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ORIGINAL PAPER

Eucalyptus grandis plantations: effects of management on soil carbon, nutrient contents and yields

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Abstract The expansion of fast-growing tree plantations is a worldwide process, with consequences on soil fertility and soil carbon storage. Disparate results were found on the effects of afforestation with *Eucalyptus* on soil carbon and other nutrient contents. These discrepancies are usually caused by differences in climate, land use history, soil texture as well as by management related factors such as plantation age, number of rotations, method of establishment (plantation or coppice), harvest residue management and soil preparation. We studied the effect of plantation age, number of rotations, and method of establishment on soils and plant nutrient concentrations in *Eucalyptus grandis* plantations in NE Argentina on different textured soils. We also determined if yields changed with nutrient variations in soils, and compared soils under plantations to soils under grasslands they replaced. Thirty-one *E. grandis* stands of different ages, number of rotations and method of establishment were evaluated as well as eight grassland sites. Levels of carbon, nitrogen, phosphorus, potassium, calcium and magnesium were determined for soils and plants. Soil carbon and nitrogen decreased over the number of rotations and were more pronounced in soils with 50–60% sand than soils with > 75% sand. Coppice stands showed higher soil carbon and nitrogen levels than plantations, suggesting a negative effect of site preparation before planting on soil nutrient conservation, especially in fine-textured soils. Foliar nutrient concentrations did not follow the trends observed for soil nutrients nor did they reflect nutrient limitations. There was no evidence of decreased yields over successive rotations. Soil carbon and nitrogen contents decrease when grasslands are replaced by *E. grandis* plantations, and therefore a yield limitation may occur in a medium to long-term frame, especially in stands re-established for short-rotation management. Harvest residue management and site preparation must be specifically designed for improving soil nutrient management.

Keywords Soil texture · Grasslands · Foliar nutrient concentrations · Successive harvest · Coppice · *Eucalyptus grandis*

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Introduction

The expansion of fast-growing tree plantations is a worldwide process, with consequences on soil fertility and carbon storage (Berthrong et al. 2009; Eclesia et al. 2012). Disparate results were found about the effects of afforestation with *Eucalyptus* on soil carbon and other nutrient contents. These discrepancies are usually caused by factors such as land use history, soil texture, management practices, plantation age, number of rotation and climate (Gonçalves et al. 2004). Many researchers found a positive effect of *Eucalyptus* on degraded soils, while little effects were observed in plantations established on natural or implanted pastures (Laganière et al. 2010; Fialho and Zinn 2012; Li et al. 2015). Moreover, soil organic carbon and nitrogen under *Eucalyptus* plantations were negatively associated with mean annual precipitation and positively with plantation age (Berthrong et al. 2012; Eclesia et al. 2012).

Soil texture is a key factor controlling carbon (C) dynamics, attributed mainly to physical C protection by clays (Oades 1988). The magnitude and direction of soil carbon changes after afforestation depend, to a substantial extent, on soil texture. Fine-textured soils exhibit a high potential for accumulating carbon either before or after conversion to grasslands. Coarse-textured soils can exhibit no effects (Laganière et al. 2010; Fialho and Zinn 2012; Cook et al. 2016) or negative effects (Zinn et al. 2002) of grassland afforestation on soil carbon contents. However, in fine-textured and carbon-rich soils, carbon storage can decrease faster than in coarse-textured soils after harvesting (Wan et al. 2018).

Forestry practices affect soil carbon and other nutrient levels (Laclau et al. 2010). Several studies have shown that a substantial proportion of soil carbon loss occurs in the first rotation as a consequence of site preparation and vegetation replacement (Laganière et al. 2010; Fialho and Zinn 2012; Temesgen et al. 2016). In successive rotations, this negative trend can be maintained if stands are replanted (Li et al. 2015) or can be reversed if coppice management is implemented (Fialho and Zinn 2012). Similar trends were observed for C and N levels with land use change (Berthrong et al. 2009, 2012; Li et al. 2015; Temesgen et al. 2016), but not necessarily for other nutrients. Zero, negative or positive effects of afforestation were found for P, Ca and K in different studies, depending on local conditions (Jobbágy and Jackson 2004; Céspedes-Payret et al. 2012; Temesgen et al. 2016).

Several studies highlight the importance of management practices on productivity and their implication in atmospheric carbon sequestration (Thornley and Cannell 2000; Jandl et al. 2007). Mendham et al. (2004) have shown that the removal of harvest residues after two successive rotations reduced plantation productivity of *Eucalyptus globulus* Labill. in south eastern Australia, even on fertile soils. The expansion of plantations in northeastern Argentina, southeastern Brazil and Uruguay have affected temperate grasslands (Pampas), among other eco-regions (Jobbágy et al. 2006). In Entre Ríos province, Argentina, these plantations cover more than 145,000 ha (Ministerio de Agroindustria de la Nación 2017) on sedimentary, low organic soils. The direct effects of *Eucalyptus* plantations on soil fertility are related to nutrient exportation, treatment of harvest residues, and reduced organic inputs from litter decomposition (Goya et al. 2008, 2009). Soil preparation may indirectly result in considerable nutrient losses (García Préchac et al. 2001; Gonçalves et al. 2004; Frangi et al. 2016). Reductions in nutrient concentrations were reported after one rotation with *Eucalyptus grandis* on sedimentary, low organic soils in northeast Argentina (Goya et al. 2013). However, some practices could reduce nutrient export, such as leaving branches and bark on site and not burning harvest debris (Goya et al. 2009). Therefore, depending on management, successive cultivations with fast-growing *Eucalyptus* could negatively affect soil fertility, endangering a sustainable production.

