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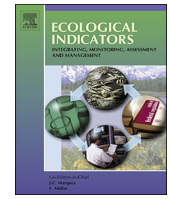


Original Articles

# Exploring management strategies to enhance the provision of ecosystem services in complex smallholder agroforestry systems

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ABSTRACT

Agroforestry systems (AFS) can provide multiple ecosystem services (ES), partly due to their high (agro)biodiversity. However, multi-criteria analyses studying trade-offs between multiple ES and exploring AFS management optimization paths are still scarce. Routine methods, such as regressions or weighted/non-weighted scorings, may reveal unsuitable because data collections hardly meet rigorous statistical designs and knowledge about ES can be limited in such complex systems. In this paper, we explore a novel approach based on algorithms identifying Pareto fronts to check for management schemes which favour the multi-functionality of complex agroecosystems. We based our study on the ground truth data from 58 cocoa-based AFS fields in Cameroon and chose to study three ES: cocoa production, aboveground tree carbon storage and natural pest control. The combination of expert knowledge and Pareto front algorithms enabled us to identify four clusters of increasing ES provision among the 58 plots: "bottom", "low-yield intermediate", "high-yield intermediate", and "top". Significant differences in associated tree communities and management strategies were identified across the four clusters. While highlighting clusters of AFS with common management strategies, the use of the Pareto front algorithm enabled us to draw significant lessons on cocoa-based AFS despite their high complexity. We believe that such an approach can be used to design suitable benchmarks for the study and improvement of multiple ES provision in complex agroecosystems.

## 1. Introduction

Agroforestry systems (AFS) are multifunctional agroecosystems providing, next to crop production (Noordwijk et al., 2016), a large range of regulating and supporting ecosystem services (ES) such as biogeochemical cycling (Pransiska et al., 2016), regulation of local climate (Ellison et al., 2017), maintenance of soil fertility, carbon (C) storage, maintenance of genetic diversity and biological control (Mortimer et al., 2017). Even though agroforestry is an ancient and traditional way of farming in many parts of the world (King, 1989), our current understanding of the functioning of AFS and best strategies of these systems to enhance the provision of multiple ES still remains limited (Rapidel et al., 2015).

Identifying the best management strategies that allow the simultaneous provision of several ES is currently a scientific quest for many types of ecosystems, such as forest (Lafond et al., 2017), cropland (De Groot et al., 2010; Perring et al., 2012) and aquatic areas (Butler et al., 2013). Several authors explored the relationships between different ES as well as the management strategies to favour multiple ES provision in different natural and agroecosystems (e.g. Kennedy et al., 2008; De Groot et al., 2012; Bugalho et al., 2016; Lafond et al., 2017, Kearney et al., 2017). In some of these studies, multi-criteria optimization methods such as the Pareto front algorithm were successfully applied and shown to be an effective method to support management decision-making processes (Kennedy et al., 2008; Bugalho et al., 2016; Lafond et al., 2017). The Italian economist Vilfredo Pareto was the first studying multi-criteria optimization using front algorithm in economics (Pardalos et al., 2008). The classic Pareto front theory allows identifying a series of scenarios forming a "front" on which one criterion cannot be improved without deteriorating the others. The method provides multiple optimal alternatives (Pardalos et al., 2008). It is therefore reasonable to further explore the potential of this

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methodology in various ecosystems, as for example in complex agroforestry systems, for which such an attempt could not be found in literature.

However, due to the high complexity of AFS, data collection and calculation of theoretical optima through the commonly used Pareto front algorithm is challenging. This is especially true in smallholder farming systems and AFS in natural forests where diversity within and between plots is high (Speelman et al., 2006). Routine methods, such as regressions or weighted/non-weighted scorings, are often unsuitable here because data collections hardly meet rigorous statistical designs. As a result, identifying best strategies and supporting management decisions for providing multiple ES in these complex systems remains highly difficult.

Cocoa-based AFS are one of the most widespread perennial cropping systems in Western and Central Africa and are largely managed by smallholder farmers. In Cameroon, cocoa-based AFS have existed for over a century and exhibit both economic and social importance to local farmers (Jagoret et al., 2011). Several studies on cocoa AFS' ES provide a first insight into the relations between their multifunctionality and ES provision (Deheuvels et al., 2012; Vaast and Somarriba, 2014; Saj et al., 2017a,b). In this context, the role of associated trees in cocoa agroforests in relation to the provision of multiple ES has received increasing attention over the last 10 years (Tscharntke et al., 2011; Jagoret et al., 2017; Blaser et al., 2017). However, strategies for associated trees management which could be implemented by farmers are not yet available (Rapidel et al., 2015).

In this paper we implement the Pareto frontier algorithm using field data from complex cocoa agroforestry systems in Central Cameroon. We show that such an implementation represents an innovative approach to assess the capacity of real agroforestry systems to provide multiple ecosystem services and to identify associated trees management strategies. We focused our analysis on the three main ecosystems services provided in these smallholder systems, namely: (a) cocoa beans production, (b) carbon sequestration, and (c) natural pest control. Meanwhile, we assessed some features from 58 randomly selected plots: cocoa stand and associated trees community structure and composition as well as the age of plot and of the cocoa stands. Those features were assumed to be relevant indicators of farmers' current and past management strategies (Jagoret et al., 2017; Saj et al., 2017a,b). The combination of the Pareto algorithm with ground truth data allowed us to address the following questions: (1) Can the Pareto front algorithm provide a sound exploration of ES trade-offs and/or synergies within an actual case study (2) How can such a method help build a renewed typology, taking into account the provision of multiple ES of complex agroecosystems such as AFS? (3) How can it then facilitate the identification of strategies favouring multiple ES provision in AFS and consequently support management decisions?

