Effects of Coffee Management on Deforestation Rates and Forest Integrity

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Abstract: Knowledge about how forest margins are utilized can be crucial for a general understanding of changes in forest cover, forest structure, and biodiversity across landscapes. We studied forest-agriculture transitions in southwestern Ethiopia and hypothesized that the presence of coffee (Coffea arabica) decreases deforestation rates because of coffee’s importance to local economies and its widespread occurrence in forests and forest margins. Using satellite images and elevation data, we compared changes in forest cover over 37 years (1973–2010) across elevations in 2 forest-agriculture mosaic landscapes (1100 km² around Bonga and 3000 km² in Goma-Gera). In the field in the Bonga area, we determined coffee cover and forest structure in 40 forest margins that differed in time since deforestation. Both the absolute and relative deforestation rates were lower at coffee-growing elevations compared with at higher elevations (−10/20% vs. −40/50% comparing relative rates at 1800 m asl and 2300–2500 m asl, respectively). Within the coffee-growing elevation, the proportion of sites with high coffee cover (>20%) was significantly higher in stable margins (42% of sites that had been in the same location for the entire period) than in recently changed margins (0% of sites where expansion of annual crops had changed the margin). Disturbance level and forest structure did not differ between sites with 30% or 3% coffee. However, a growing body of literature on gradients of coffee management in Ethiopia reports coffee’s negative effects on abundances of forest-specialist species. Even if the presence of coffee slows down the conversion of forest to annual-crop agriculture, there is a risk that an intensification of coffee management will still threaten forest biodiversity, including the genetic diversity of wild coffee. Conservation policy for Ethiopian forests thus needs to develop strategies that acknowledge that forests without coffee production may have higher deforestation risks than forests with coffee production and that forests with coffee production often have lower biodiversity value.

Keywords: certification, degradation, edge effects, Ethiopia, fragmentation, homogenization, Landsat, remote sensing, tropical forest

Efectos de la Administración Cafetalera sobre las Tasas de Deforestación y la Integridad de los Bosques

Resumen: El conocimiento sobre cómo se utilizan los márgenes de los bosques puede ser crucial para el entendimiento general de los cambios en la cubierta boscosa, la estructura de los bosques y la biodiversidad en el paisaje. Estudiamos transiciones bosque-agricultura en el suroeste de Etiopía y partimos de la hipótesis de que la presencia del café (Coffea arabica) disminuye las tasas de deforestación por la importancia del café para las economías locales y su ocurrencia extensa en los bosques y los márgenes de éstos. Usando imágenes de satélite e información de elevación, comparamos los cambios en la cubierta boscosa.
Coffee management is widely practiced under a canopy of forest trees in southwestern Ethiopia and is a great economic resource for local farmers and the government (Teketay 1999). As a result, there may be less interest in converting forests with coffee to annual crops than in converting forests without coffee. However, the possible role of coffee management in the protection of forest biodiversity would be limited due to its restricted elevation range and the effect its management has on the forest structure. The role of coffee for biodiversity conservation has garnered much attention in both Latin America and Asia (e.g., O’Brien & Kinnaird 2003; Philpott et al. 2007). Arguments regarding the benefits of shade coffee management for biodiversity conservation and the risk of increased deforestation because of the conversion of forests to coffee plantations have been proffered. The role of coffee for conservation in Africa has, however, been seldom discussed.

Highland arabica coffee (Coffea arabica) is an indigenous shrub in the montane forests of southern Ethiopia (Anthony et al. 2001). Here, it is traditionally managed in 3 different systems. There is a gradual increase in management intensity from forest coffee, to semiforest coffee, to garden coffee. More rarely, commercial plantations occur (Teketay 1999). In many areas of southwestern Ethiopia, farmers grow annual crops in fields and collect coffee from semiforested coffee systems, which are forests that are managed for coffee production by selective removal of trees and shrubs. Most of these stands have a spectral signature similar to undisturbed forests in low-resolution satellite imagery and are likely to be mapped as forests. Some more intensively managed semiforest coffee stands belong to individual farmers, but otherwise forested areas are generally formally owned by the state. However, there can be traditional user-right agreements for collecting the berries in different parts of these forests (Stellmacher & Gatzweiler 2005).

