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Semi-forest coffee cultivation and the conservation of Ethiopian Afromontane rainforest fragments

Raf Aerts[a,*], Kitessa Hundera[a,b], Gezahegn Berecha[c,d], Pieter Gijbels[c], Marieke Baeten[c], Maarten Van Mechelen[a], Martin Hermy[a], Bart Muys[a], Olivier Honnay[c]

[a] Division Forest, Nature and Landscape, Katholieke Universiteit Leuven, Celestijnenlaan 200E-2411, BE-3001 Leuven, Belgium
[b] Department of Biology, Jimma University, P.O. Box 378, Jimma, Ethiopia
[c] Laboratory of Plant Ecology, Katholieke Universiteit Leuven, Kasteelpark Arenberg 31-2435, BE-3001 Leuven, Belgium
[d] Department of Horticulture and Plant Science, Jimma University, P.O. Box 307, Jimma, Ethiopia

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ABSTRACT

Coffea arabica shrubs are indigenous to the understorey of the moist evergreen montane rainforest of Ethiopia. Semi-forest coffee is harvested from semi-wild plants in forest fragments where farmers thin the upper canopy and annually slash the undergrowth. This traditional method of coffee cultivation is a driver for preservation of indigenous forest cover, differing from other forms of agriculture and land use which tend to reduce forest cover. Because coffee farmers are primarily interested in optimizing coffee productivity, understanding how coffee yield is maximized is necessary to evaluate how, and to what extent, coffee production can be compatible with forest conservation.

Abiotic variables and biotic variables of the canopy were recorded in 26 plots within 20 forest fragments managed as semi-forest coffee systems near Jimma, SW Ethiopia. In each plot, coffee shrub characteristics and coffee yield were recorded for four coffee shrubs. Cluster and indicator species analyses were used to differentiate plant communities of shade trees. A multilevel linear mixed model approach was then used to evaluate the effect of abiotic soil variables, shade tree plant community, canopy and stand variables, coffee density and coffee shrub size variables on coffee yield.

Climax species of the rainforest were underrepresented in the canopy. There were three impoverished shade tree communities, which differed in tree species composition but did not exhibit significant differences in abiotic soil variables, and did not directly influence coffee yield. Coffee yield was primarily determined by coffee shrub branchiness and basal diameter. At the stand level a reduced crown closure increased coffee yield. Yield was highest for coffee shrubs in stands with crown closure less than median (49 ± 1%). All stands showed a reduced number of stems and a lower canopy compared to values reported for undisturbed moist evergreen montane rainforests.

Traditional coffee cultivation is associated to low tree species diversity and simplified forest structure: few stems, low canopy height and low crown closure. Despite intensive human interference some of the climax species are still present and may escape local extinction if they are tolerated and allowed to regenerate. The restoration of healthy populations of climax species is critical to preserve the biodiversity, regeneration capacity, vitality and ecosystem functions of the Ethiopian coffee forests.

1. Introduction

Coffee ranks among the world's most valuable agricultural commodities and Arabica coffee accounts for two-thirds of the world coffee market (Labouisse et al., 2008). Arabica or highland coffee (*Coffea arabica* L., Rubiaceae) has its origin in southwest Ethiopia (Anthony et al., 2001, 2002), where it is an understorey shrub of the 'moist evergreen montane rainforest' or 'Afromontane rainforest'. These forests occur in the southwestern highlands between 1500 and 2600 m, with an annual rainfall between 700 and 1500 mm (Friis, 1992). The canopy typically consists of a mixture of medium-sized, broad-leaved species (10–30 m tall) with *Afrocarpus falcatus* and *Pouteria adolfi-friederici* as emergent species that may reach a height of 30–40 m (Demissew et al., 2004). Between 1500 and 1900 m, these rainforests or '*coffee forests*' contain the reservoir of genetic diversity of *C. arabica*, the wild relative of all commercial Arabica coffee cultivars (Anthony et al.,

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* Corresponding author. Tel.: +32 16 329721; fax: +32 16 329760.
E-mail addresses: raf.aerts@ees.kuleuven.be (R. Aerts), kitessah2@yahoo.com (K. Hundera), gberecha@yahoo.com (G. Berecha), pieter.gijbels@bio.kuleuven.be (P. Gijbels), martin.hermy@ees.kuleuven.be (M. Hermy), bart.muys@ees.kuleuven.be (B. Muys), olivier.honnay@bio.kuleuven.be (O. Honnay).

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2002; Hedberg et al., 2003; Gole et al., 2008). These forests are therefore of particularly high conservation importance and have a significant economic value (Hein and Gatzweiler, 2006; Silvestrini et al., 2007). However, human pressure on the coffee forests is immense, mainly because of unsustainable resource use (e.g. for firewood and charcoal production) and deforestation for agriculture, settlement and establishment of plantations (Gole et al., 2008). Nevertheless, the economic gains from the coffee grown in the understorey have facilitated the preservation of forest cover in the southwestern Ethiopian highlands, even in densely populated areas where, for instance, fuel wood demands are extremely high.