The objective of this study was to evaluate the effects of *Eucalyptus grandis* W. Hill ex Maiden plantations on soil nutrient storage under current management practices. Specifically, we hypothesized that soil nutrient content is affected when grasslands are replaced by *E. grandis* plantations, but the effect depends on soil texture and site management. A positive effect of stand age on soil nutrient content and a negative effect of the number of rotations, especially on fine-textured and nutrient rich soils, was expected. Soil nutrient losses are expected to be greater if stands are replanted than if coppice management is implemented. Finally, as a consequence of nutrient losses, a negative effect of the number of rotations on foliar nutrients and plantation yields was expected.

Materials and methods

Study area

This study was conducted near Concordia city (31°23′S58°02′W), Entre Ríos province, Argentina. The regional climate is warm-temperate without a dry season. The mean annual temperature is 18.9 °C (absolute minimum temperature is − 4.8 °C and absolute maximum is 40.5 °C). Mean annual precipitation is 1308 mm (Garrán et al. 2007).

Soils were classified as Fluventic Haplumbrept, order Inceptisol (Dalla Tea and Marcó 1996). The soil structure is characterized by a sandy upper horizon, brown to dark brown, lying on a dense, low permeable, clayey sediment together with sand in a heterogeneous mix (Tasi 2009). *E. grandis* plantations are fast-growing (35–45 m^3 ha^{-1} y^{-1}), yielding 300–400 m^3 ha^{-1} up to 10–12 years (Goya et al. 1997), and allows for implementing short-rotation management. These plantations have been established on post-harvest stands following residue burning in some cases, or on land previously occupied by grasslands. The methods of establishment were plantations on previous grasslands, replanting between lines, and coppice management.

Soils

A total of thirty-one *E. grandis* plantations and eight grasslands sites (Fig. 1) adjacent to the plantations, were sampled for a composite sample (Cochran 1977). Soil samples were taken separately from the upper 20 cm layer and at 20–30 cm because a higher proportion of total fine roots are concentrated in these layers and reflect rapid soil changes associated with land use (Pérez et al. 2013). In each site and depth, 10 subsamples were extracted with a soil borer and combined into a composite sample for chemical analysis. Due to low spatial variation in bulk density in these soils, only three subsamples were obtained in each site with a 10 cm soil core, and 308.6 cm^3 in volume to estimate this variable. Soil samples were oven dried at 105 °C to a constant weight. Soil texture for each 20 cm depth was determined using the Bouyoucos hydrometer method (Gee and Bauder 1986). The values are shown in Table S1 (supplementary material).

Textural class was determined based on FAO (2006). Sand percentage intervals were defined to separate the predominant textural classes. These classes were 50–60% (sandy-clay-loam, loam soils), 60–75% (sandy-loam soils) and 75–95% (sand to loamy-sand soils). These sand percentage classes were used for descriptive purposes.

Plantations

In each stand, one plot was established for the estimation of stand structure. The plot area varied between 225 and 460 m^2 depending on density, since an approximately fixed number of 30 trees per plot was sampled. Diameters at 1.30 m height (DBH) were measured for all trees using a diameter tape. Total height was measured with a Vertex hypsometer for 50% of the trees in the plot. Height on DBH regressions were calculated to estimate the height of all trees in the plot, allowing for the use of equations developed by Goya et al. (1997) to estimate dry weight per tree and aboveground biomass (Mg ha^{-1}).

The sampled sites were six first rotation plantations (SS1), ranging from 2 to 11 years old; 16 coppice stands (SR) 2–12 years old and second to fourth rotation; nine replanted stands (SS2) 1–10 years old on site with second to fourth rotations, and eight grassland sites (Table S2).

Chemical analysis

Vegetation samples were obtained during the period of maximum growth in March. The samples (stem, bark, branches and leaves) were dried, milled and sieved through 20 mesh. They then were burnt in a microwave oven at 500 °C and the ashes dissolved for chemical analysis. Soil

