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Eco-hydrological impacts of *Eucalyptus* in the semi humid Ethiopian Highlands: the Lake Tana Plain

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Abstract: *Eucalyptus* is the tree of choice for wood production by farmers in Ethiopia. Although there are many claims about its harmful effect on ecology and water availability, little actual research exists. The main objective of this study was, therefore, to study the extent of harm of *Eucalyptus* on the ecosystem. This study was conducted at the Koga Watershed near Lake Tana in Ethiopia. Twenty-five farmers were interviewed and a field experiment with three replications was carried out to quantify the effect of *Eucalyptus* on various soil physical and chemical properties and maize crop measurements and to compare bulk density, soil moisture contents, maize crop counts and shading effects in fields bordered by *Eucalyptus* and *Croton macrostachyus*. Our results show that *Eucalyptus* decreased both soil nutrients and maize yields within 20 m of the trees. Although moisture content was not affected during the monsoon, it decreased faster within 30 m of the *Eucalyptus* trees than elsewhere. Soils become water repellent, too. Local farmers' perception agreed with our experimental findings and indicated that *Eucalyptus* trees are exhausting the once productive land. They also reported that *Eucalyptus* dries up springs. Despite this, the growers insist on planting *Eucalyptus* because of its cash income.

Keywords: *Eucalyptus*; Soil water repellency; *Croton machrostachyus*; Koga watershed.

INTRODUCTION

Globally, more than 80 countries have planted more than 4 million hectares of *Eucalyptus*. It is fast growing, requires minimal upkeep, grows up from its roots and has easily collected seeds and is desirable for lumber, construction and fuelwood. Therefore, *Eucalyptus* has become one of the most planted tree species in Africa in recent years.

In Ethiopia *Eucalyptus* was introduced in either 1894 or 1895 because of the massive deforestation around Addis Ababa for firewood (Pankhurst, 1961). Since then, shortages in fuel wood supplies and a need for long-term economic returns on farmers' land have made *Eucalyptus* very attractive. *Eucalyptus* is commonly planted in a farmer's cropland plot or on boundaries of cropland. In addition, they are grown on marginal lands and in some cases they are planted to stabilize gullies in wet areas.

Although quantitative evidence is scanty, there has been a perception that planting *Eucalyptus* adversely affects crop productivity (Kidanu et al., 2005). Lane et al. (2004) described that in China, the expansion of *Eucalyptus* plantations on lands previously used for crops and occupied by indigenous trees and grass lowered water tables and reduced water availability for irrigation due to soil hydrophobicity (water repellency) and its deep and dense root network. *Eucalyptus* seedlings are vulnerable to severe water stress unlike the seedlings of indigenous deciduous tree species in Ethiopia (Gindaba et al., 2004). This shows that *Eucalyptus* trees need more water and compete with neighboring plants for the available water in the soil. El-Amin et al. (2001) in Sudan reported that *Eucalyptus* caused crop yield reduction due to nutrient depletion and production of toxic exudates (allelochemicals). Finally, nutrients are exported out from the plantation's soil system by removing trees for timber sales and fuel wood (Holgén and Svensson, 1990).

The environmental impacts of vegetation on the hydrology have been studied only to a limited extent in Ethiopia and eastern Africa (Bayabil et al., 2010). This is especially true for *Eucalyptus* trees as discussed above. Therefore, this study examines the effect of *Eucalyptus* on soil physical and chemical properties, light intensity, and root distribution. The study also compares the density of undergrowth, moisture content and crop performances up to 40 m from the tree stands of two common plantation types, *Eucalyptus* stand and *C. macrostachyus*, trees used for shade coffee.

MATERIALS AND METHODS

Study area

The Koga Watershed, a 28,000 ha watershed, was selected for this study because of the presence of the Koga Watershed Irrigation and Watershed Management project. It consists of a 7,000 ha command area for irrigation agriculture and an environmental management plan for reducing upstream erosion, and it has been supported by the African Development Bank (ADB) and the Ethiopian government. The catchment area is located between 11° 10' N to 11° 25' N latitude and 37° 02' E to 37° 17' E longitude and ranges from 1800 to 3200 m in elevation. It has a mean annual rainfall of 1560 mm and mean daily temperatures range between 16 and 20°C.

The dominant soil type in the study area is nitisol (FAO, 2001). This soil is fertile, deep, porous and well drained. In addition, it has a stable soil structure permitting deep rooting, and it resists erosion. On this productive soil throughout the study area, farmers grow coffee, maize, finger millet, teff, (*Eragrostis tef*) niger seed (*Guizotia abyssinica*), lupine, legumes and vegetables (see Fig. 2). Due to its fast growth and low-input upkeep, *Eucalyptus* is planted along cropland borders and the main road for fuel wood and construction timbers, ultimately to generate income (Jagger and Pender, 2003). Although less common, *Croton machrostachyus* trees also are planted along cropland borders and as shade in coffee plantations. Indigenous trees are nearly absent due to intensive deforestation.

This study was carried out on *Eucalyptus* and *C. machrostachyus* plantations bordering maize crop fields. Maize is the major crop, and it performs well on nitisols (FAO, 2001). The maize variety, BH540, grows in these fields. It is late maturing, has good grain filling capability, and characterized by reddish tassels. Spacing between plants and between rows is 30 cm. One-hundred kg DAP and 50 kg urea per hectare were applied at sowing and vegetative stages, respectively. According to the development agents and local farmers, growers could harvest greater than 5 tons (50 quintals) per hectare with a sale price of about 600 Ethiopian birr ($55) per 100 kg in 2008.

Data collection and analysis

The experiment was carried out in three maize fields bordered by *Eucalyptus* and *Croton machrostachyus* plantations. Soil samples were taken from a single depth (0 – 20 cm) or from three profile depths (0 – 20, 20 – 40 and 40 – 60 cm) at varying distances (0.5, 1, 2, 5, 10, 15, 20, 40 meters) away from the border plantations. The data collected at the 40 m distance were used as the control value. Crop biomass and root samples and shading effects were obtained at the same distances away from the plantations while undergrowth density counts were conducted along transects under varying canopy densities in the tree plantations (Table 1). The measurements within crop fields compared between those adjacent to *Croton macrostachyus* and to *Eucalyptus* were bulk density, moisture content (September only), maize plant height, maize plant count and undergrowth density.

Statistical differences between distances within the same field, between fields, and between those fields adjacent to *Eucalyptus* and *C. machrostachyus* were determined by one-way ANOVA employing a 95% level of confidence. Besides sampling, interviews were carried out with 25 farmer representatives.

