Rodríguez-Soalleiro *et al. Forest Ecosystems* (2018) 5:35
https://doi.org/10.1186/s40663-018-0154-y

Forest Ecosystems

RESEARCH

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Exploring the factors affecting carbon and nutrient concentrations in tree biomass components in natural forests, forest plantations and short rotation forestry

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Abstract

Background: Coupling biomass models with nutrient concentrations can provide sound estimations of carbon and nutrient contents, enabling the improvement of carbon and nutrient balance in forest ecosystems. Although nutrient concentrations are often assumed to be constant for some species and specific tree components, at least in mature stands, the concentrations usually vary with age, site index and even with tree density. The main objective of this study was to evaluate the sources of variation in nutrient concentrations in biomass compartments usually removed during harvesting operations, covering a range of species and management conditions: semi-natural forest, conventional forest plantations and short rotation forestry (SRF). Five species (*Betula pubescens*, *Quercus robur*, *Eucalyptus globulus*, *Eucalyptus nitens* and *Populus* spp.) and 14 genotypes were considered. A total of 430 trees were sampled in 61 plots to obtain 6 biomass components: leaves, twigs, thin branches, thick branches, bark and wood. Aboveground leafless biomass was pooled together for poplar. The concentrations of C, N, K, P, Ca, Mg, S, Fe, Mn, Cu, Zn and B were measured and the total biomass of each sampled tree and plot were determined. The data were analysed using boosted regression trees and conventional techniques.

Results: The main sources of variation in nutrient concentrations were biomass component > > genotype (species) ≈ age > tree diameter. The concentrations of Ca, Mg and K were most strongly affected by genotype and age. The concentrations of P, K, Ca, Mg, S and Cu in the wood component decreased with age, whereas C concentrations increased, with a trend to reach 50% in the older trees. In the SRF, interamerican poplar and *P. trichocarpa* genotypes were comparatively more efficient in terms of Ca and K nutrient assimilation index (NAI) (+ 65–85%) than eucalypts, mainly because leafless biomass can be removed. In the conventional eucalypt plantations (rotation 15 years), debarking the wood at logging (savings of 225% of Ca and 254% of Mg for *E. globulus*) or the use of selected genotypes (savings of 45% of P and 35% of Ca) will provide wood at a relatively lower nutrient cost. Considering all the *E. globulus* genotypes together, the management for pulp with removal of debarked wood shows NAI values well above (× 1.7–× 3.9) the ones found for poplar or eucalypt SRF and also higher (× 1.6–× 4.0) than the ones found for oak and birch managed in medium or long rotations. The annual rates of nutrient removal were low in the native broadleaved species but the rates of available soil nutrients removed were high as compared to poplar or eucalypts. Management of native broadleaved species should consider nutrient stability through selection of the biomass compartments removed.

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Conclusions: The nutrient assimilation index is higher in poplar grown under short rotation forestry management than in the other systems considered. Nutrient management of fast growing eucalyptus plantations could be improved by selecting efficient genotypes and limiting removal of wood. The values of the nutrient assimilation index are lower in the natural stands of native broadleaved species than in the other systems considered.

Keywords: Nutrient removal, Biomass crops, Poplar genotypes, *Eucalyptus*, Oak, Birch, Plantation sustainability

Background

The proposed measures of the climate conference held in Paris in 2015 include transformation of the current fossil fuel-based energy generation systems to sustainable and renewable energy (RE)-based systems by using so-called 'carbon-neutral' alternatives (Karvonen et al. 2017). Production of forest biomass is one such RE option and can be increased by the use of specific biomass crops or changes in forest management of plantations or native species (precommercial thinning for biomass or use of logging residues, among others). However, these alternatives have raised concerns because of potentially adverse effects on forest soil productivity (Thiffault et al. 2014). Forest sustainability criteria thus usually include factors such as soil fertility and nutrient removal (Haberl et al. 2010). Short-rotation forestry (SRF) systems, with rotations of 3–7 years, are not yet widely implemented as part of European land use (Don et al. 2012). In Spain, changes in incentives policies have returned SRF to the developmental or precommercial stage (san Miguel et al. 2015). Nevertheless, SRF plantations are expected to increase within a global scenario of bioeconomy and given the commitment of the European Union (EU) for 20% of energy to be produced from renewable sources by 2020 (EU 2009). Land classification is a basic step in forest management planning, to identify areas where logging residues could be removed (Thiffault et al. 2014), to predict SRF productivity (Pérez-Cruzado et al., 2014) and to identify the most appropriate species and genotypes for different areas (Sixto et al. 2015).

The landscape in large areas of northern Spain is characterised by forest land covered by semi-natural forests of deciduous trees, alternated with fast growing plantations of exotic trees (such as eucalyptus, managed in rotations of 10 to 18 years). Eucalyptus plantations are particularly important for pulp production in southwestern Europe, covering recently planted forest land and, to a lesser extent, agricultural land (Díaz-Balteiro and Rodríguez 2006; Madeira and Araújo 2015). Pedunculate oak is a major natural forest species in Europe, covering the northern area of Spain in Galicia and the Cantabrian range (Gómez-García et al. 2015). Downy birch is one of the two commercially important *Betula* species grown in Europe (Hynynen et al. 2009); in northern Spain it acts as a pioneer species in humid or wet areas, with fast but unsteady growth.

Management of natural deciduous forest entails the removal of comparatively low amounts of biomass and the application of longer rotations than in conventional fast-growing plantations (Gómez-García et al. 2016). Provided that conventional patterns of extraction of woody components are applied, there are no major concerns about the nutrient sustainability of these native, extensively managed deciduous forests (Ranger and Turpault 1999). However, this is not true for intensively exploited forest plantations or SRF, and one of the key aims of nutrient sustainability in such cases is to obtain an overall balance by assessing the nutrient fluxes that occur throughout the rotation, including the amounts removed during clearfelling (Laclau et al. 2010; Vanbeveren et al., 2016). Estimation of the amounts of nutrients removed requires knowledge of the amounts of biomass in each compartment (stumps, wood, bark, branches of different sizes and leaves) and the nutrient concentrations in these components (Viera et al. 2016). However, the main drawback of this approach is that nutrient concentrations in biomass compartments vary depending on plantation age, site and even tree density (Judd et al. 1996; Rytter 2002; Leite et al. 2011), although the concentrations stabilize in mature stands (Augusto et al. 2008). Nutrient exportation via biomass removal is just one of the processes in the whole cycle. Nutrient losses can also occur through erosion or leaching, and the overall nutrient budgets are known to be site-specific (Ranger and Turpault 1999).

Short rotation forestry (3–7 years) management of poplar and eucalypt genotypes has been studied as a way of producing biomass to enhance the bio-economy in Spain (González-García et al. 2013; Oliveira et al. 2017). Most of the poplar genotypes used correspond to the *Populus* × *euramericana* and *Populus* × *interamericana* parental groups, the latter of which is considered less site demanding (Soulères 1984). As a rule, the harvest of SRF considers the whole tree, and thus only the leaves of perennial species are harvested (Sochacki et al. 2013). Debarking is not an option for the small diameter shoots harvested in this case, as the usual method of harvesting entails chipping all the aboveground components (san Miguel et al. 2015; Eufrade et al. 2016). For pulp plantations, which are usually felled in cycles longer than 10 years in Spain, intensive management may lead to negative budgets (Merino et al. 2005). Several management options aiming at minimizing negative nutrient budgets in forest plantations have been proposed: removal of only the wood component, leaving the bark in place; management of logging residues to enable reincorporation of the nutrients into the soil (Achat et al. 2015); and modification of soil preparation techniques (Merino et al. 2003; Viera et al. 2016). Other possible management adaptations include re-definition of rotation length (Viera et al. 2015) and the use of genetically improved materials with enhanced nutrient assimilation index (NAI), defined as the amount of biomass produced per unit of nutrient (Sochacki et al. 2013).

Carbon concentrations can also be used to predict the potential sequestration of this element in forest biomass and associated products. This application is receiving currently great interest, as the estimation of forest carbon stocks is in the core of the international agreements for greenhouse gasses emission reductions (Angelsen et al. 2012). Although the most common approach is to use a fixed C concentration in biomass components per species (Pérez-Cruzado et al. 2011), a better understanding of the sources of variation in C concentrations is required. The interest in reducing the uncertainty in C stock estimation in forest systems is twofold: the greater value of those initiatives where C emissions reductions are estimated with lesser uncertainty (Angelsen et al. 2012), and the avoidance of systematic errors causing overestimation.

The main objective of this study was to evaluate the sources of variation in the concentrations of carbon and nutrients in biomass compartments usually removed during harvesting operations, covering a range of species and management conditions: semi-natural forests, eucalypt pulp plantations and poplar and eucalypts grown as SRF. We also aimed to explore differences among species and genotypes and the effect of age and tree size on nutrient concentrations in the different compartments. We hypothesized that several genotypes of poplar and eucalypts will provide biomass at a relatively low nutrient cost.