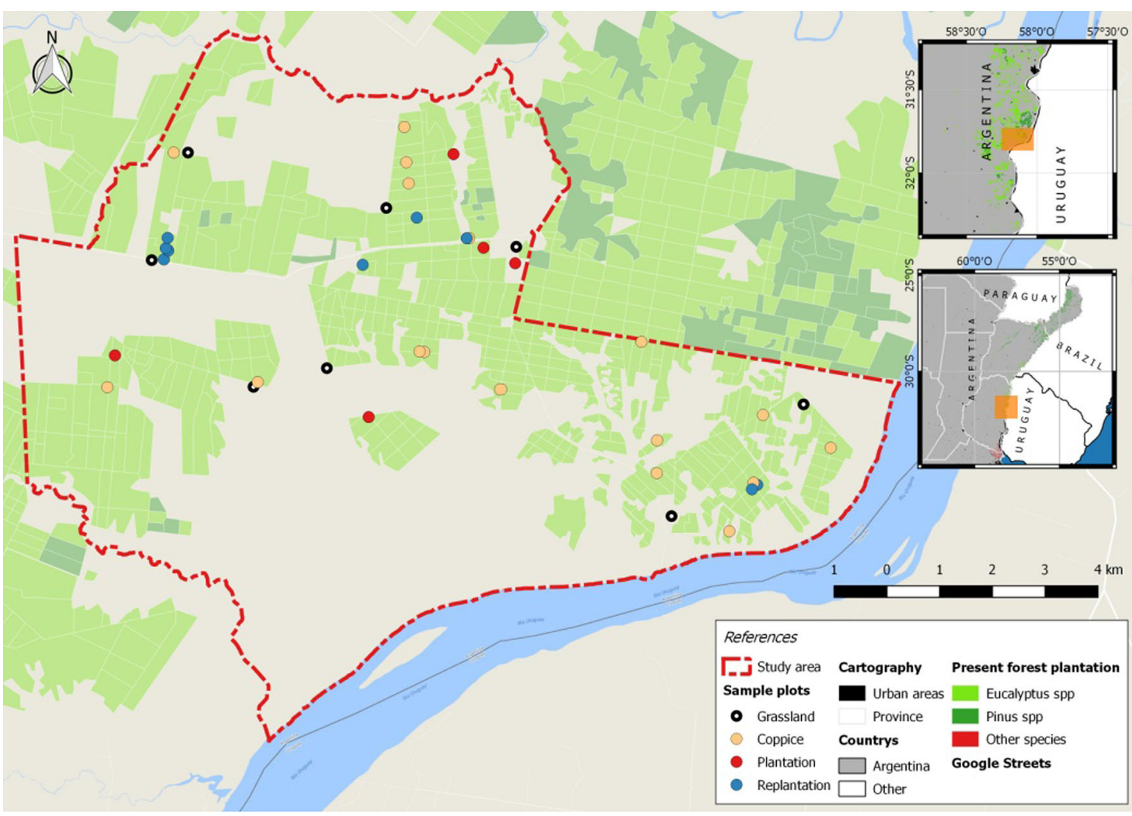

Fig. 1 Distribution of sample plots

samples were air dried, screened through 2 mesh, oven dried at 40 °C and sieved through 20 mesh. The samples were digested in acid for the determination of total nutrient concentrations. Carbon and nitrogen concentrations of plant and soil samples were determined by dry combustion using a LECO CNS-2000 (Tabatabai and Bremner 1991), and phosphorus, potassium, calcium and magnesium concentrations were carried out with a Beckman plasma emission spectrometer Spectra-scan. The values of the mineralomass are in the Table S3 and those corresponding to the soil in the Table S4.

Variables

Because soil nutrients were described by depth intervals, with possible change in bulk density, to remove this variability, nutrient concentrations (mg g^{-1}) were converted to absolute nutrient contents (Mg ha^{-1}) as the product of concentration by bulk density and by the thickness of the soil layer (Jobbágy and Jackson 2001). Plant nutrient levels were calculated as the product of nutrient concentration and the biomass of the respective compartment.

The site quality index for each stand was calculated using the mean dominant height (Assmann 1970) and site index curves (reference age 10 years), for *Eucalyptus grandis* (Crechi et al. 2011). Site quality index was only calculated for replanted stands.

Statistical analysis

The effects of plantation age (A), number of rotations (R) and the method of establishment (P: plantation, C: coppice) on soil and plant nutrients were evaluated using linear models (West et al. 2014). Grassland soils were included in the models with A = 0 and R = 0. R represents the effect of successive rotations including the conversion process. Since available sampling sites did not follow a balanced combination of the effects under evaluation, an exploratory analysis was used to avoid spurious conclusions, as recommended by Zuur et al. (2010).

The use of automatic procedures for the selection of variables was avoided because these methods inflate the type I error rate (Mundry and Nunn 2009). These authors suggested that a selection of variables based on descriptive procedures and guided by theoretical questions should be used. Following this approach, and based on our questions, we started including sand percentage (S), and the interaction sand percentage × rotation number (S × R), stand age (A) and soil depth (0–20 and 20–30 cm). Testing for the effect of such variables, we attempted to answer questions related to the effect of forest plantations on soil, throughout the growing cycle, over rotations and their interaction with soil texture.

Every sampled stand was considered as only one case with two observations made at different soil depths. Thus, soil depth was taken as a within-subject factor (within-stand) in the statistical analysis. Different random factor structures were considered following the procedure suggested by West et al. (2014). The need for a structured variance–covariance matrix was evaluated, given that the within-subject factor soil depth was included. The autoregressive structure of order 1 was selected (West et al. 2014). The need for stand-specific slopes and intercepts for the within-subject "depth" factor was evaluated using the function ANOVA in nlme package at 5% significance level (West et al. 2014), and models with lower Akaike Information Criterion (AIC) were retained. After fitting this model, significant variables were retained and then the effect of the method of establishment, assigning 1 to coppice and 0 to planted stands, was included. Therefore, a positive coefficient indicated the dependent variable was higher in coppice stands.

Models were fitted with nlme package (West et al. 2014) in R software (R Development Core Team 2017), taking "stand" as the only random factor on which different soil depth observations were made. The existence of multicollinearity among predictors was tested using the variance inflation factor (VIF) with a conservative value "3" as the acceptable limit (Zuur et al. 2010).

Soil and plant nutrient concentrations were plotted against the number of rotations separately per sand percentage class, in order to check if data trends were or were not in agreement with statistical results. Different markers were used for different methods of establishment.