Farmer perception of *Eucalyptus*: The general impact and perception of *Eucalyptus* trees on crop production, soil properties and moisture storage was assessed through interviews with key informants. Twenty-five active farmers were interviewed in two representative *kebeles* (Ambomesk and Enguty), dominated by *Eucalyptus* plantations. The primary purpose of these interviews was to gather information concerning the history and background of *Eucalyptus* and to provide direction concerning the fundamental issues and questions to be answered experimentally.

Analyses of soil physical and chemical properties: The schedule of testing for the physical and chemical properties for both the *Eucalyptus* and *Croton macrostachyus* at various distances from the trees is shown in Table 1. Fig. 2 includes photos of both *C. macrostachyus* (A and C) and *Eucalyptus* spp (B and D). To determine the soil physical and chemical properties below both *Eucalyptus* and *Croton macrostachyus* plantations, different soil properties were analysed from samples obtained at 0 – 20 cm soil depths and distance from the selected plantations (Table 1). Texture (%), soil pH (both KCl and H_2O) in moles L^{-1}, organic matter content (%), available phosphorus (mg kg^{-1}), total nitrogen (%), exchangeable calcium and potassium (cmol (+) kg^{-1} soil) were analyzed from samples obtained from a depth between 0 and 20 cm and at 0.5, 1, 2, 5, 10, 15, 20, 40 meters from the selected *Eucalyptus* plantations in July 2008. The percentages of sand, silt and clay were determined using particle-size or mechanical analysis for air-dried soil samples as described by Rowell (1994). The pH was measured potentiometrically using a digital pH meter in the supernatant suspension of 1 : 2.5 soil to liquid ratio where the liquids were water and 1 M KCl whereas the percentages of organic matter (OM) and total nitrogen (TN) were determined by titration methods by Walkley-Black (WB) (1934) and Kjeldahl (Cohen, 1910), respectively. Exchangeable bases such as calcium and potassium were extracted from the soil colloids with 1M-ammonium acetate at pH 7 (Sahlemeden and Taye, 2000). Then, exchangeable Ca was measured from the extracts using an atomic absorption spectrophotometer while exchangeable K was determined from the same extracts with flame photometer as described by Rowell (1994). Finally, available P was determined by Olsen extraction method (Olsen et al., 1954, Table 1).

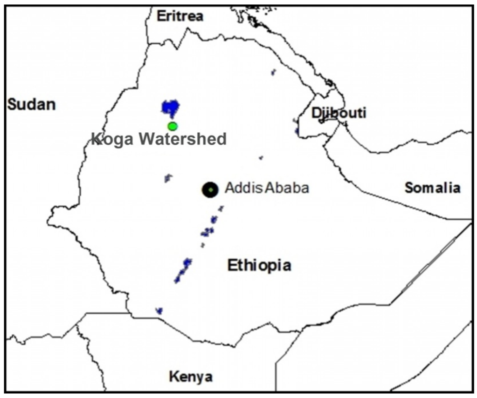

Fig. 1. Location of the Koga watershed.

Fig. 2. *Croton macrostachyus* (A) and *Eucalyptus* (B) trees along maize farm borders, and the under growth density within a coffee garden (C) and a *Eucalyptus* stand (D).

Table 1. Soil physical, chemical and biological parameters and sampling strategies.

Parameter	Sampling distances (m) from trees		Sampling depths (cm)	Sampling dates	Methods used for analysis
	Eucalyptus	*C. macrostachyus*			
Texture (%)	0.5, 1, 2, 5, 10, 15, 20, 40	No sampling	0 – 20	July	particle-size or mechanical analysis method (Rowell,1994)
Bulk density (g cm^{-3})	0.5, 1, 2, 5, 10, 15, 20, 40	0.5, 1, 2, 5, 10, 15, 20, 40	0–20, 20–40, 40 – 60	July	Tube core method (Blake,1965)
Moisture content (%)	1, 5, 10, 15, 20, 40	No sampling	0–20, 20–40, 40 – 60	July	Gravimetric method
	1, 5, 10, 15, 20, 40	No sampling	0–20, 20–40, 40 – 60	August	
	0.5, 1, 2, 5, 10, 15, 20	0.5, 1, 2, 5, 10, 15, 20	0–20, 20–40, 40 – 60	September	
	0.5, 1, 2, 5, 10, 15, 20, 40	No sampling	0–20, 20–40, 40 – 60	October	
Available water capacity (%)	0.5, 1, 2, 5, 10, 15, 20, 40	No sampling	0 – 20	October	Klute (1965)
Soil pH (by both KCl and H_2O) in mole L^{-1}	1, 5, 10, 15, 20, 40	No sampling	0 – 20	July	By a suspension of 1:2.5 soil to water and 1 M KCl
Organic matter (%)	1, 5, 10, 15, 20, 40	No sampling	0 – 20	July	Walkley-Black (WB) titration method
Total nitrogen (%)	1, 5, 10, 15, 20, 40	No sampling	0 – 20	July	Kjeldahl titration method
Available phosphorus (mg kg^{-1})	1, 5, 10, 15, 20, 40	No sampling	0 – 20	July	Olsen extraction (Olsen et al., 1954)
Exchangeable calcium (cmol (+) kg $soil^{-1}$)	1, 5, 10, 15, 20, 40	No sampling	0 – 20	July	Extraction, atomic absorption spectrophotometer (Rowell,1994)
Exchangeable potassium (cmol (+) kg $soil^{-1}$)	1, 5, 10, 15, 20, 40	No sampling		July	Extraction with flame photometer (Rowell, 1994)
Water repellency for field dried, air dried & wet soils (seconds)	0, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, 300 cm	No sampling	0 – 20	July, October	water drop penetration time (WDPT) test method (Dekker and Ritsema,1995)
Water repellency of leaf, bark root (seconds)	–	No sampling	N/A	October	
Shading effect	0, 0.5 1, 2, 5, 10, 15, 20, 40	No sampling	N/A	September	Direct measurement using light meter
Maize plant height (cm)	1, 5, 10, 15, 20, 40	1, 5, 10, 15, 20, 40	N/A	September	Direct measurement
Maize plant count (no. ha^{-1})	1, 5, 10, 15, 20, 40	1, 5, 10, 15, 20, 40	N/A	September	Direct counting
Maize yield (kg ha^{-1})	1, 5, 10, 15, 20, 40	No sampling	N/A	September	Direct weighing
Maize biomass (kg ha^{-1})	1, 5, 10, 15, 20, 40	No sampling	N/A	September	Direct weighing
Root distribution (no. ha^{-1})	1, 5, 10 meter	No sampling	0–20, 20–40, 40 – 60	September	Profile pits and direct counting
Under growth density (no. ha^{-1})	Under the shade	Under the shade	N/A		

While soil moisture depicts the water in the soil, the level of water repellency in the soil indicates the capacity of the soil to wet up. Water repellency has been often associated with soils under *Eucalyptus* trees. In July when the soils were wet, we sampled soils along transects in the different plantations for their level of water repellency. The water repellency of the soil was analyzed on field, air-dried and wetted soil samples collected at various distances (0, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, 300 cm) away from the *Eucalyptus* plantations using the water drop penetration time (WDPT) test described by Dekker and Ritsema (1995). In addition, soil water repellency was determined on a collection of the leaves, bark and roots from *Eucalyptus* trees to resolve the wetting capacity of the tree litter on the plantation floor.