The highland coffee of Ethiopia thrives best in a moist environment at relatively high elevations. In Ethiopia, the upper elevational limit of coffee is around 2000 m, which is far below the tree line in the high mountains (tree line 3000-3500 m asl) (Friis 1979). The lower limit is generally correlated to the transition to drier woodlands, typically at around 1300 m asl (Gole et al. 2008). The highest densities of coffee have been reported at various elevations in different areas (1200 m asl, Bonga [Schmitt et al. 2010a]).
We hypothesized that deforestation rates are lower from 1300 to 2000 m asl (main elevational niche of coffee) than outside this range, spatially changing forest margins in this elevational range have lower coffee cover than stable forest-agricultural margins, and stands with high coffee cover display more signs of degradation (e.g., have higher number of stumps and lower canopy cover). We used 2 approaches to test these hypotheses. First, the distribution of forest cover at different elevations was analyzed from satellite images taken since 1973 that cover 2 areas in southwestern Ethiopia. Second, we inventoried coffee cover and forest structure in 40 sites of stable or changing forest margins in one of the areas (from the edge and 200 m into forests and agriculture, respectively, in all sites).

Methods

Study Region and Landscapes

We conducted our study in southwestern Ethiopia in the states of Southern Nations, Nationalities, and People’s Region (SNNPR) and Oromia. To ensure high accuracy in our interpretations of satellite images, we selected 2 areas where we had plenty of field experience. The site in SNNPR was the 1100 km² surrounding the town of Bonga (N7°11–27’N, E36°1–22’). The site in Oromiya was 3000 km² around the administrative centers of Goma (Agaro town) and Gera (hereafter called Goma-Gera area (N7°34–58’N, E36°4–43’E). Both these areas have an undulating terrain with high elevational variation (1300–2500 m asl in Bonga and 1400–3000 m asl in Goma-Gera) and are characterized by mosaics of annual crop fields and large and small forest patches (Fig. 1). The forests in the region are mainly moist afro-montane forests dominated by trees such as Syzygium guineense, Sapium ellipticum, and Olea welwitschii (Friis et al. 2010).

Coffee is most abundant at 1750–1824 m asl in the Bonga area (Schmitt et al. 2010a), but it also occur rarely above 2000 m asl (personal observation). In the Goma-Gera area, coffee is abundant at elevations of 1500–1900 m asl (personal observations). In both of the areas, coffee occurs as forest coffee (sparse shrubs in the forest that are harvested without any management) and in semiforest coffee system (stands with high coffee cover managed with enrichment planting, removal of competing shrubs, and felling of some larger trees to get a higher yield) (cf. Aerts et al. 2011). The coffee in forest margins is mostly of wild origin, but improved cultivars are also planted occasionally. In southwestern Ethiopia, the semiforest coffee system is the most widespread way of producing coffee, and it contributes much to the local and national economy. The annual rainfall in the region is around 1500–2000 mm. Most rain falls from July to September, although occasional rainfall occurs throughout the year (Friis et al. 2010). Both areas are known for their coffee and honey production (Gobeze et al. 2009) and are representative coffee agroecosystems for this region of Ethiopia.

Satellite Image Analyses

Five multispectral Landsat images, one per decade (1973, 1984, 1995, 2001, and 2010), were analyzed (USGS 2010). Each Landsat image was clipped to retain the part of the image covering both study landscapes. Subsequently, forest-cover maps were produced for all 5 images with an isodata unsupervised classification (Jensen 1996). We compared the classifications among years to develop maps of change in forest-cover change. We made pairwise comparisons between consecutive forest-cover maps (1973–1985, 1985–1995, 1995–2001, and 2001–2010) and between the earliest and latest maps (1973–2010). This resulted in 5 maps of forest-cover change.
The maps contained the following 4 classes: other, deforestation, reforestation, and continuous forest cover.

We assessed the difference in forest cover, reforestation, or deforestation per 50-m elevation interval. Information on elevation was extracted from the 90-m SRTM Digital Elevation Model obtained from CGIAR-CSI (2010). We resampled the SRTM so resolution of 90 m would match the 30-m resolution raster of the maps of change in forest cover and stratified it over 50-m elevation intervals. The number of pixels of each class of forest-cover change was calculated per 50-m elevation interval for both study areas. From these data, we computed the percent change in forest cover (relative to the total surface area) and the change in forest cover (relative to the surface area covered by forest) at different elevations for different time intervals. In the Bonga area, we excluded the tea plantation in Wushwush (approximately 25 km²) in the calculations from the maps because the deforestation caused by its expansion was not associated with decisions by small-scale farmers. The classification of the images (including all steps) was performed in ENVI (version 4.7) (ITT Visual Information Solutions 2010). The extraction of percentages of forest-cover change was performed in ArcGIS 10.0 (ESRI 2010). For details on this procedure, see Supporting Information.

