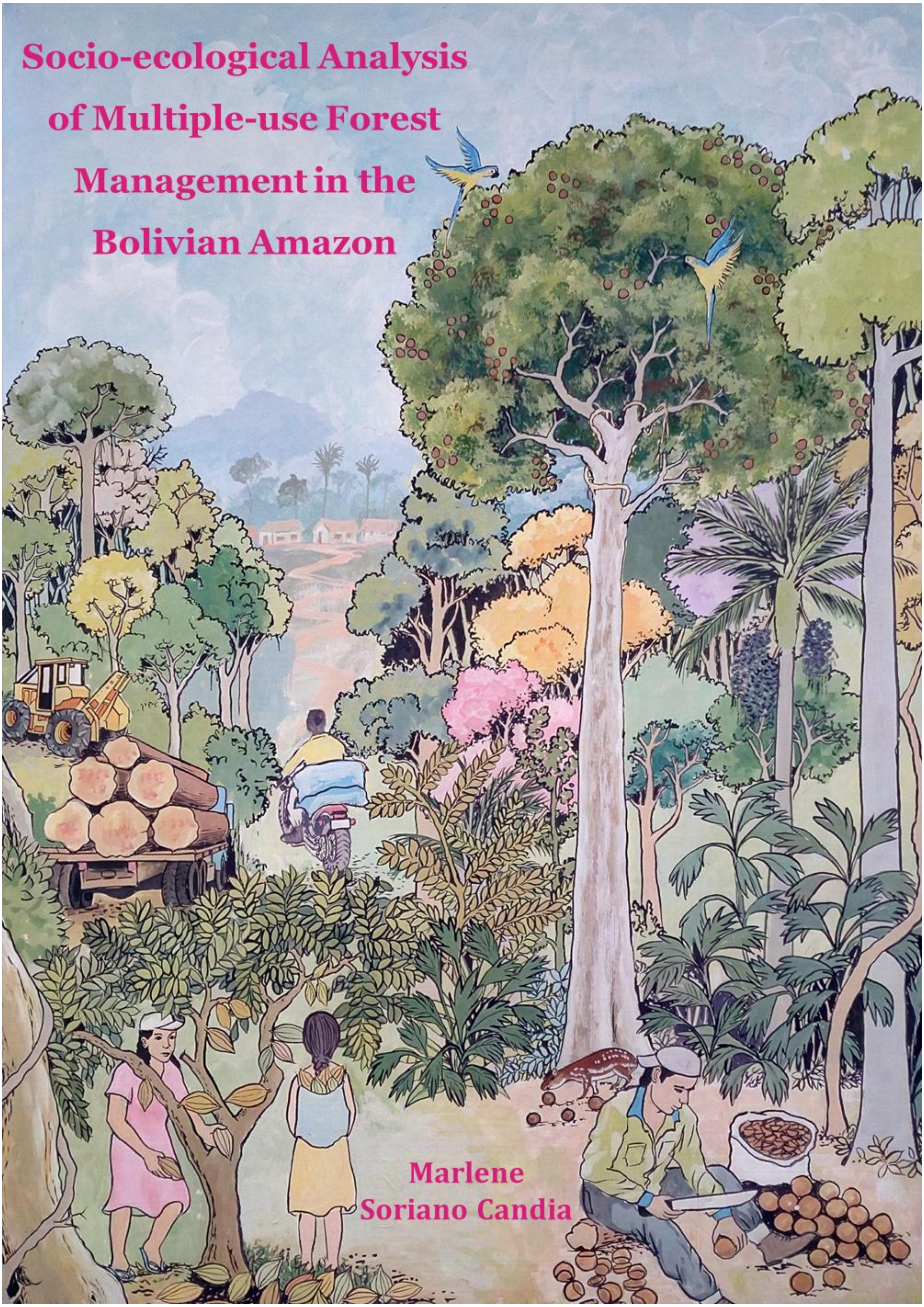
Socio-ecological Analysis of Multiple-use Forest Management in the Bolivian Amazon



Marlene Soriano Candia

Propositions

1. Sustained production of Amazon nut (*Bertholletia excelsa*) is only viable in a multiple-use forest management scheme that includes logging of timber species
   (this thesis)

2. Combination of forest and non-forest economic activities is key to reduce rural poverty and secure forest conservation in tropical regions
   (this thesis)

3. Statistical models in multidisciplinary studies require validation by expert knowledge to inform about reality

4. The only way for scientists to properly provide policy recommendations is by closely working with local stakeholders

5. A better price for Amazon nut and for timber of other tree species can help reduce deforestation more effectively and with longer lasting effects than environmental programs

6. As knowledge is power, total knowledge transfer will never occur – even in academia

Propositions belonging to the thesis, entitled

Socio-ecological analysis of multiple-use forest management in the Bolivian Amazon

Marlene Soriano Candia
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Socio-ecological analysis of multiple-use forest management in the Bolivian Amazon

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Preface

Ever since I first ventured into the Amazonian forest, I experience freedom in its highest expression. There, I get possessed by the softest embrace and get overwhelmed by the magnificent nature around me that for a moment erases any past experiences and thoughts from my mind. The environmental philosopher John Muir would have surely described this experience in an irresistible prose, and yet, I dare to share mine because my desire to repeat this experience and share it with future generations has led me to undertake the study that you are about to read. So let me take you to a Sunday morning at one of my study communities.

