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Carbon stocks and cocoa yields in agroforestry systems of Central America

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ABSTRACT

The cocoa tree (*Theobroma cacao* L.) is cultivated typically in agroforestry systems in close association with a rich list of tree species and other useful plants on the same plot. Cocoa based agroforestry systems are credited for stocking significant amounts of carbon and hence have the potential to mitigate climate change. Since cocoa yields decrease non-linearly with increasing shade, a need is to design optimal cocoa agroforestry systems with high yields and high carbon stocks. We estimated the carbon stocked in a network of 229 permanent sample plots in cacao-based agroforestry systems and natural forests in five Central American countries. Carbon stocks were fractioned by both system compartments (aboveground, roots, soil, litter, dead wood – fine and coarse, and total) and tree use/form (cocoa, timber, fruit, bananas, shade and ornamentals, and palms). Cocoa plantations were assigned to a five-class typology and tested for independence with growing region using contingency analysis. Most Central American cocoa plantations had mixed or productive shade canopies. Only 4% of cocoa plantations were full sun or rustic (cocoa under thinned natural forest). Cocoa tree density was low (548 ± 192 trees ha^{-1}). Total carbon (soil + biomass + dead biomass) was 117 ± 47 Mg ha^{-1}, with 51 Mg ha^{-1} in the soil and 49 Mg ha^{-1} (42% of total carbon) in aboveground biomass (cocoa and canopy trees). Cocoa trees accumulated 9 Mg C ha^{-1} (18% of carbon in aboveground biomass). Timber and fruit trees stored 65% of aboveground carbon. The annual rate of accumulation of carbon in aboveground biomass ranged between 1.3 and 2.6 Mg C ha^{-1} y^{-1}. Trade-offs between carbon levels and yields were explored qualitatively using functional relationships documented in the scientific and technical literature, and expert knowledge. We argue that it is possible to design cocoa-based AFS with good yields (cocoa and shade canopy) and high carbon stock levels. The botanical composition of the shade canopy provides a large set of morphological and functional traits that can be used to optimize shade canopy design. Our results offer Central American cocoa producers a rigorous estimate of carbon stocks in their cocoa plantations. This knowledge may help them to certify and sell their cocoa, timber, fruits and other goods to niche markets with good prices. Our results will also assist governments and the private sector in (i) designing better legal, institutional and policy frameworks, local and national, promoting an agriculture with trees and (ii) contributing to the development of the national monitoring, reporting and verification systems required by the international community to access funding and payment for ecosystem services.

1. Introduction

The atmospheric concentration of CO_2 and other greenhouse gases increased by 70% between 1970 and 2004 (Solomon et al., 2007). Carbon accumulates in the atmosphere at a rate of 3.5×10^9 tons a year, due mostly to fossil fuel consumption and the conversion of tropical forests into land for agriculture and pasture (Paustian et al., 2000). Industry and energy sectors (transport, industrial processes, electricity, and heat generation) are responsible for approximately 65% of all emissions. Land use change and agriculture are responsible for 18% and 14%, respectively (WRI, 2005). There are incentives to emit less and capture more greenhouse gases, such as the Joint Implementation and Clean Development Mechanisms, REDD+ (Reduced Emissions from Deforestation and Forest Degradation), and voluntary carbon

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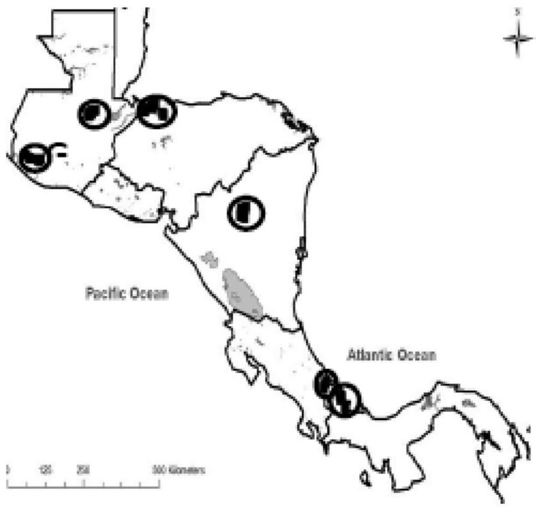

Talamanca, Costa Rica	N9 28.392	W82 52.25
	N9 38.393	W82 59.188
Bocas del Toro, Panamá	N8 59.083	W82 16.919
	N9 21.868	W82 30.411
Alta Verapaz, Guatemala	N15 29.639	W89 42.033
	N15 38.719	W89 56.082
Costa Sur, Guatemala	N14 29.788	W91 18.82
	N14 38.239	W91 45.331
Waslala, Nicaragua	N13 14.003	W85 15.097
	N13 30.882	W85 25.491
Cortés, Honduras	N15 29.829	W87 40.762
	N15 47.151	W88 16.318

Fig. 1. Name and location of the cocoa growing areas where our study was conducted in Central America.

markets (Miles and Kapos, 2008; FAO, 2010). Cocoa (*Theobroma cacao* L.) is cultivated in agroforestry systems, i.e. together with a rich list of tree species and other useful plants on the same plot.