We used nonlinear regressions (Loess smoothing with default settings) to illustrate the change in relative forest cover across elevations. We applied general additive modeling (GAM), with default settings in the mgcv package in R (Wood 2011), to the same data to evaluate the statistical significance of a smoothed function over the elevational range.

Inventory of Forest Margins

On the basis of a comparison between panchromatic aerial photos from 1967 (scale 1:30,000) over the Bonga area and a Landsat scene from 2008 over the same area, we selected 19 stable forest margins that had the same spatial location over these 41 years. We selected an additional 21 sites in which the location of the forest-agricultural margins in the latest images corresponded to a site inside the forest in the 1967 images. These 21 sites were classified as 2–15 years since forest clearance (10 sites) and 16–39 years since forest clearance (11 sites) on the basis of information from several satellite images between 1973 and 2008. Thus, we selected 3 groups of sites in which time since clearance differed that we subsequently located and inventoried in the field.

At each site, we demarcated a 50-m-long transect along the forest-agricultural edge. We also established an additional 3 transects in the forest and 3 in the agricultural land at the following distances from (and parallel to) the forest-edge transect: 20, 75, and 200 m. We divided transects into 5 plots of 10 × 10 m. In each of the plots in the 7 transects, we counted number of beehives, number of stumps, and number of paths (human activity) and counted the number and sizes of trees and estimated visually coffee ground cover, canopy cover, lianas or climbing vine cover, and bryophyte cover on tree boles (forest structure). The fieldwork was conducted from 12 October 2008 to 10 April 2009.

We evaluated how coffee cover differed across agriculture-forest transitions that had been stable for different periods with mixed-effect modeling in the nlme package in R (Pinheiro et al. 2012). As the response variable, we used the logarithm of coffee cover. We used time since margin creation (3 levels) and transect position as the explanatory variables. To make the analysis simple and robust, we pooled all 7 transects into 3 groups: −1, mean of the pooled agriculture transects; 0, edge and 20 m into forest transects; and +1, mean of 75 m and 200 m into forest transects. Site was a random variable. We evaluated possible violations from model assumptions by inspecting residual plots.

To judge how coffee management affected the disturbance level and forest structure in the forest margins, we compared environmental variables between sites with high and low coffee cover with t tests. For all sites with a coffee cover of >20% in either the 75- or 200-m transect, we selected the transect with the highest coffee cover to be included in this data set. For the rest of the sites (coffee cover <20%), we selected the transect with the lowest coffee cover. Hence, we obtained a data set with 12 sites with a high-cover transect and 28 sites with a low-cover transect replicated across the area.

Results

Deforestation and its Elevational Distribution

Net forest cover decreased from 59% to 45% in the Bonga area and from 54% to 40% in the Goma-Gera area from 1973 to 2010 (Fig. 1). Net change in cover was almost the same as the deforested area because very small areas were reforested during this period. Both deforestation and reforestation exhibited elevational variations; more forest was lost above 2000 m asl than below, and reforestation below 2000 m asl was higher than above (Figs. 2a & b). The change in forest cover was significantly and negatively correlated with elevation in both areas (Fig. 2c) (Bonga, r = −0.88; Goma-Gera, r = −0.86, p < 0.001). On the basis of the Loess regression lines and as verified by 2 GAM analyses, the change in forest cover (relative to the cover in 1973) was lowest at around 1800 m asl in both areas and increased toward lower and higher elevations (Fig. 3) (Bonga, F = 19.3, explained deviance 93.1%, p < 0.001; Goma-Gera, F = 33.6, explained deviance 93.0%, p < 0.001). Loss of forest cover (relative to cover in 1973) at the elevation where
forest coffee is most common (according to Schmitt et al. 2010a) was approximately 10% in Goma-Gera and 20% in Bonga, whereas it was 40–50% at 2300–2500 m asl (Fig. 3). Differences in deforestation rates were large among the investigated periods. Most of the deforestation occurred in the first period (1973–1984) (44% and 68% of all deforestation for Bonga and Goma-Gera, respectively) despite some reforestation in this period. Annual deforestation was 0.5–1% in Bonga and 0.4–1.6% in Goma-Gera. The lowest deforestation rates were from 1995 to 2001, when about 0.3% (Bonga) and 0.1% (Goma-Gera) of the 1973 forest cover was logged annually. The pattern of change in forest cover was in general similar among all periods in both areas; deforestation was lower at the elevation where coffee abundance peaks than at higher elevations.