In that morning, our last day of fieldwork in that community, I and don Rafael, 48 years old and father to eight children, were getting ready to search and count fallen Amazon nut fruits of reproductive trees within one of the permanent research transects established in his community. I realized at that moment that don Rafael had diligently supported me during my two field work seasons in his community. Curious about what motivated him to support me, I asked him, to which he responded: “Marlene, I support you because I recognize the importance of this research to our forest and to the well-being of the families in my community”. Don Rafael´s answer confirms to me that community-owned forests can be best managed by its owners if given the opportunity and resources.

Don Rafael´s household is a typical representation of a campesino community household in the Bolivian Amazon, entailing slash-and-burn shifting cultivation of about 1-ha a year for subsistence, the raise of domestic animals and agroforestry plants around their house, and the harvest of Amazon nut and timber for their cash income. As in many community families, Don Rafael´s older children are entering the age of deciding about their future. One of them wishes to start a professional career in the nearest regional city (about 120 km from their community). However, the options that the family have to cover these expenses are few: 1) by increasing income derived from more intensive forest use, agriculture and livestock; 2) by venturing into business, or 3) by migrating to regional cities. Certainly, forest use comes as the most viable and environmentally friendly option to cover such expenses. Community families in the region such as don Rafael's family face a constant dilemma between fulfilling their development needs and keeping their forest standing.

The unique sensation offered by the Amazonian forest motivated me to pursue my post graduate studies in this fascinating system. For my master's thesis, I investigated the impact of two forms of logging (formal and informal) on the regeneration density of Amazon nut (*Bertholletia excelsa*) and timber species. In this PhD thesis, I continued investigating the sustainable production of these two keystone forest products within a multiple-use forest management scheme from a socio-ecological point of view to be able to draw science-based management guidelines suitable for community families in this rich forest ecosystem.

Through this collaborative research, I expect to timely support these communities´ development needs and to guide multiple-use forest management in the region. I also hope that these results will direct not only national and international institutions but also consumers to support a sustainable MFM production by improving local capacities and by offering a better price to community-sourced forest products which could greatly contribute to community households´ efforts at keeping their forest standing while making a livelihood out of the Amazonian forest.

Chapter 1

General introduction

The context for multiple-use forest management in the Bolivian Amazon

Multiple-use forest management (MFM) is widely practiced throughout the tropics, representing an important part of community families' income. Multiple-use forest management is defined as the production of multiple goods and the provision of multiple services within a forest management unit area (García-Fernández et al., 2008; Sabogal et al., 2013). For example, in the Bolivian Amazon, a typical community family practices slash-and-burn shifting cultivation in about 1-ha of land a year, raises domestic animals, has agroforestry systems around its house, and harvests numerous forest products for food and shelter, mainly for subsistence. Few of these forest products also represent an important source of cash income, e.g., Amazon or Brazil nut (*Bertholletia excelsa*) and timber (Stoian and Henkemans, 2000; Zenteno et al., 2013). Amazon nut and timber are harvested from within the same forest unit, making a special case for investigating their production in a MFM scheme.

Pressure over forest products is increasing as more products initially harvested only for subsistence are being used for generating cash income due to an increasing market demand for these products and due to the low effort and investment needed in their harvest. Pressure over forest resources also increases as children in community families enter adulthood. Some decide to form a family and wait to be granted land to make a living at the community, while others migrate to the nearest city in search of a job and/or to start a professional career. Families that decide to stay in the community have few options to cover education and living expenses: 1) by increasing income derived from more intensive forest use, agriculture and/or livestock; 2) by venturing into business, or 3) by temporarily migrating to the nearest city (de Jong et al., 2014; Duchelle et al., 2014). When families choose the first option, forest use comes as the most viable and environmental friendly option to cover such expenses. Given that forest use is perceived as an environmentally-friendly and sustainable development option for rich forest ecosystems like the Amazonian forest, governments such as the Bolivian government, are putting into place forest policies that promote integrated management of forests and lands. The enactment of the directive for Integral Management of Forests and Lands

Plan in Bolivia: PGIBT (acronym in Spanish, *Plan de Gestión Integral de Bosques y Tierras*), sets the guidelines to integrate MFM within a landscape management approach that also includes other land uses such as agriculture (Administrative Resolution Nº 250/2013 of the Bolivian Forest and Land Controlling Authority – ABT, acronym in Spanish).

As by the end of 2015, 24 PGIBTs were already approved in the Bolivian Amazon, covering an area of 260,845 ha (ABT, unpublished data). Even though these plans were elaborated with the active participation of community families who incorporated their socioeconomic potential and limitations for harvesting forest products, little is known about the socio-ecological costs of timber and non-timber forest production in a MFM scheme; and even less, about the ecological feedbacks resulting from the combined harvest of multiple products and species. In this thesis, I aimed to ***increase the understanding of the social, economic, and ecological factors driving the sustainable production of the most important MFM scheme in the region, and to determine the contribution of* this *MFM to the well-being of community families and to the sustainable development of community forestry in this region*.**

Importance of multiple-use forest management for community forestry

Multiple-use forest management, including timber and non-timber forest products (NTFPs), has been proposed as an alternative to forest conversion (Putz et al., 2012), and as a way to secure food supply and reduce poverty in tropical communities. Community families in tropical regions have traditionally harvested multiple forest products for subsistence and/or cash income (Duchelle et al., 2014; Jagger et al., 2014; Zenteno et al., 2013). Hence, managing community-owned forests for multiple products is the key to avoiding not only forest conversion (Putz et al., 2012), but also to meeting communities' development goals regarding poverty reduction and environmental protection (Antinori and Bray, 2005). MFM seems like the right option for diversity-rich forest ecosystems, particularly due to the often poor forest conditions inherited from past highly-selective logging (Cronkleton et al., 2012; Menton et al., 2009; Radachowsky et al., 2012), which may have left little or no timber to sustainably manage these forests for timber production alone. One way to reduce poverty is by diversifying forest production, which reduces risks associated to economic instability (Shackleton et al., 2007; Stanley et al., 2012). However, managing these forests for multiple products comes with many challenges, from the need to have adequate managerial and negotiation skills to investments needed to obtain economic returns.

