compartments in trees are, therefore, needed to assess the biomass production potential of the plantations. Furthermore, nutrient content models for the different compartments are needed in order to assess the nutrient exportations for the different biomass production scenarios. These models can contribute to finding the best compromise between biomass production and preservation of the environment.

Allometric equations and nutrient content models have been developed for other species of eucalyptus. For example, hybrids (more particularly, *Eucalyptus urophylla* × *Eucalyptus grandis*) used in Congo have been widely studied by Laclau et al. (2000), Saint-André et al. (2005), or Nouvellon et al. (2010)). A set of equations for *Eucalyptus globulus* have been proposed by Merino et al. (2005), Antonio et al. (2007), or Mulugeta (2008) and for *Eucalyptus dunnii* by Hernandez et al. (2009).

In all cases, the models are built using the circumference (or diameter at breast height [DBH]), tree height, and/or age. Four compartments of aboveground biomass (wood, bark, leaves, and branches) are usually distinguished because they have distinct nutrient concentrations. Notably, bark has high content of calcium, leaves are rich in nitrogen and phosphorus, and wood is globally characterized by poor nutrient concentrations (Attiwil and Adams 1996).

Compartments share in total biomass and nutrient contents obviously depend on stem size and, therefore, on their age. This has been demonstrated by Laclau et al. (2003c) for eucalyptus and is also true for other species, such as maritime pine (Augusto et al. 2008). Leaves and bark represent a smaller share of the total biomass as trees become older and wood proportion increases. Nitrogen, phosphorous, and potassium concentrations in aboveground eucalyptus components decrease over tree growth (Laclau et al. 2000).

Nevertheless, it is probable that allometric equations and nutrient contents are also influenced by species, site conditions, and technical forest management (Attiwil and Adams 1996). The hybrid between *E. gunnii* and *E. dalrympleana* has never been studied because France is actually the only country where it has been developed. However, this hybrid may be interesting for biomass production in other countries under temperate climate. We aimed at testing whether allometric equations and nutrient allocation of this hybrid under cultivation in France diverged significantly from previously published results. Therefore, we developed specific equations adapted to the species, soil, and weather conditions met in France. Our results are compared to those obtained for others species in the world. The objectives were also to build allometric equations covering the whole range of diameters and ages of a typical 10-year rotation as developed in France. This study presents the results of this modeling work.

2 Material and methods

2.1 Stand characteristics

For the purpose of this work, previously existing data and new data have been gathered. The first set of data was collected in 2000 from three sites with trees aged 13 to 15 years. Furthermore, in 2009–2010, it was decided to complete the data set to cover the whole range of age for typical pulp SRC from 1- to 10-year-old plantations. To reach this objective, 13 additional plantations were sampled with a particular focus on young stages (1 to 5 years) where nutrient contents are the most likely to change. To catch the potential heterogeneity of soil and climatic conditions, three different sites for each age were selected. However, there was a lack of plantations older than 5 years and only one 6-year-old site and one 10-year-old site could be sampled. This resulted in a total layout of 16 different sites gathering 274 trees with stems' ages ranging from 1 to 15 years (Table 1). The sites cover the different situations of the present eucalyptus plantation areas in southwestern France.

All the sites sampled were commercial clonal plantations planted with a hybrid between *E. gunnii* and *E. dalrympleana*. The majority of the sites were composed of clone

Table 1 Characteristics of the stands and summary of data measured

Stands characteristics					Number of trees			Mean		
Sampling date	Name	Clone	Age of shoots (years)	Initial density (stems/ha)	Total	With DBH	With chemical analysis	Diameter at collar (cm)	DBH (cm)	*H* (m)
2000	Artigat	121	15	1,250	15	15	5	24.7	20.0	20.7
	Longages	208	14	1,250	15	15	15	25.9	21.1	24.2
	Plaisance	208	13	1,250	16	16	5	19.9	16.0	18.5
Winter 2009–2010	Escource 1	208	1	1,250	30	1	5	2.7		1.3
	Philondenx	645	1	1,250	15	9	6	3.2	2.1	2.6
	Gimbrede	208	2	1,250	30	30	0	6.6	3.4	4.2
	Escource 2	208	2	1,250	30	30	5	7.4	3.3	3.9
	Mesplede	208	2	1,250	15	15	0	7.4	4.1	4.3
	Saint-Porquier	208	3	1,250	15	15	5	9.0	5.6	6.2
	Eglisottes	208	3	1,250	15	15	5	7.0	4.2	4.2
	Montendre	645	3	1,250	15	15	5	8.0	4.6	4.9
	Labastidette	208	5	1,250	15	15	5	14.0	10.7	10.3
	Montbartier	121	5	1,250	15	15	5	14.5	10.9	10.2
	Tabaille	208	5	1,250	15	15	5	15.2	11.5	12.2
	Beaumont	208	6	1,250	12	12	0	25.6	18.4	13.3
	Vaquey	208	10	1,250	6	6	5	28.3	21.9	20.5