Stable and Changing Margins

Coffee occurred in 33 of the 40 surveyed forest margins in the Bonga area. Differences in percentage cover were large among sites and sometimes also among transects within sites. Mean coffee cover was 1.5% in agricultural land, 5.5% in the edges, and 11% in the forest transects. There was an inconsistency in the relation between coffee cover and time since forest clearance, where coffee cover was higher in stable than in changing margins in forest transects but lower in stable than changing margins in agricultural transects (Fig. 4a) ($p = 0.034$ for the interaction between transect position and time since margin creation). The proportion of sites with coffee cover $> 20\%$ in the interior transects differed among the 3 groups of sites: 0% in the youngest margin group, 10% in the intermediate group, and 42% in the oldest margins (Fig. 4b).
Coffee and Deforestation

Figure 3. Change in forest cover in 2010 relative to the cover in 1973 across elevations in Goma-Gera and Bonga, Ethiopia (curves, smoothing curves from Loess regressions).

Figure 4. Distribution of coffee across agriculture-forest margins that differ in time since conversion of forest to agriculture: (a) percent coffee cover (SE) and (b) proportion of sites with >20% cover of coffee (young \( n = 10 \) margins, 2–16 years old; intermediate \( n = 11 \) margins, 16–39 years old; stable \( n = 19 \) margins, created >40 years prior to the survey).

Coffee Cover and Forest Structure

Most forest margins were clearly affected by human activity. Tree stumps and paths were present close to the forest edge and at distances 75–200 m from the edge (Table 1). There was no statistically significant difference in canopy cover, bryophyte cover on boles, or number of stumps between sites with high (>20%, mean 34%) and low (<20%, mean 3%) coffee cover (Table 1). However, the sites with high coffee cover had a lower coverage of lianas and climbing vines (Table 1).

Discussion

Exploitation of tropical forests in general simultaneously cause habitat loss and habitat degradation (Putz et al. 2011). We suggest that moist afro-montane forests in Ethiopia instead are threatened by either deforestation or degradation. We found that deforestation rates over the last 37 years differed along an elevational gradient. Rates of deforestation were higher at elevations above the temperature limit of coffee than at coffee’s most optimal elevation (Figs. 2 & 3). Many different processes across space and time drive changes in forest cover (cf. McCann 1995). That coffee enhances forest retention across these areas is, however, consistent with our finding that a higher proportion of stable margins had high coffee cover than forest margins created recently by expanding agriculture (Fig. 4b).
It takes 4 years for coffee shrubs to produce their first fruits; thus, there is a substantial capital investment in a forest stand with dense coffee that prevents it from being chosen as a place to convert to annual-crop agriculture. Farmers retain forests because of the coffee, despite that they are a source of mammalian pests that affect their annual crops. This trade-off does not apply at higher elevations, where coffee does not grow (T. Gemechu, personal communication). Coffee cover varied a lot among the forest margins we studied, and we sometimes found stable forest-agricultural margins with low coffee cover. This indicates there may be other mechanisms (e.g., administrative borders) or values (e.g., honey, spices, building material) contributing to the stabilization of some forest-agriculture margins over time (Gobeze et al. 2009). Small-scale conversion of annual-crop agriculture and grazing land to semiforest coffee through planting of coffee and shade trees outside of the forest patches (sometimes observed in Goma-Gera), may explain part of the reforestation patterns in our data and further strengthen our conclusion that coffee plays a central role in changes to canopy cover in these areas (west African example, Correia et al. [2010]).

It is also important to study how forest structure and forest biota develop over time in forests that have not been converted and in patches that have been reforested (Putz et al. 2011). All margins had a large number of stumps, which indicated high levels of disturbance irrespective of coffee cover. That fewer lianas and climbing vines occurred in sites with high coffee cover could be explained by the generally dense shade in coffee-rich sites that prevented light-loving herb climbers from thriving. However, from the results of studies in which semiforested coffee systems were compared with more undisturbed forests, it is clear that semiforested coffee management alters forest structure where small trees and shrubs are replaced by coffee (Senbeta & Denich 2006; Hundera et al. 2012). Other researchers have found a lower species richness of specialist forest birds (Gove et al. 2008), lianas (Senbeta et al. 2005), and epiphytes (Hundera et al. 2013) and more ruderal herbs (Schmitt et al. 2010b) and early-successional tree species (Aerts et al. 2011) in stands managed for high coffee yields.