Identifying the potential of community-owned forests for MFM may help communities to set up clear targets to reduce poverty and migration altogether. Such understanding may also contribute to decreasing the long-existing mismatch between legal requirements for managing community forests and the communities' realities, a mismatch resulting from the implementation of top-down policy approaches, insufficient understanding of the factors leading to enhanced financial returns from forest products, and insufficient ecological knowledge of the species harvested in a MFM scheme (Sabogal et al., 2013).

The implementation of community forestry has been challenging and several initiatives have been undertaken to make it work. One of such initiatives is the creation of community forest enterprises (CFEs). A CFE is a productive organization within a community mainly integrated by community members who are in charge of managing financial and technical aspects of the community forest management plan (CFMP). CFEs have special importance for delivering at the same time economic equity and environmental protection to communities (Antinori and Bray, 2005). Much of CFEs' success is due to external support received from environmental NGOs and governmental programs (Benneker, 2008; Humphries et al., 2012). Communities have also been able to enhance profits by entering into business with timber companies through company-community partnership contracts to log timber, which allows communities to negotiate for better prices, increase job opportunities and capacity building around its CFMP (Antinori and Bray, 2005; Humphries and Kainer, 2006; Menton et al., 2009). However, mistrust and lack of mutual understanding have also led to failure of CFEs and company-community partnerships, which can be attributed to a variety of reasons. Among these reasons are the impoverishment of forests from past highly selective logging, forests with timber volumes that did not meet expected economic returns, lack of transparency and/or "poor book-keeping and money management" that creates confusion and suspicion even where there is no corruption (Antinori and Bray, 2005). But overall, the implementation of CFEs and company-community partnerships has brought important benefits to communities by improving community households' managerial and technical skills, indicating that MFM can be carried successfully under particular circumstances.

In addition to communities' socioeconomic constraints to implement MFM, the harvest of multiple forest products could sometimes lead to conflicting outcomes. For example, when the harvest of a multipurpose plant species requires killing the plant to extract one of its products, or when the harvest of a product disrupts the habitat of other species used to obtain other products, threatening the viability of MFM. There are cases, however, when the harvest of multiple forest products has synergic effects and effectively increases the provisioning value of a forest while diversifying rural families' income. The combined harvest of Amazon nut seeds and timber from other tree species may be such a case due to that the majority of these species require higher light levels at early stages of their life cycle like the ones created by logging disturbance (Myers et al., 2000; Schwartz et al., 2012; Silva et al., 1995; Soriano et al., 2012; Zuidema and Boot, 2002), and also because the harvest seasons of Amazon nut seeds and timber from other tree species are complementary to each other (Duchelle et al., 2012; Guariguata et al., 2009). Seemingly, knowledge on the socioeconomic factors enhancing the overall benefits from forest such as involvement in the CFMP may help improve the overall benefits that community families obtain from their forest. Thus, and considering the uncertainties related to the development of MFM in the context of community forestry, it is essential to gain further knowledge on (i) the availability of forests resources, (ii) the socioeconomic and biophysical drivers of the main sources of community families' livelihood, and (iii) the response of valuable tree species to different management practices. This knowledge could effectively contribute to the design of management strategies so that communities can achieve both their development and conservation goals.

Multiple-use forest management research in the Neotropics

NTFPs management has been widely promoted among forest communities as part of the global developmental agenda in the Amazon Basin (Brazil), Central America (Mexico and Guatemala), and Central West Africa (Gabon and Ghana) (Wollenberg and Ingles, 1998), where it has contributed to the development of community forestry. As a result thereof, and of the increasing incursion of logging to forests traditionally used for NTFP extraction, a need for integrating timber and non-timber production under a sustainable multiple-use forest management (MFM) scheme became apparent, and many forms of MFM initiatives started to take place around the 1980's, mainly in Mexico and Guatemala (Radachowsky et al., 2012). One of such examples is the joint management of the NTFP species *Manilkara zapota* and commercial timber species.

At the beginning, multiple-use forest management planning generally relied on traditional ecological knowledge and on information from forest inventories due to the lower economic value and/or impact attributed to NTFPs compared to timber (Lawrence, 2003). As some NTFPs started to gain economic value, research on the impact of logging and NTFP harvest on the ecology of valuable NTFP species started to be investigated experimentally (Herrero-Jáuregui et al., 2011; Klimas et al., 2012a). However even today, research on the ecology of joint management of NTFPs and timber species is scarce (Sabogal et al., 2013). In the Neotropics, only seven NTFP species have been so far investigated in this regard (Table 1.1). Studies that investigated NTFPs and timber production from a single or multiple species concur on that the extent of logging disturbance and NTFP harvest matter for the sustainable production of multiple forest products (Guariguata et al., 2009; Herrero-Jáuregui et al., 2011; Klimas et al., 2012a; Menton, 2003; Radachowsky et al., 2012; Rist et al., 2012; Shanley et al., 2012; Soriano et al., 2012). The impact of logging on NTFP species varies with the rate of timber extraction. For example, low logging intensities, such as the ones occurring in the Bolivian and Peruvian Amazon (1 - 2 trees logged ha^{-1}), did not cause significant damage, nor reduced fruit production of reproductive *Bertholletia* trees (Guariguata et al., 2009; Rockwell et al., 2015). In general, logging had no significant impact on small individuals of *Bertholletia*, but their density and recruitment rates were higher in highly logging-disturbed areas such as logging gaps and log landings (Moll-Rocek et al., 2014; Soriano et al., 2012). The fact that these studies looked at different tree size classes to investigate the impact of logging on species density and demographic rates has led to contrasting conclusions on the extent of logging impact on NTFP and timber species.