Soil samples for bulk density, moisture content and *Eucalyptus* root distribution were taken from three profile depths at each distance interval while the remaining parameters were sampled from the 0 – 20 cm profile at each distance.

Available water capacity (AWC, %) was analyzed at field capacity (FC, 0.33 bars) and permanent wilting point (PWP, 15 bars) (Klute, 1965) from three samples obtained in the soil profile between 0 and 20 cm depth and at 0.5, 1, 2, 5, 10, 15, 20, 40 m away from the selected plantations in October 2008. Gravimetric soil moisture content (%) was determined from soil samples taken from depths, 0 – 20, 20 – 40 and 40 – 60 cm and at distances of 1, 2, 5, 10, 15, 20, 40 m in July and August 2008 and at distances of 0.5, 1, 2, 5, 10, 15, 20, 40 m in September and October 2008 (Table 1). The different sampling months represented vegetative, flowering, tasseling and grain filling stages, respectively, of the maize crop. Moisture content was determined for soils in fields adjacent to *Eucalyptus* for all four sampling months while it was only determined in September in those soils adjacent to *C. machrostachyus*. Bulk density was determined using tube core method described in Blake (1965) from soil samples collected from the soil profile at three depths (0 – 20, 20 – 40 and 40 – 60 cm) and at distances of 0.5, 1, 2, 5, 10, 15, 20, 40 meters into maize fields adjacent to both *Eucalyptus* and *C. macrostachyus* plantations in July 2008 (Table 1).

Shading and undergrowth density: Shading (lux) effect was measured using a light meter at multiple times throughout a day (9:00am, 12:00pm, 12:30pm, 3:00pm and 4:00pm) at the edge of the *Eucalyptus* plantations and crop field and in the maize field (above the canopy of the maize plants) at 0.5, 1, 2, 5, 10, 15, 20, 40 m away from the trees. Light intensity is a critical growth factor for neighboring crops and undergrowth vegetation. Therefore, in addition to shading intensity, the density of undergrowth vegetation (no. ha^{-1}) growing in very sparse, sparse, dense and very dense canopied areas within *Eucalyptus* and *C. macrostachyus* plantations was also estimated by totaling the number of individual shrubs, herbs, climbers and others (less than 3 m in height) in 3m x 3m sampling points in each canopy condition along three transects in each plantation.

Maize plant measurements: Plant measurements, such as height, count, biomass, root distribution and yield, were conducted on the maize plants directly adjacent to the tree plantations. In September 2008, near the time of harvest, the number of plants (no. ha^{-1}) and the plant height (cm) of individual maize plants were recorded at three sampling areas of 4 m^2 (2 m x 2 m) per distance (1, 5, 10, 15, 20 and 40 m) in fields adjacent to both *Eucalyptus* and *C. macrostachyus*.

The above-ground plant biomass (kg ha^{-1}) of Eucalyptus plants adjacent to *Eucalyptus* was determined at three sampling points at each distance: 1, 5, 10, 15, 20, 40 m from the tree plantation edge. Furthermore, the root distribution (no. ha^{-1}) of maize plants was also determined at 0 – 20, 20 – 40 and 40 – 60 cm depths in three sampling pits at each distance of 1, 5 and 10 m from the *Eucalyptus* plantation edge. The sampling pits measured 1 m in length by 0.2 m wide. At harvest time, the yield (kg ha^{-1}) from three sampling locations at each distance 1, 5, 10, 15, 20 and 40 m from the tree plantations was recorded.

RESULTS

Farmers' perception about the environmental impact of *Eucalyptus* plantation

Twenty-five respondents, all male, were interviewed and ranged in age from 36 to 45 years old with education levels varying from illiterate and non-formal education to grade eight or higher. Female respondents were not involved in the interviews since they were less familiar with the day-to-day agricultural activities, and there was little exchange of information from males to females even in the same household. Sixty percent of the respondents had attended at least grade 1 while only 12% continued beyond fourth grade. All respondents possessed land ranging from 0.25 to 3 hectares with half of them owning farms of 0.25 to 1 ha size. All landowners utilized their land for a combination of crop production, tree plantation and grazing.

Tree planting in the area was intended for fuel wood (100%), income generation (96%) and construction (84%). Environmental conservation was not indicated as an intention of planting. The most commonly planted tree species in the Koga Watershed was *Eucalyptus*, the planting of which began during the reign of Emperor Haile Selassie (1915–1974) with a very fast expansion rate since 1991 (Table 2). The *Eucalyptus* trees were planted on former cropland (40%) and along cropland borders (60%) and the majority on marginal lands (Table S1). The area on the farm covered by trees was usually between 0.15 and 0.25 ha. The few large farms had plantings in the 1–2 ha range (Table S1). In the watershed, all farmers perceived that *Eucalyptus* plantations have a negative environmental impact because of the shading effect, water and nutrient competition, thinning of seedlings and forcing poor grain filling (100 %). Almost half of the local farmers professed that there is no difference between crops species in resisting the negative effect, i.e. all are susceptible (Table S2). According to farmer opinion, the *Eucalyptus* trees affected soil property by drying out the soil (92%), making soil unfertile (8%) and reddish (4%). Most farmers (96%) in the watershed suggested that *Eucalyptus* trees affect soil moisture through excessive root suction. Soil moisture stores dried up due to the nearby *Eucalyptus* plantation (80 %) (Table S3). The responses from the interviewees showed that *Eucalyptus* trees adverse effects are more pronounced on reddish soil (96%), sloping land (84%), and dry land (96%) instead of on black soil, flat and wet lands. It is interesting that according to the view of the respondents, the most adverse effects of *Eucalyptus* can be seen if the trees are planted east and least if planted north (20 %) of the cropland (Table 3).