Results

Soil texture, nutrient concentration and content

Sand percentage ranged between 50.4 and 93.7%. The number of stands in each soil sand percentage class were 16 (50–60%), 26 (60–75%) and 36 (> 75%).

Soil bulk density increased significantly with sand content (1.30–1.40 g cm^{-3}) (b = 0.003; $p < 0.005$) but there was no significant relationship with other variables ($R^2 = 0.16$, model $p < 0.05$). Soil C, N, P, K and Ca concentrations decreased with increasing sand percentage. Fitted models explained 50–60% of the variance C, N, Ca and Mg concentrations (Table 1).

Independent variables exhibited a maximum VIF = 1.7, indicating that no problems related to multicollinearity are likely to have occurred. No model improvement was observed by including a structured variance–covariance matrix in any case. Soil sand content and its interaction with R were the most important effects, accounting for up

Table 1 Parameters of linear models relating soil nutrient concentrations (mg g^{-1}) and nutrient ratios to explanatory variables (n = 78)

	C	N	P	K	Ca	Mg	C:N	C:P	N:P	pH_{Clk}
Interception	**31.12**	**2.77**	**0.17**	**1.82**	**6.04**	**1.91**	11.95	**249.7**	**21.06**	**5.17**
Sand (%)	**− 0.25**	**− 0.02**	**-7×10^{-4}**	**− 0.02**	**− 0.07**	**− 0.02**	− 0.03	**− 2.06**	**− 0.15**	-7×10^{-3}
Sand (%) × R	**− 0.02**	**-2×10^{-3}**	2×10^{-5}	-3×10^{-5}	-1×10^{-3}	-3×10^{-4}	0.01	**− 0.20**	**− 0.02**	**1×10^{-3}**
Age (years)	0.02	-7×10^{-4}	-9×10^{-4}	4×10^{-3}	− 0.05	-4×10^{-4}	− 0.12	1.32	0.09	**− 0.06**
SR (1: coppice; 0: plantation)	**3.39**	**0.26**	-2×10^{-3}	0.012	0.10	0.06	− 0.56	**37.18**	**2.95**	**− 0.41**
Depth (0: 0–20 cm; 1: 20–30 cm)	**− 2.40**	**− 0.25**	**− 0.02**	0.02	0.30	0.09	0.77	− 2.65	− 0.28	9×10^{-3}
Adjusted R^2	0.56	0.61	0.15	0.37	0.61	0.54	0.02	0.56	0.51	0.19
P model <	1×10^{-6}	1×10^{-6}	0.005	1×10^{-6}	1×10^{-6}	1×10^{-6}	0.28	1×10^{-6}	1×10^{-6}	0.001

R number of rotations, *SR* coppice

Significant values ($p < 0.05$) are given in bold to 75% of the variance of C and N concentrations. These decreased with increasing number of rotations, and this trend was weaker in soils with more than 75% sand (Figs. 2 and 3). Soil C and N levels were higher in coppice soils than in soils under replanted stands (Table 1). This trend was especially apparent in soils with > 75% sand (Figs. 2 and 3). For both C and N concentrations, the method of establishment accounted for approximately 15% of the variance.

Carbon, N and P concentrations were higher in the upper layer (0–20 cm depth) than in the deeper layer (20–30 cm), and showed similar trends in both layers with the number of rotations and sand content. In such analysis, stand-specific slopes and intercepts were retained, since lower AIC´s were observed for models including these random effects ($p < 0.01$ for all comparisons). No significant differences between soil depths were found for K, Ca, Mg concentrations, nor for the nutrient ratios C:N, C:P and N:P. Sand content × R interaction effect was observed for the C:N ratio, indicating a positive relationship with increasing R, and this was stronger in sandier soils. Sand content × R interaction was also significant for C:P and N:P ratios (Table 1). Models for soil nutrient contents showed the same significant effects as nutrient concentrations, except soil depth was not evaluated since upper and lower layer content were pooled (Table 2).

Soils were acidic to very acidic. In the upper 20 cm layer, the pH varied between 4.5–5.3 in grasslands and 4.0–4.3 in plantations. Soil pH was not affected by depth but decreased with stand age and was lower in coppice than under planted stands. Sand percentage × R interaction was observed, indicating that pH diminished with R and that this was stronger as sand percentage increased (Table 2).

Aboveground biomass, growth and site quality index

Aboveground biomass for 8–10-year-old stands was 114.3–192.9 Mg ha^{-1} with mean annual increments (MAI) ranging between 12.7 and 24.1 Mg ha^{-1} a^{-1} for that age (Fig. 4). A positive effect of stand age on biomass ($b = 19.1$; $p < 0.0001$) and MAI ($b = 1.7$; $p < 0.0004$) were the only significant results. Mean site quality index for *E. grandis* was 36.4 ± 1.4 m (mean ± standard error), which was not related to soil sand content or to number of rotations.