DBH diameter at breast height, *H* total height

208. Others were composed of clones 121 and 645, which have similar shapes. All the stands were in there first rotation.

2.2 Measurements

In each site, at least 15 trees representing all diameter classes were selected and cut down. For each tree, the following parameters were systematically measured, all during the winter period (December to April):

– Circumference or DBH when stems were not too small
– Circumference or diameter at collar (only measured for small stems)
– Total height
– Fresh weight of the stem (wood and bark) to cross cut
– Fresh weight of the tree top (stem below 7 cm diameter)
– Fresh weight of crown (branches and leaves)
– Fresh weight of leaves

The distinction of branches and leaves in the crown was easily done on small trees (1–3 years) for which all the leaves could be stripped off and weighted separately. For bigger trees (>5 years), this task was done only on a sample of six branches of different sizes and representing the crown (for each tree, all branches have been sorted into three size classes and then two branches were selected randomly in each class). For these six branches, leaves were weighted separately to calculate afterwards the proportion of leaves in branches. In the same way, the proportion of bark was measured by sampling a stem-cut of a few centimeter width, extracted every meter for small trees (<10 years) and every 2 m for bigger trees (more than 10 years). Wood and bark of the stem-cut were separated and the two compartments weighted separately in order to calculate the proportion of bark and wood in the stem. The biomass of the four compartments (leaves, branches, wood, and bark) was further calculated from the leaves/crown ratio and the bark/stem ratio.

Subsamples of the four compartments of each tree were further dried in an oven at 65 °C until constant weight to determine their moisture content. This measurement allows computing the dry weight of each compartment. The dried samples were finally ground for chemical analyses. From the initial 274 trees sampled, 76 trees from 13 sites were analyzed. Total nitrogen (N) in each sample was analyzed following the Dumas method (NF ISO 13878). Phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) were determined using inductively coupled plasma atomic emission spectroscopy methodology (NF X31-108).

2.3 General model for total aboveground biomass estimation

The basic equations for total biomass modeling relate the biomass of each component to tree diameter and height. In our study, equations were established with several input variables to stick to different situations in the field. Indeed, forest managers can easily measure tree circumference at breast height, but when stems are too small, only a circumference at collar can be measured. Height is a key parameter, but rather difficult to measure and not systematically available at forest management scale.

In our modeling approach, we established several models corresponding to the different crossed situations:

- No measured height: two entry variables using circumference (at DBH or at collar) and age
- Average tree height: three entry variables with the mean height of the stand, circumference (at DBH or at collar), and age
- Individual height: three entry variables with individual tree height, circumference (at DBH or at collar), and age

As commonly used for volume or biomass estimation (Saint-André et al. 2005; Antonio et al. 2007), the form of the model tested is:

$$\mathrm{Biomass} = a + (b_1 + b_2 \cdot \mathrm{age}) \cdot X^c \qquad (1)$$

where Biomass is the total dry weight in kilograms, age is the age of the tree in that year, X is the independent variable (either D or D^2H where D and H are, respectively, the diameter at collar or at breast height in centimeters and the total tree height in meters), and a, b_1, b_2, and c are the parameters to be estimated.

To respect the homoscedasticity of the residues, the regressions were weighted by $1/X^k$ (Laclau et al., 2000). To find the optimal value for k, we tested several values and kept those that minimized Furnival's index of fit (Furnival 1961). The models were fitted using the REG procedure of SAS® Software. Only significant variables were kept in the model (at 5 % threshold). The model form was chosen in order to have the minimum value of Furnival's index and no bias in the distribution of the residues.