Ethiopian forest coffee is predominantly produced by smallholders, who harvest coffee from undomesticated coffee shrubs in more or less managed forests (Gove et al., 2008; Hylander and Nemomissa, 2008; Labouisse et al., 2008). The intensity of management varies between little or no interventions in '*forest coffee*' systems, and annual slashing of the herbs, shrubs and emerging tree seedlings in the understorey and selective thinning in the upper canopy in '*semi-forest coffee*' systems (Senbeta and Denich, 2006; Labouisse et al., 2008; Schmitt et al., 2009). In semi-forest coffee systems, farmers usually do not plant coffee cultivars but transplant semi-wild coffee plants that regenerate spontaneously inside the forest to fill open spaces (Labouisse et al., 2008). Forest and semi-forest coffee systems are expected to have fewer negative impacts on biodiversity than shaded or non-shaded coffee plantations (Perfecto et al., 2003; Philpott and Dietsch, 2003; Philpott et al., 2008) because they have a higher structural and floristic diversity (Cruz-Angón and Greenberg, 2005). Thus, like shade coffee agro-ecosystems elsewhere (e.g. Bandeira et al., 2005; Gordon et al., 2007; Ambinakudige and Sathish, 2009; Correia et al., 2010), traditional coffee cultivation in Ethiopia has a high potential to be conservation-oriented (Gove et al., 2008; Hylander and Nemomissa, 2008). Ethiopian coffee cultivation has the unique additional ecological advantage that *C. arabica* is an indigenous forest plant and thus a natural component of the ecosystem and the food web (Summers, 2010).

Because yield of truly wild coffee shrubs in natural forest is extremely low (15 kg ha^{-1} yr^{-1}; Schmitt et al., 2009), the traditional shade coffee management system in Ethiopia reduces the density of trees and understorey shrubs to improve the productivity of the coffee plants (Senbeta and Denich, 2006; Schmitt et al., 2009). Especially in areas with high and increasing population, small-holder coffee farmers depend on a limited amount of land and are forced to maximize coffee yield. This implies a shift towards more intensively managed, less complex coffee systems. Effects of this simplification on forest biodiversity and associated functions are expected to be detrimental (Philpott et al., 2008; Gordon et al., 2009). Thus, although the extent of the semi-forest coffee area may remain more or less stable, the quality of the forests may strongly deteriorate with increasing coffee yield.

In this study we wish to extend the attention given to coffee forest management, in particular to semi-forest coffee systems, and from the perspective of the coffee farmer. What maximizes coffee yield? Understanding how coffee yield is maximized is necessary to evaluate how, and to what extent, coffee production can be compatible with conservation of forest cover, structure and species composition in the long term. To that end, we analyzed how abiotic and biotic characteristics of coffee forests influence coffee yield. We focused on the following questions:

(i) What is the variation in soil fertility, tree plant community composition and forest stand variables across a series of forest fragments managed as semi-forest coffee systems in southwest Ethiopia?
(ii) How are these variables related to coffee yield?
(iii) Are high coffee yields compatible with the preservation of forest cover, structure and species diversity?

2. Methods

2.1. Site description

The study was conducted near the village of Garuke (7°44′ N, 36°44′ E; elevation 2000–2100 m), 10 km northwest of Jimma in southwest Ethiopia (Fig. 1). The undulating landscape consists of a mosaic of crop land, pasture, forest fragments managed for coffee production, riverine wetland, small human settlements and isolated farmsteads, and patches of exotic timber tree species. While there is no general pattern in their location, most forest fragments are found in the middle of the slopes and along streams. The deep soils are nitisols, which belong to the most productive soils of the humid tropics, although P fixation may be a problem (Driessen and Dudal, 1991).

According to local elders, the forest was relatively intact, with few coffee shrubs and only sparse human settlement until 90–100 years ago. After the recognition of the importance of coffee and its role in sustaining local livelihood approximately 60–70 years ago, farmers started to manage the forest to improve the productivity of forest coffee. Management included the introduction of coffee seedlings from neighbouring forests, thinning whenever the farmer thinks the coffee needs more light, and slashing of the understorey shrubs and weeds once or twice per year, in particular one or two weeks before harvesting the berries. The intensity of forest management generally depends on availability of labour, in turn depending on farm size and family size, and experience and knowledge of the farmers about the role of management in enhancing productivity.

2.2. Data collection

Data were collected from August to October 2008. A two-stage sampling design was used to select 26 random plots within 20 forest fragments which represented the range of fragment sizes in the semi-forest coffee system in the area (0.2–33 ha) (Fig. 1). The size of the plots was $20 \times 20\,\text{m}^2$.

Species, girth at 1.30 m and height for all woody plants other than *C. arabica* and taller than 2 m in every plot (including *Dracaena* species and palms) were recorded. Stem number (ha^{-1}), basal area ($\text{m}^2\,\text{ha}^{-1}$) and average height (m) were calculated for each plot. Stem coordinates and four crown coordinates were measured along a local grid for every recorded individual. Crown cover was calculated (%) from vertical crown projections using SVS (Stand Visualization System, USDA Forest Service). Crown closure (%) was calculated from four readings in the cardinal directions with a spherical densiometer. Crown cover determines direct overhead light while crown closure is also related to indirect, oblique light. The density of coffee shrubs (m^{-2}) was calculated from the total number of coffee shrubs counted in the plot. Ten soil samples (0–10 cm depth) were collected in each plot. These were bulked and analyzed for pH(KCl), cation exchange capacity and nutrient concentration (available Ca, Mg, K, P; total C, N).

In each plot, four coffee shrubs were sampled by subdividing the plot into four $5 \times 5\,\text{m}^2$ quadrants and selecting the four coffee shrubs growing nearest to the quadrant centres. For each coffee shrub, the number of productive plagiotropic shoots and the number of berries on three of these shoots[1] were counted. Basal

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[1] *C. arabica* only produces berries on plagiotropic (horizontal) end-shoots, not on orthotropic (vertical) shoots.