Aboveground nutrient concentrations and content

Significant models were fitted for foliar N, P and K concentrations (nitrogen Adj. $R^2 = 0.45$, $F(4,25) = 7.0$, $p < 0.0006$; phosphorus Adj. $R^2 = 0.45$, $F(4,25) = 7.6$, $p < 0.0004$; potassium Adj. $R^2 = 0.53$, $F(4,25) = 9.3$, $p < 0.00009$) but not for calcium or magnesium. Plantation age negatively affected foliar concentrations of N ($b = -1.2$, $p < 0.00004$), P ($b = -0.09$, $p < 0.00004$) and K ($b = -0.3$, $p < 0.00003$). In coppiced stands, foliar P ($b = -0.2$, $p < 0.01$) and K ($b = -1.0$, $p < 0.003$) levels were lower than in planted stands (Fig. 5). Sand content and number of rotations affected foliar K concentrations, which decreased with number and sand content, but the number of rotations effect was higher with decreasing sand percent, yielding a significant interaction ($b = -0.005$, $p < 0.01$). Plant nutrient content increased

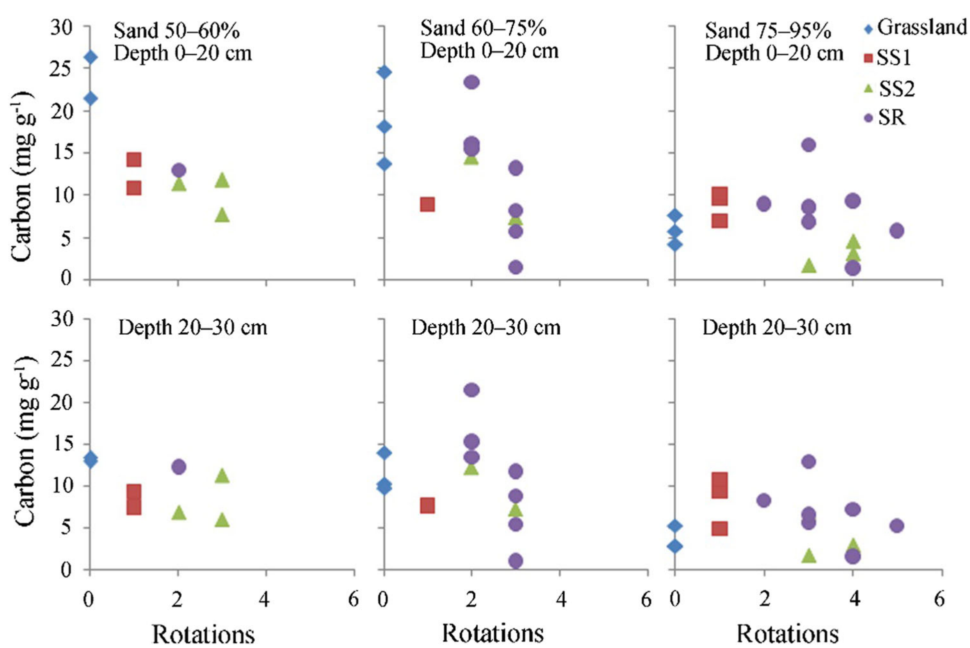

Fig. 2 Soil carbon concentration (mg g^{-1}) as a function of rotations at 0–20 and 20–30 cm depth in each range of percentage of sand. SS1: planting, SS2: replanting, SR: coppice

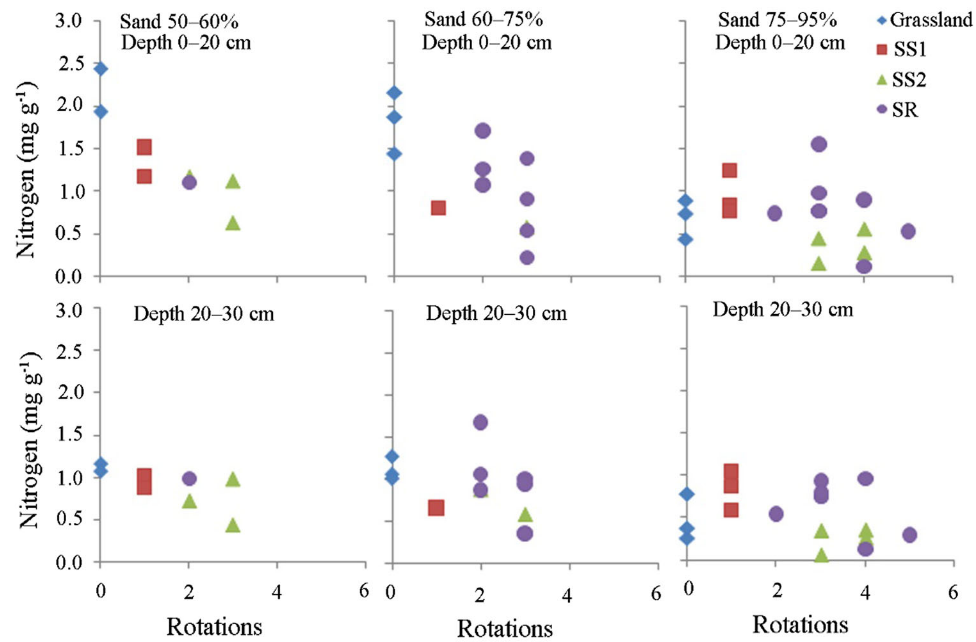

Fig. 3 Soil nitrogen concentration (mg g^{-1}) as a function of rotations at 0–20 and 20–30 cm depth in each range of percentage of sand. SS1: planting, SS2: replanting, SR: coppice

Table 2 Parameters of linear models relating soil nutrient content (Mg ha^{-1}) to explanatory variables (n = 78)

	C	N	P	K	Ca	Mg
Interception	**111.84**	**9.80**	0.61	**9.36**	**33.39**	**10.52**
Sand (%)	**− 0.98**	**− 0.08**	− 0.003	**− 0.09**	**− 0.34**	**− 0.11**
Age (years)	0.05	− 0.01	− 0.004	0.03	− 0.24	0.01
Sand (%) × R	**− 0.08**	**− 0.008**	0.00004	− 0.0003	− 0.006	− 0.002
SR (1: coppice, 0: plantation)	**13.79**	**1.04**	− 0.01	0.10	0.64	0.35
Adjusted R^2	0.60	0.66	0.06	0.34	0.68	0.61
P model <	1×10^{-6}	1×10^{-6}	0.19	0.001	1×10^{-6}	1×10^{-6}

R number of rotations, *SR* coppice

Significant values ($p < 0.05$) are given in bold

with age for all analyzed nutrients which was the only significant effect.