2.4 Methodology used for the other measurements

Models for biomass allocation, as to the aboveground biomass model, are expressed in terms of circumference at breast height or circumference at collar. Since we had less nutrient concentration data, it was not relevant to split the data set by making a distinction between the trees with circumference at collar and trees with circumference at breast height. To gather the trees and process in one only data set, the small trees (total height lower than 1.30 m) were removed.

This way, it was possible to calculate one unique model with the circumference at breast height as input variable. Using this method, we calculated independent models for each of the 5 major nutrient element (N, P, K, Ca, and Mg) in each of the 4 compartments (wood, bark, branches, and leaves), which represents 20 models in total.

For all these variables (allometric relation and nutrient concentration), different forms of models were tested:

$$y = a \ (\text{if} \ \ y \text{ is constant}) \qquad (2)$$

$$y = a \cdot \mathrm{Diam} + b \cdot \mathrm{age} + c \qquad (3)$$

$$y = c \cdot \mathrm{Diam}^a + b \cdot \log(\mathrm{age}) \qquad (4)$$

$$y = ((a + b \cdot \mathrm{Diam} \cdot 100)/(c + \mathrm{Diam} \cdot 100)) + d \cdot \mathrm{age} \qquad (5)$$

$$y = \mathrm{Diam}^a + b \cdot \log(\mathrm{age}) + c \qquad (6)$$

All these models are polynomial models that make possible to take into account the form of the relation between the dependent and independent variables, except model 5 which is derived from a model proposed by Augusto et al. (2008)). As for the estimation of the total biomass, only variables of significance (at 5 % threshold) were conserved. The regressions were weighted by $1/\mathrm{Diam}^k$ to respect the homoscedasticity of the residues. We tested different values of k and chose the one that minimized Furnival's index of fit. The criteria applied to choose between the different models were a minimum value of Furnival's index in the case of weighted regressions, a minimum root mean square error (RMSE) in the case of unweighted regressions, and globally no bias in the distribution of the residues. The models were fitted using the REG and NLIN procedures of SAS® Software.

3 Results

3.1 Models for aboveground biomass estimation

Table 2 displays the parameters and the form of the model adopted for each of the six crossed cases (diameter at collar or at breast height, total height of each tree, mean height of the stand, or no height). They enable calculating the total biomass in kilograms using:

- The diameter whether at breast height or at collar expressed in centimeters
- The height, whether individual or average expressed in meters, or without height

The results show that, when no height was available, the age (parameter b_2) became a significant variable and that, in

Table 2 Summary of the models adopted and corresponding coefficients used for aboveground biomass estimation

Diam	Height	Model	Values of coefficient				*n*	Pond (*k*)	RMSE
			a	b_1	b_2	*c*			
At collar	Individual	1	0.133	138.0		0.9411	274	+1	16.4
	Mean	1	0.161	144.4		0.9667	274	+1	16.8
	No height	1	0.060	2,022.2	265.3	2.4439	274	+5	18.6
At breast height	Individual	1	0.833	212.4		0.8701	239	+1	13.1
	Mean	1	0.940	217.2		0.8954	239	+1	14.3
	No height	1	0.718	4,585.1	190.3	2.2822	239	+3	11.3

The form of the model is Biomass $= \mathrm{a} + (\mathrm{b}_1 + \mathrm{b}_2 \cdot \mathrm{age}) \cdot \mathrm{X}^{\mathrm{c}}$ where Biomass is the total dry weight in kilograms, age is the age of the tree in that year, *X* is the independent variable (either *D* or $D^2 H$ where *D* and *H* are, respectively, the diameter at collar or at breast height in centimeters and the total tree height in meters), and *a*, b_1, b_2, and *c* are the parameters to be estimated

this case, the same precision was obtained with age or with height. It is probably because all the stands used for the modeling have grown in conditions of similar fertility and are characterized by similar height at the same age. The RMSE would be certainly higher in more contrasted situations. Height remained as a valuable information that can improve model prediction accuracy.

With these equations, typical trees in stands after 10 years (with a diameter of approximately 0.175 m and with a height of 18 m) had a weight a bit <130 kg of aboveground biomass.

3.2 Biomass allocation to tree compartments

Equations have been established to estimate the proportion of foliage in total biomass and, subsequently, to obtain the proportion of leaves in the crown. In the same way, equations estimate the proportion of bark in the stem. The type of model used and the coefficients calculated are summarized in Table 3. In each case, two situations were considered, depending on whether DBH or diameter at collar was available.