Methods

Species and plots sampled

A network of 60 plots covering five species (*Betula pubescens*, *Quercus robur*, *Eucalyptus globulus*, *Eucalyptus nitens* and *Populus* spp.) was established for evaluation of biomass and nutrient concentrations in Galicia (NW Spain). The native species were sampled in plots established in semi-natural stands managed on intermediate to long rotations, and the range of ages and tree sizes was thus very broad (Table 1). The stands of both eucalypt species were managed as conventional forest plantations for pulp production (average initial density 1125 trees·ha^{-1}). These plots were established as a chronosequence, with ages ranging from 1 to 17 years. In the case of poplar, the four plots were managed as short rotation crops, with rotation of 4–7 years and initial stocking of 6700 cuttings·ha^{-1}. The total sample size was 430 trees, including a very variable number of each species, ranging from the 12 *E. nitens* trees sampled to 150 or 154 in the case of stools of *Populus* SRF (Table 1). The plant material used in the study was a local provenance in the case of each of the two autochthonous species and different number of genotypes of the fast growing species (poplar and eucalypts). These were three for *E. globulus* (commercial seeds, Anselmo and Odiel) and one *E. nitens* (McAlister). The eucalypts were selected from blue gum stands or from crosses of F0 clones developed for drought resistance, rooting ability, growth, pest resistance and pulp yield, and the plants were raised from mini cuttings (López et al. 2010). Among the 8 poplar genotypes, three corresponded to *P.* × *euramericana* (I-214, AF2 and AF6), one to *P.* × *interamericana* × *P. nigra* (Monviso), three of *P.* × *interamericana* (Unal, Beaupre and Raspalje) and one for *P. trichocarpa* (Trichobel).

The four poplar SRF plots are located in a flat area in fluvial terraces of tertiary materials consisting of gravels of quartz, sandstone and slates bound in a matrix of clay and sand. The soil texture is sandy clay loam, with average percentages of sand (56%), silt (21.4%) and clay (22.6%). Average soil depth is 80 cm and the soil can be classified as Regosol (IUSS Working Group WRB 2015). The soil is acidic, with high saturation of Al in the exchange complex, and a very low availability of P. The chemical parameters of the first 40 cm soil layer are presented in Table 2. As for the other species studied, the plots were mainly established in forest land not previously used for agriculture and the soils were mainly classified as Regosols and Umbrisols, with a relevant proportion of Cambisols for the native species and a minor presence of leptosols in the eucalypt plantations, according to the FAO classification (IUSS Working Group WRB 2015). The combined information on chemical soil properties of the upper 40 cm soil layer, without separation of the samples of each species, is shown in Table 2.

The climate in the study region is characterized by mild temperatures (annual average temperature 9 °C–14 °C) and a slight water deficit in summer (average annual rainfall, 1000–2000 mm; average annual evapotranspiration, 700–850 mm; water deficit, 150–40 mm). Within this general framework, birch stands are frequent in the moister areas, oak stands are widespread but occur more frequently in hilly areas, whereas eucalypt plantations mainly cover coastal areas with mild temperatures. The annual rainfall is lower and water deficit is higher in the basins where poplar is frequently planted.

Management of each stand involves a specific pattern of harvesting biomass components, as well as management of logging residues and reapplication of nutrients through fertilization. Such management can be considered relatively homogeneous for each species or group of species (Table 3).

Table 1 Descriptive statistics (mean and standard deviations, range of diameter and age) of the sampled trees ($n = 430$)

	Quercus robur	*Betula pubescens*	*Eucalyptus globulus*	*Eucalyptus nitens*	*Populus euramericana* and *P.* × *interamericana* × *P. nigra*	*Populus* × *interamericana* and *P. trichocarpa*
Management	Semi-natural forest	Semi-natural forest	Forest plantation	Forest plantation	SRF	SRF
Plots	6	9	25	12	4	4
Tree number	19	34	61	12	150	154
Diameter (cm)	18.1 (6.1) 5.8–37.7	13.9 (5.9) 7.7–27.1	15.3 (8.0) 5.8–37.7	20.8 (5.9) 13.3–34.1	4.4 (1.5) 1.9–9.1	5.0 (1.5) 2.0–8.6
Age (years)	74 (20.2) 53–108	33 (11.0) 22–64	8.6 (3.0) 1–17	10.8 (1.4) 9–13	5.6 (1.5) 4–7	5.3 (1.5) 4–7
Clones/ genotypes	1	1	3	1	4	4

The diameter refers to breast height diameter, except for the poplars, for which the basal diameter is provided

The site index values for *E. globulus* ranged from 7 to 25, with an average of 16 m for dominant height (reference age 7 years). The SI was calculated for each plot with the EucaTool® application (Rojo-Alboreca et al. 2015). The average site index of the oak plots was 15.5 m (reference age $t_r = 60$ years), whereas the mean site index of birch was 11.6 m ($t_r = 20$), both of which are intermediate-high values for the region (Diéguez-Aranda et al. 2009). This variable was not included as a source of variation in the analysis because it could not be estimated for the very young poplar crops.

Tree sampling

The tree sampling differed slightly for the different groups of species. For birch, oak and eucalypts, three trees were selected per plot, to provide a good representation of the diameter range. Each plot corresponded to a specific genotype, and the sampling was carried out in summer. For poplar, the four plots under study each included 8 genotypes, and 10 (only 9 available in some cases) stools were thus chosen per plot and genotype, also with the aim of fully representing the diameter range. Bare poplar trees (without leaves) were sampled in winter, the usual time for harvesting SRF.

In each harvested tree, we separated aboveground biomass into the following components: wood and bark (portion between ground level and tree apex), split into one m-long logs; thick branches (2.5 to 7 cm over bark); thin branches (0.6 to 2.5 cm over bark); twigs (< 0.6 cm over bark); and leaves including petiole. The components considered for oak and birch had to consider branches of more than 7 cm, along with minor differences in the thin-end diameters, as is detailed in Gómez-García et al. (2015). The fresh weight of each tree component was measured and samples were obtained to determine the dry weight, percentage of bark in the stem and nutrient contents and thus enable application of the complete weighting procedure (Pérez-Cruzado and Rodríguez-Soalleiro 2011). Wood with bark was sampled by removal of three disks along the stem, considering relative heights of 0.15, 0.33 and 0.75. The disks were processed to remove and measure the bark component and thus the three samples were pooled together. Branches were sampled at random along the canopy, with at least one sample taken from each 1 m log, by applying a sampling intensity of 15%–20% (maximum, 20 kg) of the

Table 2 Descriptive statistics of the chemical parameters of the soils (mean value and standard deviations)

	Oak and birch ($n = 15$)	*Eucalyptus* ($n = 15$)	*Populus* ($n = 15$)
Soil types	Cambisols, Umbrisols, Regosols	Leptosols, Regosols, Umbrisols, Cambisols	Regosols
pH_{KCl}	3.9 (0.2)	3.8 (0.4)	4.3
pH_{H_2O}	5.2 (0.3)	4.9 (0.7)	5.4
C (%)	6.4 (2.8)	7.8 (4.5)	3.8
N (%)	0.5 (0.2)	0.5 (0.4)	0.3
P Olsen (ppm)	6.5 (2.8)	6.8 (3.2)	12.4
Ca ($cmol^{+}\cdot kg^{-1}$)	0.46 (0.13)	0.44 (0.30)	1.41
Mg ($cmol^{+}\cdot kg^{-1}$)	0.40 (0.10)	0.70 (0.40)	0.52
K ($cmol^{+}\cdot kg^{-1}$)	0.32 (0.16)	0.15 (0.05)	0.49
CEC ($cmol^{+}\cdot kg^{-1}$)	2.70 (0.90)	2.11 (1.30)	4.8
Al saturation (%)	55 (15)	61 (20)	46.7

CEC refers to cation exchange capacity

Table 3 Management of the plots of the species considered

	Oak and birch	*Eucalyptus*	*Populus*
Type of stand	Semi-natural forest	First rotation to be coppiced	First rotation to be coppiced
Previous use	Deciduous forest	Eucalypt plantation or shrub cover	Pasture/agricultural land
Components removed	Wood and bark, thinning + regeneration felling every 40–90 years	Wood and bark, rotation of 10 to 18 years	Wood, bark and branches, rotation of 4–7 years
Fertilization at planting	None	40 g plant of slow release coated fertilizer 9/23/24 + 4% MgO + 1% B	Legume shrub chopping and incorporation to soil through harrowing
Maintenance fertilization	None	None	Surface spread of 15:15:15 (240 kg·ha^{-1}) + limestone (400 kg·ha^{-1})

total number of both sizes of branches in each tree. The same sampling intensity was applied to leaves, thus removing a subsample of the total amount. For poplar the subsampling did not include leaves, and all woody components and bark were pooled. The dead branches along the stem were pooled with the thin branches in the case of *E. nitens*.

