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Biodiversity and carbon storage co-benefits of coffee agroforestry across a gradient of increasing management intensity in the SW Ethiopian highlands

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ABSTRACT

Agroforestry has been proposed as a way to reconcile biodiversity conservation, food production and the delivery of other ecosystem services in tropical landscapes. One such a key ecosystem service, especially in the light of climate change mitigation, is carbon storage. Increasing human disturbance and management intensification, however, are known to affect the carbon storage potential of forests. Here we assessed how the above- and belowground carbon stocks in Ethiopian moist evergreen Afromontane forest co-varied with their biodiversity, and with increasing agroforestry management intensity for the production of Arabica coffee (*Coffea arabica* L.). We assessed above- and belowground carbon storage in 60 plots across a gradient of agricultural intensification ranging from natural forest, over two different coffee agroforestry systems, to intensified shade plantations. We quantified the diversity of ground beetles and woody plants in the same plots. Carbon stocks in natural forests (413 ± 55.6 S.E. Mg ha^{-1}) and in the most extensively managed agroforestry systems (387 ± 50.0 Mg ha^{-1}) were significantly higher than those in the more intensified agroforest system (258 ± 39.4 Mg ha^{-1}) and in shade plantations (219 ± 22.8 Mg ha^{-1}). Diversity of woody plants, but not of ground beetles, declined with increasing management intensity and decreasing carbon stocks. Overall, this study demonstrates that extensive coffee farming in Ethiopian moist Afromontane forests is able to deliver important co-benefits in terms of woody plant species conservation and carbon storage. Given the associated coffee yield cost, it is most likely, however, that supporting payments from certification or policy mechanisms such as REDD+ are required to keep these extensive coffee agroforestry systems economically viable, which is required to avoid management intensification and associated carbon and biodiversity losses.

1. Introduction

In the context of human population growth and the increasing demand for food, agroforestry has been proposed as a way to reconcile biodiversity conservation, food production and the delivery of other ecosystem services in tropical landscapes (e.g. Gardner et al., 2009; Perfecto et al., 2014). Agroforests are agricultural areas with more than 10% tree cover, and they account for 46% of the agricultural area, covering around one billion hectares worldwide (Neufeldt et al., 2009). Agroforestry can be considered as a typical "land sharing" strategy where both biodiversity conservation and agricultural production occur at the same site (Phalan et al., 2011; Fischer et al., 2014). It is not yet fully understood, however, to what extent agroforestry actually contributes to biodiversity and ecosystem service conservation (Jose, 2009; Tscharntke et al., 2015), in particular because it has already been shown that primary forests are irreplaceable regarding biodiversity conservation (Gibson et al., 2011). As agroforest typically conserves less species than natural forest, also the number of ecosystem services provided by agroforest can be expected to be lower (Cardinale et al., 2012; Naeem et al., 2012; Gascon et al., 2015). In cacao and coffee agroforestry systems, for instance, a decline of 11% in the number of species and a loss of 37% of ecosystem services as compared to natural forest has been observed globally (De Beenhouwer et al., 2013).

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In the light of climate change mitigation, carbon (C) storage in both living biomass and in the soil is a key ecosystem service provided by forests and agroforests (Bonan, 2008; Miles and Kapos, 2008). A number of processes may affect the C storage capacity of forests following human interventions. In general, management intensification negatively affects the number and diversity of emergent shade trees, which can strongly reduce the aboveground C storage capacity of agroforestry systems (Dantas de Paula et al., 2011; Tadesse et al., 2014). Reducing the number of stems and changing the tree species composition may also affect C accumulation through root mortality, and through changes in litter production and humus formation (Post and Kwon, 2000; Tadesse et al., 2014). Human impacts may further induce soil C losses through mineralization of soil organic matter as decreasing shade increases soil temperature and thus heterotrophic respiration (Whalen et al., 2000; Davidson and Janssens, 2006). In Indonesia, for example, coffee agroforestry was shown to store only 60% of the above-ground C stored in the adjacent remnant forests (Kessler et al., 2012). Below-ground C as well was found to be higher in natural forest as compared to agroforestry systems (Guillaume et al., 2015). Nonetheless, the scale, rate and even the direction of soil C change is highly context-dependent (Don et al., 2011; Ziegler et al., 2012; Nair and Nair, 2014).

One of the major challenges at the interface of climate change and ecosystem science is to identify points of convergence between C storage and biodiversity conservation (Phelps et al., 2012). In general, a higher C storage potential is assumed to co-occur with biodiversity conservation (Venter, 2014). Accordingly, it was recently demonstrated that both birds and dung beetles benefit from increasing carbon storage in secondary forests in Costa Rica (Gilroy et al., 2014). Further, ground beetles or Carabidae are a family of insects which are often used as indicators of the impact of management changes and of the assessment of the abiotic state of the environment in general (Fuller et al., 2008; Sadej et al., 2012).