The proportion of crown in total biomass increased with decreasing diameter, to the extent that the smallest trees were composed almost completely of crown. The proportion of crown decreased sharply until the trees reached roughly 0.12 m in diameter where it seemed to stabilize between 10 and 20 % of the total biomass (Fig. 1). The proportion of crown was also clearly affected by age. This can be explained by the fact that, for a given circumference, the older the trees are, the more likely they are suppressed by higher ones. Their crown was, therefore, probably less developed. Figure 1a depicts this effect of age for young trees and Fig. 1b for older trees. Figure 1b also shows the particular position of the stand in the site of Beaumont where the proportion of foliage was very important. The high proportion of branches in this particular site was indeed observed in the field during measurements and is explained by a high fertility due to former agricultural use.

For the stem of big trees, the distinction between biomass above and below 7 cm cut can be interesting. For these trees, the top of the stem is estimated by the following equation:

$$\mathrm{Y} = -19.4735 \cdot \mathrm{Diam}^2 + 4.1643$$

Table 3 Summary of the models adopted and corresponding coefficients used for aboveground biomass allocation between compartments (in percent)

	Diameter	Model	Values of coefficient				*n*	Pond (*k*)	RMSE
			a	*b*	*c*	*d*			
Percent crown in total dry biomass	At collar	6	−0.019	−0.2091	−0.331		274	0	0.007
	At breast height	5	2.967	0.4171	3.691	−0.0256	239	0	0.007
Percent bark in stem dry biomass	At collar	5	3.985	0.0081	14.889		274	−1	0.0214
	At breast height	5	4.363	−0.0182	19.065		239	−1	0.0262
Percent leaves in crown dry biomass	At collar	5	16.163	0.0422	20.383		274	+1	0.0665
	At breast height	5	10.018	0.1391	13.641		239	0	0.0680

The form of the models are $y = ((a + b \cdot \mathrm{Diam} \cdot 100)/(c + \mathrm{Diam} \cdot 100)) + d \cdot \mathrm{age}$ (model 5) and $y = \mathrm{Diam}^{\mathrm{a}} + \mathrm{b} \cdot \log(\mathrm{age}) + \mathrm{c}$ (model 6) where *y* is the dependent variable (in percent), age is the age of the tree in years, Diam is the diameter at collar or at breast height in centimeters, and *a*, *b*, *c*, and *d* are the parameters to be estimated

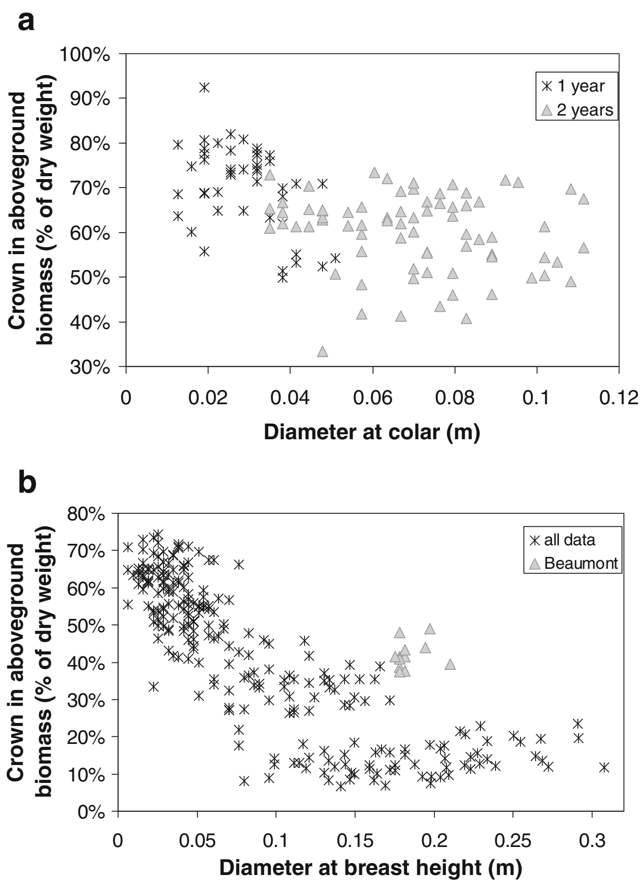

Fig. 1 Crown to aboveground biomass ratio. Relationships between the measured relative part of crown (branches+leaves) in the aboveground biomass and the stem diameter for young trees (**a**) and for old trees (**b**)

where *Y* is the dry weight of the top of the stem (in kilograms) and Diam is the DBH (in meters).

