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SELECTION OF TREE SPECIES AND SOIL MANAGEMENT FOR SIMULTANEOUS FUELWOOD PRODUCTION AND SOIL REHABILITATION IN THE ETHIOPIAN CENTRAL HIGHLANDS

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ABSTRACT

In the Ethiopian Central Highlands, a serious soil degradation occurs while fuelwood demand is high. This study consists of an evaluation of seven tree species for fuelwood and soil restoration under three soil management options: control, manure and manure + mulch, in degraded highlands of Ethiopia. The experimental design was a split-plot, species as the main plot and treatment as subplot, with three replicates. Survival count, height and root collar diameter growth measurements were measured annually until 48 months. Biomass production for fuelwood was inferred at the end of the experiment. Before and after the experiment, soil parameters (pH, organic carbon, N, P, K and cation exchange capacity) were measured to test changes in soil condition because of species plantation. A mixed model and repeated analysis of variance was performed. *Grevillea robusta* A. Cunn. ex R. Br. showed maximum survival (100%), followed by *H. abyssinica* (Bruce) J.F.Gmel. (93·52%); while the lowest survival rate was recorded for *A. decurrens* Willd. (57·41%). *Hagenia abyssinica* (Bruce) J.F.Gmel. and *Chamaecytisus palmensis* (Christ.) Hutch showed the lowest growth rates but both species showed the highest soil condition improvement. *E. globulus* Labill. and *Acacia* species presented the highest growth rates and biomass although *Eucalyptus* depleted soil nitrogen. *Hagenia abyssinica* (Bruce) J. F.Gmel. is recommended for soil rehabilitation, whereas *Grevillea robusta* A. Cunn. ex R. Br. can be used for simultaneous fuelwood production and soil rehabilitation. An ecological based study on *E. globulus*' Labill. effects in Central Highlands is recommended before recommendation for large scale fuelwood plantations. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS: tree growth; survival; biomass; nitrogen depletion; mixed model

INTRODUCTION

Sub-Saharan Africa accommodates one of the world's fastest growing populations, and it is significantly affected by land degradation because of deforestation, poor land management and conversion of fragile natural habitats into fields for crops. The forest area in East Africa was reduced by 783,000 ha between 2000 and 2010: equivalent to an annual loss rate of 1.01% (FAO, 2011). Shortages of forest products, loss of soil fertility and disruption of the water cycle are followed by poverty, hunger and social unrest in the region (Barrowclough & Ghimire, 1996).

This general layout of deforestation and its consequences is similar to other tropical and sub-tropical areas (López-García & Ayala-Alcántara, 2012; De la Paix *et al*., 2013) and has made restoration of degraded land an essential challenge. John *et al*. (1997) identified some of the factors that act as catalyst of such situation: intensive crop expansion, overgrazing and unsustainable fuelwood harvesting. In recent years, the fuelwood crisis that links deforestation with fuelwood consumption has been discarded as many of the harvest occurs on species growing 'outside' the forest (Mahiri & Howorth, 2001; Bensel, 2008). This pattern of fuelwood consumption is improved by householders' tree plantations, where natural forests are scarce (Bewket, 2003). As a consequence, tree planting has emerged as a plausible option to fulfil the fuelwood demand (Lemenih & Bongers, 2010). However, there may not be a link between tree planting and fuelwood consumption (Gebreegziabher & van Kooten, 2013).

In Ethiopia, nearly 1·5 billion tons of topsoil is lost every year (Tadesse, 2001). Despite efforts to combat land degradation in all Sub-Saharan Africa, and Ethiopia in particular (Yitbarek *et al*., 2012), the scope and magnitude of the problem continues, and the country is identified among those, which has expanded cropland area at the expense of natural habitats (Phalan *et al*., 2013). Currently, the seemingly contradictory objective of restoring vegetation cover and production of fuelwood is a key environmental issue.

With this regard, species selection for afforestation is crucial as the tree species may affect soil properties differently (Li *et al*., 2012). However, interim management solutions such as physical soil retention structures are needed prior to establishing vegetation (Yitbarek *et al*., 2012). Exclosures

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have been identified as a valuable rehabilitation option when the main driver of land degradation is grazing (Mekuria & Ayenekulu, 2011) or intense recreational use (Özcan *et al.*, 2013). However, these measures are expensive for local communities. Effective restoration practices should be based on local perceptions of soil erosion and should include easily available management options (Kiome & Stocking, 1995). The application of manure has demonstrated to positively affect the infiltration capacity of soils and plant production on grazed lands (Tadesse *et al.*, 2003) at low cost. In addition, mulching can both enhance conditions for plant growth in harsh environments (Blanco-García & Lindig-Cisneros, 2005) and protect topsoil against erosion (Roose & Barethès, 2001). The correct selection of plant species and soil management is vital for both fuelwood production and soil rehabilitation.

Motivation for this study stems from the lack of research on species selection for plantations that pursues two objectives: land rehabilitation while assuring fuelwood production in the Ethiopian Central Highlands. The aim was to determine which species and soil management options are better adapted to current Highlands conditions. On the basis of the observations and previous studies, we hypothesized that native tree species might not show better performance for both objectives in this harsh environment.

MATERIAL AND METHODS

Study Area

The study was conducted from 2005 to 2009 in the central highlands of Ethiopia. The study site was located at 9°38'19.66'N latitude and 38°49'34·46'E longitude, at 2600 m a.s.l. (Figure S1). Metereological data were obtained from Ethiopian Metereological Agency in Addis Ababa. The 5-year (2005–2009) averaged mean annual maximum and minimum temperature of the study area were 21°C and 8°C, respectively, with 5-year annual mean averaged precipitation 1,200 mm falling mostly in July and August (Figure S2). Köppen's classification is temperate highland tropical climate with dry winters.

The experimental site was selected through a participatory process with local stakeholders. A focus group discussion was conducted with district agricultural experts, development agents and farmers. The farmers were selected on the basis of age (young: 18–35 years old; adult: 35–55 and old: >55), average income per household per year (poor: $232; medium: $407; rich: $700) and gender. Ten key informant interviewers (development agents, agricultural experts and community administrators) and 40 random households were selected to ascertain commitment and attitude towards the project, in order to avoid a negative impact on the experimental layout. The experimental site was selected on the basis of accessibility and representativeness of degraded land on sandy soil, rock outcrops and without vegetation cover. The experimental site was a cultivated land until 1995 when it was abandoned because of soil fertility depletion.

Species Selection and Experimental Design

The same participatory process as for selection of experimental site was used for the selection of tree species and soil management options. Species were selected on the basis of local adaptability. A total of seven species were identified in this study: two native tree species [*Dombeya torrida* (J.F.Gmel.) Bamps and *Hagenia abyssinica* (Bruce) J.F.Gmel.], four exotic tree species [*Acacia decurrens* Willd., *A.saligna* (Labill.) H.L.Wendl., *Eucalyptus globulus* Labill. and *Grevillea robusta* A.Cunn. ex R. Br.] and one exotic shrub *Chamaecytisus palmensis* (Christ.) Hutch. All seeds were directly sown in polyethylene bags for 8 months and were exposed to similar watering, shading, weeding and hardening off practices until 20–30 cm high.

Three soil management options were applied, based on local perceptions of erosion control: i) a control treatment where nothing was performed to correct the initial degraded condition; ii) application of manure; and iii) application of manure and mulching. Three kilogrammes of decomposed manure were added to the planting pits (40 cm deep) during seedling planting on 12th July, 2005, while 0·5 kg of mulching with air dried grass was applied in the preceding dry season to conserve moisture and avoid the desiccation of soil and seedlings.

The experimental layout was organized as a split-plot design, with tree species as the main plot and soil management options as subplots; it was organized in three blocks to control variation along a slope gradient and three replicates for each species. The main plot consisted of 90 trees divided into three groups of 30 trees; each arranged into five rows, with six trees in each row. The distance between trees in the same row and between rows in the same subplot was 1·5 m, whereas the distance between treatments in the main plot and sub-plots was 2 m. Weeding and hoeing were applied uniformly to the entire plot on 10th of August and 12th of September 2005 (Figure S3).

Data Collection and Procedure

The 12 inner trees in every sub-plot were assessed for data collection, and the rest were considered border trees. Survival counts, along with tree height and root collar diameter measurements were taken at 12, 24, 36 and 48 months after planting.

Volume was calculated from the average height and diameter of the experiment trees; total biomass calculations were based on tree volume and specific gravity, using values obtained from the specific gravity. Table I provides a summary of data 1 and 4 years after planting.