## 2. Materials and methods

### 2.1. Case study

Data was collected in three villages in Central Cameroon (2.1° − 5.8° N;10.5° − 16.2° E): Bokito, Zima and Ngomedzap. Local elevation is between 600 and 800 m. Local climate is hot and humid with an annual average temperature of 25 °C (Santoir and Bopta (1995)) and an annual average rainfall of around 1400 mmyr$^{-1}$ in Bokito, 1600 mm yr$^{-1}$ in Zima and 1800 mm yr$^{-1}$ in Ngomedzap (Santoir and Bopta, 1995). Central Cameroon is characterized by slightly acid ferralitic soils which saturation level varies with latitude. Bokito's soils are slightly desaturated while those of Ngomedzap are highly desaturated. Zima exhibits in-between saturation levels (Santoir and Bopta, 1995). Bokito is located in a forest-savannah transition zone with low human activity (29 inhab. km$^{-2}$), whereas Zima and Ngomedzap are both located in originally evergreen forested areas. Zima has a considerably higher human activity (111 inhab. km$^{-2}$) compared to Ngomedzap (37 inhab. km$^{-2}$). Cocoa production in form of AFS is the traditional and principal economic activity in the three villages studied (Jagoret et al., 2011). These systems are highly heterogeneous with numerous associated woody species including both African and exotic trees (Sonwa et al., 2008; Saj et al., 2017a). Farmers plant and preserve these species along with cocoa trees with the expectation that it makes AFS notably multifunctional (Jagoret et al., 2014, 2017). In Central Cameroon, associated tree community density ranges from 20 to 30 individuals ha$^{-1}$ to more than 200 individuals ha$^{-1}$. Species richness varies between 4 and 5 sp ha$^{-1}$ to more than 20 sp ha$^{-1}$. Both density and diversity of associated trees usually depend on local pedoclimatic conditions as well as on the management and use of the trees (Jagoret et al., 2014; Saj et al., 2017a). In these systems, large trees (diameter at breast height over 30 cm) often represent the largest C pool of the living biomass (Saj et al., 2017a). In Central Cameroon cocoa stand density ranges from 700 to 800 to over 2000 trees ha$^{-1}$, with a mean between 1100 and 1300 trees ha$^{-1}$. Stand densities depend on the farmers' culture and economic environment (which often varies from site to site), management (rejuvenation and cutting-back practices) and age of the system (Jagoret et al., 2011, 2017).

### 2.2. Ecosystem services and their indicators

We focused on three ecosystem services (ES): cocoa bean production, carbon sequestration and natural pest control. Those ES were chosen given the following. Cocoa production is considered the most important ES for smallholders (Jagoret et al., 2011). Carbon (C) sequestration in living biomass helps mitigating global climate, but also contributes to other ecological services such as biodiversity conservation (Saj et al., 2013, 2017a). The level of natural pest control is crucial in such systems since pests and diseases can profoundly impact cocoa yields (i.e. Williams, 1953, Norgrove and Hauser, 2005). In these systems an equilibrium is to be found between fungal diseases – which are favoured by higher air relative humidity, and pests – which may be favoured by canopy openness (Mortimer et al., 2017). Hence, pest and disease occurrence/regulation may depend on the systems' structure and composition which influence both trophic networks and physical conditions (see i.e. Bianchi et al., 2006; Gidoin et al., 2014; Maas et al., 2013).

Cocoa bean production was estimated by pod counting in 2008 and 2009 as in Jagoret et al., 2011. Pods of < 10 cm in length are susceptible to physiological wilt (Wood and Lass, 2001) and were thus discarded from counting. Accessible cocoa yield (as defined by Saj et al. (2017b) for a stand was then calculated as follows:

$$Y = (NP \times FB \times TC) \times CD \quad (1)$$

where, Y is yield (in kg of dry cocoa beans yr$^{-1}$ ha$^{-1}$), NP is the mean number of pods per cocoa tree, FB is the mean weight of fresh beans per pod (in kg), TC is the fresh bean weight conversion coefficient, which was considered constant at 0.35 (Lachenaud, 1984); and CD is cocoa tree density, i.e., the number of cocoa trees per ha.

The total amount of C stored in living tree biomass was estimated using Chave et al. (2005) allometric model for both cocoa and associated trees. To account for differences in annual precipitation in the three study sites we used Eqs. (2a) for Bokito and (2b) for Zima and Ngomedzap (more details in Saj et al., 2013):

$$AGBi = \exp[-2.187 + 0.916 \ln(Wi \times (DBHi2) \times Hi)] \quad (2a)$$

$$AGBi = \exp[-2.977 + 0.94 \ln(Wi \times (DBHi2) \times Hi)] \quad (2b)$$

where, $AGB_i$ represents aboveground biomass of individual trees (in kg dry weight), $H_i$ individual tree height (in m), $W_i$ specific wood gravity of the tree (in g cm$^{-3}$ dry weight) and DBH is diameter at breast height (in cm).

The level of natural pest control was estimated by building a "Pesticides Cost Saved" (PCS) indicator as a proxy. We assumed that