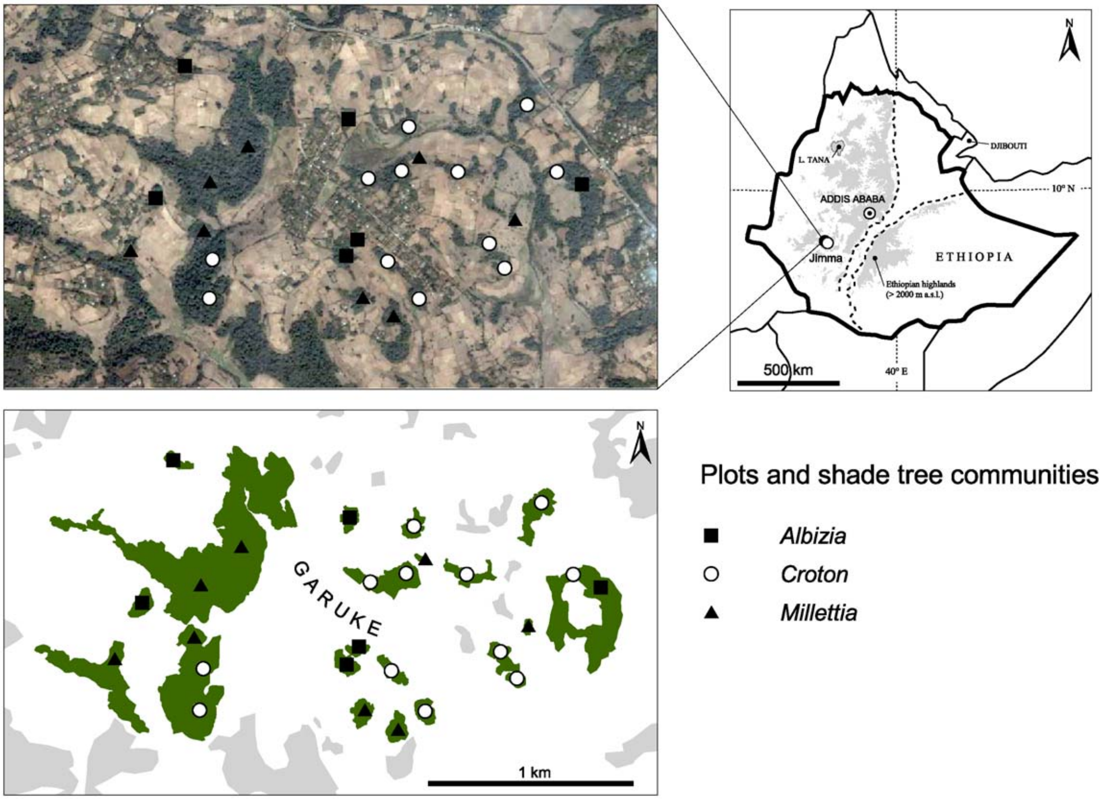

Fig. 1. Location of sample plots in selected Afromontane rainforest fragments in Garuke, Jimma zone, Southwest-Ethiopia. Sample plots are labeled according to three shade tree communities produced by cluster and indicator species analysis. Satellite imagery© 2009 DigitalGlobe, Google Earth.

diameter, coffee shrub height and two perpendicular crown diameters were measured and the number of primary and secondary orthotropic shoots (i.e. main vertical branches and secondary, vertical branches, respectively) were counted. Coffee yield was estimated by calculating the number of berries and the berry density (m^{-3}) of the coffee shrub. The number of berries was calculated by multiplying the mean number of berries on a shoot by the number of productive shoots. The berry density was calculated as the number of berries divided by the crown volume, which was approximated by the volume of an inverse cone defined by the coffee shrub height and the two perpendicular crown diameters. For comparison with other studies, the number of berries was converted to clean coffee yield. An average weight of 0.33 g per berry (Schmitt et al., 2009) and the average coffee plant density calculated from our own data were used. All measured coffee shrubs were semi-wild according to their owners. No improved cultivars were used in this study.

2.3. Data analysis

The sample plots were clustered into three groups using canopy tree stem number data, the Sørensen distance measurement and flexible beta linkage ($\beta = -0.25$) (McCune and Mefford, 2006). Indicator species analysis (Dufrêne and Legendre, 1997) was applied to calculate indicator values for all species and their significance for the emerging groups. Homogeneity within groups was tested with a multiresponse permutation procedure (MRPP) test. Non-metric multidimensional scaling (NMS) was used to investigate indirect gradients influencing species distribution. NMS was run using the Sørensen distance measure, six starting dimensions, 40 iterations, an instability criterion of 10^{-5} and a rotation for maximum variance (McCune and Mefford, 2006). NMS dimensions were related to environmental variables of fragments by use of Pearson correlations. Differences in biotic and abiotic variables between communities were analyzed with multivariate ANOVA after verification of the assumptions of normality and homoscedasticity.