As a general trend, the proportion of bark in stem (Fig. 2) and the proportion of leaves in crown (Fig. 3) decreased

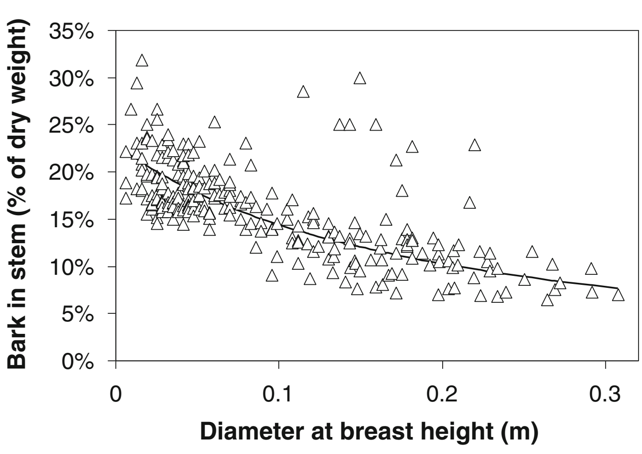

Fig. 2 Bark to stem biomass ratio. Relationships between the measured relative part of bark in the stem biomass and the stem diameter. *Open triangles* measured ratio, *solid line* regression function

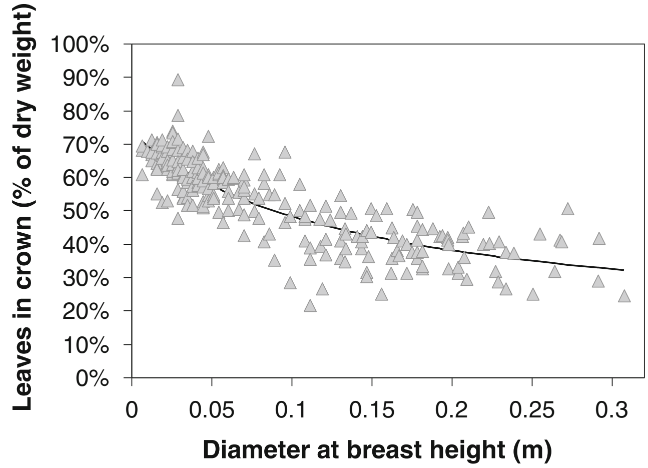

Fig. 3 Leaves to crown biomass ratio. Relationships between the measured relative part of leaves in the crown (branches+leaves) biomass and the stem diameter. *Closed triangles* measured ratio, *solid line* regression function

with increasing tree size. The biomass of the four compartments could be calculated as shown in Fig. 4. Typically, trees with an average diameter of around 0.175 m at the end of a 10-year rotation are thus composed of 66 % wood, 8 % bark, 17 % branches, and 9 % leaves.

3.3 Nutrient concentration models

The type of models and coefficients used to calculate the nutrient concentrations in the four studied compartments are summarized in Table 4 and depicted in Fig. 5.

Age did not play a role in the nutrient concentration modeling of each compartment, but it became a significant parameter for the calculation of the nutrient concentration in the aboveground tree biomass because, for this, the

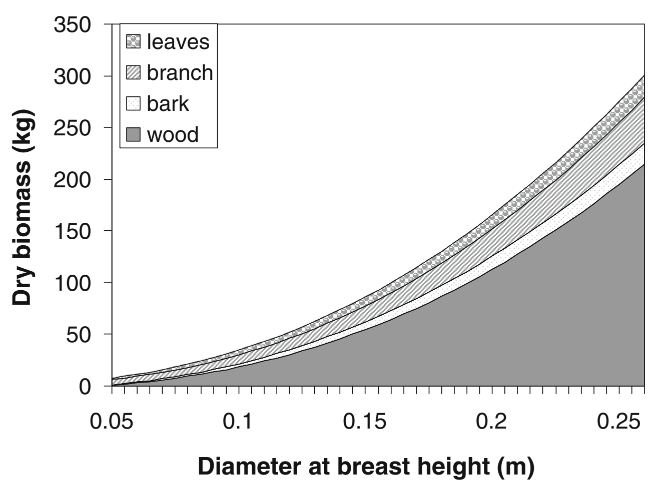

Fig. 4 Estimation of biomass per aboveground compartment (10-year-old trees)