In this study, we aim to quantify how aboveground and belowground carbon stocks vary with increasing management intensity for coffee production, across a full gradient from natural Afromontane forest, over two different agroforestry systems, to coffee shade plantations, in the Southwest Ethiopian highlands. Moreover, we aim to assess the biodiversity co-benefits of agroforestry and carbon storage in terms of woody plant and ground beetle species diversity. It is our expectation that both biodiversity and the above- and belowground carbon stocks will decrease with increasing coffee forest management intensity.

2. Materials and methods

2.1. Study area

This study was conducted in the Jimma zone, Southwest Ethiopia (Fig. S1). As one of the major coffee growing regions in the country, coffee agroforestry, rain-fed agriculture and cattle grazing are the main land uses in the undulating landscape (1500–2200 m asl). The natural Ethiopian montane forest is known as the origin of Arabica coffee, and is characterized by a high biodiversity (Anthony et al., 2002; Schmitt et al., 2010; Mittermeier et al., 2011). However, as coffee consumption on a global scale increases with 1.2% every year since the 1980s (ICO, 2014), there is a demand for both additional suitable land for coffee production and for higher yields, resulting in a continuously expanding and intensifying coffee cultivation (Hylander et al., 2013).

Based on previous research, we identified four common types of coffee production systems: natural forest, semi-forest, semi-plantation and shade plantation (Fig. S2) (Aerts et al., 2011; Hundera et al., 2012; De Beenhouwer et al., 2015a). The forest coffee system (FC) represents the practice of coffee harvesting in natural forests with no or very little anthropogenic disturbance (Schmitt et al., 2010). The most often encountered tree species in the canopy are *Olea capensis, Pouteria adolfi-friederici* and *Syzigium guineense*. In the semi-forest coffee system (SFC), there is limited anthropogenic disturbance of the soil through local replanting of coffee seedlings (Hundera et al., 2012). The canopy is more open through selective thinning of emergent tree species and saplings (Aerts et al., 2011), but no fertilizers are used (De Beenhouwer et al., 2015b). The most abundant tree species are *Millettia ferruginea*,*Teclea nobilis* and *Syzigium guineense*. In the semi-plantation coffee system (SPC), there is a high anthropogenic disturbance resulting in a relatively species poor canopy consisting of tree species such as *Albizia schimperiana*, *Albizia gummifera* and *Croton macrostachyus*. Mulching is common practice and organic fertilizers are used locally. The plantation coffee system (PC), finally, represents shade plantations with only few, large canopy trees. Shade trees are mainly indigenous species (most dominantly *Acacia* spp. and *C. macrostachyus*), although recently, fast-growing exotic species have been introduced (e.g. *Grevillea robusta*). Herbicides and chemical fertilizers are applied regularly and mulching is common practice (De Beenhouwer et al., 2015b).

The natural forest and semi-forest systems were sampled in the Gera area, a forested landscape with natural moist evergreen forest (Fig. S1). Natural forest plots were sampled deep inside the large (>100,000 ha) Gera forest, whereas semi-forest plots were established at the edges of the forest. Semi-plantation plots were sampled in the Garuke area, representative for a typical rural landscape matrix where all former Afromontane forest was cut or converted into small coffee production forest fragments (Aerts et al., 2011). Finally, plantation plots were established in the Goma area where large shade plantations can be found (Fig. S1). Changes in environmental properties (elevation and crown closure) and soil chemical properties (soil pH, relative soil humidity, soil phosphorus and nitrogen content) across the management intensity gradient can be found in De Beenhouwer et al. (2015b) and are summarized in Table S1.

2.2. Carbon assessments

A stratified random sampling design was adopted across the four management types. In each management type, fifteen $25\,m \times 25\,m$ plots ($625\,m^2$) were sampled between August and November 2014, using a nested design consisting of one large plot ($25\,m \times 25\,m$) for the measurement of large trees (girth at breast height or GBH > 15 cm) and a smaller subplot ($7\,m \times 7\,m$) for surveying all woody plants (GBH > 3 cm). This nested plot design results in a manageable plot size to record all woody species including saplings, which can become very abundant at disturbed sites. To standardize the sampling effort, plot area was adjusted in function of slope angle so that the vertically projected plot area was the same for all plots (see also Vanderhaegen et al., 2015). In this study, we established a rather large number of relatively small plots (60 in total) to better capture variation within each of the four different management systems (Gilroy et al., 2014).

The above-ground C stock was measured from two different C pools: above-ground living biomass C and above-ground coarse woody debris (deadwood and litter) (IPCC, 2006). The dry weight of the above-ground biomass was calculated based on a set of allometric relations (Table S2). Field-measured variables were tree species, tree height (m) and girth at breast height (cm). Dry wood density values ($g\,cm^{-3}$) for the individual woody species were obtained from Tadesse et al. (2014), who worked in a very similar geographical environment in Southwest Ethiopia. For unidentifiable deadwood, a default wood density of $0.5\,g\,cm^{-3}$ was used (IPCC, 2006). Litter dry biomass ($10^6\,g\,ha^{-1} = Mg\,ha^{-1}$) was