Soil Sampling and Analysis

Soil augering was carried out in 3m × 3m subplot at the initial and final stage of the experiment, at 0–10, 10–30 and 30–50 cm depth. A total of 72 composite soil samples were collected for analysis. Three random sampling points were mixed to form one composite sample. The collected samples were air dried, sieved (2 mm diameter) and grounded before analysis.The samples were analyzed for pH (1:2·5 soil : water ratio), total N (%) using Kjeldahl's method, organic carbon (%) according to Walkely–Black's method, available

Table I. Mean values of response variables 12 and 48 months after planting

					pH			% OC			% N			P (ppm)			K (meq/100 g soil)			CEC (meq/100 g soil)		
Species	Period	Height (m)	RCD (cm)	Survival (%)	0–10 cm	10–30 cm	30–50 cm	0–10 cm	10–30 cm	30–50 cm	0–10 cm	10–30 cm	30–50 cm	0–10 cm	10–30 cm	30–50 cm	0–10 cm	10–30 cm	30–50 cm	0–10 cm	10–30 cm	30–50 cm
Acacia	12	0·97	1·33	83·2	7·99	8·05	8·15	0·91	0·75	0·51	0·063	0·047	0·033	1·67	1·60	1·67	0·89	0·90	0·84	20·27	22·18	23·48
decurrens		(0·30)	(0·39)	(11·0)	(0·20)	(0·10)	(0·10)	(0·10)	(0·14)	(0·20)	(0·01)	(0·01)	(0·01)	(0·12)	(0·20)	(0·23)	(0·14)	(0·21)	(0·10)	(4·27)	(5·69)	(0·83)
	48	6·52	7·34	56·4	7·96	7·78	7·74	0·85	0·62	0·63	0·053	0·057	0·053	2·60	2·53	2·80	0·84	0·71	0·73	16·50	17·99	22·92
		(2·07)	(2·09)	(19·3)	(0·14)	(0·47)	(0·52)	(0·15)	(0·40)	(0·20)	(0·01)	(0·011)	(0·012)	(0·40)	(0·70)	(1·06)	(0·10)	(0·30)	(0·32)	(1·95)	(4·24)	(4·96)
Acacia	12	1·12	1·98	88·1	7·99	8·05	8·15	0·91	0·75	0·51	0·063	0·047	0·033	1·67	1·60	1·67	0·89	0·90	0·84	20·27	21·86	23·50
saligna		(0·32)	(0·63)	(12·1)	(0·20)	(0·10)	(0·10)	(0·10)	(0·14)	(0·20)	(0·01)	(0·01)	(0·01)	(0·12)	(0·20)	(0·23)	(0·14)	(0·21)	(0·10)	(4·27)	(4·46)	(0·82)
	48	5·24	8·68	68·3	7·96	7·78	7·74	0·79	0·84	0·57	0·05	0·053	0·043	2·13	1·87	2·27	0·82	0·71	0·57	19·03	21·32	17·78
		(1·33)	(3·03)	(24·2)	(0·14)	(0·47)	(0·52)	(0·37)	(0·10)	(0·12)	(0·01)	(0·01)	(0·02)	(0·76)	(0·04)	(1·50)	(0·41)	(0·48)	(0·42)	(1·57)	(1·53)	(2·81)
Chamaec·	12	1·02	1·40	91·7	7·99	8·05	8·15	0·91	0·75	0·51	0·063	0·047	0·033	1·67	1·60	1·67	0·89	0·90	0·84	20·27	21·86	23·48
palmensis		(0·34)	(0·37)	(11·1)	(0·20)	(0·10)	(0·10)	(0·10)	(0·14)	(0·20)	(0·01)	(0·01)	(0·01)	(0·12)	(0·20)	(0·23)	(0·14)	(0·21)	(0·10)	(4·27)	(4·46)	(0·88)
	48	3·34	5·33	70·4	7·64	7·57	7·57	1·89	1·40	0·81	0·107	0·077	0·107	2·93	2·20	2·67	1·07	1·03	1·11	18·75	20·59	24·28
		(1·61)	(2·87)	(22·1)	(0·14)	(0·15)	(0·25)	(0·50)	(0·17)	(0·37)	(0·03)	(0·05)	(0·08)	(0·99)	(0·60)	(0·46)	(0·04)	(0·11)	(0·14)	(2·16)	(2·48)	(7·76)
Dombeya	12	0·84	1·62	99·1	7·99	8·05	8·15	0·91	0·75	0·51	0·063	0·047	0·033	1·67	1·60	1·67	0·89	0·90	0·84	20·27	21·86	23·50
torrida		(0·15)	(0·34)	(2·7)	(0·20)	(0·10)	(0·10)	(0·10)	(0·14)	(0·20)	(0·01)	(0·01	(0·01	(0·12	(0·20)	(0·23)	(0·14)	(0·21)	(0·10)	(4·27)	(4·46)	(0·82)
	48	3·13	4·86	58·3	7·96	7·96	7·93	1·17	0·86	0·71	0·08	0·073	0·05	2·73	2·35	2·33	1·08	1·08	0·89	20·71	23·21	18·54
		(0·97)	(1·25)	(19·4)	(0·10)	(0·47)	(0·24)	(0·45)	(0·14)	(0·24)	(0·03)	(0·05)	(0·03)	(0·70)	(0·96)	(0·64)	(0·17)	(0·18)	(0·16)	(3·86)	(1·72)	(0·89)
Eucalytus	12	0·79	1·14	88·93	7·99	8·05	8·15	0·91	0·75	0·51	0·063	0·047	0·033	1·67	1·60	1·67	0·89	0·90	0·84	20·27	21·86	20·60
globulus		(0·16)	(0·23)	(10·3)	(0·20)	(0·10)	(0·10)	(0·10)	(0·14)	(0·20)	(0·01)	(0·01)	(0·01)	(0·12)	(0·20)	(0·23)	(0·14)	(0·21)	(0·10)	(4·27)	(5·47)	(5·53)
	48	8·63	8·92	76·9	7·83	7·62	7·85	0·79	0·64	0·39	0·043	0·03	0·03	1·93	1·83	2·03	0·90	0·65	0·93	16·42	13·85	25·94
		(1·65)	(2·19)	(18·7)	(0·18)	(0·47)	(0·23)	(0·09)	(0·23)	(0·13)	(0·01)	(0·01)	(0·01)	(0·06)	(0·35)	(0·74)	(0·19)	(0·04)	(0·04)	(1·87)	(1·08)	(0·55)
Grevillea	12	0·50	1·18	100	7·99	8·05	8·15	0·91	0·75	0·51	0·063	0·047	0·033	1·67	1·60	1·67	0·89	0·90	0·84	20·27	21·86	23·50
robusta		(0·12)	(0·22)		(0·20)	(0·10)	(0·10)	(0·10)	(0·14)	(0·20)	(0·01)	(0·02)	(0·01)	(0·12)	(0·20)	(0·23)	(0·14)	(0·21)	(0·10)	(4·27)	(5·47)	(0·82)
	48	3·41	6·22	100	7·72	7·85	7·86	1·36	1·22	0·60	0·063	0·047	0·03	2·60	2·07	2·37	0·98	1·08	0·93	20·51	25·45	21·84
		(0·89)	(1·91)		(0·28)	(0·38)	(0·20)	(0·60)	(0·78)	(0·58)	(0·01)	(0·02)	(0·01)	(0·87)	(0·31)	(0·74)	(0·08)	(0·19)	(0·19)	(1·70)	(7·98)	(9·56)
Hagenia	12	0·25	1·20	97·3	7·99	8·05	8·15	0·91	0·75	0·51	0·063	0·047	0·033	1·67	1·60	1·67	0·89	0·90	0·84	20·27	21·86	23·48
abyssinica		(0·08)	(0·24)	(4·0)	(0·20	(0·10)	(0·10)	(0·10)	(0·14)	(0·20)	(0·01	(0·01)	(0·01)	(0·12)	(0·20)	(0·23)	(0·14)	(0·21)	(0·10)	(4·27)	(4·46)	(0·84)
	48	1·78	4·47	90·7	7·60	7·65	7·68	1·62	1·13	0·51	0·097	0·083	0·053	2·30	2·27	2·40	1·05	0·89	0·75	18·73	21·42	18·36
		(0·85)	(1·45)	(9·5)	(0·28)	(0·22)	(0·24)	(0·25)	(0·41)	(0·36)	(0·01)	(0·01)	(0·01)	(0·50)	(0·46)	(0·35)	(0·04)	(0·19)	(0·24)	(2·18)	(4·29)	(0·09)

Standard deviation of the mean in parenthesis·
TSP, time since planting; RCD, root collar diameter; OC, organic carbon; CEC, cation exchange capacity·

phosphorus (units) using Olsen's method, pH was determined using a suspension of 1:5 soil : water ratio. Ammonium and sodium acetate were applied to determine cation exchange capacity (CEC). Exchangeable K were measured with flame photometer.

The mean values and standard errors for soil variables at the beginning and end of the experiment are shown in Table I.