Principal components analysis (PCA) was applied to reduce the number of soil characteristics, using the first two axes to describe the major abiotic variation among plots (explaining 51.7 and 26.0% of the variance, respectively). A multilevel linear mixed model approach (Singer, 1998) was used to estimate the effect of shade tree plant community, canopy variables (cover, closure, height), stand variables (stem number, basal area, tree species diversity), abiotic soil variables (condensed in two principal components), coffee shrub density and coffee shrub variables (number of secondary orthotropic shoots, basal diameter) on coffee productivity (number of berries, berry density). The number of berries and the berry density were square-root transformed to meet assumptions of normality. Basal diameter and the number of secondary orthotropic shoots were the only level 1 variables, all the variables measured at the plot level were the level 2 variables (Singer, 1998). Tree plant community was used as fixed-effects factor and the other variables (levels 1 and 2) were used as covariates in the model. The level 1 variables were included in the random statement, together with an intercept. Plot was treated as the subject grouping variable. All two-way interactions at the coffee shrub level (i.e. between level 1 and the plot level variables) were included. The Akaike information criterion (AIC) was used to compare a set of reduced models to the full model and to select the best model (lowest AIC). A variance–covariance structure (variance components, or an unstructured variance structure) was used (Ngo and Brand, 1997). Clustering, ordination, MRPP and indicator species analysis were performed using PC-ORD 5 (McCune and Mefford, 2006) and SPSS 15.0 (SPSS Inc., Chicago, IL) was used for all other statistical tests.

3. Results

3.1. Patterns in shade tree communities

The forest was species-poor in terms of canopy tree species, with on average only 3.8 (standard error 0.4) tree species per plot (α diversity) and 28 tree species in all plots (γ diversity) (Table A.1). Three shade tree plant communities were identified: a plant community dominated by *Croton macrostachys* (indicator value IV = 67.4, $P = 0.002$), a second plant community with *Millettia ferruginea* (IV = 90.0, $P < 0.001$) and a third plant community with *Albizia gummifera* (IV = 65.6, $P = 0.004$) and *Albizia schimperiana* (IV = 49.4, $P = 0.04$) as significant indicator species. The two *Albizia* species and *Bersama abyssinica*, another pioneer species, were the only species present in all three communities. The *Albizia* plant community was the least diverse: the two *Albizia* species were practically the only species present in the canopy (Table A.1). *Syzygium guineense*, a climax tree species of the Afromontane rainforest, was an accompanying species in the *Croton* plant community, along with the two *Albizia* species and a variety of tree species typical for the lower canopy of the rainforest (Table A.1). *Prunus africana* and *P. adolfi-frederici*, also climax species of the rainforest, were accompanying species in the *Millettia* plant community, along with *Croton*, *Schefflera abyssinica* and several lower canopy species (Table A.1). The communities had a more homogenous species composition within groups than can be expected by chance (MRPP $A = 0.20$, $P < 0.001$) but plots belonging to the same community were not geographically clustered (Fig. 1).

3.2. Environmental correlates and stand characteristics of shade tree communities

In the ordinations, the communities were separated when the ordination was based on species composition (Fig. 2a), but not when based on abiotic variables (Fig. 2b). Accordingly, the tree communities did not reflect differences in site potential (multivariate ANOVA; overall $P = 0.46$; Table B.1). No significant correlations were found between the abiotic variables and the NMS dimensions (all $P > 0.05$). The chemical fertility of the soil was poor compared to other nitisols. Low P and Mg content and high acidity suggest low site potential (Table B.1).

Apart from differences in species composition, the communities had comparable stand and canopy features (multivariate ANOVA; overall $P = 0.55$) (Table 1). The overall average stem number of the studied semi-forest coffee agro-ecosystems was 178 ± 26 trees ha^{-1}, with a basal area of 19.5 ± 3.5 m^2 ha^{-1}. The average crown closure was 57 ± 2% and the crown cover was 59 ± 4%. The average tree height was 11.9 ± 0.8 m.