The biomass components were dried at 65 °C until constant weight (i.e. for on average 3 days for the wood + bark component) and the material was ground to pass through a 0.5 mm sieve. The C concentration was determined by combustion in a LECO CNS-ICP analyser. Total N was determined in a LECO-2000 analyzer, and the plant material was digested with HNO_3 in a microwave oven for determination of nutrient concentrations. After the samples were digested, the concentrations of P, K, Ca, Mg, S and micronutrients were measured by ICP-OES, with Barley 502–227 and EDTA included as certified reference materials. Twelve variables were measured for each sample. At the plot scale, biomass was calculated from measurements of each tree and application of genotype-specific equations of biomass estimation (Diéguez-Aranda et al. 2009; Oliveira et al. 2017).

Data analysis

The boosted regression tree (BRT) approach was used to explore the dependence between the five major explanatory variables (biomass component, species, genetics, age and tree diameter) and nutrient concentrations. The final BRT model is an additive regression model in which individual terms are simple trees fitted in a stepwise process. We followed the procedure, code and the tutorial developed by Elith et al. (2008). Tree complexity was established at an intermediate value ($tc = 4$), relative to the sample size (total number of observations, 1059), and the proportion of data to be selected at each step was set at 0.5 (bag fraction). The learning rate was slow enough to always produce more than 1000 trees ($lr = 0.01$, $nt > 1000$), and the response type considered was Gaussian. The previously mentioned code first determines the optimal *nt* and then fits a final model to all the data (Elith et al. 2008).

For each variable of interest (12 concentrations), the deviance explained by the BRT model and the relative contributions of predictor variables were computed. The contributions are based on the number of times a variable is selected for splitting, weighted by the squared improvement to the model in each split, averaged over all trees (Friedman 2001). Some of the variables are nested to others (Genotype to Species) and so it would be difficult to explore the real contribution of each of them. In this case, we tried to derive the contribution of each variable by running a BRT analysis removing the other. The models were fitted using the gbm package 2.1.3 (Ridgeway 2017) implemented in R (version 3.4.2, R Core Team 2017).

Conventional statistical techniques were also used for each group of exploratory variables. Subsets of data were produced, as the effects (Species, Genetics, Age or size) should be adequately separated in the data. Diameter and age would be highly correlated and the relative contribution of each variable in the BRT model would be related to the correlation between variables. The woody component of poplar was assumed to be wood, to enable comparisons among the six species. The effect of genetics was only able to be studied for those species in which several genotypes were sampled (poplar and *E. globulus*). Likewise, the effect of age was only able to be studied for those species for which a wide range of ages were sampled in a chronosequence (*E. globulus*, *B. pubescens*, *Q. robur*). The size effect was only examined in poplar, in which the effect could be separated from the age effect. We applied one-way analysis of variance or covariance (ANCOVA), considering age or diameter as covariables when necessary. The analysis was implemented in R by using the following model:

$$y_i = \mu + G_i + t + \varepsilon_{j(i)} \quad (1)$$

where y_i is the variable analysed (concentrations of the macro and micronutrients), μ is the mean value, t is stand age or the tree size, G_i is the effect of each factor considered and ε_i is the error term.

The Tukey's studentized range test was used for pairwise comparisons. A logarithmic base model was used to model nutrient concentrations in biomass components when the ANCOVA indicated an age effect. The adjusted coefficient of determination (R_a^2) and the mean square error (MSE) were used to evaluate the performance of the fitted models.

Results

Exploring the contribution of each source of variation

The BRT approach failed to provide a model for the (highly variable) concentrations of three of the micronutrients analysed (Fe, Mn and Zn). The regression tree analysis showed that the biomass component was the most important explanatory variable, always explaining ≥33% of the variance. The biomass component was particularly important for explaining the variation in N, S, P and C concentrations, and it was less important for Ca, Mg or K concentrations. The combination of the factors species and genotypes accounted for between 15.2% (K) and 39.6% (C) of the total deviation, and the genotype was much more important than the species itself. The factors age and diameter were comparatively more important for explaining Ca, K, Mg and Cu concentrations (Fig. 1).

Most nutrient concentrations varied widely depending on the component analysed, and followed one of three patterns. The pattern generally observed for several macronutrients (N, P, K, S) was leaves > > twigs > thin branches ≥ bark > thick branches ≈ wood. A different pattern was observed for Ca and Mg, exclusively in eucalypts: leaves ≈ bark ≈ twigs > thin branches > thick branches ≈ wood, indicating the relatively high content of both macronutrients in the bark component. A third pattern was observed for C: leaves > twigs > thin branches ≈ thick branches ≈ wood > bark, indicating the relatively low content of C in the bark (with the exception of birch, as we will detail afterwards). The boxplots for macronutrients are shown in Fig. 2.

The general pattern observed for micronutrients (with slight variations) was leaves > twigs > thin branches ≈ thick branches ≈ bark ≈ wood (Fig. 3).

Effects of species and genotype for each component

The contribution of the Species given by the BRT analysis is limited if the genotype is included as an explanatory variable. If the genotype was removed, the Species factor increased their contributions to 20%–37% of the variation, depending on the nutrient. Analysis of the effect of species on each biomass component revealed significant differences in most cases, particularly for the wood component (Table 4). The C concentrations in wood were highest in *E. nitens* and lowest in the poplars, probably because the poplar trees were relatively young. The difference between both species of eucalypts was noteworthy, as the C concentration in all components was lower in *E. globulus* than in *E. nitens*. The C concentrations in wood are higher than the ones in bark for all species, with the exception of birch. The concentrations of the other macronutrients (particularly N and P) were usually highest in poplar, intermediate in some birch and oak and lowest in the eucalyptus species. This general trend was not observed for Ca, the concentrations of which were highest in birch and oak wood.

More specifically, the nutrient concentrations were slightly higher in *P.* × *euramericana* than in the *P.* ×

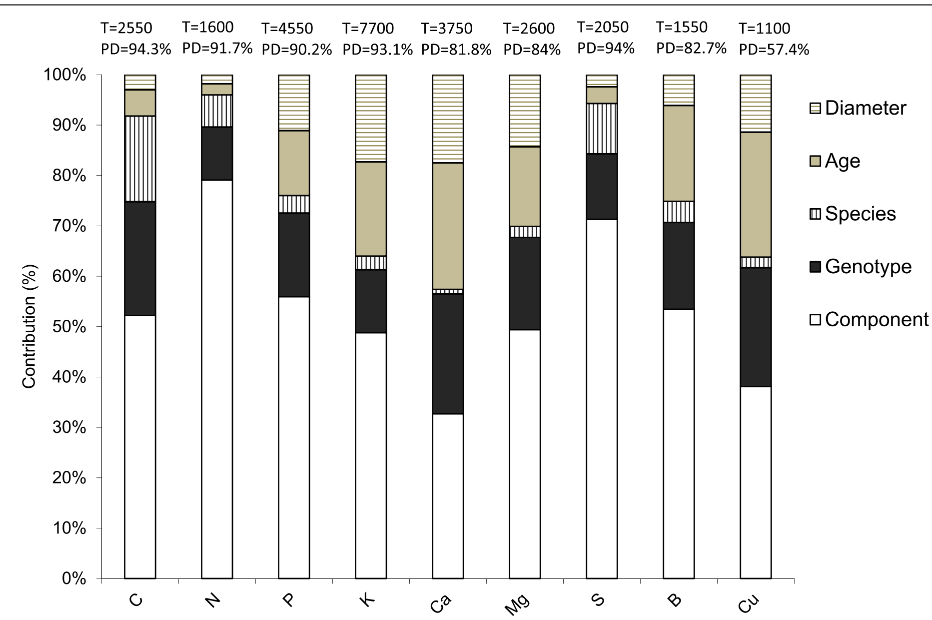

Fig. 1 Summary of relative contributions (%) of predictor variables in the boosted regression tree model for each nutrient concentration analysed. *T* is the number of regression trees and *PD* the percentage of deviance explained