Table 4 Summary of the coefficients used for nutrient concentration modeling by compartment

		Wood			Bark			Leaves			Branches		
		Model	RMSE	Coefficient	Model	RMSE	Coefficient	Model	RMSE	Coefficient	Model	RMSE	Coefficient
N	*a*	5	0.60	70.047	5	0.89	49.104	2	1.80	16.74	5	1.29	22.508
	b			−0.4175			3.3094						4.1460
	c			16.9588			5.9133						1.5340
P	*a*	4	0.26	−0.1474	5	0.13	5.236	2	0.51	1.00	4	0.21	−0.1194
	b						0.2904						
	c			0.3109			5.7224						0.4603
K	*a*	3	0.55	−5.958	2	1.04	4.425	3	1.35	9.519	2	1.02	5.075
	b												
	c			2.357						4.013			
Mg	*a*	5	0.09	15.093	2	0.76	2.459	3	0.43	1.226	2	0.70	1.685
	b			−0.0781									
	c			33.944						2.087			
Ca	*a*	5	0.22	0.2214	4	0.13	0.191	4	0.27	0.1069	2	2.35	15.21
	b			0.7800									
	c			−0.1818			54.413			16.048			

The form of the models are $y = a$ (model 2), $y = a \cdot \mathrm{Diam} + \mathrm{b} \cdot \mathrm{age} + \mathrm{c}$ (model 3), $y = c \cdot \mathrm{Diam}^{\mathrm{a}} + \mathrm{b} \cdot \log(\mathrm{age})$ (model 4), and $y = ((a + b \cdot \mathrm{Diam} \cdot 100)/(c + \mathrm{Diam} \cdot 100)) + d \cdot \mathrm{age}$ (model 5) where *y* is the dependent variable (concentration), age is the age of the tree in years, Diam is the diameter at breast height in centimeters, and *a*, *b*, and *c* are the parameters to be estimated. N=67 for all these models