Statistical Analysis

Correlation among observations and plausible blocking random effect were accounted for by fitting a multilevel linear mixed model for longitudinal data, using SAS v. 8·01 PROC MIXED software (SAS Institute Inc, 1999). Species and soil management options were considered as fixed effects, block and tree were considered as random effects, and age at time of measurement was considered a covariate. Fixed interaction between treatment and species, and random interactions were considered because visual inspection of the interaction plots showed clear patterns. All interactions were considered to affect the slope of the relationship between response and predictors. Interaction plots were performed with R statistical software, version 2·15·0 (R Development Core Team, 2012).

The linear mixed model requires a linear relationship between response and predictors, as well as normality in residuals. Because survival data is a proportion, normality and homogenous variance were not expected. Consequently, we applied a squared *arcsine* transformation to the response variable (Sabin & Stafford, 1990), that is, $z = \arcsin(sqr(p))$, *where*: z is the squared arcsine transformed response variable for survival data and p is the proportion of individuals.

Height and root collar diameter were plotted over time to discern both heteroscedasticity in data, indicated by greater variability in the response variable, and curvature in the temporal pattern (Figure S4). Heteroscedasticity was treated by logarithmic transformation of the response variable to $ln(y + 0{\cdot}5)$, where y is the height or root collar diameter. Curvature was taken into account by logarithmic conversion of time according to Verbeke & Molenberghs (2000). Plotting individual height or root collar diameter trajectories over time also served to reveal any random tree effect for individual trees, in both the intercept and the slope (Figure S5).

We tested the following general structure to obtain a model of survival, height and root collar diameter:

$$y_{ij} = \mu + \beta_{1i} + \beta_{2i}t_{ij} + \varepsilon_{ij} \quad (1)$$

Where: y_{ij} is the response variable of the i-th tree at time j, and μ is the intercept or grand mean, $\beta_{1i} = \beta_1 AD_i + \beta_2 AS_i + \beta_3 CP_i + \beta_4 DT_i + \beta_5 EG_i + \beta_6 GR_i + \beta_7 HA_i + b_{1i}, \beta_{2i} = \beta_0 + \beta_8 AD_i + \beta_9 AS_i +, \beta_{10} CP_i + \beta_{11} DT_i + \beta_{12} EG_i + \beta_{13} GR_i + \beta_{14} HA_i + \beta_{15} C_i + \beta_{16} M_i + \beta_{17} MM_i + \gamma_{2i} + b_{2i} + p_{2i} + u_{2i}$, *AD*: *A. decurrens*, *AS*: *A. saligna*, *CP*: *C. palmensis*, *DT*: *D. torrida*, *EG*: *E. globulus*, *GR*: *G. robusta*, *HA*: *H. abyssinica*, *C*: Control, *M*: Manure and *MM*: Manure + Mulch. The parameter β_0 reflects the overall slope for the time effect and makes it possible to test group differences in species or treatment, β_{1-17} are parameters for species and treatment fixed effects, γ_{1i} is any fixed interaction, b_{1i} and b_{2i} are random tree parameters with variance σ^2_{b1} and σ^2_{b2} , p_{1i} is the block random effect with variance σ^2_{p1}, u_{1i} is random interaction effect with variance σ^2_{u1i}, and ε_{ij} accounts for within-tree random variation $\sigma^2_{\varepsilon_{ij}}$. Because of both the randomized experimental layout and time transformation, the subject-specific intercepts were considered to be independent of the treatment (Verbeke & Molenberghs, 2000).

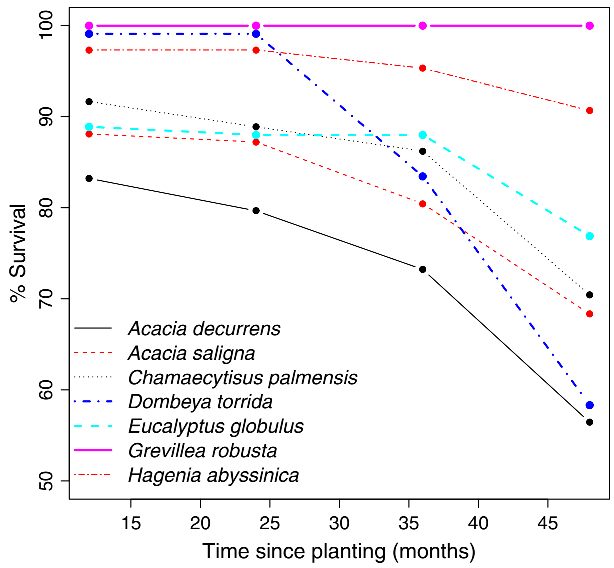

Figure 1. Percentage of trees alive by species throughout the lifespan of the experiment. Points indicate the month of measurement 12, 24, 36 and 48. EG, *Eucalyptus globulus*; AS, *Acacia saligna*; AD, *Acacia decurrens*; CP, *Chamaecytisus palmensis*; GR, *Grevillea robusta*; DT, *Dombeya torrida*; HA, *Hagenia abyssinica*. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

Biomass data were analyzed with a mixed linear model approach in order to avoid an error term construction in the generalized linear model (SAS Institute Inc, 1999). The model tested was

$$y_{skb} = \mu + \alpha_s + \beta_k + \gamma_{sk} + b_b + v_{kb} + \varepsilon_{skb} \quad (2)$$

Where: y_{skb} is the biomass of the average tree of species s under k treatment in the bth block, is the intercept, α_s,is the species fixed effect (*i.e.* $\alpha_s = \alpha_1 AD_i + \alpha_2 AS_i + \alpha_3 CP_i + \alpha_4 DT_i + \alpha_5 EG_i + \alpha_6 GR_i + \alpha_7 HA_i$), β_k is the treatment fixed effect (i.e. $\beta_k = \beta_1 C_i + \beta_2 M_i + \beta_3 MM_i$), γ_{sk} is the interaction fixed effect between species and treatment, b_b is the block random effect with variance $\sigma^2_{b_b}$, v_{kb} is the interaction random effect between treatment and block with variance $\sigma^2_{v_{kb}}$, and ε_{skb} accounts for error due to within-species variation and variance parameter $\sigma^2_{\varepsilon_{skb}}$.

A paired-wise mean comparison by species was made using Tukey's test to reveal the differences in the response variable at every measurement time.

Soil data are repeated measures in both time (before and 4 years after planting) and space (soil depth). We conducted a multivariate approach in which both repetition patterns are taken into account using SAS v. 8·01 PROC GLM software

(SAS Institute Inc, 1999). A least squares means comparison for the main effect is performed to analyze differences between solid depths before and after plantation. A significance level of 0·05 is assumed across the analysis.

RESULTS

Planted Tree Species Survival Rate

Grevillea robusta showed the highest overall survival rate (100%), followed by native *H. abyssinica* (93·52%) (Figure 1). The Figure 2(a) and (b) showed interaction between treatment and species, whereas the effect of block-treatment interaction was slightly lower. The final significant model included the species fixed effect in both the intercept and the slope and a random interaction between block and treatment in the slope (Table II).

Differences among species appear when they were compared at time points. *A. decurrens* showed the lowest survival rate at all measurement times. Although it was similar to *A. saligna* throughout the experiment, stronger differences appeared as early as 24 months after planting (Table III). The variance of the random interaction between treatment and block was low (0·001386) compared with the residual variance (0·03735); however, the null model likelihood ratio test for appropriateness of the model with the variance component was significant (p-value 0·0273).