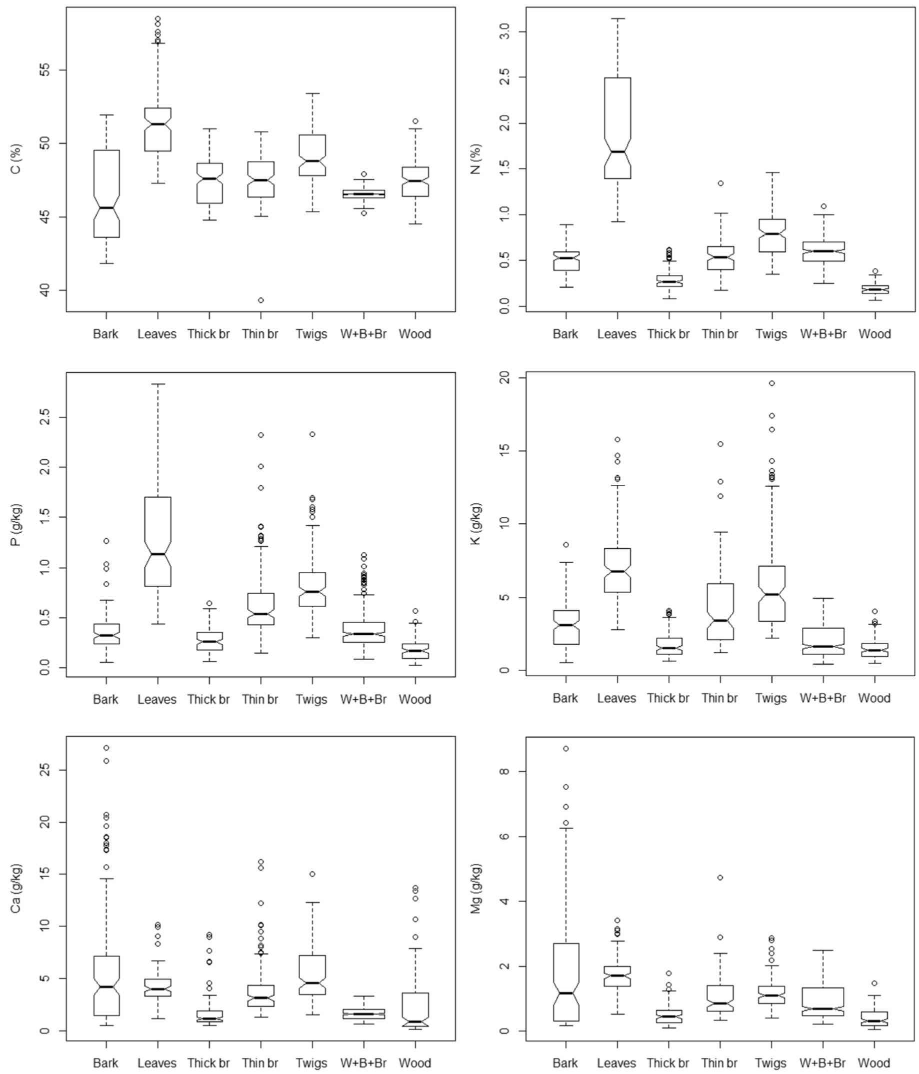

Fig. 2 Boxplots of macronutrients concentrations in each biomass component analysed. W + B + Br is for poplar SRF (leafless aboveground components are considered together)

interamericana or *P. trichocarpa* genotypes (data not shown). Thus, the latter group needed immobilization of 22% less N, 25% less P, 23% less K, 9% less Ca and 26% less Mg than *P.* × *euramericana* in the woody components to produce a ton of wood. A similar result was obtained for the comparison between *E. globulus* and *E. nitens*, and the latter required 44% less N, 36% less P, 37% less K, 42% less Ca and 29% less Mg than *E. globulus* per unit of wood produced. Indeed, *E. nitens* contains the lowest concentrations of these nutrients of the five species studied. The ratio of Ca:Mg concentrations in wood was very different in the three groups of species: 6.5 for oak and birch, 2.8 for poplar and only 1.9 for eucalypts.

The foliar concentrations of the following nutrients were higher in both deciduous species than in the eucalypts: N (+ 69%), P (+ 97%), K (+ 53%), Mg (+ 32%), S (+ 81%) and B (+ 46%) (Table 4). The Ca concentrations did not differ significantly between species. The foliar C concentrations were higher in the eucalypts, particularly *E. nitens*, than in the other species. Comparison with poplar was not possible, as leaves were not collected from this species. Considering the bark, the mean concentrations of the alkaline elements were higher in both eucalypt species than in the birch and oak. *E. nitens* shows particularly high Ca concentrations in bark. The K, Ca and Mg concentrations in the bark of birch and oak were similar to those in wood. The nutrient concentrations in the branches and twigs of eucalypts are generally similar to those in the autochthonous species.

The genotype contributed notably to explain the variance of nutrient concentrations (Fig. 1). If the species factor is removed from the BRT, it is the genotype which

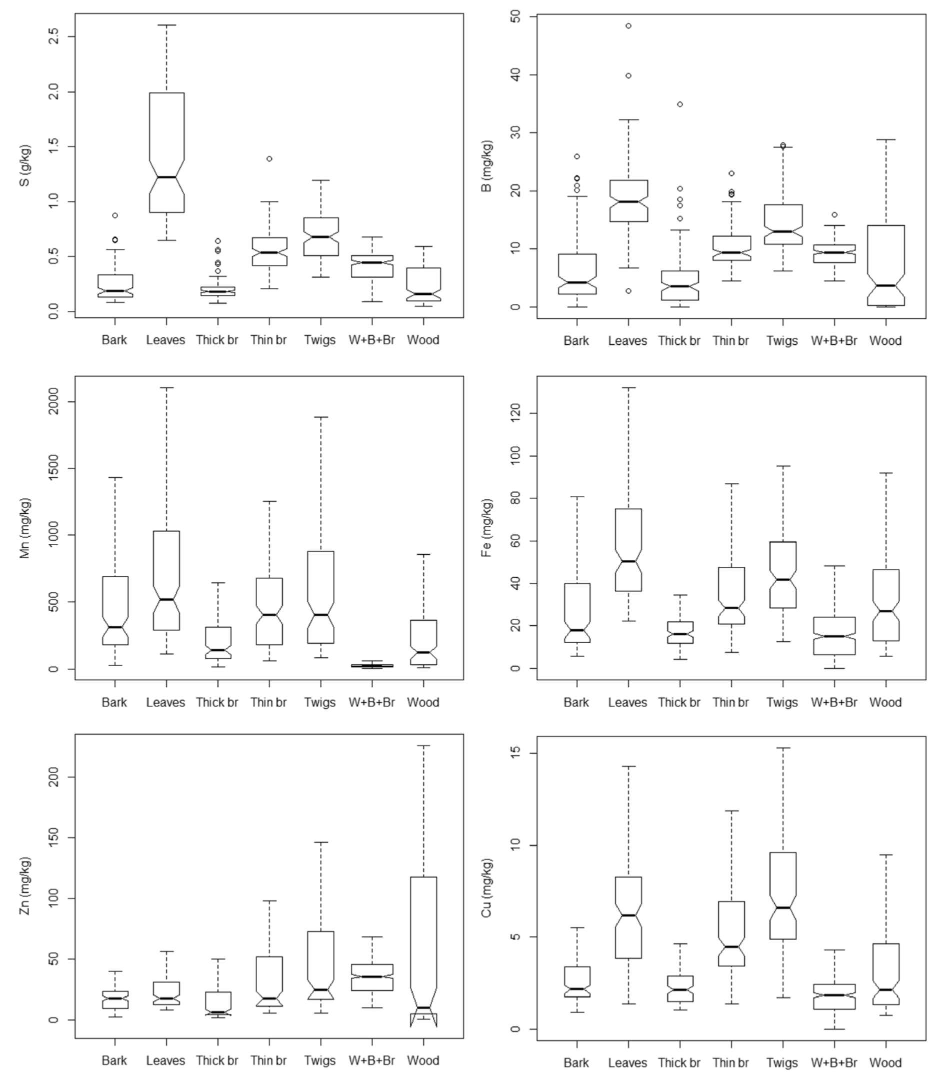

Fig. 3 Box plots of micronutrient concentrations in each biomass component analysed. W + B + Br was used for poplar SRF (i.e. leafless aboveground components were considered together)

assumes its contribution (data not shown). The concentrations of N, K, P, Ca, Mg, S and B in wood components differed in genotypes of the same species of *E. globulus* and of poplar. The concentrations were always lowest in the three *E. globulus* genotypes (Table 5). The concentrations were usually highest in four poplar genotypes (I-214, AF2, AF6 and Monviso), but with some overlap with a second group formed by Raspalje, Beaupré, Unal and Trichobel (particularly for P, Ca and S). This finding indicates the importance of choosing efficient genotypes that can immobilize low amounts of nutrients per unit biomass produced. Nutrient concentrations were much higher in commercial *E. globulus* seedlings than in the clones, especially for P, Ca and Mg. The F1 clone Odiel was much more efficient than Anselmo.

Effects of age and size

Tree age did not appear to affect the nutrient concentrations in leaves, bark or twigs. However, P and K concentrations in the branches of the eucalypts were negatively correlated with age. The concentrations of nutrients in the wood component were also usually negatively correlated with age. This was observed for N ($\rho = -0.45$, $p = 0.0003$), P ($\rho = -0.50$, $p < 0.0001$), K ($\rho = -0.47$, $p = 0.0002$), Ca ($\rho = -0.19$, $p = 0.04$), S ($\rho = -0.22$, $p = 0.03$) and Cu ($\rho = -0.31$, $p = 0.001$) in the eucalypts and for P ($\rho = -0.31$, $p = 0.015$), K ($\rho = -0.25$, $p = 0.03$), Ca ($\rho = -0.25$, $p = 0.03$), Mg ($\rho = -0.14$, $p = 0.04$), S ($\rho = -0.42$, $p = 0.001$), Cu ($\rho = -0.34$, $p = 0.005$) and B ($\rho = -0.36$, $p = 0.008$) in the deciduous species. The nutrients affected by this trend were thus slightly different in both groups of species, as was the intensity of the relationship. It was not possible to fit an