Table 2. Farmers' perception concerning tree planting in the locality (N = 25). *Eucalyptus* plantations were begun either during the reign of Emperor Haile Selassie (1915 – 1974) or Mengistu Haile Mariam (1974 – 1987).

Issues regarding to trees planting	% of farmer respondents in parenthesis			
Source of energy in the area	Wood (100)	Manure (12)		Others (12)
Purpose of tree planting in study area	For fuel (100)	Income (96)	Construction (84)	Others (4)
Mostly planted tree	*Eucalyptus* (100)		Others (0)	
Start of *Eucalyptus* plantation	During emperor Mengistu (36)		Haile Selassie (64)	
Eucalyptus plantation expansion	Very fast (56)	Fast (24)	Average (12)	Slowly (8)

Table 3. Conditions at which the farmers perceive the effect of *Eucalyptus* plantations is more pronounced (N = 25) according to perceptions of the farmers.

Conditions	% of farmer respondents in parenthesis			
Soil	Unfertile soil (40)	Red soil (96)	Black soil (36)	
Slope	Sloping land (84)		Flat land (48)	
Drainage systems	On dry land (96)		On wet land (12)	
Management system (direction of *Eucalyptus* trees to adjacent plantation)	East (88)	West (20)	North (20)	South (32)

Experimental findings about the effect of *Eucalyptus* plantation on the ecosystem

Soil physical properties: In both texture and bulk density comparisons of soils at different distances and depths, non-significant differences were detected. The soil textural classes for all soil samples taken in 0 – 20 cm depth and all distances in the study area were clay loam (Table S4). The remainder of the profile was also clay loam. Because of the volcanic origin of the soils, all the bulk densities at all depths and distances from *Eucalyptus* and *C. macrostachyus* stands were low and ranged from 1.0 to 1.1 g cm^{-3}. *Eucalyptus* trees did not affect organic matter content in the soil significantly. The organic matter varied from 2 – 4% with an average of approximately 3% (Fig. S1).

Soil chemical properties: In the study area, the surface soils (in 0 – 20 cm depth) were very acidic and did not significantly differ ($p > 0.05$) with distance to the *Eucalyptus* stand (Fig. S2). Although not significant, the pH value at 5 m from the tree was the lowest after intense rains. Unlike pH, there were significant differences in macronutrient concentration with distance from *Eucalyptus* tree (Fig. 3). In general, the macronutrient status increased with distance from the *Eucalyptus* stand. Total N (TN), nearest to the *Eucalyptus* stand however, was significantly ($p < 0.001$) above average. Next to it at 5 m TN was at its minimum (Fig. 3A). Farther from the trees at 40 m, it increased up to the same value as the values at 1 m from the trees. Although the overall available P content of the fields' soil was in the very low range (< 5 mg kg^{-1}), the one-way ANOVA showed that there was a highly significant difference ($P < 0.001$) in an upward trend with distance from the *Eucalyptus* stand (Fig. 3B). Exchangeable Ca concentrations, at 1 m distance was 7.8 cmol per kg of soil and significantly ($P < 0.05$) less than the values at the other sampling points along the transect (Fig. 3C) which were in range that was considered in the high range (10 – –20 cmol per kg of soil) in Ethiopia. Finally, the exchangeable K concentrations at all distances were in high range, and independent of distance to the *Eucalyptus* stand at the 5% significant level (Fig. 3D).

Moisture contents: In July and August when it rains almost continuously, there was not a significant difference between moisture contents at the various distances from the *Eucalyptus* stand (Fig. 4A and 4B). Only in the 40 – 60 cm depth in July, the moisture content at 5 m from the tree was significantly lower than values at 1 and 40 m. In September, at the end of the monsoon period, the moisture content measurements near the *Eucalyptus* stand at all three depths were significantly less ($p < 0.001$) than the moisture contents farther away (Fig. 4C). This trend was not observed for *C. macrostachyus* where no significant difference in moisture content was observed with increasing distance from the trees. Interestingly, at 15 m and greater from the trees, the moisture contents near the

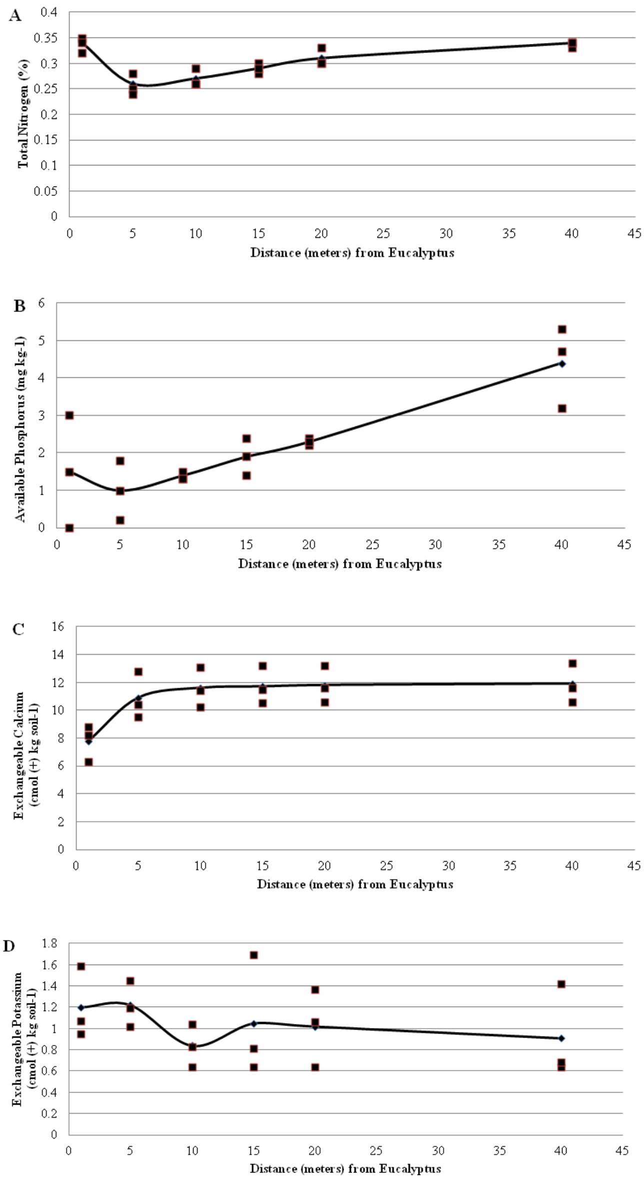

Fig. 3. Percentage of available phosphorus (A) total nitrogen (B) exchangeable calcium (C) and exchangeable potassium (D). All samples from each distance and field were graphed.