Discussion

Soil C and N concentration and content

Carbon and nitrogen levels were negatively affected by grassland afforestation and by successive rotations with *Eucalyptus grandis*. However, carbon loss was not homogeneous across the range of soil sand contents. In sandy or loamy-sandy soils (75–95% sand content), the differences in C and N contents between grasslands and third rotation plantations were − 5 Mg ha^{-1} and − 1.5 Mg ha^{-1}, respectively. In sandy-clay-loam soils and loam soils (50–60% sand content), these differences in C and N content were − 42.1 Mg ha^{-1} and − 3.9 Mg ha^{-1}, respectively (Table 3). Grasslands lost 23% of soil C content and 60% of soil N content in sand and loamy-sand soils, while those losses were 53% in C content and 55% in N in sandy-clay-loam and loam soils. Clay and silt particles can prevent the decomposition of soil organic matter since complex organic-mineral compounds are formed. These play a central role in soil organic carbon stability (Oades 1988; Six et al. 2002). However, in our study, fine-textured soils experienced greater carbon and nitrogen losses than coarse-textured soils. It is well known that humid-sub-humid grasslands on fine-textured soils are more productive than on sandy soils due to higher nutrient availability (Sala et al. 1988; Burke et al. 1989). This may explain the higher initial C and N observed in grasslands on sand and loamy-sand soils. Moreover, *E. grandis* plantations on fine-textured soils exhibited higher decomposition rates than those on coarse-textured ones (Goya et al. 2008), which can reinforce C and N loss rates. Wan et al. (2018) found that

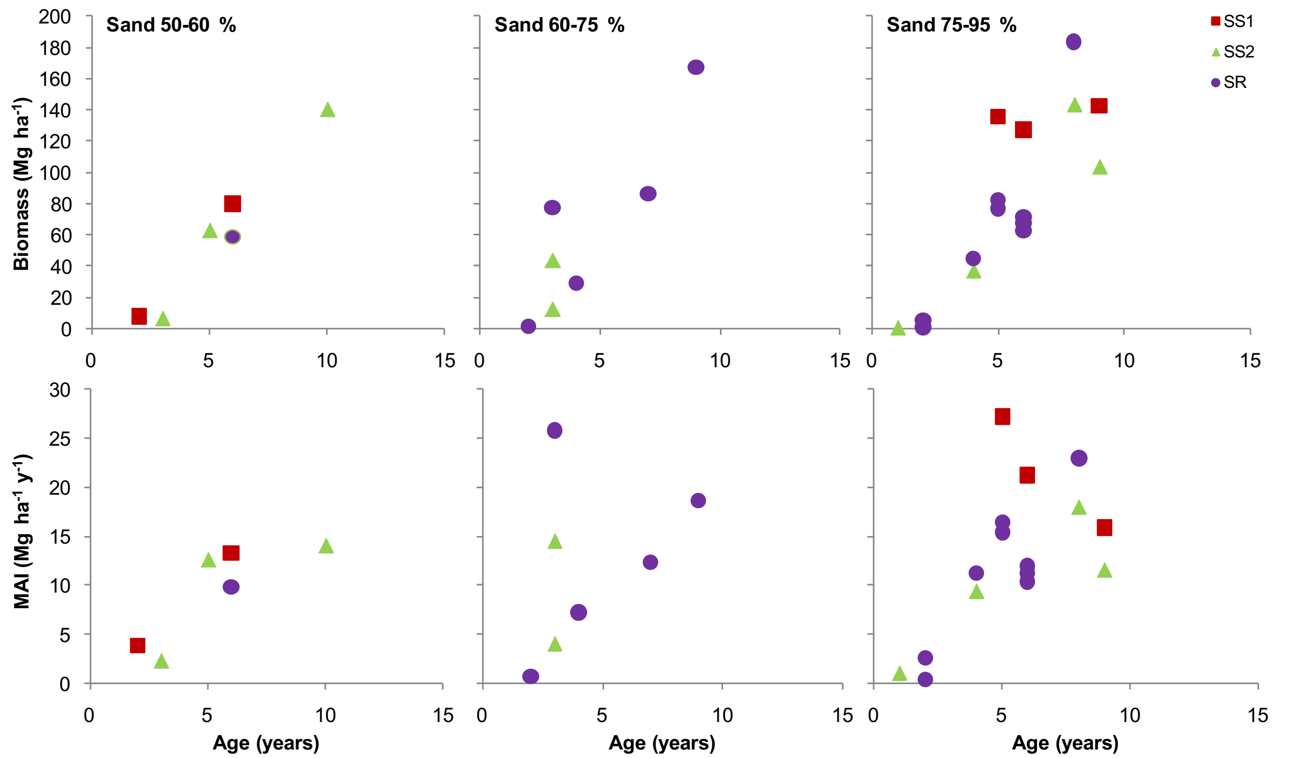

Fig. 4 Aboveground biomass (Mg ha^{-1}) and MAI (Mg ha^{-1} y^{-1}) of *E. grandis* plantations as a function of plantation age. SS1: planting, SS2: replanting, SR: coppice