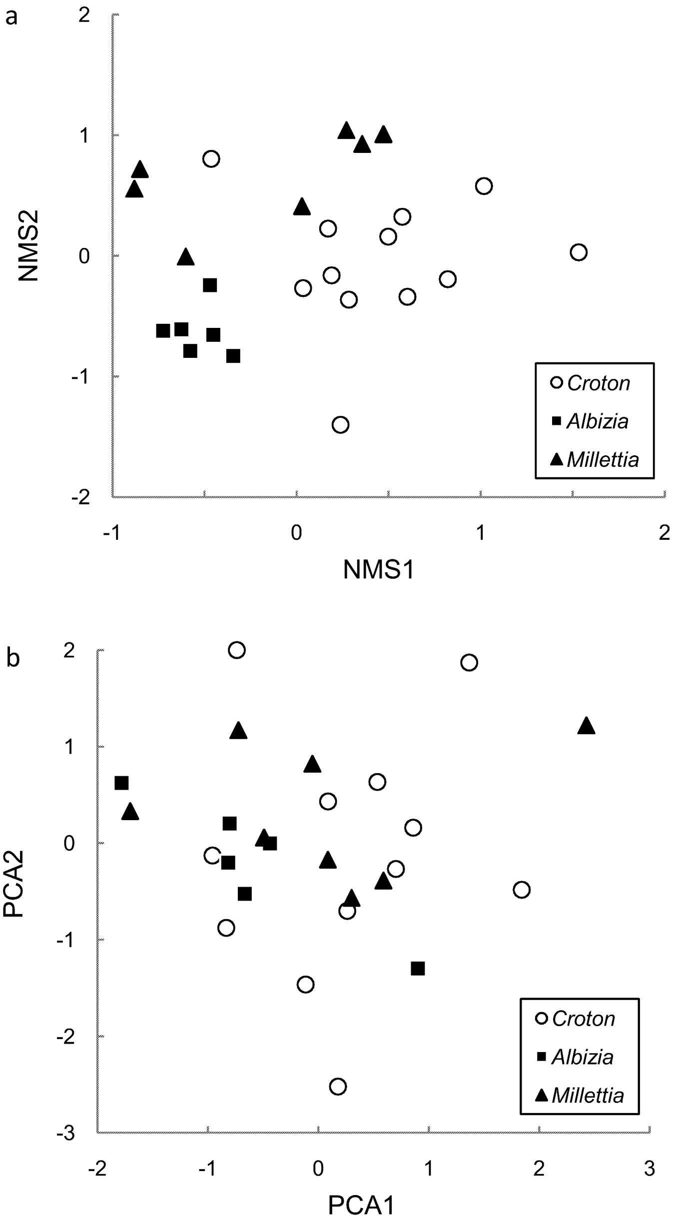

Fig. 2. Ordination of 26 plots within 20 Afromontane rainforest fragments managed as semi-forest coffee systems in Southwest-Ethiopia: (a) nonmetric multidimensional scaling (NMS) of canopy tree species and (b) principal component analysis (PCA) of abiotic variables. Sample plots are labeled according to shade tree communities produced by cluster and indicator species analysis.

3.3. Variables driving coffee yield

Shade tree community and abiotic variables (soil fertility) did not have a significant effect on coffee yield (Table C.1). At the coffee shrub level, a positive effect of coffee shrub basal diameter on coffee yield (number of berries) was found ($F_{1,87} = 10.5$, $P = 0.002$), with a negative, interacting effect of crown closure ($F_{1,88} = 6.1$, $P = 0.02$) (Fig. 3a and b). The main effect of crown closure was not significant ($F_{1,98} = 3.2$, $P = 0.08$) (Table C.1). Coffee shrub basal diameter and the number of secondary orthotropic shoots were significantly correlated (Pearson $r = 0.40$, $P < 0.001$). Consequently, there was a similar positive effect of the number of secondary orthotropic shoots on coffee yield ($F_{1,87} = 13.7$, $P < 0.001$), also with a negative, interacting effect of crown closure ($F_{1,88} = 10.58$, $P = 0.002$) (Fig. 3c and d). Crown closure also had a significant negative effect on berry density, but only in a model without interaction terms ($F_{1,25} = 4.4$, $P = 0.046$). The negative interaction implied that the degree of crown closure determined the effect of coffee shrub size variables: in stands with less shade (more indirect light, mean crown closure 49%), coffee shrub size variables had a stronger positive effect on coffee yield (Fig. 3).

The average density of coffee shrubs (mean ± SE) was 0.41 ± 0.01 m^{-2}. This corresponds to 2.4 m^2 per coffee shrub, a spacing of 1.56 m × 1.56 m or 4100 coffee shrubs ha^{-1}. Yield tended to be higher in the *Millettia* plant community (2.6 ton clean coffee ha^{-1}) than in the other shade tree communities (1.7 ton clean coffee ha^{-1}) (Table 2), but these differences were not statistically significant (univariate ANOVA $F_{2,100} = 974.6$, $P = 0.115$).

Table 1
Mean (and standard error) values for stand variables of three shade tree communities produced by cluster and indicator species analysis of 26 plots within 20 Afromontane rainforest fragments managed as semi-forest coffee systems in Southwest-Ethiopia.

	Shade tree plant community			$F_{2,23}$	P^a
	Croton	*Albizia*	*Millettia*		
	$N = 12$	$N = 6$	$N = 8$		
Stem number (ha^{-1})	183 (50)	133 (15)	203 (37)	0.48	0.62
Basal area (m^2 ha^{-1})	19.1 (6.2)	12.8 (1.9)	25.1 (6.4)	0.81	0.46
Crown closure (%)	55 (3)	62 (3)	55 (4)	1.21	0.32
Crown cover (%)	55 (5)	67 (11)	59 (6)	0.66	0.52
Canopy height (m)	11.7 (1.4)	12.2 (1.2)	12.2 (1.2)	0.06	0.94
α-Diversity (tree species plot^{-1})	4.1 (0.7)	2.3 (0.3)	4.5 (0.8)	2.00	0.16

[a] Multivariate ANOVA, Wilks' lambda = 0.590, $F_{12,36} = 0.90$, $P = 0.55$.

4. Discussion

4.1. Ecological consequences of shade tree management

The intensive management of the canopy in function of coffee production has had important consequences for the composition and diversity of the Afromontane rainforest. Selective thinning has resulted in a degeneration from a climax forest vegetation with Afromontane endemics and near-endemics such as *Elaeodendron buchananii*, *P. adolfi-friederici*, *P. africana*, *Macaranga capensis*, *Ilex mitis* and *Olea welwitschii* (see e.g. Gole et al., 2008; Schmitt et al., 2009; Schmitt et al., 2010) to an impoverished forest with gap and pioneer species such as *Croton macrostachys*, *M. ferruginea* and *A. gummifera* dominating the canopy. Stem numbers are reduced by more than 70% and the α-diversity by more than 25% compared to less managed Afromontane rainforest (e.g. Bonga forest:

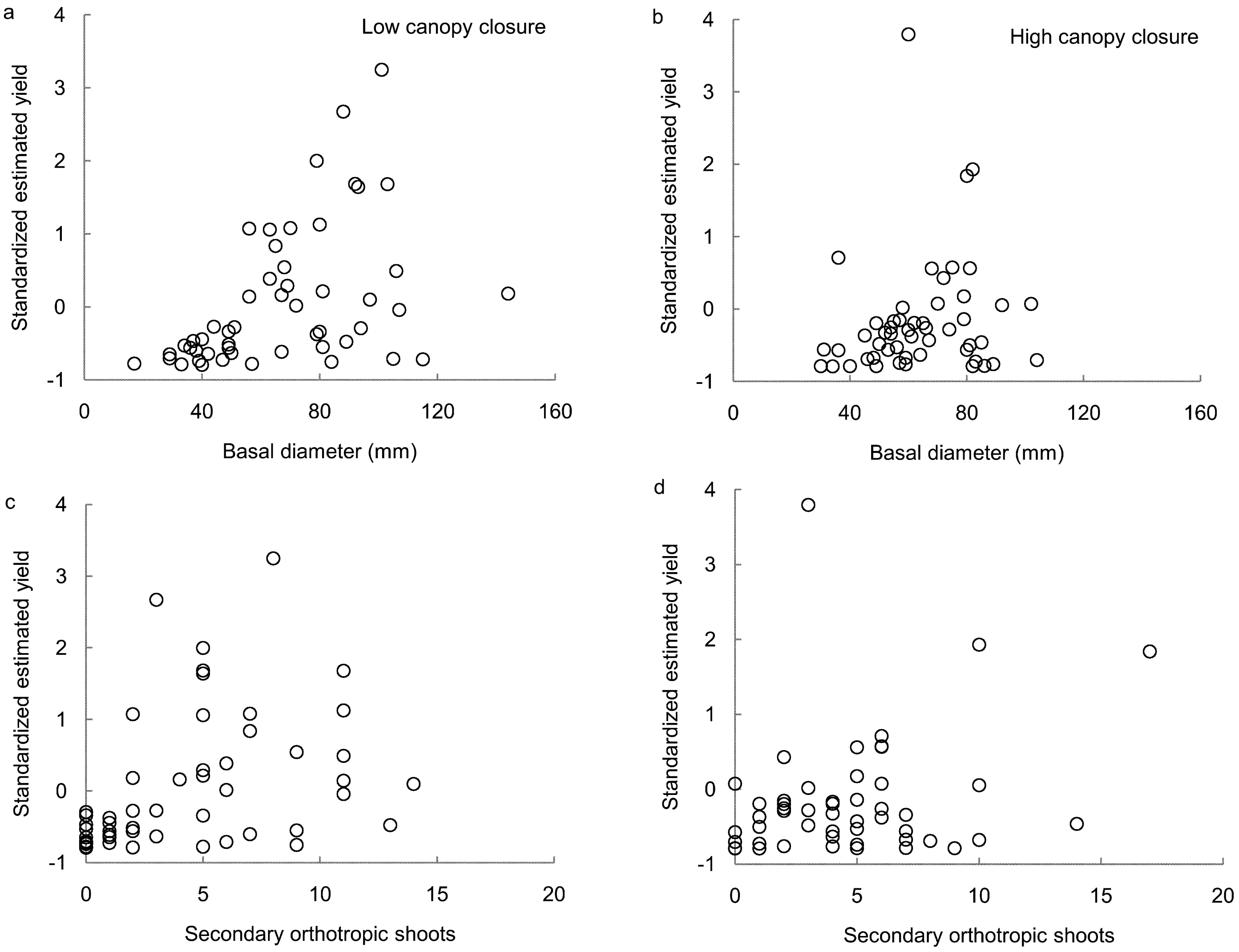

Fig. 3. Estimated yield of coffee shrubs in semi-forest coffee systems in Southwest-Ethiopia in function of (a and b) coffee shrub basal diameter and (c and d) number of secondary orthotropic shoots. Panels (a and c) show coffee shrubs in forest fragments with low crown closure (less than median (56%); average 49 ± 1%; $N = 52$ coffee shrubs) and (b and d) shrubs in forest fragments with high crown closure (exceeding the median; average 65 ± 1%; $N = 51$ coffee shrubs).

Table 2
Estimated coffee yield (SE) in three shade tree communities produced by cluster and indicator species analysis of 26 plots within 20 Afromontane rainforest fragments managed as semi-forest coffee systems in Southwest-Ethiopia, compared to coffee yields recorded in experimental stands.

	Croton	*Albizia*	*Millettia*
	$N = 12$	$N = 6$	$N = 8$
Berries per shrub	1261 (269)	1277 (371)	1933 (332)
Berry density (m^{-3})	246 (36)	233 (44)	370 (70)
Clean coffee yield[a]			
kg $shrub^{-1}$	0.42 (0.09)	0.42 (0.12)	0.64 (0.11)
ton ha^{-1}	1.71 (0.36)	1.73 (0.50)	2.62 (0.45)
Experimental yield[b]			
ton ha^{-1}	0.72 (0.12)	0.95 (0.11)	0.60 (0.10)

[a] For conversion to clean coffee yield, an average weight of 0.33 g per berry (Schmitt et al., 2009) and an average planting density of 0.41 coffee shrub m^{-2} = 4100 coffee shrubs ha^{-1} were used.

[b] Obtained with cultivars in shading trials at Jimma Research Center (Kufa et al., 2007) ($N = 9$).

38 species and 625 trees ha^{-1}; Schmitt et al., 2009). The simplification of the canopy composition (reduced tree species diversity) and of the canopy structure (reduced stem number, absence of emergent trees and a true upper canopy >15 m typical for undisturbed Afromontane rainforest – Demissew et al., 2004) are substantial anthropogenic influences of coffee cultivation on the Ethiopian rainforest. This process leads to homogenization (Senbeta and Denich, 2006), and this may have contributed to the obscured relationship between shade tree communities and abiotic variables. Species in disturbed and fragmented forests are typically drawn from a restricted species pool and habitat-specialist species are most likely to disappear first (Lewis, 2009). Biotic homogenization (BH) is a widespread trend in tropical forests (Lewis, 2009), but *in sensu strictu* BH involves 'the replacement of local biotas with non-indigenous species' (McKinney and Lockwood, 1999). Because *C. arabica* is indigenous and because non-native shade trees are still rare in the semi-forest coffee system (Table A.1), it would be more appropriate to conclude that taxonomic and functional homogenization (Olden and Rooney, 2006) affect the Ethiopian coffee forests.