Table 4 Concentrations of macronutrients in the wood of five species

Biomass compartment	Species	C (%)	N (%)	P ($g{\cdot}kg^{-1}$)	K ($g{\cdot}kg^{-1}$)	Ca ($g{\cdot}kg^{-1}$)	Mg ($g{\cdot}kg^{-1}$)	S ($g{\cdot}kg^{-1}$)	Fe (ppm)	Mn (ppm)	Cu (ppm)	Zn (ppm)	B (ppm)
Wood	*Q. robur*	48.1b	0.24b	0.21b	1.60ab	3.28b	0.57b	0.32b	35.5b	368b	3.89b	70b	10.7b
	B. pubescens	48.1b	0.22b	0.25b	1.96a	4.81a	0.67ab	0.45a	56.2a	603a	7.31a	135a	16.7a
	E. globulus	46.3c	0.16bc	0.14bc	1.24bc	0.74d	0.24c	0.10c	18.3c	109c	1.78c	6d	0.5d
	E. nitens	50.1a	0.09c	0.09c	0.78c	0.43d	0.17c	0.13c	42.1b	25c	1.15c	9d	5.4c
	Populus	46.5c	0.60a	0.38a	2.02a	1.67c	0.92a	0.41a	17.8c	25c	2.13bc	36c	9.3b
Bark	*Q. robur*	47.6b	0.64a	0.32	1.33c	3.3c	0.37c	0.24bc	28.6b	291	3.46ab	25.3a	6.39ab
	B. pubescens	50.2a	0.55a	0.45	1.78c	2.8c	0.45c	0.32ab	33.5b	347	4.36a	22.5ab	9.17a
	E. globulus	43.6c	0.46b	0.32	4.44a	6.5b	3.15a	0.19c	18.2b	1223	2.18bc	16.6bc	4.19b
	E. nitens	46.9b	0.38b	0.38	3.23b	14.9a	1.88b	0.40a	63.3a	355	1.74c	9.5c	8.40ab
Thick branches	*Q. robur*	48.0c	0.46a	0.39a	1.33b	1.91	0.31c	0.25a	33.0	181	3.46a	36.1a	8.2ab
	B. pubescens	48.7b	0.29b	0.34a	1.19b	1.60	0.33bc	0.21ab	24.8	236	3.07ab	33.4a	6.0b
	E. globulus	45.9d	0.26b	0.21b	2.16a	1.52	0.69a	0.18b	25.3	357	2.11bc	4.8b	1.3c
	E. nitens	49.7a	0.16c	0.20b	1.50b	1.91	0.53ab	0.22ab	41.8	109	1.55c	8.0b	11.1a
Thin branches	*Q. robur*	48.5b	0.73a	0.58a	3.23b	5.70a	0.79b	0.63a	47.7a	572a	6.74ab	36.2b	16.2a
	B. pubescens	48.4b	0.55b	0.56a	1.89b	2.72b	0.73b	0.41b	38.2ab	339ab	4.08bc	67.6a	9.1b
	E. globulus	46.3c	0.52b	0.79a	6.33a	4.28ab	1.48a	0.65a	42.3a	713a	7.87a	14.0c	9.7b
	E. nitens	49.8a	0.24c	0.28b	2.07b	2.46b	0.60b	0.27c	11.9b	148b	1.98c	10.2c	8.3b
Twigs	*Q. robur*	49.1a	1.09a	0.94a	5.57b	6.47a	1.08b	0.92a	55.1a	792a	10.1a	41b	21.3a
	B. pubescens	50.8b	0.92b	0.87a	3.15c	3.80b	0.88b	0.72b	59.1a	518ab	6.37b	107a	12.0bc
	E. globulus	47.7d	0.68c	0.81a	8.05a	6.01a	1.44a	0.66b	41.7ab	648a	8.65ab	21c	14.6b
	E. nitens	51.5a	0.45d	0.53b	3.42c	4.92ab	1.15ab	0.41c	21.2b	219b	2.76c	12c	10.3c
Leaves	*Q. robur*	48.6d	2.50a	1.78a	7.86ab	3.81	1.84b	1.95a	219	828ab	10.03a	24.6b	22.5a
	B. pubescens	49.7c	2.51a	1.73a	8.63a	4.55	2.24a	2.07a	92	1207a	6.75ab	67.3a	22.2a
	E. globulus	52.0b	1.39b	0.86b	6.54b	4.18	1.49b	0.91c	46	617bc	6.58ab	15.6b	16.6b
	E. nitens	57.2a	1.57b	0.92b	4.21c	4.24	1.59b	1.31b	47	329c	3.04b	13.2b	14.1b

For each biomass component, different letters in the same column indicate significant differences in the mean values (Tukey test)

Table 5 Concentrations of macronutrients in wood of 11 genotypes corresponding of two species of *Populus* and one species of *Eucalyptus*

N (%)	P (g·kg^{-1})	K (g·kg^{-1})	Ca (g·kg^{-1})	Mg (g·kg^{-1})	S (g·kg^{-1})	B (mg·kg^{-1})
0.78a AF6	0.57a AF6	2.53a AF6	1.99a I-214	1.29a I-214	0.50a UNAL	10.9a AF6
0.66b MON	0.46ab I-214	2.28ab I-214	1.81a MON	1.12ab AF2	0.47ab I-214	10.5a AF2
0.64bc I-214	0.40bc MON	2.22abc MON	1.68a AF2	0.99bc AF6	0.43abc AF6	10.4a MON
0.63bc AF2	0.36bc BEA	2.17abc AF2	1.63a RAS	0.91bc MON	0.43abc RAS	10.1ab I-214
0.57bcd BEA	0.35bc RAS	1.96abcd TRI	1.60a BEA	0.83bc TRI	0.42abc BEA	8.6bc TRI
0.56cde RAS	0.34bc TRI	1.91abcd BEA	1.58a TRI	0.83bc BEA	0.42abc MON	8.0c UNAL
0.52de UNAL	0.32bcd AF2	1.68bcd RAS	1.58a AF6	0.79bc RAS	0.35bc TRI	7.7c RAS
0.46e TRI	0.27cde UNAL	1.45 cd UNAL	1.57a UNAL	0.67 cd UNAL	0.34c AF2	7.6c BEA
0.18f SEED	0.20def SEED	1.32d ANS	1.47a SEED	0.32de SEED	0.13d SEED	1.1d SEED
0.18f ANS	0.15ef ANS	1.24d ODI	0.50b ANS	0.20e ANS	0.10d ANS	0.3d ANS
0.14f ODI	0.10f ODI	1.16d SEED	0.44b ODI	0.20e ODI	0.08d ODI	0.2d ODI

Different letters in the same column indicate significant differences in the mean values between genotypes (Tukey test). Only the nutrients showing significant differences are shown

accurate regression model to the pattern due to the high level of intrinsic variation in the data, although the values for eucalypts appeared to stabilize from age 7–12 years onwards.

Although no age-related trends in C concentration were observed for any individual species, the pooled data for woody components (excluding bark, leaves and twigs) showed a pattern of increasing C concentrations with age. A parametric log-linear fit is provided for prediction purposes (Fig. 4). This finding indicates the need to consider an appropriate rate of C sequestration per unit of woody biomass depending on the type of management (SRF, plantation for small timber production or semi-natural forests), as an average value of 50% could only be sustained in long rotations.

As regards the effect of size of the tree, no correlations between nutrient concentrations and size were found in the case of poplar SRF data, which is the information able to clearly separate the effect of age from that of the tree dimension.

Nutrient content at the end of the rotation

In the poplar plantations, as all the genotypes were present in each plot, it was possible to compare the total amount of nutrients accumulated in the woody biomass (and thus likely to be removed from site by harvesting the biomass). Comparison of the two groups (Fig. 5) revealed that the Raspalje, Beaupré, Unal and Trichobel genotypes were able to absorb more nutrients from the same soil than the other genotypes (91% more Ca and

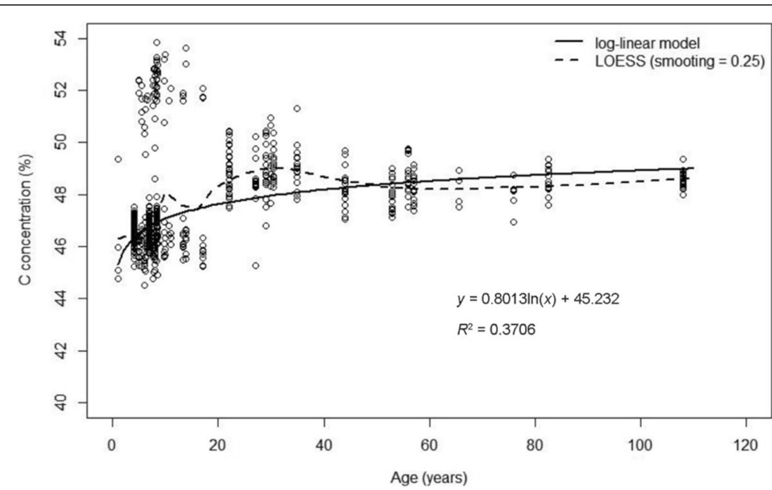

Fig. 4 Relationship between C concentrations for the wood and branches components (excluding bark) and age of the sampled trees. The dashed line corresponds to a local regression model (LOESS) fitted by using the loess function of R (R Core Team 2018) and a smoothing factor of 0.25. All the species studied are pooled together