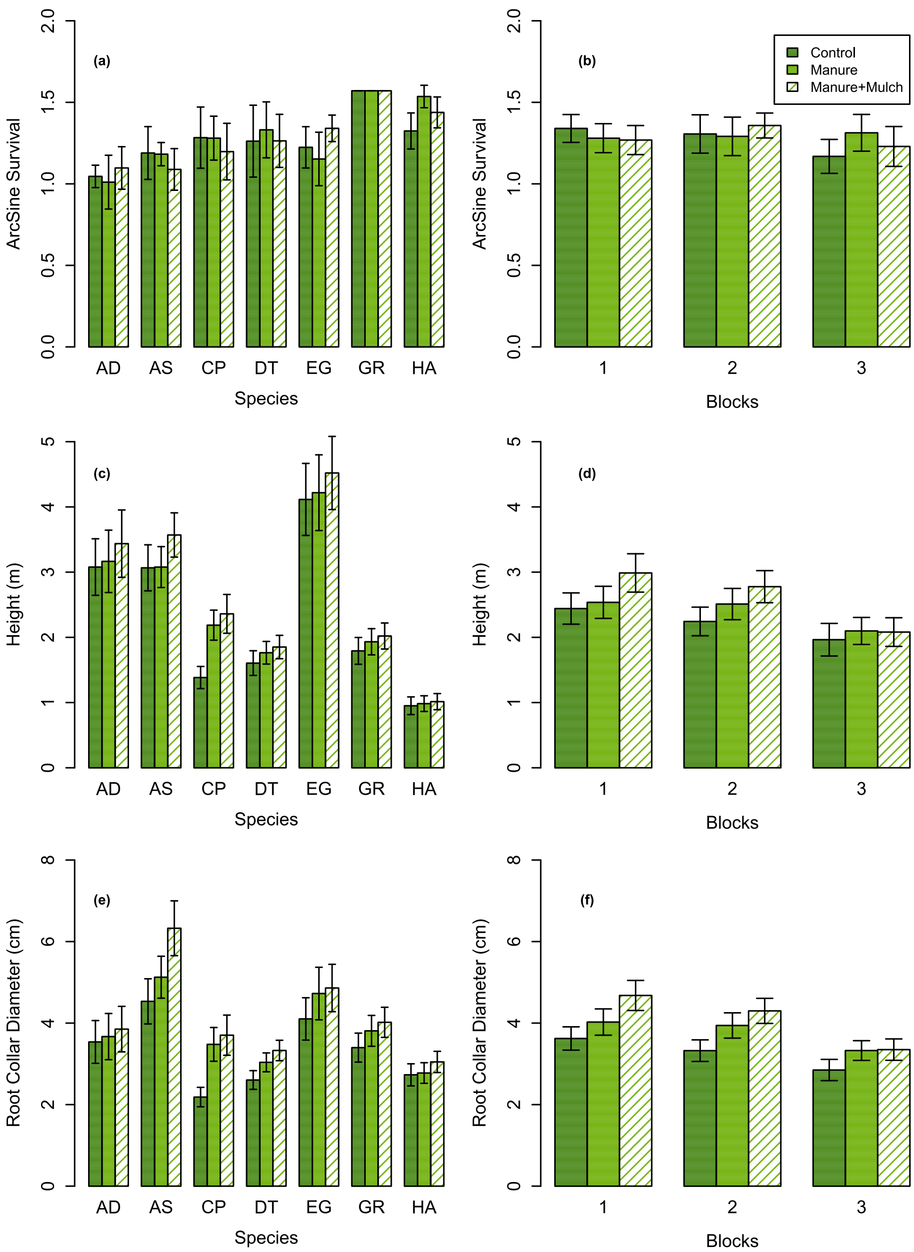

Figure 2. Interaction plots for the covariates tested. From top to bottom: survival, height growth and root collar diameter growth. Species × Treatment interaction (left panel). Block × Treatment interaction (right panel). EG, *Eucalyptus globulus*; AS, *Acacia saligna*; AD, *Acacia decurrens*; CP, *Chamaecytisus palmensis*; GR, *Grevillea robusta*; DT, *Dombeya torrida*; HA, *Hagenia abyssinica*. Thin lines indicate standard error of the mean. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

Table II. Solution for fixed effects and covariance parameter estimates for survival data

Fixed effects	Parameters in model (1)	Estimate	S.E.	*p*-value
Intercept	μ	1·5866	0·182	<0·0001
species	$\beta 1$	−0·1158	0·1659	0·4857
	$\beta 2$	−0·1064	0·1659	0·5218
	$\beta 3$	0·0522	0·1659	0·7533
	$\beta 4$	0·5643	0·1659	0·0008
	$\beta 5$	−0·1274	0·1659	0·4431
	$\beta 6$	−0·01585	0·1659	0·924
	$\beta 7$	0	·	·
Time	$\beta 0$	−0·1286	0·09423	0·1738
Time*species	$\beta 8$	−0·222	0·1333	0·0972
	$\beta 9$	−0·1445	0·1333	0·2792
	$\beta 10$	−0·1931	0·1333	0·1487
	$\beta 11$	−0·5945	0·1333	<0·0001
	$\beta 12$	−0·05538	0·1333	0·6781
	$\beta 13$	0·1286	0·1333	0·3357
	$\beta 14$	0	·	·
Random effects				
Block*treatment	$\sigma 2_{u2}$	0·001386		
Residual variance	$\sigma 2$	0·03735		

S·E·, standard error of the mean; β_1–β_7 and β_8–β_{14} stand for *A· decurrens*, *A· saligna, C· palmensis, D· torrida*, *E· globulus*, *G· robusta* and *H· abyssinica*, respectively·

Table III. Differences of least squares means for survival and statistical significance of null hypothesis according to Tukey–Kramer's adjustment

Species comparison	Time since planting							
	12 months		24 months		36 months		48 months	
	Estimate	*p*-value	Estimate	*p*-value	Estimate	*p*-value	Estimate	*p*-value
AD-AS	−0·063	0·987	−0·094	0·425	−0·117	0·2796	−0·134	0·499
AD-CP	−0·188	0·241	−0·200	**0·001**	−0·208	**0·0017**	−0·215	**0·046**
AD-DT	−0·422	**<0·0001**	−0·271	**<0·0001**	−0·164	**0·0313**	−0·081	0·919
AD-EG	−0·104	0·861	−0·171	**0·007**	−0·219	**0·0007**	−0·257	**0·007**
AD-GR	−0·343	**0·001**	−0·485	**<0·0001**	−0·586	**<0·0001**	−0·664	**<0·0001**
AD-HA	−0·270	**0·018**	−0·360	**<0·0001**	−0·424	**<0·0001**	−0·473	**<0·0001**
AS-CP	−0·125	0·721	−0·105	0·2904	−0·091	0·5827	−0·081	0·919
AS-DT	−0·359	**0·000**	−0·176	**0·0047**	−0·047	0·9724	0·054	0·989
AS-EG	−0·041	0·999	−0·077	0·6696	−0·103	0·4389	−0·123	0·608
AS-GR	−0·280	**0·012**	−0·391	**<0·0001**	−0·469	**<0·0001**	−0·530	**<0·0001**
AS-HA	−0·207	0·148	−0·265	**<0·0001**	−0·307	**<0·0001**	−0·339	**<0·0001**
CP-DT	−0·234	0·065	−0·071	0·7468	0·044	0·979	0·134	0·499
CP-EG	0·084	0·945	0·028	0·9969	−0·011	1	−0·042	0·997
CP-GR	−0·155	0·477	−0·285	**<0·0001**	−0·378	**<0·0001**	−0·450	**<0·0001**
CP-HA	−0·082	0·952	−0·160	**0·0153**	−0·216	**0·001**	−0·259	**0·007**
DT-EG	0·318	**0·002**	0·099	0·36	−0·056	0·937	−0·176	0·179
DT-GR	0·079	0·959	−0·214	**0·0002**	−0·422	**<0·0001**	−0·584	**<0·0001**
DT-HA	0·152	0·499	−0·089	0·5018	−0·260	**<0·0001**	−0·393	**<0·0001**
EG-GR	−0·239	0·054	−0·314	**<0·0001**	−0·367	**<0·001**	−0·408	**<0·0001**
EG-HA	−0·166	0·391	−0·188	**0·0019**	−0·204	**0·0023**	−0·217	**0·043**
GR-HA	0·073	0·972	0·125	0·1189	0·162	**0·0336**	0·191	0·110

In bold: significant differences among species at 95% of confidence·
EG, *Eucalyptus globulus*; AS, *Acacia saligna*; AD, *Acacia decurrens*; CP, *Chamaecytisus palmensis*; GR, *Grevillea robusta*; DT, *Dombeya torrida*; HA, *Hagenia abyssinica*·

Height Growth

The interaction plot showed species and treatment interaction in all soil management options applied [Figure 2(c) and (d)]. The subplot treatment factor had little influence on *H. abyssinica* height growth, whereas *E. globulus* presented greater height values with soil management options. For the remaining species, the response was less pronounced. The response of *A. decurrens* and *A. saligna* height growth was similar across the soil management options. The block effect and the interaction between treatment and block were also weak (Figure 2(d)).

Time since planting (age) was also an important variable with considerable variation across species. For example, *A. saligna* height growth was faster up to 24 months after planting and then decreased' whereas *E. globulus* experienced fast height growth throughout the experiment (Figure S4).

Species and treatment effects were significantly different, though the difference between soil management options was not significantly different. The random effect for the intercept and the slope revealed the covariances for both effects (0·0393 and 0·0984, respectively) to be higher than the residual variance (0·0195), indicating the strong random effect associated with individuals (Table IV). On average, the fixed effects revealed that *G. robusta* and *H. abyssinica* showed the same height growth pattern, and the application of either soil management option resulted in similar height growth, which was higher than that of the control treatment.

Height growth differences were noticeable 12 months after planting. *H. abyssinica* and *E. globulus* showed the lowest and highest mean difference, respectively (Table V).

Root Collar Diameter Growth Performance

Visual inspection of the interaction plot showed that the interaction between species and treatment was more pronounced than in height growth [Figure 2(e)], *A. saligna* showed a stronger response to manure + mulch treatment than other species, whereas *C. palmensis* exhibited increased root collar diameter when either soil management options were applied.