Our analyses of satellite data suggest that local decisions at the forest margins across the entire landscape over decades have been a major force behind the current pattern of forest and agricultural matrix configuration (cf. Dessie 2007). However, we also found that rates of deforestation shifted over time, which indicates other mechanisms at larger scales have large effects on overall levels of forest clearance. To examine all these aspects is beyond the scope of this paper, but there have been 2 changes in government during the study period (1974 and 1992), and governmental instability may have increased deforestation (Teketay et al. 2010). It is difficult to understand fully deforestation and forest degradation patterns across vast landscapes because many such processes can be affected by many things. Influential aspects could be local attitudes toward forests, inaccessibility of parts of a landscape, and major socioeconomic and political trends.

Major, but mostly local, human activities in our study areas included logging north of Gera during the 1980s (T. Gemechu, personal communication), expansion of the Wushwush tea plantation in Bonga, and immigration into some high-elevation sites in the 1980s (McCann 1995; Tadesse 2007). Alternative or complementary explanations for the higher deforestation rates at higher elevations in these areas over the last decades include lower levels of control of logging activities by authorities (because roads are located mostly in lower elevations) and influx of immigrants from central Ethiopia, where forest resources are scarcer. However, it is likely that local and regional authorities have avoided giving land where coffee production is high to forestry enterprises and new migrants. This explains why such activities are likely to
According to climate change scenarios, temperatures will least the tree cover of future landscapes is climate change. If this continues, it could be questioned whether our sug-
teral new small- and medium-sized coffee plantations on
study area) (Tadesse 2007), and there are plans for sev-
forests or semiforest coffee systems with mod-
differentiation of processes across elevations seems to have occurred also after 1974 (according to our data) even though political (concentration of housing to villages, resettlement) and environmental (coffee berry disease) changes led to an overall decrease in coffee production and an increase in cultivation of annual crops in the 1980s and 1990s across all elevations (McCann 1995).

The role of coffee in biodiversity conservation has been discussed before, for example, in the context of shade coffee farms in Central America and in rainforest disturbance in Indonesia and India (O’Brien & Kinnaird 2003; Philpott & Dietsch 2003; Ambinakudige & Choi 2009). At the center of the issue is the question of the capacity of different certification systems to promote biologically diverse shade-grown coffee systems without increasing conversion of natural forests to coffee plantations (Rap-
averse to semiforest coffee systems, garden-coffee systems, or
regular coffee plantations (e.g., Senbeta & Denich 2006); and the threats to genetic variation of coffee from de-
ethic and climate change perspectives (e.g., Senbeta & Denich 2006; Hundera et al. 2013). Thus, conservation efforts in these regions of Ethiopia, initiated by the government and nongovern-
ment organizations or driven by certification schemes (cf. Wiersum et al. 2008), need to consider the positive role of coffee in conservation (e.g., O’Brien & Kinnaird 2003; Philpott et al. 2007). We propose, however, that the positive role of coffee can have for mitigation of forest conversion to annual crops (our results; McCann 1995); the negative effect of coffee management on forest biodiversity following the conversion of natural coffee to semiforest coffee systems, garden-coffee systems, or regular coffee plantations (e.g., Senbeta & Denich 2006); and the threats to genetic variation of coffee from deforestation, forest degradation, and spread of genes of different coffee varieties into forests (Aerts et al. 2012).

There has been much focus on the need to protect forests with wild coffee in Ethiopia (Davis et al. 2012). Our results also highlight the importance of not forgetting other forested areas because deforestation rates may be even higher at elevations where coffee is not growing (cf. Hall et al. 2009).

Some of our conclusions are specific to Ethiopia, whereas others relate to the overall debate about the role of coffee in conservation (e.g., O’Brien & Kinnaird 2003; Philpott et al. 2007). We propose, however, that conservation policy should more generally acknowledge possible trade-offs between forest loss and forest degra-
dation created by spatial variation in the valuation of different resources across landscapes.
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Supporting Information

Details on the satellite-image analyses are available online (Appendix S1). The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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