Cocoa based agroforestry systems are credited for stocking significant amounts of carbon and hence have the potential to mitigate climate change. Carbon stocks in shaded agroforestry systems with perennial crops—such as coffee (*Coffea arabica* L.), rubber (*Hevea brasiliensis* (HBK) Muell.-Arg.), and cocoa—may vary between 12 and 228 Mg ha^{-1} and could help to mitigate climate change (Winjum et al., 1992; Schroeder, 1994; Dixon, 1995; Albrecht and Kandji, 2003; Montagnini and Nair, 2004; Nair et al., 2009). In Central America, 24,000 ha of cocoa are grown without inorganic inputs or pesticides, plantations are small (0.25–3.0 ha) and yield only 250 kg dry cocoa ha^{-1} y^{-1} (Deheuvels et al., 2012; Whelan et al., 2007; Somarriba et al., 2009). Central American cocoa agroforestry systems have high plant species richness and structural complexity (Deheuvels et al., 2012), product diversification for self-consumption and sale (Dalquist et al., 2007), and permanent soil cover and large amounts of organic matter. These later conditions promote soil and water conservation (Adejumo, 2005; Verchot et al., 2007; Binternagel et al., 2010). Taxonomically diverse shaded cocoa plantations share many features usually recommended to adapt farming to climate change (Smit and Skinner, 2002).

Cocoa yields decrease non-linearly with increasing shade (Zuidema et al., 2005; Stephan-Dewenter et al., 2007; Wade et al., 2010; Gockowski and Sonwa, 2011), and shade in turn increases – albeit not deterministically – with carbon stock level. This raises the question whether optimal cocoa agroforestry systems can be designed that simultaneously produce high yields (cocoa and products from the shade canopy species) and retain high carbon stock levels. We quantified carbon stocks in Central American cocoa agroforestry systems and local forests patches, and qualitatively explored the trade-offs of maintaining both high carbon levels and high crop yields.

2. Materials and methods

2.1. Definitions, terms and concepts

We use the following definitions: **A cocoa growing area** is the territory where farms having cocoa plantations are located. **A farm** is the land unit (in a single block or not) managed by the family or enterprise, which typically includes several cropping systems, one of which may be cocoa. **A cocoa plantation** is a single block of land, of variable size and form, dedicated to cultivating cocoa with or without other associated plants. **A plot** is a 50 m × 20 m representative sample area within the cocoa plantation. A plot may be divided into sub-plots. A cocoa plantation has **two components**: cocoa and shade canopy (or simply, the canopy). **The cocoa component** includes all cocoa plants. **The canopy component** includes all non-cocoa plants taller than cocoa trees. A cocoa plantation under shade trees is a cocoa based agroforestry system (**cocoa AFS**). As young cocoa trees grow in height and develop their crowns, upper leaves shade those underneath, producing **self-shading**. **The site** is the set of biophysical conditions (soil, climate, biology and local culture) that determines growth and yield of cocoa and canopy components.

2.2. Description of cocoa plantations and sample plots

We sampled 229 cocoa plantations in six cocoa growing areas in five Central American countries (Fig. 1). In each cocoa growing area, we established a network of permanent sample plots located in 36–40 cocoa-based AFS and in 3–4 mature or secondary natural forest patches, as control. The natural forest present in the area at the time of sampling may be a degraded version of the original native primary forest at the site. Cocoa-based AFS in each growing area were selected in order to sample as much variability as possible in terms of farm typology and biophysical conditions. Further details of the criteria used to develop the research network are given in Deheuvels et al. (2012) and Deheuvels (2011).

2.3. Field measurements and data analysis

Tree biomass was estimated using locally derived allometric equations (Table 1).

The carbon content was 0.5 of dry biomass (IPCC, 2003b). Carbon per plot was fractioned into: (i) system's compartments [above-ground, litter (leaves and fine branches ≤2 cm diameter), coarse (>10 cm) and fine (>2 and <10 cm) dead wood, coarse (>2 mm in diameter) and fine roots (<2 mm in diameter), soil, total] and (ii) plant type: cocoa, timber trees, fruit and medicinal trees, other shade and ornamental trees, bananas, and palm trees. We measured carbon in soil organic matter, litter, soil bulk density, fine roots density, and fine dead wood in composite samples of 10 sub-samples