Table 1.1. Examples of non-timber forest species investigated either from an ecological or socioeconomic perspective in the context of multiple-use management with timber harvesting in the Neotropics.

Species	Ecological	Socioeconomic
Amapá amargoso (*Parahancornia fasciculata*)	Impact of logging on tree density, seed production and management (Shanley et al., 2012).*	Income and trade deals from latex and timber (Shanley et al., 2012).
Amazon nut (*Bertholletia excelsa*)	Logging damage to nut producing Amazon nu trees (Guariguata et al., 2009). Local perceptions on ecology and management (Duchelle et al., 2012). Regeneration response to formal and informal logging (Soriano et al., 2012). Regeneration in logging gaps (Moll-Rocek et al., 2014). Nut production along a gradient of logging intensity (Rockwell et al., 2015).	Identification of barriers for the implementation of MFM in the MAP region (Duchelle et al., 2012).
Andiroba (*Carapa guianensis*)	Viability of combined timber and non-timber harvests (Klimas et al., 2012a).	The economic value of sustainable seed and timber harvest (Klimas et al., 2012b).
Chicle (*Manilkara zapota*)	Assessment of ecological integrity through rapid rural appraisal (Radachowsky et al., 2012).*	Socioeconomic and biophysical factors affecting its multiple-use (Radachowsky et al., 2012).
Copaiba (*Copaifera reticulata*)	Temporal and spatial variability in recruitment, growth, and mortality rates (Herrero-Jáuregui et al., 2011).	
Cumaru (*Dipteryx odorata*)	Temporal and spatial variability in recruitment, growth, and mortality rates (Herrero-Jáuregui et al., 2011). Impact of logging on tree density, seed production and management (Shanley et al., 2012).*	Income and trade deals from seeds and timber (Shanley et al., 2012).
Uxi (*Endopleura uchi*)	Impact of logging on tree density, fruits production and management (Shanley et al., 2012).*	Income and trade deals from fruits and timber (Shanley et al., 2012).

*Research that investigated the ecological viability of NTFP harvest with timber logging using social research methods such as participant observations and rapid rural appraisal.

While logging generally affects negatively on the production of NTFPs by reducing the density of reproductive trees and/or accessibility to the forest (Rist et al., 2012; Salick et al., 1995), it has little impact on tree diversity of small individuals of NTFP and timber species (de Avila et al., 2015; Duah-Gyamfi et al., 2014; Salick et al., 1995). These results imply that logging may not necessarily reduce overall species diversity due to the species' capacity to grow, survive and persist under disturbance (de Avila et al., 2015; Duah-Gyamfi et al., 2014; Salick et al., 1995). Research looking at the overall impact of logging on the population growth rate of most valuable species are few, and even fewer research have looked at the combined impact of harvesting timber and non-timber forest products (NTFPs) on the population growth rates of logged and harvested NTFP species.

Studies on the socioeconomics of MFM are even scarcer than ecological ones in spite of the many potentially unfavourable feedbacks between co-occurring species with harvest, and of increasing socioeconomic pressure to intensify their use (Belcher, 2005; Sills et al., 2011). Research mainly focused on the income generated by, and marketability of non-timber products and timber from single tree species such as *Carapa guianensis* (Klimas et al., 2012b), *Dipteryx odorata, Parahancornia fasciculate* and *Endopleura Uchi* (Shanley et al., 2012). Only Duchelle et al. (2012) and Radachowsky et al. (2012) have looked at the socioeconomic and biophysical factors enabling MFM production (Table 1.1).

From the abovementioned research in this section, only Klimas et al. (2012a, 2012b) and Shanley et al. (2012) investigated the economic and ecological compatibility of managing timber and NTFP species in a MFM (Klimas et al., 2012b), and only Radachowsky et al. (2012) looked at the viability of MFM from social, economic and ecological viewpoints. Such studies, accounting for the long-term socioeconomic and ecological dynamics of harvested species are essential for understanding the sustainable production of timber and non-timber forest products in a MFM scheme as part of a complex socio-ecological system.

The study area

The Bolivian Amazon region encompasses the entire Department of Pando and the provinces of Vaca Díez of the Beni Department and Iturralde of the La Paz Department (Fig. 1.1). This research took place in the Department of Pando and Vaca Díez Province of the Beni Department only due to the similarities in terms of tenure and forest use arrangements of community families. Approximately 95% of the study region is covered by forest (Marsik et al., 2011), and comprises 30% of Bolivia's timber production forests (8.8 out of 28.8 million ha; Hjortsø et al., 2006). Tree diversity ranges from 52 - 122 species ha^{-1} with a density between 544 - 627 trees ha^{-1} of trees ≥10 cm diameter at 1.3 m aboveground (DBH) (Mostacedo et al., 2006). The annual rainfall varies between 1,774 - 1,934 mm, while the mean annual temperature differs slightly between the two main regional cities: Cobija (25.4°C) and Riberalta (26.2°C) (Zonisig, 1997).