soil texture was an important influence on soil C depending on the type of harvesting method. In a meta-analysis, they compared soil carbon differences between two harvest residue management practices (retention vs. removal). Residue retention showed less C gain in high clay content soils than in coarse-textured soils since clay can increase rates of soil respiration (Wan et al. 2018). In this study, carbon and nitrogen were higher under coppiced stands where harvest residues are retained, than under replanted stands. This difference was more apparent in soils with $> 75\%$ sand. This suggests an interaction between sand content and the method of plantation establishment. This was not evaluated because there were no balanced combinations of soil sand levels and method of establishment available in our data. However, the trend is in agreement with results of Wan et al. (2018). Precipitation was also identified as an influential factor on soil respiration and on soil C dynamics. Berthrong et al. (2012) and Eclesia et al. (2012) found that soil C and N losses in *Eucalyptus* plantations in South America occurred only on sites where the annual precipitation was above 1200 mm. Precipitation in this study area is about 1300 mm per year, thus a net C loss is expected. In summary, soil carbon losses appear greater in humid grasslands on fine-textured soils because their high productivity promotes greater C and N contents, which rapidly decompose after conversion, compared to grasslands on coarse-textured soils or in a dry climate. Under ideal conditions of precipitation and soil texture, site preparation previous to plantation establishment, which implies breaking down structure and increasing aeration, can greatly accelerate carbon oxidation (Burke et al. 1989; Six et al. 2002).

In this study, there was no effect of stand age on soil carbon and nitrogen concentrations or contents. Conversely, Berthrong et al. (2012) and Eclesia et al. (2012) found a positive relationship between C and N levels and a plantation age of 26 years. The usual rotation age for the plantations in this study was 12 years. Taking into account the slow decomposition rates of *E. grandis* litter, rotation age appears insufficient to have a positive effect on soil C and N contents. Laganière et al. (2010) suggest that, if the litter layer is considered part of the soil carbon content, the effect of commercial plantations on such a variable could shift from negative to zero or even to positive. However, they stated that the organic matter in litter will not necessarily increase soil C content because it is strongly affected by burning and other harvest residue management practices. In an 11-year-old *E. grandis* plantation, the litter layer was approximately 28 Mg ha^{-1} (Goya et al. 2009). Our results do not include the litter layer and thus constitute a conservative baseline of the effect of plantations on soil C content. The plantations are approximately seven-