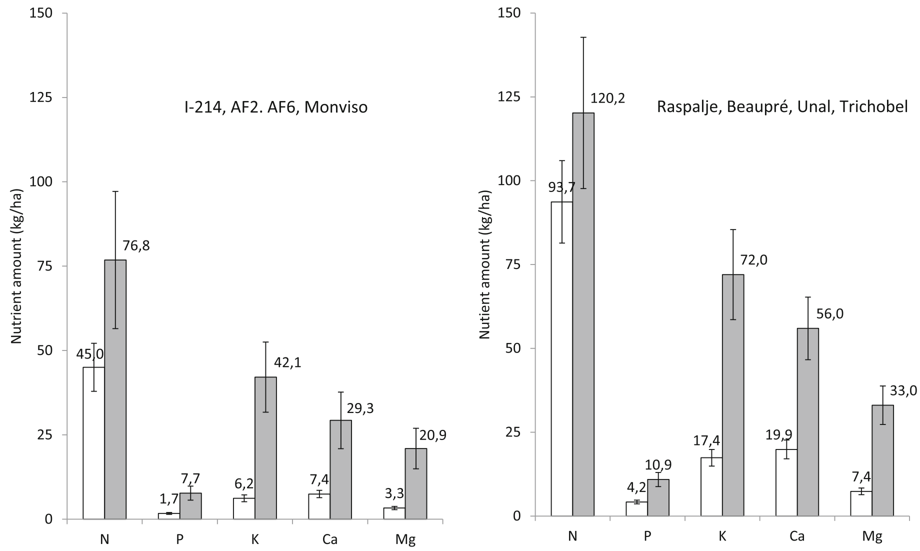

Fig. 5 Nutrient amounts in poplar SRF. White bars represent the 4-year-old plots and grey bars the 7-years-old plots

71% more K for an age of 7 years). The most efficient group of poplar genotypes showed an average productivity of 5.5 Mg·ha^{-1}·year^{-1}, which is 2.4 times higher than the average yield of the first group, which mainly comprises Euro-American crosses.

The N, P, K, Ca and Mg contents in blue gum were calculated on a per ha basis for 4 age classes (5–7, 7–9, 9–12 and 12–18 years). The number of plots available for each class ranged between 5 and 9. The results of Fig. 6 show the pattern of nutrient accumulation in aboveground biomass, which keeps increasing from age 9–12 to the 12–18 age class. The standard errors are lower for the 7–9 age class because 9 plots were available in this case. The relative contribution of wood increased with age (50, 48, 51, 34 and 33% of N, P, K, Ca and Mg, respectively, is contained by the wood at rotation age), indicating that the increase in biomass largely compensated for the decreases in nutrient concentrations. The share of bark, particularly important for Ca and Mg, also increased with age. The results for *E. nitens* after grouping all the plots together are also shown in Fig. 6.

The nutrient amounts in native broadleaved species were calculated as mean values after grouping the plots available for each species. The results of Fig. 7 show that the oak stands hold in the aboveground biomass large amounts of nutrients (750, 65, 383, 755 and 117 kg·ha^{-1} of N, P, K, Ca and Mg, respectively), as a result of an average age of 74 years. The average age of birch plots is 33 years and the total content of nutrients is lower: 410, 40, 209, 371 and 64 kg·ha^{-1} of N, P, K, Ca and Mg, respectively. For both species, but more clearly in the case of oak, the proportion of thick branches is very relevant.

Comparison of 4 scenarios of species and management

In order to facilitate discussion of the results, we considered four different combinations of species and management regimes:

1) PoplarSRF7. Poplar SRF with efficient poplar genotypes, rotation length of 7 years and removal of leafless aboveground biomass.
2) EucaSRF6. Eucalypt SRF considering all genotypes of *E. globulus* (represented by the plots in the age interval 5–7 years), rotation length of 6 years and removal of whole aboveground biomass.
3) Eucapulp15. Conventional forest plantation of Eucalypt blue gum (considering all genotypes) with rotation length of 15 years and removal of only the wood component.
4) Oakbirch. Combined Oak and birch management with rotation of 35 (birch) or 75 (oak) years, removal of wood, bark and thick branches to produce timber and firewood.

Three sets of variables were calculated: the nutrient assimilation index (NAI), as an indicator of efficiency in biomass production per unit nutrient; the mean annual nutrient removal (MANR) on a per ha basis; and the percentage of the available soil nutrients removed during harvesting (PASNR). For N removal, the percentage removed refers to the total N mineralization expected with a fixed annual rate of 1% of N mineralization. The values obtained are presented in Table 6.

The mean annual nutrient removals, except for N, were higher for eucalypt SRF than for poplar. The lower values are associated with intermediate or long

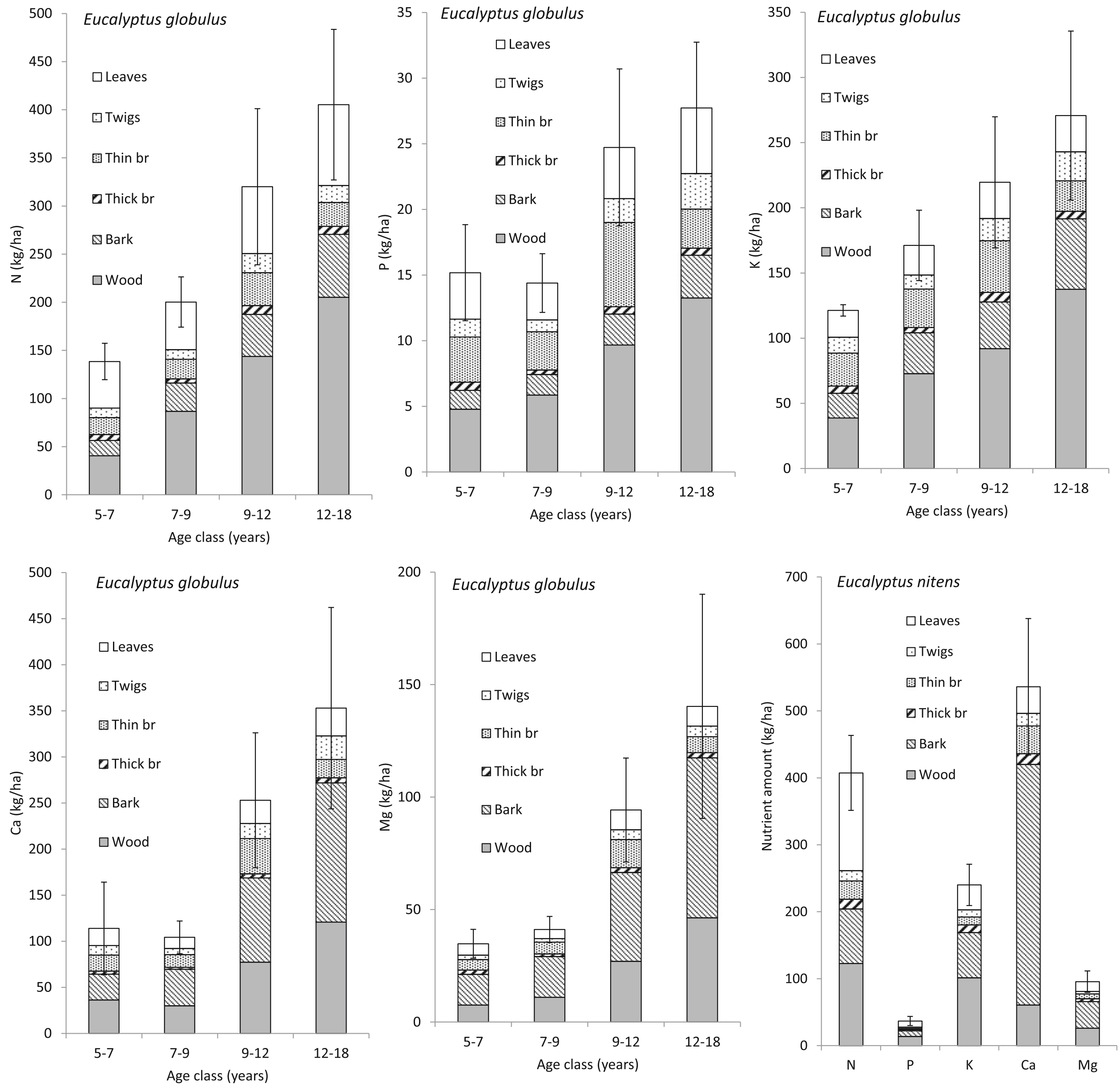

Fig. 6 Nutrient amounts in aboveground biomass components of *Eucalyptus globulus*, considering 4 age classes

rotations in the regimes including both autochthonous species. The scenario of eucalypt managed for pulp show lower MANR values than the SRF of eucalypts and the NAI is 1.7 to 3.9 times higher than the values for poplar and eucalypts SRF. The MAI associated to this alternative is 16.3 under bark ($m^3 \cdot ha^{-1} \cdot year^{-1}$), which using the values of specific wood consumption at that age (SWC, under bark ($m^3 \cdot Mg_{ADP}^{-1}$), i.e. the amount of debarked wood required to produce a ton of air dried pulp, Resquin et al. 2012), means a productivity of 5.51 $Mg_{ADP} \cdot ha^{-1} \cdot year^{-1}$.