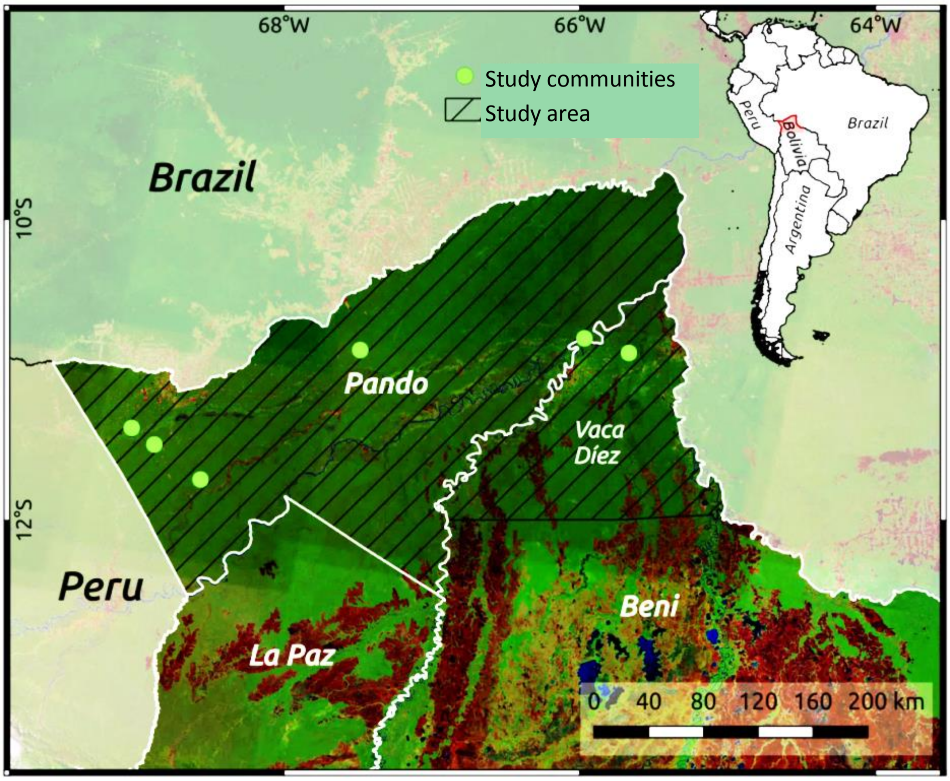

Figure 1.1. Study area indicating the location of the six communities selected for this study in the Pando Department and Vaca Díez province of the Beni Department in the Bolivian Amazon. Credit: Loïc Dutrieux.

The region presents a relatively dry season from May through September with less than 60 mm of precipitation per month. Its topography varies from *terra firme* forests to seasonally flooded areas. In general, *terra firme* forests grow on soils with low fertility (i.e., high aluminium toxicity), while seasonally flooded areas have relatively high nutrient-rich soils due to the sediments carried by rivers originating in the Andes (Zonisig, 1997). *Terra firme* or upland forest represents about 60% of Amazonian forests, and has greater diversity index and species richness than other types of forests present in the region (Mostacedo et al., 2006). Most valuable commercial timber species in the Bolivian Amazon also occur in *terra firme* forests together with Amazon nut trees and other species used for NTFPs extraction (Mostacedo et al., 2006).

Six *campesino* communities were selected for this study (Fig. 1.1, Table 1.2). Studied communities were selected based on their long-standing engagement in formal timber management. These six communities represent 2.5 % of *campesino* communities in the Bolivian Amazon (out of 245; Pacheco et al., 2009), are 30-130 km distant from one of the two main regional cities, and together comprise an area of 80,711 hectares (Table 1.2). The community area in the majority of *campesino* communities is internally delimited per community household to enable household-level decision-making to harvest forest resources (Urapotina, 2011). However, collective decision-making is required for logging timber in a community; even in cases in which logging occurs at the household forest-level. The harvest of forest products at the household forest-level allowed us to use households and their forest as our main sampling unit. We selected 24 households and their household forests representing a wide range of Amazon nut harvesting and logging intensities. We selected 2 - 5 households per community, equivalent to 3.7 - 36.4% of the household members forming these communities. The large variation in the percentage of participating households is due to differences in the number of community households among studied communities which ranged between 11 - 135 households. Women as household heads represented 20.8% of the participating households. Selected households lived between 50 m and 20 km away from their forest from where they customarily collect Amazon nut, timber and other NTFPs.

Table 1.2. Demographic, organizational and spatial characteristics of *campesino* communities in the Bolivian Amazon included in this PhD thesis. All studied communities have defined and have implemented community forest management plans (CFMPs).

Community	Primero de Mayo	12 de Octubre	Limón	Loma Alta	Puerto Oro	San Antonio
Number of household	19	79	20	135	18	11
Distance to nearest city (km)	110	42	122	29.5	72.9	73.6
Community area (ha)	4,943	16,378	16,137	24,604	12,583	6,067
Forest area under management (ha)	4,943	2,281	16,137	16,300	12,583	2,839
Annual logging compartment (ha)	204	180 - 198	435 - 660	844 - 907	497 - 531	182 - 204
Length of Cutting Cycle (Years)	20	20	20	20	20	20
Year of first logging	2007	2000	2004	2006	2007	2004
Number of logging events	1	6	7	8	6	5
Timber benefits sharing type*	Individual	Collective	Mostly Collective	Collective	Mostly Individual	Individual

* 'Timber benefits sharing type' indicates that timber benefits obtained from a household forest were: never shared with other community households (individual); once collectively shared, but not shared with other community households in most recent years (mostly individual); once individual, but collectively shared with other community households in most recent years (mostly collective); and always shared collectively with other community households (collective).