Time since planting was also an important variable and notably different: the root collar diameter of *A. saligna* increased for 36 months after planting. At 48 months, *E. globulus* showed higher average root collar diameter (RCD) values. The other species showed similar values at 12 and 24 months after planting; from that point on, root collar diameter differences became more pronounced. *C. palmensis*, *D. torrida* and *H. abyssinica* had the lowest RCD values at the end of the experiment (Figure S4).

The final model for root collar diameter included random individual effect on the intercept and the slope. Neither the fixed effects for species and treatment in the slope nor the interaction between species and treatment were significant. The solution for fixed effects gave results similar to those of the height model (Table IV), although none of the species had RCD values similar to those of *H. abyssinica*. Comparison of the species at each time point showed fewer RCD differences between species than in the height growth comparison (Tables V and VI): *E. globulus* outperformed all species in height growth but had almost the same root collar diameter as *A. saligna* at the end of the experiment.

Biomass Production

Tree biomass production was similar in all soil management applications (Table VII), except for *E. globulus* (11·71 kg tree^{-1}), *A. saligna* (8·76 kg tree^{-1}) and *A. decurrens* (6·41 kg tree^{-1}). Mulching induced overlaid results between the control and

Table IV. Solution for fixed effects and covariance parameters estimates for height and root collar diameter

Fixed effects parameters in model (1)		Height Estimate	S.E.	*p*-value	Root collar diameter Estimate	S.E.	*p*-value
Intercept species	μ	−1·066	0·031	<0·0001	−0·777	0·039	<0·0001
	$\beta 1$	0·400	0·048	<0·0001	−0·119	0·060	0·049
	$\beta 2$	0·714	0·046	<0·0001	0·448	0·058	<0·0001
	$\beta 3$	0·888	0·046	<0·0001	0·227	0·058	<0·0001
	$\beta 4$	0·717	0·045	<0·0001	0·503	0·057	<0·0001
	$\beta 5$	−0·182	0·045	<0·0001	−0·673	0·057	<0·0001
	$\beta 6$	0·046	0·043	0·2807	−0·258	0·055	<0·0001
	$\beta 7$	0·000	·	·	0·000	·	·
Time	$\beta 0$	1·185	0·039	<0·0001	1·485	0·042	<0·0001
Time*species	$\beta 8$	0·358	0·057	<0·0001	0·225	0·062	0·0003
	$\beta 9$	0·154	0·055	0·0051	0·105	0·059	0·0769
	$\beta 10$	−0·335	0·543	<0·0001	−0·149	0·059	0·0115
	$\beta 11$	−0·220	0·540	<0·0001	−0·301	0·059	<0·0001
	$\beta 12$	1·022	0·054	<0·0001	0·851	0·058	<0·0001
	$\beta 13$	0·339	0·052	<0·0001	0·392	0·056	<0·0001
	$\beta 14$	0·000	·	·	0·000	·	·
Time*treatment	$\beta 15$	−0·124	0·020	<0·0001	−0·189	0·025	<0·0001
	$\beta 16$	−0·036	0·020	0·0708	−0·062	0·024	0·0113
	$\beta 17$	0	·	·	0	·	·
Random effects							
Intercept slope	$\sigma 2_{b1}$	0·0393			0·0495		
	$\sigma 2_{b2}$	0·0984			0·0929		
Residual variance	$\sigma 2$	0·0195			0·0324		

β_1–β_7 and β_8–β_{14} stand for *A· decurrens*, *A· saligna, C· palmensis, D· torrida*, *E· globulus*, *G· robusta* and *H· abyssinica*, respectively· β_{15}–β_{17} stands for control, manure and manure + mulch interaction with time, respectively·

Table V. Differences of least squares means for height growth and statistical significance of null hypothesis according to Tukey–Kramer's adjustment

Species comparison	Time since planting							
	12 months		24 months		36 months		48 months	
	Estimate	*p*-value	Estimate	*p*-value	Estimate	*p*-value	Estimate	*p*-value
AD-AS	−0·172	**<0·0001**	−0·063	0·710	−0·002	1	0·046	0·994
AD-CP	−0·008	1·000	0·360	**<0·0001**	0·569	**<0·0001**	0·729	**<0·0001**
AD-DT	0·084	**0·025**	0·905	**<0·0001**	0·565	**<0·0001**	0·699	**<0·0001**
AD-EG	0·122	**<0·0001**	−0·230	**<0·0001**	−0·431	**<0·0001**	−0·585	**<0·0001**
AD-GR	0·367	**<0·0001**	0·376	**<0·0001**	0·382	**<0·0001**	0·386	**<0·0001**
AD-HA	0·648	**<0·0001**	0·838	**<0·0001**	0·946	**<0·0001**	1·029	**<0·0001**
AS-CP	0·164	**<0·0001**	0·423	**<0·0001**	0·571	**<0·0001**	0·684	**<0·0001**
AS-DT	0·256	**<0·0001**	0·454	**<0·0001**	0·567	**<0·0001**	0·653	**<0·0001**
AS-EG	0·294	**<0·0001**	−0·167	**0·0006**	−0·429	**<0·0001**	−0·631	**<0·0001**
AS-GR	0·538	**<0·0001**	0·440	**<0·0001**	0·383	**<0·0001**	0·340	**<0·0001**
AS-HA	0·820	**<0·0001**	0·901	**<0·0001**	0·948	**<0·0001**	0·983	**<0·0001**
CP-DT	0·092	**0·006**	0·031	0·9847	−0·004	1	−0·030	0·999
CP-EG	0·130	**<0·0001**	−0·590	**<0·0001**	−1·000	**<0·0001**	−1·314	**<0·0001**
CP-GR	0·374	**<0·0001**	0·017	0·9995	−0·187	**0·0052**	−0·343	**<0·0001**
CP-HA	0·656	**<0·0001**	0·478	**<0·0001**	0·377	**<0·0001**	0·300	**<0·0001**
DT-EG	0·038	0·750	−0·621	**<0·0001**	−0·996	**<0·0001**	−1·284	**<0·0001**
DT-GR	0·283	**<0·0001**	−0·014	0·9997	−0·183	**0·0053**	−0·313	**<0·0001**
DT-HA	0·564	**<0·0001**	0·447	**<0·0001**	0·381	**<0·0001**	0·330	**<0·0001**
EG-GR	0·244	**<0·0001**	0·606	**<0·0001**	0·813	**<0·0001**	0·971	**<0·0001**
EG-HA	0·526	**<0·0001**	1·068	**<0·0001**	1·377	**<0·0001**	1·614	**<0·0001**
GR-HA	0·282	**<0·0001**	0·462	**<0·0001**	0·564	**<0·0001**	0·643	**<0·0001**

In bold: significant differences between species at 95% of confidence·
EG, *Eucalyptus globulus*; AS, *Acacia saligna*; AD, *Acacia decurrens*; CP, *Chamaecytisus palmensis*; GR, *Grevillea robusta*; DT, *Dombeya torrida*; HA, *Hagenia abyssinica*·

Table VI. Differences of least squares means for root collar diameter growth and statistical significance of null hypothesis according to Tukey–Kramer's adjustment

Species comparison	Time since planting							
	12 months		24 months		36 months		48 months	
	Estimate	*p*-value	Estimate	*p*-value	Estimate	*p*-value	Estimate	*p*-value
AD-AS	−0·483	**<0·0001**	−0·420	**<0·0001**	−0·384	**<0·0001**	−0·355	**<0·0001**
AD-CP	−0·087	0·270	0·112	0·229	0·225	**0·00149**	0·311	**0·001**
AD-DT	−0·258	**<0·0001**	0·021	0·999	0·180	**0·047**	0·302	**0·001**
AD-EG	0·120	**0·034**	−0·213	**0·000**	−0·402	**<0·0001**	−0·548	**<0·0001**
AD-GR	0·023	0·996	−0·066	0·791	−0·116	0·4375	−0·155	0·300
AD-HA	0·037	0·956	0·157	**0·014**	0·225	**0·0034**	0·277	**0·002**
AS-CP	0·397	**<0·0001**	0·531	**<0·0001**	0·608	**<0·0001**	0·667	**<0·0001**
AS-DT	0·226	**<0·0001**	0·441	**<0·0001**	0·564	**<0·0001**	0·658	**<0·0001**
AS-EG	0·603	**<0·0001**	0·207	**0·0002**	−0·019	0·9999	−0·192	0·103
AS-GR	0·506	**<0·0001**	0·345	**<0·0001**	0·267	**<0·0001**	0·201	0·054
AS-HA	0·521	**<0·0001**	0·576	**<0·0001**	0·608	**<0·0001**	0·632	**<0·0001**
CP-DT	−0·171	**<0·0001**	−0·090	0·4239	−0·044	0·9886	−0·001	1·000
CP-EG	0·206	**<0·0001**	−0·325	**<0·0001**	−0·627	**<0·0001**	−0·859	**<0·0001**
CP-GR	0·110	**0·039**	−0·177	**0·0016**	−0·341	**<0·0001**	−0·466	**<0·0001**
CP-HA	0·124	**0·012**	0·045	0·9553	0·000	1	−0·035	0·999
DT-EG	0·377	**<0·0001**	−0·234	**<0·0001**	−0·583	**<0·0001**	−0·850	**<0·0001**
DT-GR	0·281	**<0·0001**	−0·087	0·4259	−0·296	**<0·0001**	−0·457	**<0·0001**
DT-HA	0·295	**<0·0001**	0·135	**0·0365**	0·044	0·9867	−0·025	1·000
EG-GR	−0·096	0·111	0·147	**0·0193**	0·286	**<0·0001**	0·393	**<0·0001**
EG-HA	−0·082	0·270	0·370	**<0·0001**	0·627	**<0·0001**	0·824	**<0·0002**
GR-HA	0·014	1·000	0·222	**<0·0001**	0·341	**<0·0001**	0·432	**<0·0003**