Eucalyptus stand showed no statistical difference from those moisture contents near the *C. macrostachyus* stands (Fig. 5). In October, at the maize grain filling stage, the trend in moisture content at increasing distances from the *Eucalyptus* trees was similar to that in Sepember with moisture contents near the *Eucalyptus* stand significantly ($p < 0.001$) less than those

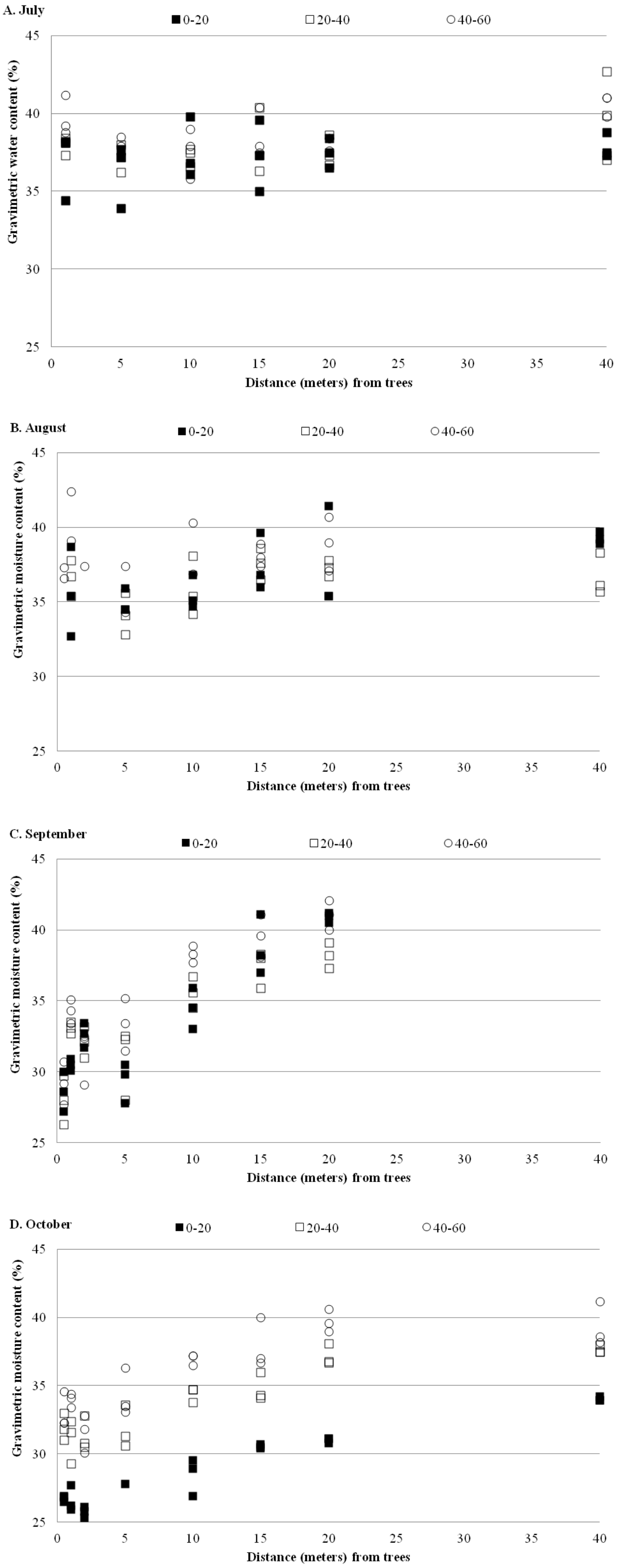

Fig. 4. Gravimetric moisture content values at 0 – 20 cm, 20 – 40 cm and 40 – 60 cm sampling depths at increasing distance from *Eucalyptus* stands in July (A), August (B), September (C) and October (D) 2009. All samples at each depth and each distance graphed.

further away (Fig. 4C). In addition for this month, the moisture content in the 0 – 20 cm depth was significantly less than the moisture contents in 20 – 40 and 40 – 60 cm depths.

Water repellency of soil: Under these wet conditions, the soils were wettable with WDPT value < 4s (Table 4). However, when the soils were air or oven dried, they became highly hydrophobic especially close to the *Eucalyptus* stand as shown by the WDPT test (P < 0.001). The WDPT test showed that for the field-dried soils at 0 to 80 cm from the trees, the soils were severely water repellent, from 100 to 160 cm strongly water repellent, from 180 to 220 cm slightly water repellent and over 240 cm, non-water repellent. For the air-dried soil, the same trend was observed but water repellency was less severe. The dried *Eucalyptus* plant parts (leaf, bark and root) were found to be slightly water repellent. The WDPT value of the leaf was significantly (P < 0.001) greater than the values of bark and root.

Light intensity: Highly significant difference (p < 0.001) in light intensity at different distances from the *Eucalyptus* stand was found for all measurement times. The trees caused serious light intensity reduction up to 5 and 10 m distances at 9:00am and 12:00am in the west direction, up to 10 m at 12:30pm in the north and up to 15 m at 3:00pm in the east direction (Fig. 6).

Root distribution: The *Eucalyptus* root was significantly (p < 0.001) more dense at 5 meter from the tree than at either 1 m or 10 m (Table 5). At 5 m distance, 600 roots per square meter were counted over the first 60 cm of the profile. That means that there was one root in every 1.8 cm^2. The variation of root density over the first 60 cm in depth was not significant.

Crop performance: The number of plants and plant height is given as function of distance from the tree for both the *Eucalyptus* and *C. macrostachyus* spp. (Fig. 7A and 7B). Obviously, the crop was not affected by the proximity of the *Croton* spp. while the effect on the maize near the *Eucalyptus* faired much worse than farther away. There was a similar trend for both the maize yield and the biomass as a function of distance to the *Eucalyptus* stand (Fig. 7C). There was a 10-fold difference in biomass for the 1 and 20 m sampling points. The yield and biomass between 20 and 40 m was not significantly different.

Undergrowth status of shade trees: The average undergrowth density of the coffee garden (*C. machrostachyus*) plantation was significantly (P < 0.01) greater than that of under *Eucalyptus* trees (Fig. S4). Although the undergrowth density under both species of tree plantations decreased as the canopy closure increased, the undergrowth density in the *C. machrostachyus* stand is greater than that of the *Eucalyptus* stand at all the different densities of the canopy.