Discussion

The study findings emphasize the importance of the biomass component as the main factor explaining nutrient concentrations in a variety of combinations of broadleaved species and management regimes. This has been shown in several studies and for different species (Merino et al. 2005; Hernández et al. 2009; André et al. 2010) and is the main basis for proposing management scenarios in which the compartments to be removed are selected according to their impact in terms of nutrient removal per unit of biomass (Achat et al. 2015; Viera et al. 2015).

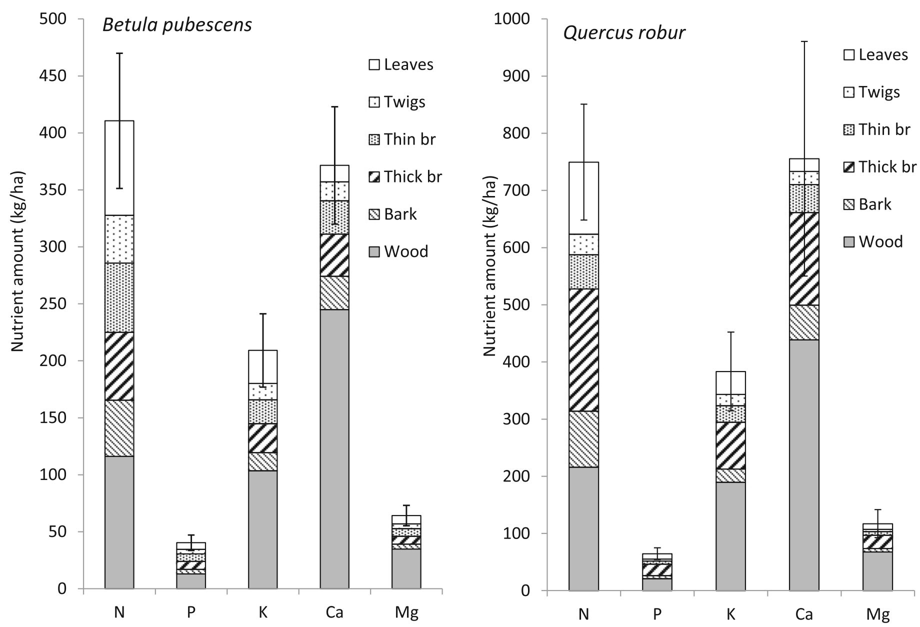

Fig. 7 Nutrient amounts in aboveground biomass components of *Betula pubescens* (*n* = 9 plots, left) and *Quercus robur* (*n* = 6 plots, right). Note the difference in the scale of the *y*-axis

The three types of management covered by the data represent specific systems with very different goals and products, and applied to different species and in specific locations. Comparative studies of several species growing on the same soils enable a better understanding of differences between species under similar conditions of nutrient availability (Hagen-Thorn et al. 2004). A limitation of this study is the lack of representation of all the species studied in the same sites. Even so, the dataset used shows that N, P, K, Ca and Mg concentrations in the woody components (except bark) are consistently higher in poplar, oak and birch than in eucalypts, and these macronutrients are greater than the ones reported for conifers in the same region (Merino et al. 2005). The variability among broadleaved species found in this study is consistent to the range of values reported in the literature (Wang et al. 1991; André et al. 2010; Gómez-García et al. 2016) although studies of the group of species considered here are scarce.

Calculation of carbon storage in biomass components should take into account tree age rather than average carbon concentration in biomass components. Longer rotations would be beneficial for carbon stock in biomass and products, as well as for bioenergy substitution (Pérez-Cruzado et al., 2012). The present findings also show that C concentrations did not reach 50% at older ages for any of the biomass components studied, except leaves. Previous studies have shown that average C concentrations are variable depending on species, tree size and/or age, and that the measured values in the trunk do not reach 50% (Elias and Potvin 2003), but can be very closed to this figure for wood of a 14 years-old poplar plantations (Cruz Calleja, 2005). Overall, considering all the plots studied, the mean C concentration averaged with biomass was 46.5% for poplar SRF and 45.6% for wood and bark in eucalypts. Considering the whole aboveground biomass, these figures are 47.7% for eucalypt, 48.3% for oak and 49.3% for birch. These results indicate the need to consider the variation in C concentration with age to simulate the amount of carbon captured and the limitations of the studies that used a fixed concentration (Giménez et al. 2013).

Table 6 Comparison of nutrient assimilation index (NAI), mean annual nutrient removal (MANR) and percent of available soil nutrients removed (PASNR) for five species-forest management combinations

Regime	N° Plots	MANR (kg·ha^{-1}·year^{-1})					PASNR (%)					NAI (Mg·kg^{-1}) of nutrient				
		N	P	K	Ca	Mg	N	P	K	Ca	Mg	N	P	K	Ca	Mg
PoplarSRF7	4	23.5	1	4.5	5	2.0	19	29	16	7	18	0.21	2.94	0.51	0.63	1.20
EucaSRF6	6	20.0	3	20	23	7.0	15	75	69	43	14	0.28	2.57	0.31	0.34	1.12
Eucapulp15	5	13.7	0.9	9.2	8	3.1	9	65	78	46	18	0.64	9.95	0.96	1.09	2.84
Oak-birch	15	7.0	0.7	4.2	9.3	1.3	6	238	79	239	67	0.35	3.60	0.60	0.27	1.80

Short rotation forestry

The SRF approach, which is applicable to both poplar and eucalypts, is devoted to the growth of small trees for biomass production in the short term. This management system provides little opportunity to remove but the whole aboveground biomass (Morhart et al. 2013), and it thus entails the extraction of large amount of nutrients every few years. In the case of the more efficient genotypes of poplar, with an average yield of 5.5 (t·ha^{-1}·year^{-1}), comparison between the removal rates and the available amounts of nutrients in the soil show that 29% of the available P and 19% of the expected periodic N mineralization would be retained in the aboveground biomass after 7 years of growing poplar. Even if nutrient concentrations of poplar in this study are high compared to the other species studied, it is known that poplar has lower concentrations when compared to other biomass fuels, as Miscanthus (Jenkins et al. 1998), but also higher than willow (Tharakan et al. 2003).

The average yearly removal rates are lower (particularly for P and Ca) than reported for more productive plantations (Adegbidi et al. 2001; Morhart et al. 2013). This is a result of lower nutrient concentrations, if compared to the combined wood + branches + bark component reported by other authors, particularly in the case of Ca and P (Jug et al. 1999; Tharakan et al. 2003) or to the proleptic branches reported by (Vanbeveren et al., 2016). The macronutrient concentrations found in poplar plantations for wood production in Spain were also higher than the ones of this study (Cruz Calleja, 2005). The concentrations of Mg and N are comparatively high in this study. The rates of removal found in 7-years old hybrid aspen plantations in Estonia are nevertheless comparatively lower than the ones found in this study (Tullus et al. 2009).

The poplar data reported in the present study, which correspond to only two age groups, enable separation of the effects of age and size. The results do not support the existence of different nutrient concentrations in trees of different sizes. Different studies have reported that the reduction of bark percentage decreases with tree size (Morhart et al. 2013), and thus the management alternatives of lengthening the rotation or reducing the stool density have been proposed. A reduction of nutrient concentrations with age has been previously reported for aspen (Rytter 2002), but considering a rotation longer than the 7 years considered in our study would be inoperative.

With the results of the present study, the management alternative more prone to savings of nutrient removal is the selection of efficient genotypes, even within a particular crossing. Nutrient efficient aspen clones have been identified, yielding a potential saving of 5% of nutrients (Rytter and Stener 2003). As these authors did not find either significant relationships between nutrient concentrations and size, they suggested the possibility to select nutrient-efficient clones without significantly sacrificing genetic gain for growth. The most productive clone in this study (TRICHOBEL) show nutrient assimilation indices of 0.22, 2.94, 0.51, 0.63, 1.20, 2.86, 117, 49, 74, 27 and 600 Mg·kg^{-1} for N, P, K, Ca, Mg, S, B, Mn, Fe, Zn and Cu, respectively. Even so, with the results provided, it would be difficult to select a poplar clone more efficient for all macronutrients than the others belonging to the same crossing. It is also clear that low nutrient concentrations enhanced feedstock quality decreases the fouling and corrosion processes on furnace walls and increases the ash quality (Vega-Nieva et al. 2016).