4.2. Shade reduction and coffee yield

Despite being an understorey plant of the rainforest, *C. arabica* performs well when shade is reduced and sun coffee can even out-yield shaded coffee (Matos et al., 2009). Nevertheless, shade reduces alternate bearing and the risk of over-bearing (increased productivity followed by tree die-back) and is therefore useful to ensure long-term productivity of the coffee shrubs (Vaast et al., 2006). Shade also improves bean characteristics (Muschler, 2001; Vaast et al., 2006), and offers several advantages for coffee cultivation, including temperature regulation, suppression of weeds, reduction of hail damage, prevention of soil erosion and better growth under high altitude conditions (Beer et al., 1997; Soto-Pinto et al., 2002). As a result, there is a trade-off between retaining a sufficient amount of trees to keep the benefits of shade, and removing trees to increase the light availability to provide acceptable yields.

The shade reduction level was comparable to the one in rustic coffee farms in Mexico, where coffee is grown in native forest with the understorey replaced by coffee (Hernández-Martínez et al., 2009). In these coffee forests, yields decreased when shade cover exceeded 50% (Soto-Pinto et al., 2000). The specific thinning regime applied by farmers in the semi-forest coffee systems favours trees with open, wide-spreading crowns (e.g. *Albizia* spp.). Because of the wide-spreading crowns, sufficient cover can be realized with a minimum number of trees, maximizing the space available for coffee shrubs. Trees like *A. gummifera* also provide a nutrient-rich and fast decomposing litter, know by farmers to improve the soil nutrient status (Teklay and Malmer, 2004). As a consequence, climax trees with unsuitable crown and litter characteristics such as *A. falcatus* are felled, and trees with preferred traits such as *A. gummifera* are retained. In coffee agro-ecosystems worldwide, compatibility with coffee indeed is the foremost criterion for shade tree species selection (see e.g. Soto-Pinto et al., 2007; Souza et al., 2010).

4.3. Coffee shrub management and coffee yield

Within the semi-forest coffee system, coffee yield increases with increasing management interventions in the canopy and the understorey. At the shrub level, large basal diameters and high numbers of secondary orthotropic shoots were related to higher yields. Coffee plants with a large basal diameter are old, and could, in principle, have large crowns that can support many productive shoots. But in the semi-forest coffee system, coffee shrubs with large basal diameters are often coppiced coffee shrubs (pers. obs.). Coppicing is applied to rejuvenate coffee shrubs (Arantes et al., 2009). The numerous resprouts (orthotropic shoots) support many plagiotropic shoots, increasing yield. Thus, at the coffee shrub level, not only removing competing understorey shrubs, but also coppicing helps to maximize coffee yield. Also in Brazil, narrow spacing and pruning are applied to regulate yield. A large variety of pruning systems (lopping, pruning, coppicing) exists and effects vary, but drastic pruning just after harvest tends to increase yield (De Toledo and De Barros, 1999; Pereira et al., 2007).

4.4. Conservation management of coffee forest

Although coffee production in the semi-forest coffee system of SW Ethiopia guarantees that forest will remain an important land cover in the region, there is a clear trade-off between coffee productivity and forest quality. The specific thinning regime applied by farmers to maximize productivity results in low species diversity and simplified forest structure (reduced number of stems, lower canopy). Many climax species of the Afromontane rainforest have all but disappeared, most likely because of their usefulness as timber (e.g. *O. welwitschii*, *P. adolfi-frederici*) and because early-successional species like *A. gummifera* have canopy traits which are more suitable for coffee production (e.g. wide-spreading crowns). Despite intensive human interference some of these Afromontane climax species are still present and they may escape local extinction if they are tolerated and allowed to regenerate. Due to the annual slashing of the understorey, however, regeneration is impossible and these species will eventually become locally extinct, thus representing an extinction debt (Tilman et al., 1994).

We suggest that trees which are considered suitable as shade for coffee can act as temporary shade for seedlings of longer-living climax species (Soto-Pinto et al., 2007). Because of the slashing, recruitment of canopy trees may only be feasible in small exclosures within the forest fragments, i.e. small fenced plots where annual slashing is temporarily banned (Aerts et al., 2009). Exclosures may assist rejuvenation of both preferred shade trees and climax species. Preferred shade trees are needed to maintain the productivity of the semi-forest coffee system and therefore play a vital role in the preservation of forest cover. The restoration of healthy populations of climax species is critical to preserve the biodiversity, regeneration capacity, vitality and ecosystem functions of the Ethiopian coffee forests.

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Table A.1
Indicator values (% of perfect indication, based on relative abundance and relative frequency) for three shade tree communities produced by cluster and indicator species analysis of 26 plots within 20 Afromontane rainforest fragments managed as semi-forest coffee systems in southwest Ethiopia. *P*-values are for the highest indicator value and indicate the proportion of randomized Monte Carlo trials with indicator value equal to or exceeding the observed indicator value.