In bold: significant differences between species at 95% of confidence·
EG, *Eucalyptus globulus*; AS, *Acacia saligna*; AD, *Acacia decurrens*; CP, *Chamaecytisus palmensis*; GR, *Grevillea robusta*; DT, *Dombeya torrida*; HA, *Hagenia abyssinica*·

Table VII. Solution for fixed effects and covariance parameters estimates for biomass 48 months after planting

Fixed effects	Parameters in model (2)	Estimate	S·E·	*p*-value
Intercept	μ	1·7251	1·4712	0·3617
Species	$\alpha 1$	5·6933	1·9071	0·0114
	$\alpha 2$	8·0367	1·9071	0·0012
	$\alpha 3$	2·0844	1·9071	0·2959
	$\alpha 4$	0·6144	1·9071	0·7529
	$\alpha 5$	10·9856	1·9071	<0·0001
	$\alpha 6$	1·3967	1·9071	0·478
	$\alpha 7$	0	·	·
Treatment	$\beta 1$	−2·0543	0·7102	0·0062
	$\beta 2$	−0·961	0·7102	0·1837
	$\beta 3$	0	·	·
Random effects				
Block	$\sigma 2_{bb}$	0·5331		
Species*block	$\sigma 2_{vkb}$	3·69		
Residual variance	$\sigma 2_{\varepsilon}$	5·2966		

α_1–α_7 stand for *A· decurrens*, *A· saligna, C· palmensis, D· torrida*, *E· globulus*, *G· robusta* and *H· abyssinica*, respectively· β_1–β_3 stands for Control, Manure and Manure + Mulch treatment, respectively·

Table VIII. Repeated multivariate analysis of variance for soil parameters

	Between effects			Within effects		
Soil parameter	Effect	F	*p*-value	Effect	F	*p*-value
pH	Species	0·31	0·9193	Time	43·87	**0·0001**
				Time × species	0·74	0·6264
				Depth	5·05	**0·0134**
				Depth × species	1·08	0·4139
				Time × depth	2·62	0·0904
				Time × depth × species	0·49	0·905
Carbon (%)	Species	2·08	0·1217	Time	6·59	**0·0224**
				Time × species	1·76	0·1799
				Depth	59·25	**0·0001**
				Depth × species	1·41	0·221
				Time × depth	5·9	**0·0073**
				Time × depth × species	2·93	**0·0093**
Nitrogen (%)	Species	3·87	**0·0174**	Time	8·81	**0·0102**
				Time × species	3·13	**0·0368**
				Depth	21·66	**0·0001**
				Depth × species	0·68	0·76
				Time × depth	1·68	0·2042
				Time × depth × species	0·91	0·5497
P (ppm)	Species	0·56	0·7557	Time	21·8	**0·0004**
				Time × species	0·54	0·7729
				Depth	4·18	**0·0258**
				Depth × species	0·41	0·9451
				Time × depth	1·19	0·3192
				Time × depth × species	0·33	0·9773
K (meq/100 gr)	Species	0·93	0·5038	Time	0·04	0·8379
				Time × species	1·48	0·2538
				Depth	5·22	**0·0118**
				Depth × species	1·38	0·2312
				Time × depth	1·59	0·2216
				Time × depth × species	1·18	0·3429
CEC (meq/100 gr)	Species	0·47	0·8179	Time	2·43	0·1413
				Time × species	0·24	0·9577
				Depth	5·78	**0·0079**
				Depth × species	0·86	0·5955
				Time × depth	0·04	0·9641
				Time × depth × species	2·39	**0·0282**

Bold values indicate significance at 0·05 level·

mulching + manure treatment. Comparison of control with mulching + manure treatments revealed the treatment fixed effect to be highly significant ($p < 0{\cdot}0001$), with a biomass production gradient from 3·79 kg tree^{-1} for the control to 4·88 kg tree^{-1} with manure to 5·84 kg tree^{-1} with mulching + manure treatment. The interaction between species and treatment was highly insignificant in all cases.

Differences of least squares means showed that *E. globulus* produced more biomass than other species, followed closely by *A. saligna*. These were significantly greater than *D. torrida* and *H. abyssinica*, which presented the lowest biomass production (Table S1).

Soil Condition

The significance of treatment effects on growth and biomass production was not very high, indicating that tree species is the main factor controlling the performance of indicator variables (i.e. growth, survival and biomass). For this reason, we tested species effect on soil properties. In so doing, we also avoid expensive analysis of soil depths across treatments. Statistical analysis of between and within effects in the multivariate repeated analysis are shown in Table VIII.

Nitrogen concentration was affected by species, time, depth and the interaction of time and species, indicating a strong species control on this soil parameter. Time was significant for all soil properties except for K and CEC, whereas depth within effect was significant for all soil properties. The significant interaction effect of species, time and depth for organic carbon and cationic exchange capacity was mainly controlled by depth.

Differences in some soil parameters within species between initial conditions and 4 years after planting were detected. After 4 years since planting, pH did not change. Soil parameter values increased in native *H. abyssinica* and *D. torrida* (Figures 3 and 4), whereas nitrogen and carbon concentration decreased in *E. globulus* plantation along the whole profile [Figure 5(c) and (e)]. *Chamaecytisus palmensis* showed the highest N and carbon increase 4 years after plantation [Figure 6(c)]. *Acacia* spp showed a decreasing pattern in nitrogen and carbon concentrations and available potassium in top soil [Figures S6 and S7 (c), (d) and (e)], whereas *G. robusta* showed increased nitrogen and carbon contents [Figure S8(c) and (e)]. All species increased available P in soils.

The higher differences between species are in the top mineral soil and later up to 30 cm, and they are mainly due to changes in carbon, nitrogen from 0 to 10 cm, K concentrations from 10 to 30 cm and CEC (Table SII). pH and P

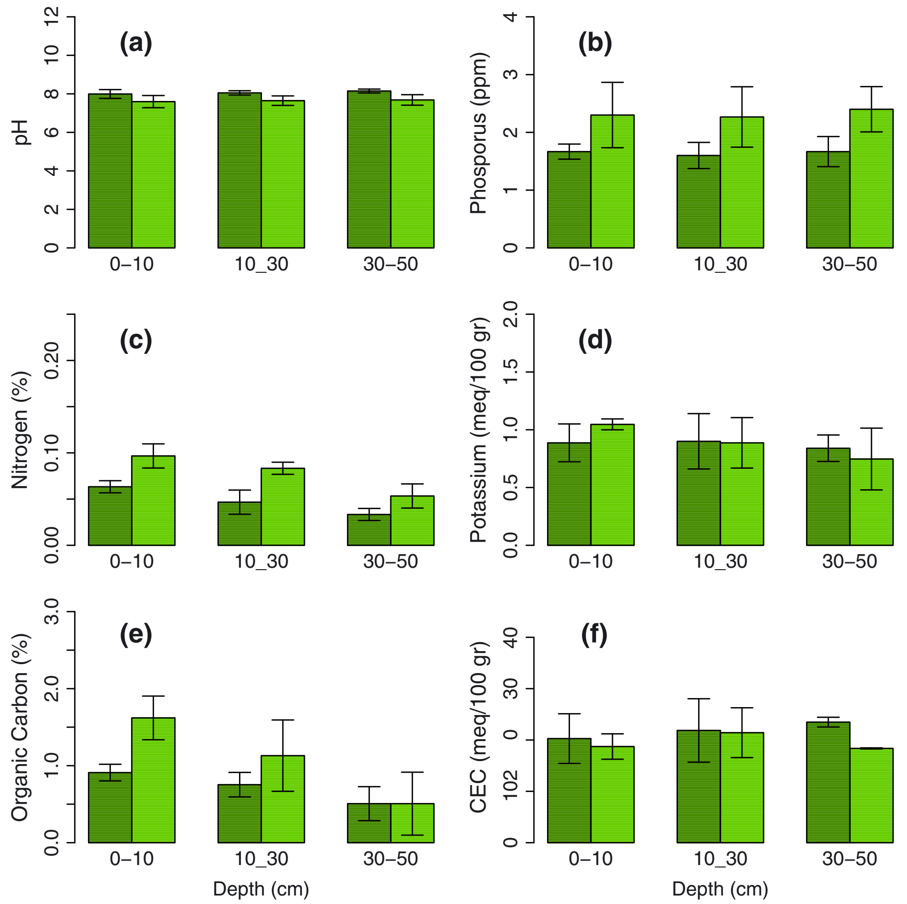

Figure 3. Mean value and standard error bars for soil properties at the beginning and at the end of the experiment in native *Hagenia abyssinica* plots. Dark bars are mean value before planting. Light bars are mean value after 48 months. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