The application of SRF to eucalypts leads to the removal of large amounts of nutrients, because harvesting in this case includes a rule the leaves, bark and branches, as long as wood (Guo et al. 2002; Eufrade et al. 2016). The data of this study for eucalypts in the age class 5–7, even if the stand density is the usual one for pulp forest plantations (average density for these plots is 1120 trees·ha^{-1}) could be representative of the large amounts of nutrients removed if the whole tree is removed, as shown in Table 6 for an average yield of 6.5 Mg·ha^{-1}·year^{-1}. If compared to the poplar figures, these values means a similar amount of N or K, but 3–4 times more P, Ca and Mg removed per year to produce just 20% more biomass and less NAI, except for N. As the soils are on average poorer than the poplar ones, these figures suppose the extraction of large percentages of available P and exchangeable K and Ca amounts. Eufrade et al. (2016) and Guo et al. (2002) reports average yearly removal rates well above the ones proposed in this study, along with consistently higher biomass yield. Sochacki et al. (2013) reported for *E. globulus* very similar rates of removal than the ones of this study.

Conventional pulp plantations

Study of biomass production, nutrient removal during logging operations and management of logging residues is essential to prevent negative effects on sustainable productivity and soil fertility in this management system (Gonçalves et al. 2013; Rubilar et al. 2018). Unlike the previous type of management, several commercial forestry operations leave different biomass compartments as logging residues in this case (Achat et al. 2015). The findings of this study confirms the importance of stem bark in terms of the Ca and Mg aboveground amounts of *E. globulus*, as removal at age 15 years would increase 32%, 24%, 39%, 225% and 254% if undebarked wood is removed from the forest. In the case of *E. nitens*, the ratios of Ca concentrations in bark related to wood found in this study were clearly higher for *E. nitens* (34.6) than for *E. globulus* (8.8), thus showing that the relevance of bark as an aboveground compartment storing Ca is more marked for *E. nitens*, as has been previously shown (Madgwick et al. 1981; Thiers et al. 2007). This reflects the recommendation to leave in place this biomass component, whose value as a product is only related to the generation of energy at the pulp factories. The present study findings indicate that the average rates of nutrient removal for a rotation of 15 years and harvesting exclusively the wood component are lower than the eucalypt SRF scenarios and similar (N, P, Mg) or higher (K, Ca) than the poplar SRF scenario (Fig. 7). At this stage, the proportion of aboveground nutrients accumulated in the wood ranged between 33% for Mg till 51% for K and N. These figures are higher than those reported by Hernández et al. (2009) when bark is left in place and similar to the ranges reported by Merino et al. (2005) for the same region. The percentage of nutrients found in the trunk of *E. globulus* (wood and bark) at the end of rotation in this study are similar to the ones reported for tropical plantations in the case of N, Ca and Mg, but higher for K and lower for P (Laclau et al. 2010; Rocha et al. 2016).

The recommendations for nutrient management should be based not only on the amount of nutrients removed at clearfelling, but also on the entire budget of inputs and outputs of nutrients, including the levels of soil supply needed to maintain production (Laclau et al. 2005). The information already available shows that the overall budgets may be negative if the parent materials have a low content of Ca and Mg, the soil reserves are scarce, the rate of rainwater inputs are low and the stands have strong mineral uptake (Dambrine et al. 2000; Merino et al. 2005). The intensity of losses of non-acidic cations is directly related to the soil nutrient status and also to the management practices used (Madeira and Araújo 2015).

Age and genetic material directly affect the concentrations of nutrients in each component and, consequently, the estimation of nutrients removal, thus giving differences among different decisions in the management of these plantations. On the one hand, comparing the data of this study for clones and seedlings, the NAI, or cost per unit of wood yield in terms of two of the most limiting nutrients in the area (P and Ca) may therefore be reduced considerably (45 and 35% less, respectively) by using genetically improved material. The selection of genotypes with more efficiency in the use of nutrients has been applied for hybrid eucalypts in Brazil (Rosim et al. 2016). In a study carried out in Congo, Safou-Matondo et al. (2005) demonstrated the superiority of several clones of *Eucalyptus urophylla* regarding P (+ 72%) and Ca (+ 43 to + 59%) assimilation index. Santana et al. (2002) indicated that as differences in NAI are also influenced by site parameters. Tree breeding programmes should therefore select genotypes with NAI compatible with natural soil fertility or with fertilization practices. NAI is a measure of the ability of plants to respond to fluctuating resource availability and has been shown to increase with nutrient availability (Santana et al. 2000). A limitation of the present study is therefore the lack of information of different eucalypt genotypes in the same site, even if seedlings plots were not apparently placed in sites more productive than the clonal plots. We have also to consider that the total amount of nutrients removed may be similar if more biomass is removed in the case of clones. With the overall data of this study, we estimate that clones are 14% more productive than seedlings at the same rotation age.

The influence of age on nutrient concentrations in tree parts, particularly for the wood component, provides an opportunity to lengthening the rotation to increase the biomass yield per unit of nutrient stored in the removed compartment. Such possibility can come along with decreases in mean annual increment of timber volume. The values shown were obtained for the set of plots used in this study (average site index slightly above the average for the region, SI = 17 m), and we have to consider that the pattern of mean annual increment depends on site productivity, peaking before for very productive sites. Negative trends of nutrient concentration with age were previously demonstrated by Laclau et al. (2000) for a hybrid eucalypt chronosequence or by Rocha et al. (2016). The influence of age on wood nutrient concentrations is due to the higher nutrient concentrations in the younger and more physiologically active tree tissues, leading to higher nutrient concentrations in sapwood than in heartwood (see Grove et al. 1996 for eucalypts and Augusto et al. 2008, for maritime pine). For *Eucalyptus globulus* in the Iberian Peninsula, heartwood of 9 years old trees has been shown to correspond to 17%–30% of the total tree volume (Gominho and Pereira 2000), showing that the sapwood component of the tree bole probably represents only the outer 7–8 years of tree growth. Older trees will have a narrow band of nutrient rich sapwood surrounding a relatively nutrient poor woody biomass enriched in carbon.

Extensively managed stands of native species

The results of this study show that for plots within the same region, nutrient concentrations were higher in aboveground biomass components of the native broadleaved species than in other species. This may be associated with the slightly better nutrient conditions in soils (Table 2). The concentrations determined in this study are higher than those reported for oak and birch by Hagen-Thorn et al. (2004). These authors observed relatively small differences between this pair of broadleaved species, although, as in the present study, the concentrations of Mg were higher in birch leaves than in oak leaves. The share of wood in the nutrient amounts found in this study are higher than the ones reported previously for oak in the same region (Balboa-Murias et al. 2006), as a result of the comparatively higher nutrient concentrations, particularly for Ca. An hypothetical clearfell with removal of wood, bark and thick branches would suppose the average annual removals lower than the other scenarios, except for Ca, a result already shown previously (Gómez-García et al. 2016). The removals would represent a large proportion of the available nutrient contents in soils, indicating that, even in these species, care should be taken as to the biomass components removed and the felling pattern applied. As a result of a lower productivity (2.4 Mg·ha^{-1}·year^{-1} for oak and 2.5 Mg·ha^{-1}·year^{-1} for birch), the NAIs for these species are much lower than for poplar or eucalypts in this study. This is not surprising if we consider that these native species are not specifically bred or managed to maximize biomass production. The removal of additional biomass components would increase the nutrient removal, and the harvesting methods and management of logging residues should therefore be adapted to the tree species and site fertility (Helmisaari and Kaarakka 2013).

Conclusions

Nutrient concentrations in biomass components varied with the component considered, plantation age (the concentrations of most nutrients, except C, tended to decrease) and genetic material (several clones were more efficient regarding nutrient removal per unit of wood volume). Nutrient sustainability was lower in SRF than in forest plantations, and it was lower in forest plantations than in natural stands. Poplar in SRF has the great advantage that the lifeless aboveground biomass can be removed.

Additional file

Additional file 1: Nutrient database. (XLSX 214 kb)

Abbreviations

ADP: Air dried pulp; ANCOVA: Analysis of covariance; BRT: Boosted regression trees; CEC: Cation exchange capacity; EDTA: Ethilenediaminetetraacetic acid; EU: European Union; MAI: Mean annual increment; MANR: Mean annual nutrient removal; MSE: Mean square error; NAI: Nutrient assimilation index; PASNR: Percent of available soil nutrients removed; RE: Renewable energy; SRF: Short rotation forestry; SWC: Specific wood consumption

Acknowledgements

The authors thank Prof. Gadow for encouraging the development of this study and to Dr. Diéguez-Aranda for providing oak and birch data.

Funding

Funding for this research was obtained from MINECO (Spain) through the project RTA2014–00007-C03–02. Additional funding was derived from the projects AGL2010–22308-C02–01 and AGL2007–66739-C02–01/FOR.

Availability of data and materials

Presented as an Additional file 1.

Collection of plant samples

The authors declare that the collection of plant samples was done according to the Spanish and European regulations with the required permissions.

Authors' contributions

RRS conceived the experiment, performed the analysis of data and lead the writing. CEF, JDGV, ARA and NO carried out the sampling and experiments. EGG, FM, HS and CPC provided critical feedback and helped to shape the analysis and the manuscript. All authors read and approved the final manuscript.

Authors' information

RRS, HS, ARA lead the projects that provide the dataset used in this study.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

TThe authors declare that they have no competing interests.

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Received: 30 April 2018 Accepted: 5 September 2018
Published online: 05 November 2018

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