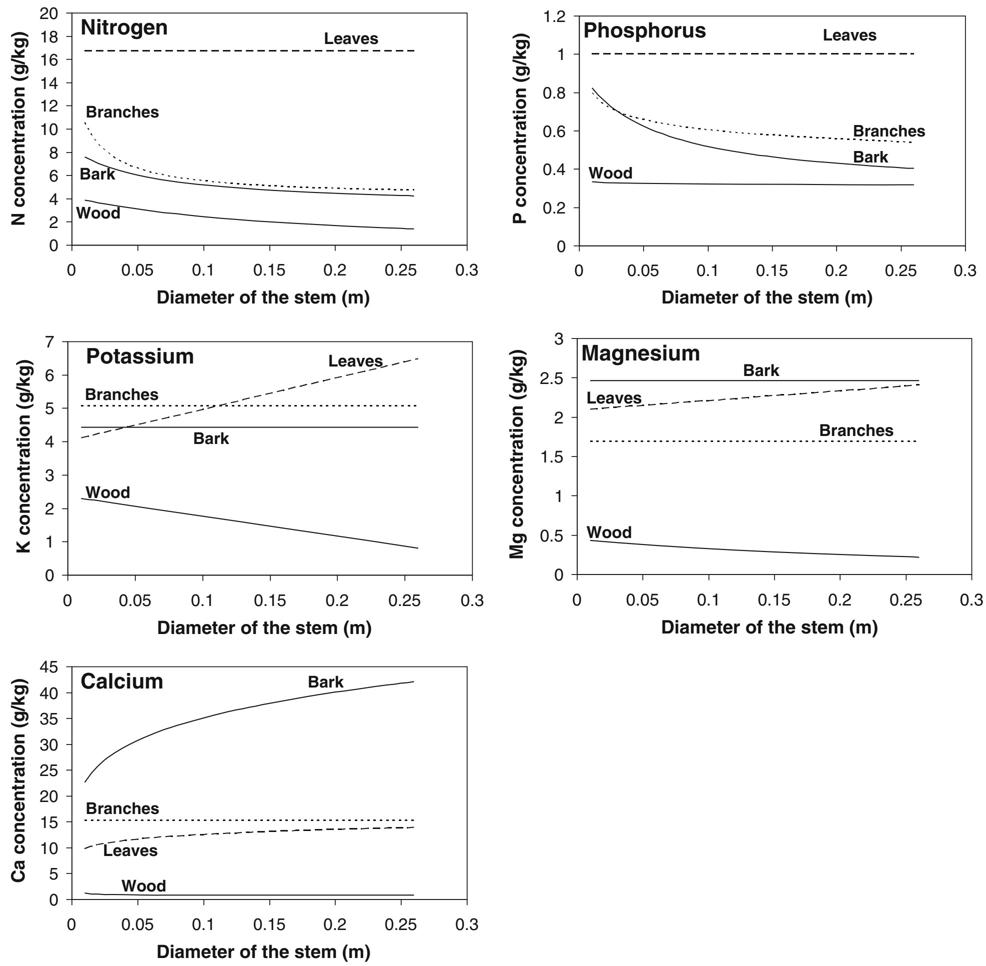

Fig. 5 Simulated nutrient concentrations in each tree compartment

proportion between the different compartments was used and was explained partly by age.

For leaves, the concentration was independent of tree diameter for N and P and was slightly increasing with tree size for K, Mg, and Ca. In tree bark, K and Mg concentrations were not influenced by tree diameter, a neatly decreasing trend for young stems for N and P and, conversely, an increasing trend versus diameter for Ca was observed. Wood showed a slight decrease in concentration depending on the diameter for all the elements and a neat decreasing trend for K.

Leaves had the highest N concentrations (16.7 g/kg) and the highest P concentrations (1 g/kg) of the four compartments studied. K and Mg concentrations proved rather similar between the leaves and the branches and bark, with values ranging, respectively, from 4 to 7 g/kg and from 1.5 to 2.5 g/kg. Wood had globally the lowest nutrient concentrations and was particularly lower than other compartments as K (0 to 2 g/kg), Mg (<0.5 g/kg), and Ca (<1 g/kg) are concerned. The most interesting trends are the sharp decrease of N and P concentrations in the 0- to 5-cm diameter range, which can be observed notably for bark and branches, and the net increase of Ca concentration with increasing diameter that was found particularly for bark and also for leaves.

In the whole tree (Fig. 6), the highest concentrations were those of N and Ca. Conversely, Mg and P had the lowest concentrations. There was a global decreasing trend with increasing tree diameter, particularly strong for N and Ca.

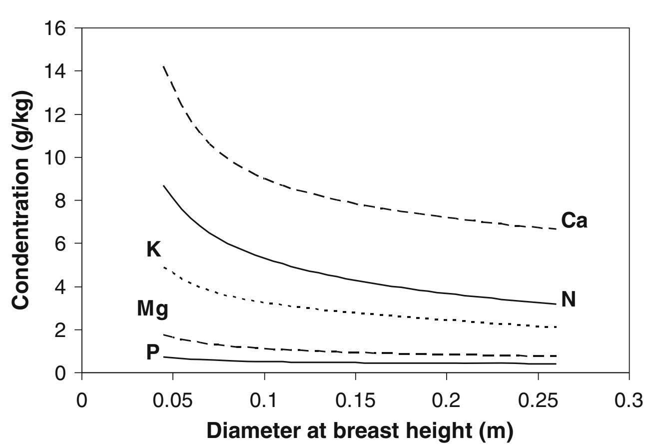

Fig. 6 Nutrient concentrations in the aboveground tree biomass (10-year-old trees)

4 Discussion

The work carried out in this study led to suggesting a set of models to estimate the biomass and nutrient concentrations of the *Eucalyptus* hybrid of *E. gunnii* and *E. dalrympleana* cultivated in short rotation in France. The models cover the whole range of diameter and age of a typical commercial first rotation. The models will allow calculating mineral exportations depending on tree dimension and age at harvest.