In this thesis, I studied the socioeconomic and ecological processes enabling the sustainable production of Amazon nut and timber in a multiple forest management (MFM) scheme in the Bolivian Amazon. To do so, I determined the following objectives (Fig. 1.2):

- To identify the socioeconomic and biophysical factors determining the income derived from different sources by community households in the Bolivian Amazon (chapter 2).
- To determine the impact of Amazon nut harvesting and logging intensity on *Bertholletia excelsa* populations in the medium and long-term (chapter 3).
- To investigate differences in density and timber volume of eight commercial timber species among community-owned forests,

and to evaluate the impact of logging on key ecological tree characteristics of congeneric species (chapter 4).

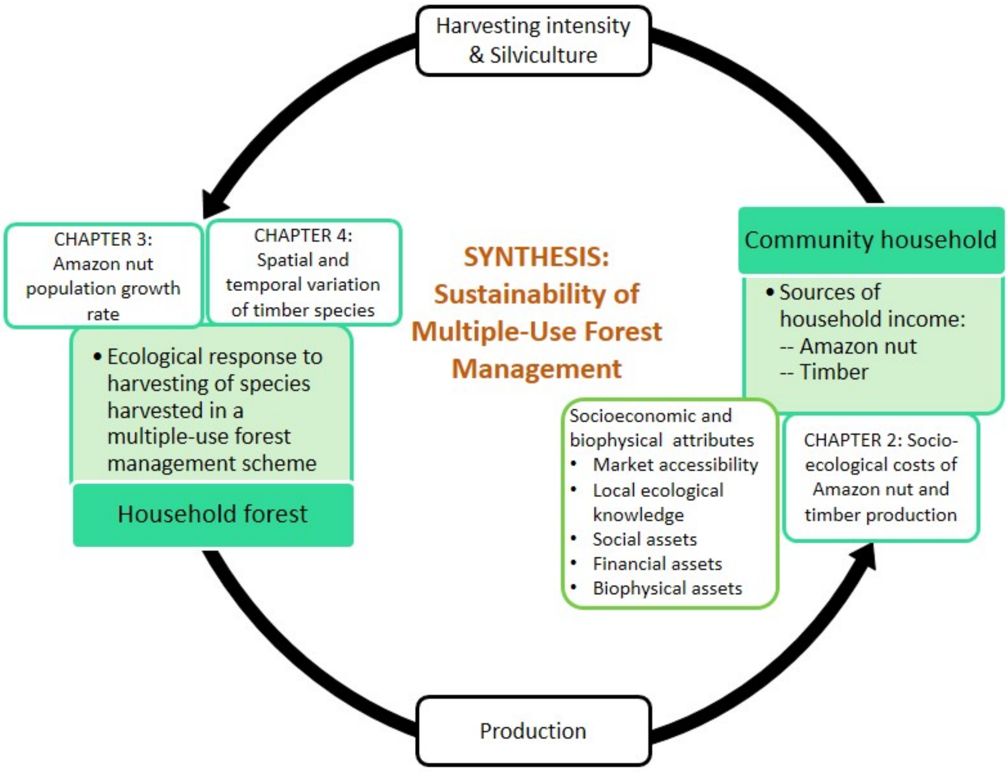

Figure 1.2. Diagram showing the links between the different chapters of this thesis. The different elements in this graph aim to determine the sustainable multiple-use production of Amazon nut and timber at community household forests in the Bolivian Amazon. Community households' socioeconomic and biophysical attributes determine the income these households derive from difference sources, e.g., forest, timber, and Amazon nut (*Bertholletia excelsa*) (chapter 2). The amount of income families can derive is related to the intensity of harvesting and silvicultural intervention they carry, which in turn, determine Amazon nut population growth rate (chapter 3) and the spatial and temporal variation of commercial timber species in relation to logging (chapter 4). The production of forest products, resulting from species population growth rates after intervention will determine the income that community households can derive from these products.

Evolution of community forestry in the Bolivian Amazon

The economic development of the Bolivian Amazon has historically relied on NTFP exploitation such as rubber tapping during the late 1890s to early 1980s, and on Amazon nut gathering since the early 1990s (Bojanic, 2001). Timber production has increasingly contributed to the regional economy since the 1960s (Bojanic, 2001). From the 1970s to the mid-1990s, the rights to log timber were granted through contracts to timber companies over a pre-determined timber volume (Peña-Claros et al., 2011), and after the enactment of the Forestry Law (1997), through the granting of concessions over a determined area. Contracts and concessions often overlapped with forests that were customarily used for NTFP extraction by private owners "*barraqueros*", rural settlements, and indigenous communities (Pacheco, 2006). In the Bolivian Amazon, indigenous communities obtained tenure rights over a vast area of forest preceded by numerous social and political contests. A different way of collective tenureship were obtained by a variety of social actors: already established settlers and communities mixed up with temporary nut gatherers, nut gatherers subjugated to *barracas*, and ex-timber concession workers, who together formed *campesino* communities. *Campesino* communities and many indigenous ones only attained tenure rights in 2008 (Pacheco et al., 2009). Indigenous and *campesino* communities differ on the time of occupation over forested lands, with *campesino* communities having obviously a most recent occupation. A most recent type of settlements are intercultural communities formed by migrants from Bolivia's highlands, a politically driven recent colonization that is planned to continue over the next decade (Urapotina, 2011). As of 2009 the legal tenureship of 5 indigenous territories, 245 *campesino* communities, and about a handful of intercultural communities were reported, which together occupy over 60% of the area in the study region (Pacheco et al., 2009). The adoption of community forest management plans (CFMPs) for timber production in the region and elsewhere in the country was largely supported by local NGOs, projects and governmental institutions (Benneker, 2008; Humphries et al., 2012), and became an effective way to secure collective tenure rights.