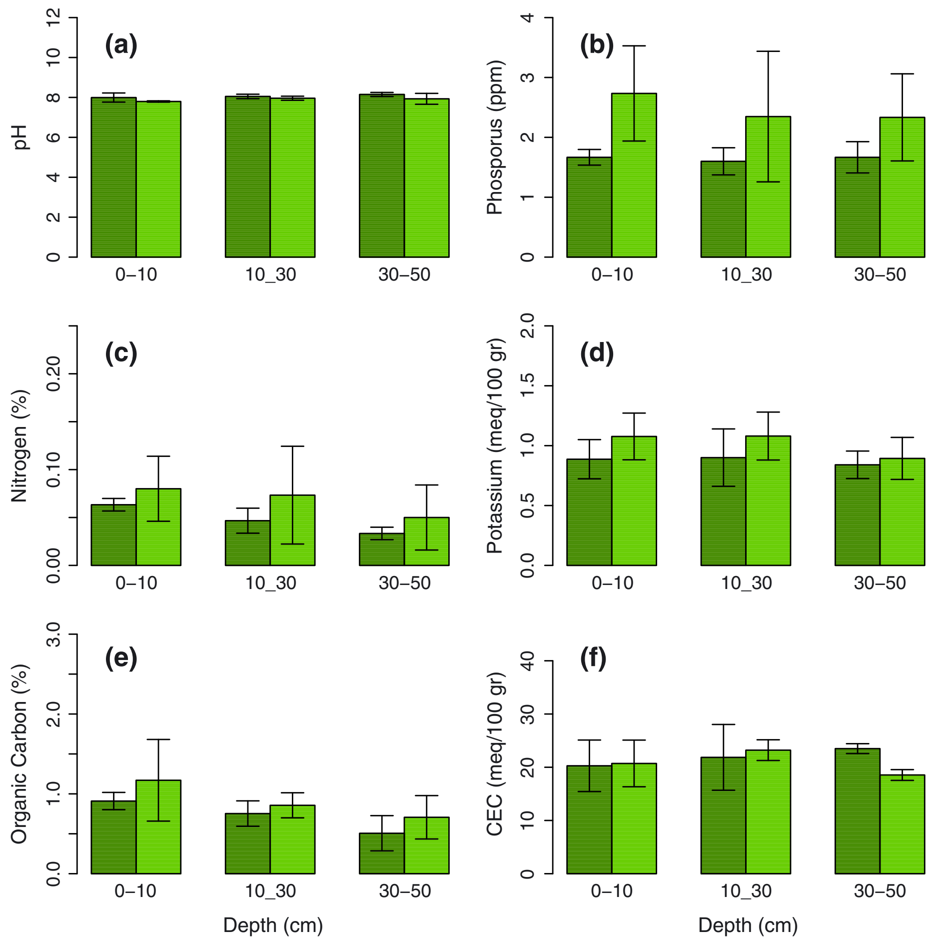

Figure 4. Mean value and standard error bars for soil properties at the beginning and at the end of the experiment in native *Dombeya torrida* plots. Dark bars are mean value before planting. Light bars are mean value after 48 months. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

concentration did not show differences across species. *Acacia* spp. and *Ecualyptus globulus* had significantly less organic carbon in the top mineral soil (0–10 cm) than *H. abyssinica*, *G. robusta* and *C. palmensis*. The concentration of nitrogen is significantly low in *Acacia* spp. and *E. globulus* as compared with *C. palmensis* that showed the highest amount of nitrogen (0·11%) in the topsoil (0–10 cm) 4 years after plantation followed by *H. abyssinica* (0·09%) and *D. torrida* (0·08%). Differences in K concentration are found in 10–30 cm. *Acacia* spp and *E. globulus* showed the minimum K values, which were significantly different from the rest of species. CEC in *E. globulus* and *A. decurrens* (16·4 and 16·5 meq/100 g soil) plots is significantly lower than that found in *D. torrida* and *G. robusta* plots (20·7 and 20·5 meq/100 g soil). The same pattern occurs from 10 to 30 cm deep.

DISCUSSION

This study presents a screening of six tree species and one shrub species for use in the restoration of degraded land and fuelwood production in the Central Highlands of Ethiopia. The combination of survival, height, root collar diameter growth, total biomass production and soil condition change after 48 months provides a five-dimensional indicator of species suitability for both objectives. The best option would always be that with the highest values in all five indicators; however, none of the species studied perfectly fulfilled these requirements. In fact, contradictory results for restoration and fuelwood production were found.

Native *H. abyssinica* and exotic *G. robusta* and *E. globulus* had the highest survival rates; the lowest survival rates were recorded for native *D. torrida* and exotic *A. decurrens*. An intermediate group was formed by *C. palmensis* and *A. saligna*. Peter *et al.* (2005) reported a survival rate of 100% for *G. robusta* on a mixed rainforest tree plantation in Australia after 6 years. In Chile, a screening trial for degraded highlands reported a survival rate of less than 25% for *A. saligna* and less than 60% for *C. palmensis* (Arredondo *et al.*, 1998).

Exotic *E. globulus, A. saligna* and *A. decurrens* had faster root collar diameter and height growth than other species, and the soil management significantly impacted their growth. Mekonnen *et al.* (2006) also found that *E. globulus* had greater height and root collar diameter growth compared with other species growing on nitisols of the Ethiopian

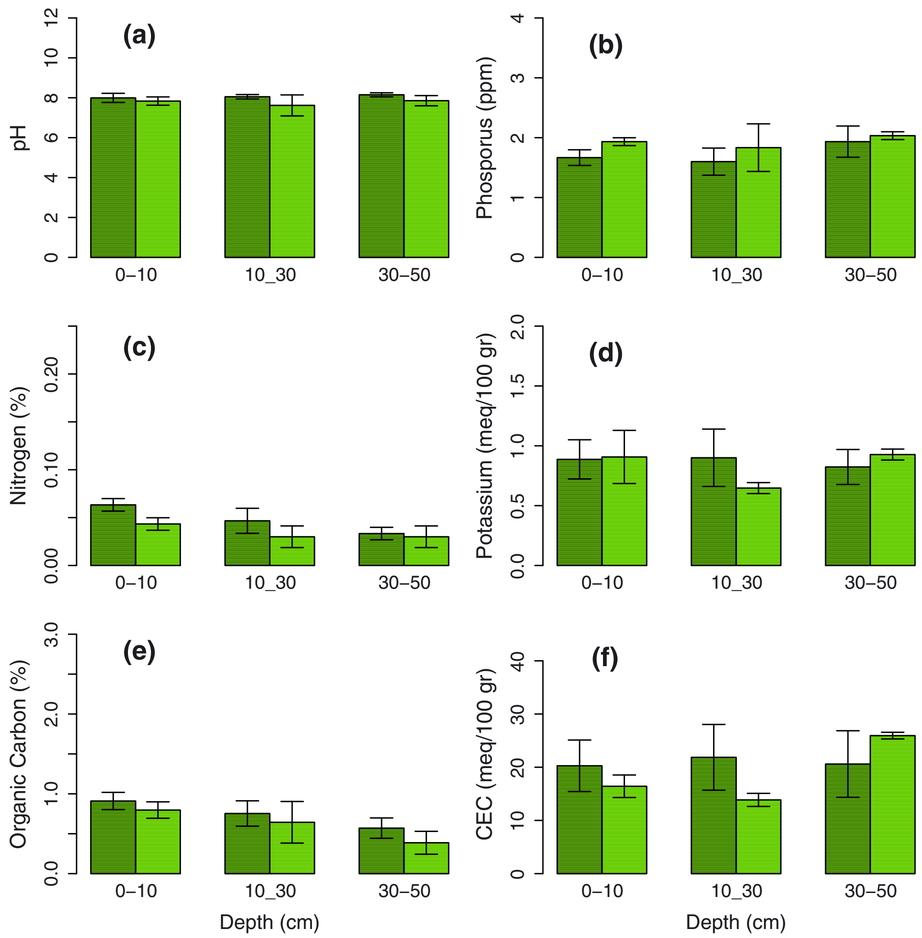

Figure 5. Mean value and standard error bars for soil properties at the beginning and at the end of the experiment in exotic *Eucalyptus globulus* plots. Dark bars are mean value before planting. Light bars are mean value after 48 months. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

Central Highlands. *A. decurrens* and *A. saligna* had rather similar growth patterns, although some reduction in height growth occurred after 24 months in the ground. Although *G.robusta* showed the highest survival rate, its height and root collar growth was intermediate. Although soil conditions were enriched by management options, we suspect the improvement was insufficient to meet the fertility requirements for the species, although the species can slightly improve soil conditions (Figure S8). This species is highly palatable to sheep so illegal grazing in reforestation areas is common. The species is therefore not recommended for widespread rehabilitation of degraded lands, unless local laws are formulated and implemented to protect from free animal grazing.