The allometric equations developed are specific of the species studied. However, some results are very consistent with other results obtained for other eucalyptus species in other countries. The proportion of bark in the stem was similar to that proposed by Antonio et al. (2007) for *E. globulus* Labill. or to that proposed by Saint-André et al. (2005) for the hybrid *E. urophylla* S. T. Blake × *E. grandis* W. Hill ex Maiden, that is, in the range of 10–15 % for a tree of 10–15 cm diameter. In the same way, the proportion of leaves in the crown was very consistent with that proposed by Laclau et al. (2000), Saint-André et al. (2005), and Razakamanarivo et al. (2011), with values of approximately 40–50 % for trees of 10–15 cm diameter, although this value was much higher than the 15 % of leaves in the crown proposed by Antonio et al. (2007) for this tree dimension. On the contrary, the proportion of leaves in total biomass turned out to be very high compared to what was stated by the other authors. Indeed, rates of approximately 15 % of leaves for trees of 10–15 cm diameter were found in our study, while figures are usually lower than 5 % (Laclau et al. 2000; Saint-André et al. 2005; Antonio et al. 2007; Hernandez et al. 2009). This can be explained by differences between species and clones, but it should be taken into account that leaves are also subject to important changes according to the season as reported by Nouvellon et al. (2010) or according to climate conditions affecting tree physiology, such as droughts (Moreaux et al. 2012). In the end, the age of the stands turns to be a very significant variable that can explain differences between trees of the same dimension, which is consistent with the findings of Saint-André et al. (2005).

Nutrient concentrations were in the range of other references for eucalyptus (Judd et al. 1996), although there is probably a site effect. This appeared clearly for phosphorus (P). Differences for calcium (Ca), which is known to be subject to luxurious consumption, were expected, but it was clearly more influenced by age. A clear increase of Ca concentration in bark and leaves with increasing tree dimension was indeed observed. It suggests an effect of capitalization versus time, which is a well-known effect for other species, such as pine (Augusto et al. 2008).

It was not possible to separate the site effect, although it proved to be significant in some cases. For instance, the P concentration in wood in 2- to 3-year-old sites ranged from 0.2 g/kg (Escource 2 and Montendre) to 0.9 g/kg (Saint-Porquier) for trees of the same circumference (Fig. 7). The same effect was observed for 5-year-old sites with P concentration ranging from 0.3 g/kg (Montbartier) to 0.7 g/kg (Tabaille and Labastidette). The same trend with low P concentration was also observed for bark, branches, and leaves in Escource 2, Montendre, and Montbartier, but to a lesser extent. For the other elements, the site effect was less strong and not generalized to all compartments. Differences between sites are probably due to differences in soil characteristics but can be explained also by the former land use. Where agricultural crops existed, fertilization residues might have influenced the nutrient content of the trees.

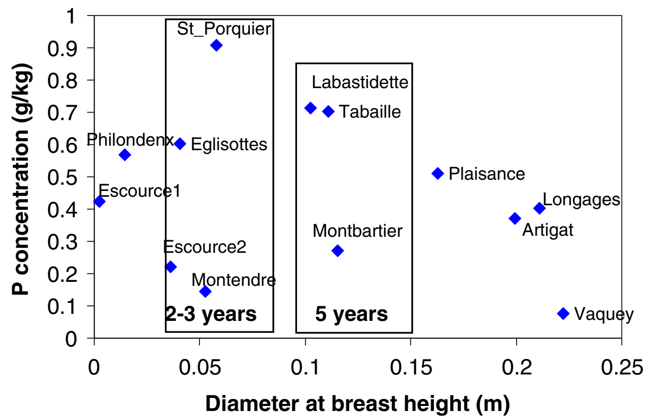

Fig. 7 Phosphorus concentration in wood (average by site). For each stand, the mean of the measured concentration of phosphorous in wood is presented. Fifteen trees were sampled in the stand of Longages, 6 in Philondenx, and 5 in other stands. A special focus is made on 2- to 3-year-old stands and on 5-year-old stands

Lastly, as observed by Augusto et al. (2008) for maritime pine, there was a clear influence of stem diameter on P and N concentrations in wood and bark with a sharp decrease for smallest diameter and stabilization at a certain stem diameter. It could be explained by the fact that the proportion of functional tissues of each ligneous component is higher in young trees and the effect of the remobilization of elements during the aging process (Laclau et al. 2001). In the same way, for the whole tree, concentrations of all nutrients and particularly N and Ca decrease with increasing diameter because the proportion of wood in total biomass rises with time. Cutting young stems of <20 cm in circumference, which is around 6.5 cm in diameter, leads to a harvest of biomass with very high nutrient concentrations. This can be an asset if wastewater recycling was to be considered and a drawback if this was to be compensated by high fertilization levels.

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