While indigenous communities have been able to secure vast tracks of indigenous territories due to their customary occupation, *campesino* communities in the Bolivian Amazon could only access land upon forming a community with at least ten other families. In this way, each community member could gain access to ~500 ha of land (Pacheco et al., 2010). This 500 ha per household criteria was mainly based on the number of *estradas* (paths opened for rubber tapping) that a person is capable of tapping daily (L. Rojas, personal communication, June 6, 2015). We chose to work with *campesino* communities to reduce heterogeneity on the background, livelihood strategy and access to forest resources of community households (Stoian and Henkemans, 2000; Zenteno et al., 2013). Additionally, these communities comprise the majority of the rural population in the region (58%; Pacheco et al., 2009) and have a relatively long tradition of extracting forest products. Community members extract multiple forest products from internally divided household forests or from a collective forest area.

Until recently, the extraction of forest products was not completely regulated within *campesino* communities. Community households can decide to harvest nearly every forest product from their internally assigned individual forest (Cronkleton et al., 2012). The consent of the rest of the community members is only required to harvest timber individually either under the CFMP or under the small-volume logging operation modality (ABT Directive Nº 001/2014). Under the latter one – the most recent logging modality – each community household can harvest about 7 m^3 of timber six times a year, except for timber of species listed in CITES appendices I and II (ABT Administrative Resolution Nº 250/2013, ABT Directive Nº 001/2014). As of 2009, about 80% of approved CFMPs have been elaborated by logging enterprises through contracts (Cronkleton et al., 2012). Various community forest organizations (CFOs), equivalent to the CFEs explained earlier, emerged in the Bolivian Amazon over the last decade. A handful of them supported by environmental NGOs, and about 27 supported by the largest Amazon nut processing industry Tahuamanu (M. A. Albornoz, personal communication, Feb 2, 2017). Currently, the extraction of timber and non-timber forest products is regulated through the technical directive on integral management of forests and lands (ABT Administrative Resolution Nº 250/2013). As of 2015, among the 245 *campesino* communities in the Bolivian Amazon (Pacheco et al., 2009), 77% had a CFMP to extract timber already, and only 8.6% counted with an approved PGIBT (ABT, unpublished data), although CFMP could be adapted to form part of a PGIBT (ABT Administrative Resolution Nº 250/2013).

Selective logging has historically predominated in the region focusing on few species such as mahogany (*Swietenia macrophylla*), South American oak (*Amburana cearensis*) and Spanish cedar (*Cedrela odorata*) (Stoian 2005, Cronkleton et al., 2012). With the enactment of the 1996 Forestry Law, the basket of commercial timber species in the Bolivian Amazon has almost tripled. Selective logging predominates even among *campesino* communities due to difficulties at adopting CFMPs (Villegas, 2012) and lack of access to markets. The number of species harvested at community forests (7 - 10 species; (Soriano et al., 2012) is slightly lower than the number of species harvested at timber concessions (8 - 12 species; Guariguata et al., 2009), Licona Vasquez et al., 2007). Between 2005 and 2009, about 6 - 10 species constituted the majority of timber volume produced within community-owned forests (Cronkleton et al., 2012; Stoian, 2005), which is worrisome for the continued production of highly valuable timber species.

Socioeconomic and biophysical aspects of Amazon nut and timber production in the Bolivian Amazon

Amazon nut

The Amazon nut tree is protected by law and only naturally fallen trees can be logged for their timber (Supreme Decree Nº 27572/2004 (re-stated in the ABT Administrative Resolution Nº 250/2013 on PGIBTs. The legal framework for Amazon nut management requires to leave 10% of the area under management unharvested (ABT Administrative Resolution Nº 174/2008), and prohibits making a re-entrance to harvest the remaining area under management (ABT Administrative Resolution Nº 250/2013). Socioeconomically, the Amazon nut is the most important NTFP species harvested from natural forests in the Bolivian Amazon (Duchelle et al., 2014; Thomas et al., 2014). Region-wide, Amazon nut production has increased by 71% from 1997 to 2009 (Zenteno et al., 2014). Only in 2011, it contributed to 10% and 22% of the gross domestic production (GDP) of Pando and Beni Departments, respectively (INE 2012; in Zenteno, 2013), and employed around 20% of the population in the region (Zenteno, 2013). Amazon nut has also been a source of conflict for communities during and after the forest and land acquisition processes due to an unequal access to reproductive trees by community households (Cronkleton et al., 2012). Households with a longer time of occupation were often entitled to denser Amazon nut stands (Cano et al., 2013). Among community households, the head of the household decides when to collect and which household members can collect Amazon nut from their household forest.

The harvest of Amazon nut implies long walks through paths in the forest that connect producing trees. Often, young producing trees are left behind because their low production does not justify the time spent reaching these trees. Once a producing tree is reached, the collector begins to gather the naturally-fallen woody fruits without venturing to gather its fruits underneath the crown, for a fruit falling on them could be lethal. In this position nut collectors cut the fruits with a machete to obtain the seeds out of the fruits, put them in a bag and repeat this procedure at the nearest producing tree until they reach their *quota* for carrying the nuts to collection points. These points could be at the border of their forest, at their house or at an intermediary's storage room located in the community. In the first two cases, households sell their Amazon nut to either sporadic buyers or directly to a nut processing industry. Amazon nut harvesting is rather labour demanding, i.e., it implies carrying approximately 70 kilos over long distances at once. In such case, older residents often give the responsibility of harvesting the Amazon nut from their forest to their offspring, without necessarily receiving a share from the harvesting. In addition, sons (dependent and independent household members) living in the city usually help their parents with the harvest as the school holiday season coincides with the Amazon nut production season.