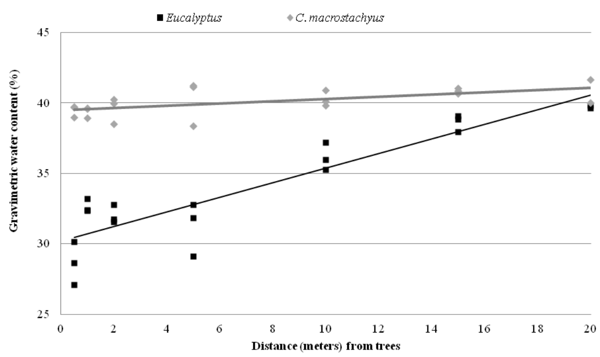

Fig. 5. Comparison of gravimetric moisture content averaged over three profile depths at increasing distances from *Eucalyptus* (black line with black squares) and *C. macrostachyus* (gray line with gray diamonds).

Table 4. Persistence of water repellency (WDPT (s)) of the soil at different distances from *Eucalyptus* stand for soils in the field and sampled soils in the lab in July and October.

Sampling Distance (cm)	WDPT values (seconds)		
	Field dry soils	Air-dried soils samples	Wetted soils samples
T1 (0 cm)	2740 a ***	110.7 a **	3.0 a *-
T2 (20 cm)	2640 b ***	106.3 b **	2.4 b *-
T3 (40 cm)	2220 c ***	44.7 c *	1.5 c *-
T4 (60 cm)	1980 d ***	1.3 d *-	0 d *-
T5 (80 cm)	1680 e ***	0 e *-	0 d *-
T6 (100 cm)	110 f **	0 e *-	0 d *-
T7 (120 cm)	80 fg **	0 e *-	0 d *-
T8 (140 cm)	74 fg **	0 e *-	0 d *-
T9 (160 cm)	70.8 fg **	0 e *-	0 d *-
T10 (180 cm)	22 g *	0 e *-	0 d *-
T11 (200 cm)	19.67 gh *	0 e *-	0 d *-
T12 (220 cm)	14.67 gh *	0 e *-	0 d *-
T13 (240 cm)	< 1 h *-	0 e *-	0 d *-
T14 (260 cm)	< 1 h *-	0 e *-	0 d *-
T15 (180 cm)	< 1 h *-	0 e *-	0 d *-
T16 (300 cm)	< 1 h *-	0 e *-	0 d *-
C.V (%)	5.7	11.6	25.1
LSD at 0.05	68.7!!!	3.2!!!	0.2!!!

WDPT = water drop penetration time, *- = non-water repellent (WDPT < 5 sec), * = slightly water repellent (WDPT = 5–60 sec), ** = strongly water repellent (WDPT = 60–600), *** = severely water repellent (WDPT = 600–3600 sec).
Mean values followed by the same letters are not significantly different at 0.05 level LSD test.
!!! = Significant at the 0.001 level.

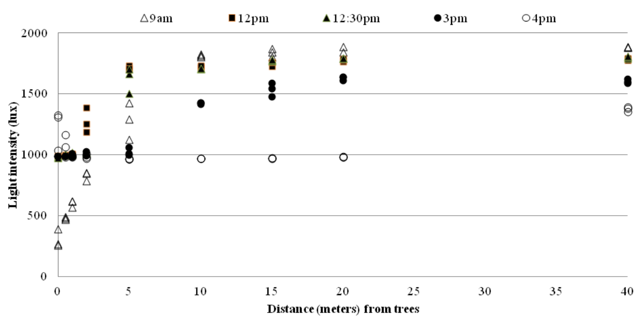

Fig. 6. Light intensity values at different times within a day and at increasing distances from the *Eucalyptus* tree plantations. The measurements were taken in west direction at 9:00 and 12:00am, north direction at 12:30pm and east direction at 3:00 and 4:00pm. All data points graphed.

Table 5. Mean *Eucalyptus* tree root distribution at different distances and depths (no. 0.2m^2).

Sampling depth (cm)	Root distribution (no. 0.2m^2) at different sampling distances from *Eucalyptus* stand (m)		
	1	5	10
20	22.7	135.0	13.3
40	26.3	144.0	14.7
60	37.7	177.0	16.3

DISCUSSION

The three different plantations of *Eucalyptus* spp. and *Croton macrostachyus* were grown on three different clay loam soils (Table S4) with medium organic matter content (Fig. S1), low pH (Fig. S2) and low organic matter, respectively. The results of the sampling from the fields bordered by *Eucalyptus* and within the *Eucalyptus* stands were remarkably similar. The root density was greatest at 5 m from the tree (Table 5), and the macronutrients (with the exception of potassium) were most depleted at this point. Moisture contents were also the lowest here, but not always statistically significant (Fig. 4). Soil pH (Fig. S2), organic matter (Fig. S1), exchangeable K and bulk density were not affected by *Eucalyptus*. Yield and biomass of maize were most reduced near the *Eucalyptus* stand (Fig. 7C). This was not only due to the effect of the *Eucalyptus* on the soil, but also because the light intensity was greatly reduced as well (Fig. 6) in accordance with findings of Agele et al. (2007) and Kotowski et al. (2000). The competition of *Eucalyptus* for nutrients can be overcome somewhat by adding fertilizers (Ayoola and Makinde, 2008; Cahill, 1999).

The reduced moisture availability near the *Eucalyptus* stands (Fig. 4 and Fig. 5) is in partial agreement with those of Kidanu (2004) who reported that irrespective of crop species, less water remained in the soil in the tree-crop system than in the sole cropping. In our case when there is sufficient rain, *Eucalyptus* trees do not affect the moisture content, but only when rainfall decreases *Eucalyptus* dries out the soil faster. This is in accordance with Susiluoto and Berninger (2007) who reported that *Eucalyptus* trees have roots that are well developed in the dry areas and enable them to use the water stored in the soil during the dry season. In the semi humid highlands during the rainy season, there is sufficient water for both crops and trees and other factors (such as shading and reduced nutrient status) are responsible for the decrease in yield (Table 5).

In accordance with findings of Abelho and Graça (1996), *Eucalyptus* trees cause soil hydrophobicity up to 2 m from the tree during the dry season through leaf litter incorporation at the surface of the soil (Table 4). Hydrophobicity not only affects water infiltration, but also can affect soil microorganism activity and plant growth (Florenzano, 1957).