Higher dry biomass production occurred with *E. globulus*, *A. decurrens* and *A. saligna*, whereas *C. palmensis, G. robusta, H. abyssinica* and *D. torrida* presented lower dry biomass production. Contrary to biomass production, the impact of species plantations in soil conditions reversed the ranking. Native *H. abyssinica* and *D. torrida* and exotic *C. palmensis* are the species that best improve nitrogen, carbon and available potassium in soils 48 months after plantation. *E. globulus* plantations depleted nitrogen from soils significantly in the first 10 cm, whereas *Acacia* species did not show a clear pattern. In our results, it is surprising that *Acacia* species did not increase nitrogen concentrations in the topsoil, which can suggest strong leaching from top soil to deeper layers (Figures S6 and S7). This might affect groundwater as strong NOx contamination has been found in catchments afforested with *Acacia saligna* (Jovanovic *et al*., 2009), so large restoration programs with these species should take into account long-term negative effects.

Wood energy dependence has traditionally seen as a deforestation and land degradation vector in developing countries (Geist & Lambin, 2002), although it has been also argued that fuelwood collection impacts can be mitigated adapting new managerial practices (Hiemstra-van der Horst & Hovorka, 2009) or collecting species other than the native found in natural forests. Plantation of selected native or exotic species can play a major role in rehabilitating degraded land with little enhancement of biodiversity (Chazdon, 2008). However, *Eucalyptus* plantations in Ethiopia have a high potential for restoring species diversity (Yirdaw & Luukkanen, 2003). In this regard, plantations of exotic species are considered as buffers or biological corridors that prevent deforestation in natural forests and foster rapid succession as well as provide fuelwood for local population (Lemenih & Bongers, 2010).

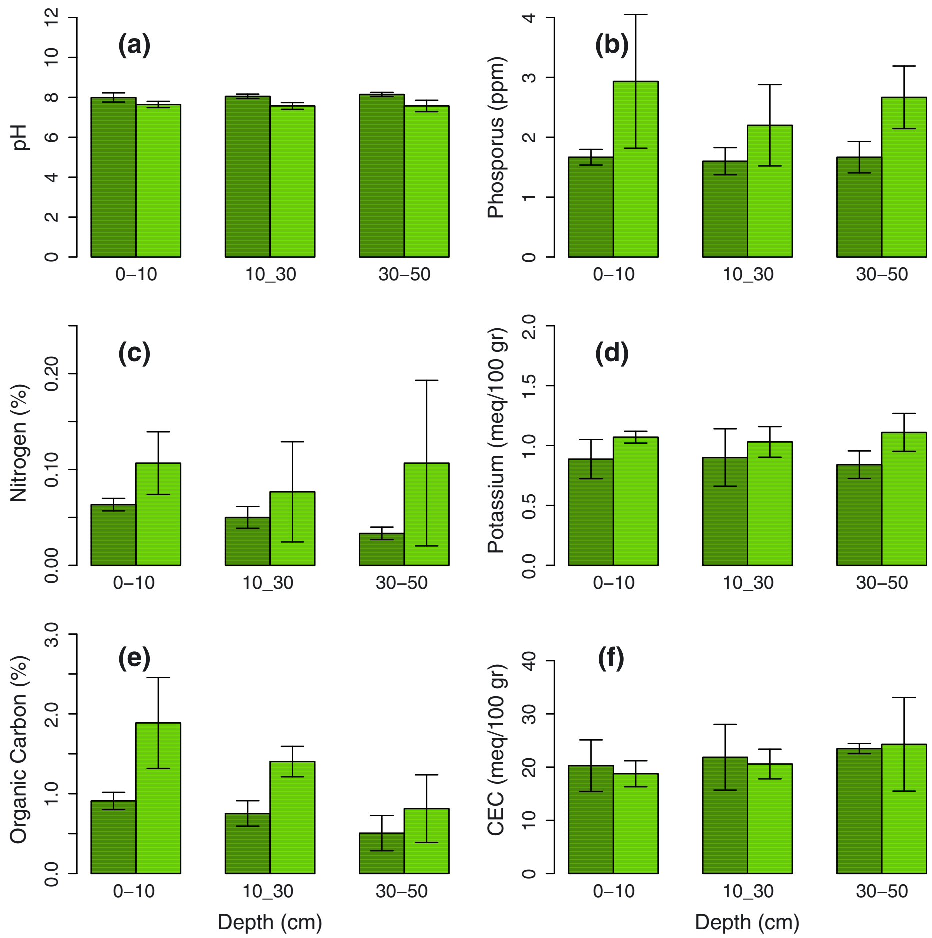

Figure 6. Mean value and standard error bars for soil properties at the beginning and at the end of the experiment in exotic *Chamaecytisus palmensis* plots. Dark bars are mean value before planting. Light bars are mean value after 48 months. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

Although our results clearly indicated *E. globulus* to be the best performing species for fuelwood production with high survival rates, the best growth rates for height and root collar diameter, and largest biomass production, it should be noted that the species do not improve soil conditions and can even deplete nitrogen concentrations 48 months after plantation. Nevertheless, soil carbon concentration is not affected by *Eucalyptus* as earlier noted by Fialho & Zinn (2012) in Brazil. With regard to carbon dynamics, it must be considered to analyze *Eucalyptus*' effects on a case by case basis as such species group can have a negative effect on dissolved organic carbon concentration 5 years after plantation (Wu *et al*., 2013). A balance between wood production for fuel and land reclamation is difficult to meet in areas where scarcity of natural resources is high.

Fast-growing trees help in ameliorating harsh and fluctuating microclimate conditions. This creates potential for rapid restoration of degraded lands through the accumulation of organic matter and for future development of mixed stands that combine fast-growing exotics and naturally regenerated native species (Otsamo, 2000).

With this regard, *H. abyssinica* increased significantly the amount of organic carbon in the top soil, and the tendency continues up to 30 cm deep [Figure 3(e)]. *G. robusta* also improved soil condition (Figure S8), and it is the best option in terms of survival and has been considered to possess excellent firewood properties in its natural distribution area (Jaing & Singh, 1999). *E. globulus* is the most productive species in terms of biomass production for firewood, and it has shown a good survival rate and growth performance; it is usually preferred as an alternative for farmers and household needs (Bewket, 2003); however, as pointed by our results, a thorough study on the ecological impact of *E. globulus* is needed for the Central Highlands in Ethiopia. With the information obtained from our experiment, native *H. abyssinica* might be considered for reforestation programs to rehabilitate degraded lands and exotic *G. robusta* and to a lesser extend *E. globulus*, as a preliminary step to natural vegetation recovery and as good providers of raw material for fuel production.

CONCLUSIONS

The results of this study confirm that: i) *G.robusta* showed the highest overall survival rate followed by *H. abyssinica*. *A. decurrens* showed the lowest survival rate; ii) *E.globulus* outperformed all species in height growth and biomass production and had a similar root collar diameter growth as *A. saligna*; however, it depleted nitrogen in the top soil; iii) *H. abyssinica, C. palmensis* and *D. torrida* showed the lowest growth and biomass production, but all of them improved soil conditions 48 months after plantation; iv) *G. robusta* and *H. abyssinica* resulted in similar height growth pattern over application of soil management options. *A. saligna* showed a stronger response to manure + mulch than other species; v) dry biomass production was highly significant for *E. globulus*, although it was non-significant across soil management options; and vi) there is not a clear effect of any of the soil management options in growth. Finally, we have to modulate our working hypothesis that native tree species might not show better growth performance in harsh environment because native species improved soil conditions. We recommend the use of native *H. abyssinica* for improving soil conditions of degraded land and exotic *G. robusta* for both soil rehabilitation and firewood production, whereas *E. globulus* plantations should be considered a good alternative for firewood production after a complete study upon the ecological impact of the species has been performed. More research is needed to confirm if planting native *H. abyssinica* in the understory of those species is appropriate to reclaim natural vegetation cover.

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