	Plant community			*P*
	Croton	*Albizia*	*Milletia*	
	N = 12	*N* = 6	*N* = 8	
Croton macrostachys Hochst. ex A. Rich	67	0	17	0.002
Maesa lanceolata Forssk.	25	0	0	0.175
Brucea antidysenterica Lam.	17	0	0	0.328
Syzygium guineense DC.[a]	17	0	8	0.598
Dodota (Or.)	8	0	0	1.000
Carissa spinarum L.	8	0	0	1.000
Erythrina brucei Schweinf.	8	0	0	1.000
Ficus sycomorus L.	8	0	0	1.000
Galiniera saxifraga (A. Rich.) Bridson	8	0	0	1.000
Grevillea robusta A. Cunn.[b]	8	0	0	1.000
Kofoli (Or.)	8	0	0	1.000
Psidium guajava L.[c]	8	0	0	1.000
Tasfania (Or.)	8	0	0	1.000
Albizia gummifera C.A.Sm.	5	66	6	0.004
Albizia schimperiana Oliv.	14	49	13	0.041
Millettia ferruginea Hochst.	0	1	90	0.000
Clausena anisata (Willd.) Hook.f.	0	0	13	0.521
Dracaena steudneri Engl.	0	0	13	0.527
Calpurnia aurea Benth.	0	0	13	0.527
Prunus africana (Hook f.) Kalkman[a]	0	0	13	0.527
Topano (Or.)	0	0	13	0.527
Unidentified species 1	0	0	13	0.534
Schefflera abyssinica Harms[a]	0	0	13	0.534
Unidentified species 2	0	0	13	0.534
Pouteria adolfi-frederici (Engl.) A.Meeuse[a]	0	0	13	0.534
Bersama abyssinica Fresen.	11	3	19	0.627
Psychotria orophila E.M.A.Petit	1	0	11	0.652
Vernonia auriculifera Hiern.	10	0	11	0.693

[a] Climax tree species.
[b] Exotic timber tree.
[c] Exotic fruit tree.

Table B.1
Mean values (SE) for abiotic variables in three shade tree communities produced by cluster and indicator species analysis of 26 plots within 20 Afromontane rainforest fragments managed as semi-forest coffee systems in southwest Ethiopia.

	Plant community			$F_{2,23}$	*P*[a]
	Croton	*Albizia*	*Milletia*		
	N = 12	*N* = 6	*N* = 8		
pH(KCl)	4.17 (0.09)	3.99 (0.09)	4.19 (0.15)	1.26	0.30
CEC (cmol kg^{-1})	15.90 (0.75)	13.55 (0.76)	15.45 (1.34)	1.77	0.19
Ca (cmol kg^{-1})	7.36 (0.68)	5.46 (1.09)	7.06 (1.24)	0.79	0.46
Mg (cmol kg^{-1})	1.92 (0.17)	1.28 (0.2)	1.82 (0.37)	1.36	0.28
K (cmol kg^{-1})	0.65 (0.17)	0.35 (0.08)	0.25 (0.04)	0.95	0.40
P (cmol kg^{-1})	1.81 (0.43)	2.97 (0.84)	2.04 (0.49)	1.52	0.24
N (%)	0.44 (0.02)	0.42 (0.01)	0.46 (0.01)	2.46	0.11
C (%)	4.44 (0.16)	4.20 (0.07)	4.68 (0.16)	1.06	0.36

[a] Multivariate ANOVA; Wilk's lambda = 0.437, $F_{16,32}$ = 1.02, *P* = 0.46.

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Appendix A. Indicator values

See Table A.1.

Appendix B. Abiotic variables

See Table B.1.

Table C.1
Type III tests of fixed effects of shade tree plant community, coffee shrub basal diameter, stand characteristics and abiotic variables (condensed in two PCA dimensions) on coffee yield (square-root transformed number of berries per coffee shrub) in 26 plots within 20 Afromontane rainforest fragments managed as semi-forest coffee systems in southwest Ethiopia.

Source	df	df (error)	*F*	*P*
Linear mixed model[a]				
Intercept	1	79	1.61	0.21
Community	2	79.9	0	1
Basal diameter (Dbase)	1	60.1	5.04	0.03
Coffee shrub density	1	79.6	0.04	0.84
Crown closure	1	77.1	0.97	0.33
Crown cover	1	80.6	0.03	0.86
Stem number	1	60.7	0.07	0.79
Basal area	1	81	0.24	0.62
Average canopy height	1	80.8	0.19	0.66
Soil PCA1	1	77.2	0	0.97
Soil PCA2	1	81	0.66	0.42
Dbase × Community	2	64.1	0.23	0.79
Dbase_mm × coffee shrub density	1	68.7	0.29	0.59
Dbase_mm × Crown closure	1	60.5	2.15	0.15
Dbase_mm × Crown cover	1	76.7	0.02	0.88
Dbase_mm × Stem number	1	27.5	0.48	0.49
Dbase_mm × Basal area	1	51.3	1.12	0.29
Dbase_mm × Average canopy height	1	71.8	0.09	0.77
Dbase_mm × Soil PCA1	1	79.8	0.02	0.88
Dbase_mm × Soil PCA2	1	74.2	0.88	0.35
Restricted linear mixed model[b]				
Intercept	1	98.9	2.58	0.11
Basal diameter	1	86.9	10.54	0.002
Crown closure	1	98.9	3.22	0.08
Dbase_mm × Crown closure	1	88.3	6.11	0.02

[a] All variables and the coffee shrub-level (level 1) × plot-level (level 2) variable interactions. AIC = 913.9.
[b] Restricted model only includes variables or interactions that were significant or near-significant in the full model. AIC = 899.4.

Appendix C. Linear mixed models

See Table C.1.

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