Total nitrogen content in the plough zone from 0 to 20 cm depth at all distances was in the very high range (Fig. 3A). Near the *Eucalyptus* stand, this might be due to its allelopathic effect, which prevents N uptake by the plants (Bernhard-Reversat, 1987). The available phosphorus content (Fig. 3B) was in the very low range (< 5 mg kg^{-1}) because the acidic soil fixed the phosphorus. Similar to other Ethiopian soils, we found that the exchangeable calcium and potassium were all in the high range (Ilaco, 1985)

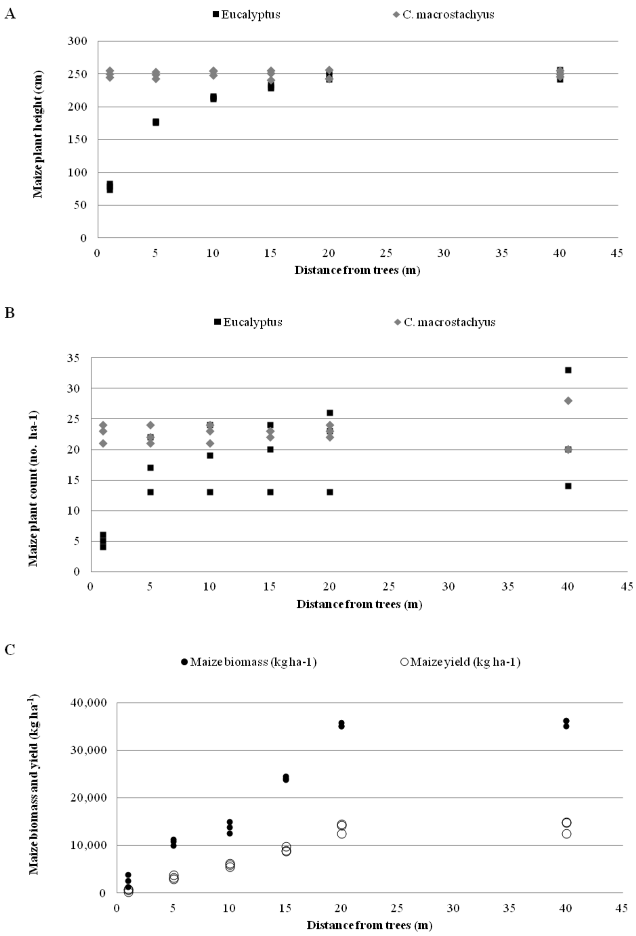

Fig. 7. Comparison of maize plant count (A) and plant height (B) in crop fields adjacent to *Eucalyptus* and *C. macrostachyus* tree plantations, and biomass and grain yield (C) of maize in fields adjacent to *Eucalyptus* plantations. All samples from each distance and field were graphed.

In the Koga Watershed, trees like *Acacia* species serve as shade for coffee and allow for the undergrowth of grasses, shrubs and ferns. In addition there are other manageable, fast maturing and widely adaptable leguminous tree species (*Leucaena leucocephala, Prosopis juliflora* and *Albizia procera*), which improve the productivity of the adjacent plantation (Mahmud et al., 2005). In contrast, *Eucalyptus* species have less understory vegetation (Fig. S4, Fabiã et al., 2002). The good performance of *Leucaena* and *Acacia* species) is due to the absence of competition for resources with the understory plants (such as coffee) due to a deeper rooting system (Lehmann, 2003), nitrogen fixation (Ramadhanil et al., 2008) and a diverse and rich microbial habitat (Dupuy and Dreyfus, 1992; Parker and Brown, 1999). This is not true for *Eucalyptus* since local farmers tried and failed growing coffee under its shade. In addition, *Eucalyptus* leaf extracts inhibited the germination of several plants (Watson, 2000) and reduces seedling emergence of maize (El-Khawas and Shehata, 2005). Therefore, *Eucalyptus* trees have drawbacks to improving the performance of the undergrowth vegetation. However, because of its predominance in the landscape, the overall economic benefits of *Eucalyptus* must outweigh the benefits of increased undergrowth of indigenous trees.

CONCLUSIONS

Farmers perceived that *Eucalyptus* plantation depreciates the potential of the environment even though they continue to plant the trees because of the relative short time required to produce wood biomass for fuel, construction and cash.

Experimentally, it was proven that the poor performances of the adjacent plants, particularly maize and undergrowth plants, were due to light, water and nutrients (total nitrogen, available phosphorus and exchangeable calcium) competition and soil water repellency. Based on these results, the impacts of *Eucalyptus* on soil properties and moisture content are limited to a great extent to 20 m away from the tree. Since *Eucalyptus* spp. are fast growing, and deep and dense rooted, the reduction and drying out of previously functional water stores nearby in the watershed is a result of its great water suction ability in addition to it causing water repellency in the soil and poor undergrowth, both reducing infiltration and the water table. Thus, the potential ecosystem will be exhausted in the future because of the negative impact of *Eucalyptus*.

Ultimately, farmers should change their management within this 20 m zone between crops and trees. Crops (maize and undergrowth) should be cultivated at distances greater than 15 – 20 m from *Eucalyptus* stands. For the sustainability and efficiency of the Koga irrigation project, it is important to note that, according to the respondents in the survey, *Eucalyptus* is reducing the quantities of water available. This is important when we consider that this limits the amount of water available for irrigation. Therefore, from the food security point of view, priority should be given to crop production. In other words, productive lands should be left for crops, and *Eucalyptus* trees should be limited to marginal lands, such as wetlands. This too has been suggested by the farmers for better ecosystem and agricultural land management.

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Note: Supplementary Tables (S1–S4) and Figures (S1–S3), as well as colour version of Figures 1 and 2 can be found in the web version of this article.

SUPPLEMENTARY MATERIAL

Table S1. Activities performed by a farmer on his land in the Koga watershed (N = 25).

Farmer's land holding and uses	% of farmer respondents in parenthesis			
Possession of land	Yes (100)			No (0)
Farmer's total area of land in hectare	0.25–1 (48)	1.25–2 (36)		2.25–3 (16)
Activities a farmer performs	Crop production (100)	Tree planting (100)		Grazing (100)
Tree sp. Planted by a farmer	*Eucalyptus* (100)		Others (28)	
Farmer's reason for *Eucalyptus* planting	Fast growth (84)	Cash (100)	Fuel wood (4)	Easy management (4)
Farmer's location to plant *Eucalyptus*	On crop land (40)	Along crop border (60)		On marginal land (64)
Land area covered by *Eucalyptus* (ha)	0.13–0.25 (44)	0.26–0.5 (32)	0.51–1 (16)	1–2 (8)

Table S2. Farmers' perception about environmental impact of *Eucalyptus* plantation in the Koga Watershed (N = 25)

Impact of *Eucalyptus*	% of farmer respondents in parenthesis					
Effect on crop production, soil and water	Yes (100)			No (0)		
Resistance difference with crops	Yes (56)			No (44)		
Resistant crops	Maize (20)	*F. millet* (4)	teff (28)	noug (12)	bean (4)	others (8)
Susceptible crops	Maize (80)	*F. millet* (96)	teff (56)	noug (52)	bean (44)	others (44)

Table S3. Mechanisms and conditions by which *Eucalyptus* plantation affects the ecosystem (N = 25) according to farmers' perceptions.