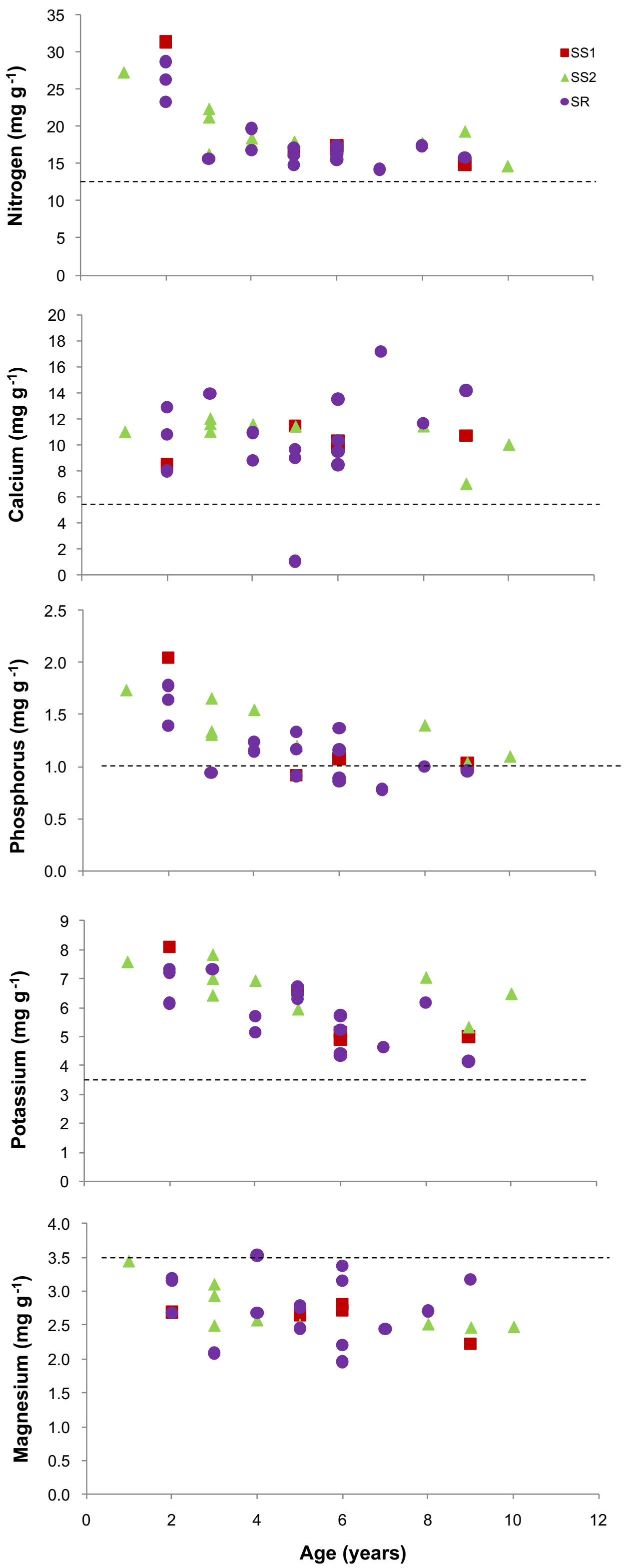

Fig. 5 Leaf nutrient concentration (mg g^{-1}) as a function of plantation age. The critical values established by Binkley and Fisher (2013) for *E. grandis* are indicated with dotted lines. SS1: planting, SS2: replanting, SR: coppice

fold more productive than the grasslands they replaced, but soil C content has not increased. This is mainly due to a high proportion of productivity allocated to the stem which is harvested. Litter C is lost when harvest residues are burned or decomposed after tillage prior to plantation establishment. Thus, a short rotation age, burning harvest residues, and soil tillage prior to planting greatly contribute to soil C and N losses over rotations. This highlights the strong incidence of management on the environmental effects of plantations as proposed by Kimmins (1997).

Soil nutrient ratios

Soil C:N ratios were not significantly related to any variable because C and N responded similarly to them. This was attributed to litter decay of both nutrients which are closely associated (McGroddy et al. 2004). Soil C:P and N:P ratios decreased over the number of rotations because of C and N losses. Soil P, K, Ca and Mg concentrations and contents were negatively associated with sand content, possibly because sand and loamy-sand soils have lower organic matter and a lower cation exchange capacity than the fine-textured soils we studied. In addition, P, K, Ca and Mg were unchanged over the number of rotations both in fine-and coarse-textured soils. Sand content was negatively related with the concentration of all the nutrients analyzed, and thus, the sand and loamy-sand soils in this study were poorer than the fine-textured ones. However, mean annual increment in biomass did not follow the same trend as soil nutrient concentrations and content, since the MAI of *E. grandis* plantations did not decrease over rotations nor with increasing soil sand content. This suggests that other limiting factors are involved in the nutrient-rich soils.

Foliar nutrients

Foliar nutrient levels can indicate the adequacy of soil nutrient supply. In South Africa, field trials assessed critical values of foliar nutrient concentration in *E. grandis* plantations under which nutrient availability could constraint plant growth (Binkley and Fisher 2013). These critical values for N, P, K, Ca and Mg were 12.5, 1.0, 3.6, 5.6, 3.5 mg g^{-1}, respectively (Binkley and Fisher 2013). Using these as a reference, foliar concentrations of the stands in this study are not constrained by nutrient availability, except for magnesium and phosphorous. Thus, only Mg and P might be considered as nutrition deficiencies in the studied plantations (Fig. 5).

Table 3 Soil C and N contents per class of soil sand content for grasslands and *Eucalyptus grandis* plantations with different rotation number and different method of establishment

	Carbon (Mg ha^{-1})			Nitrogen (Mg ha^{-1})		
	Sand 50–60%	Sand 60–75%	Sand 75–95%	Sand 50–60%	Sand 60–75%	Sand 75–95%
Grassland	79.4	63.6	21.5	7.2	6.2	2.6
Plantation 1	43.7	34.7	36.2	4.7	3.1	3.8
Plantation 3	37.3	27.7	16.5	3.2	2.2	1.0
Coppice 3		40.9	22.4		4.0	2.5
Differences between grasslands and plantations						
Grassland/plantation 1	− 35.7	− 29.0	14.8	− 2.4	− 3.1	1.2
Grassland/plantation 3	− 42.1	− 36.0	− 5.0	− 3.9	− 4.0	− 1.5
Grassland/coppice 3		− 22.8	1.0		− 2.2	− 0.1

Plantation 1: plantation of first rotation (n = 6); plantation 3: plantation of third rotation established by replanting (n = 3); coppice 3: plantation of third rotation established by coppice management (n = 2)

Conclusions

The replacement of grasslands by plantations of *Eucalyptus grandis* caused significant losses in soil carbon and nitrogen concentrations and contents and this loss was strongly dependent on soil texture. Losses were greater in sandy-clay-loam or loam soils than in sand or loamy-sand soils. Coppice stands had higher soil carbon and nitrogen contents than plantations. This suggests a negative effect of the burning of harvest residues and site preparation before planting on nutrient contents.

No significant differences were observed in above-ground biomass contents of carbon, nitrogen and other nutrients between methods of establishment. The contents changed with age as is the expected pattern for plantations. Foliar nutrient concentrations do not follow the trends for soil carbon and nitrogen, nor do they reflect nutrient limitations. There was no evidence of decreased yields over successive rotations but yield limitations are expected to occur over a medium to long-term period, especially in stands reestablished by planting under short-rotation management.

Most of the commercial plantations of this species have been established on soils similar to those studied here. The effect of litter dynamics and different residue management practices on nutrient dynamics, as well as their interaction with soil texture, need further study. Moreover, since coppicing is becoming less practiced, the sustainability of site productivity for the application of site-specific silviculture, such as soil preparation, should be restricted to plantation lines and proper residue management. The use of mixed plantations with nitrogen-fixing species should be also considered as a compensation for nitrogen losses.

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