Mechanisms	% of farmer respondents in parenthesis				
Affect on crop production	Shading effect (4)	Nutrient competition (28)	Moisture competition (28)	Seedling thinning (56)	Affecting grain filling (8)
Causing alteration of soil property	Causing unfertility (8)		Changing soil color to red (4)		Drying out (92)
Effect on water bodies	Sucking much water (96)			Have no idea (4)	
Presence of dried up water bodies	Yes (80)			No (20)	

Table S4. Mesm soil fractions and textural classes of the different sites at different sampling distances from *Eucalyptus* hedge rows.

	Percent soil texture at sampling point distances from tree stands							
	0.5 m	1 m	2 m	5 m	10 m	15 m	20 m	40 m
Sand	27.0	30.7	27.7	29.7	30.3	31.7	32.3	32.0
Silt	36.0	31.7	33.7	32.3	33.0	29.7	30.3	33.7
Clay	37.0	37.7	38.7	38.0	36.7	38.7	37.3	34.3
Class	Clay loam	Clay loam	Clay loam	Clay loam	Clay loam	Clay loam	Clay loam	Clay loam

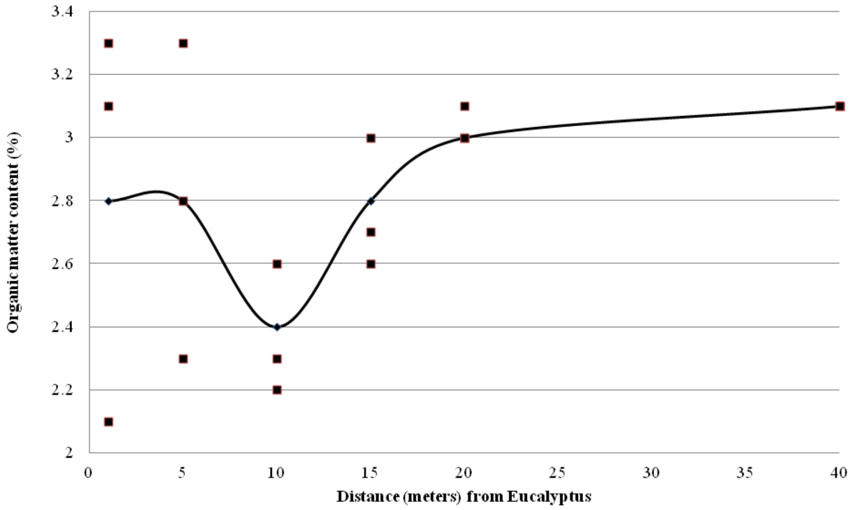

Fig. S1. Organic matter values comparison along distance from *Eucalyptus* stand in the plough depth. Mean values are represented by the line. All samples from each distance and field were graphed.

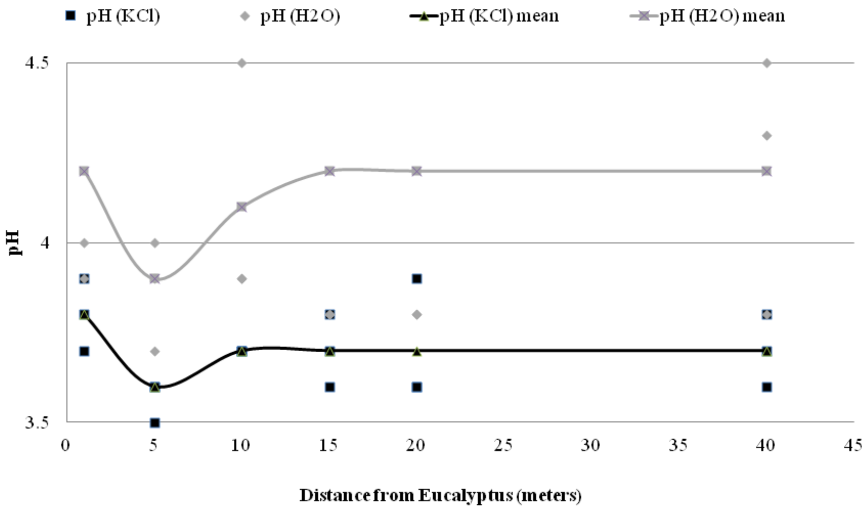

Fig. S2. pH values at increasing distances from *Eucalyptus* stands. The lines represent the mean of the samples graphed. All samples from each distance and field were graphed.

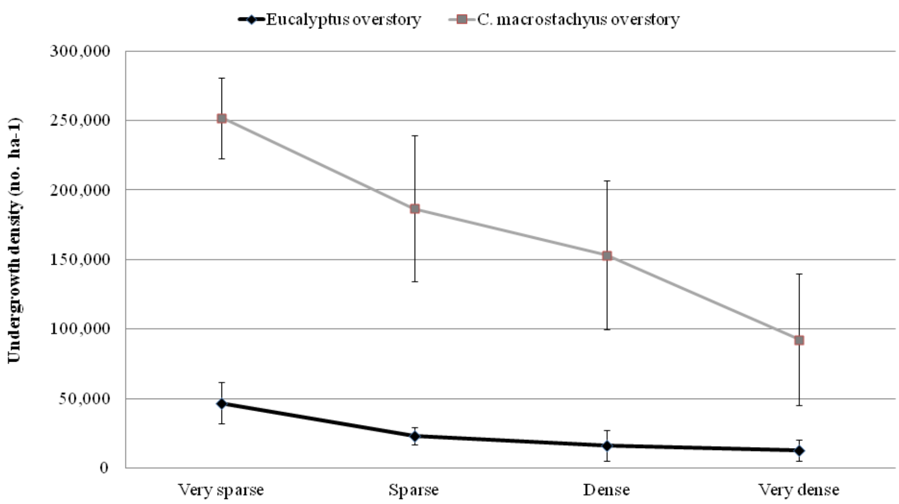

Fig. S3. Comparison of coffee undergrowth density (no. ha^{-1}) values between plantations of *Eucalyptus* and *C. macrostachyus*, the common coffee garden shade.