Ecology

Amazon nut (*Bertholletia excelsa*) trees are generally found in *terra firme* forests and is widely distributed throughout the Amazon basin and the Guianas (Mori and Prance, 1990; Thomas et al., 2014). Large trees and saplings often present clumped distribution patterns, attributed to human interventions in the past such as enrichment planting and the unintended positive impact of abandoned fallows (Paiva et al., 2011; Shepard Jr and Ramirez, 2011). Under natural conditions, tree size explains a large part of the variation on *Bertholletia* vital rates; larger trees have higher survival and reproduction rates, but a reduced growth rate (Zuidema and Boot, 2002). Human-induced disturbances via their impact on light conditions also affect some of *Bertholletia* vital rates. Higher regeneration density (Cotta et al., 2008), survival and growth (Peña-Claros et al., 2002) was found at abandoned fallows when compared to untouched forests as a result of increased light exposure and dispersers' preference to feed below dead debris (Haugaasen et al., 2012). Natural and logging gaps also favour its regeneration density and growth rate (Moll-Rocek et al., 2014; Myers et al., 2000; Soriano et al., 2012; Zuidema and Boot, 2002) likely due to the same reasons provided for abandoned fallows. Relatively low logging intensities (up to 2 trees removed ha^{-1}) had no impact on the rate of fruit production, but fruit production may decrease at greater logging intensity due to increased damage to the crown of producing trees (Rockwell et al., 2015).

The agouti (*Dasyprocta* spp.) is the main disperser of *Bertholletia* seeds. Agouties are rodents that scatter and bury *Bertholletia* seeds as food reserve (Zuidema and Boot, 2002). Agouties disperse seeds within 15 - 30 m distance from the parent tree, reaching a maximum of 60 m (Haugaasen et al., 2012). Occasionally agouties forget buried seeds, which increases the chances of these seeds to germinate (Haugaasen et al., 2012; Zuidema and Boot, 2002). Thus, hunting activities that accompany the Amazon nut collection and timber logging activities may reduce *Bertholletia* regeneration by reducing agouties´ density.

Commercial timber species

Timber extraction is the second most important source of forest income for communities in the Bolivian Amazon, after the Amazon nut. Before forest rights were given to forest communities, timber companies and independent loggers logged timber in a highly selective manner (Cronkleton et al., 2012). Hence, the majority of forest communities have settled down in previously selectively logged forests (Pacheco et al., 2009) and, in most cases, were left with few trees of harvestable size (Cronkleton et al., 2012). Current forest policies demand CFMPs to comply with forest management rules designed to maximize profits from timber that require high capital investment and managerial and technical skills, which communities lack, limiting the wider implementation of CFMPs among communities (Benneker, 2008; Cronkleton et al., 2012). Under this legal framework, a CFMP is mainly based on the general forest inventory of the entire area under management, based on which the harvest rotation cycle (minimum of 20 years) and designation of protection zones are defined. Annually, communities need to census harvestable trees of commercial timber species, and based on this information develop annual operational plans for the logging compartment to be logged in a specific year (Ministerio de Desarrollo Sostenible y Medio Ambiente, 2000). An annual operational plan involves as well the planning of roads and other logging activities for timber production. A minimum diameter cutting (MDC) was set between 50 - 70 cm diameter at 1.3 m aboveground (DBH) varying by species, which together with the retention of 20% of trees >MDC as seed trees and the application of reduced-impact logging techniques to log trees are the main ecological foundations for the approval of an annual operational plan by the Bolivian Forest and Land Controlling Authority – ABT (Ministerio de Desarrollo Sostenible y Medio Ambiente, 2000).

Logging in 80% of communities with approved CFMP in the Bolivian Amazon are often planned and implemented by timber companies under a contract (Cronkleton et al., 2012) in which the company agrees to pay the community for the timber extracted each year. In the best circumstances, though rare in the region, communities negotiate prices on the basis of timber volume rather than per tree, and demand inclusion of community members in the planning and execution of activities within the CFMP. The area of the annual operational plan is commonly assigned to one or two household forest areas. Benefits obtained from timber are often for the household from whose forest timber was logged (individual). There are also communities that decide to share timber benefits collectively and do it in two ways: equal share of the whole or a proportion of the overall timber benefits. If only a proportion of the benefits are shared, an important share is assigned to the household from whose forest timber was logged in a given year. Some communities with individually assigned timber benefits decide to share timber benefits later on, and vice versa. Only until recently, Bolivia has adapted its legal forestry framework to the skills and needs encountered within communities by allowing community families to commercialize small timber volumes from small-scale timber logging operations (ABT Directive Nº 001/2014).

Misidentification of timber species is a major problem of forest inventories and censuses carried under the CFMPs (Baraloto et al., 2007), and of small-scale logging operations. A major source of misidentification is when two or more species are lumped under the same common and/or genus name (Baraloto et al., 2007; Rockwell et al., 2007a), which could have unfavourable outcomes for the medium to long-term population growth of many timber species.

Ecology

Valuable timber species usually have low population densities ranging from 4 - 40 individuals per hectare in their regeneration stage (individuals ≤10 cm DBH) (Soriano et al., 2012), and 0.5 - 5 individuals per hectare in their juvenile and adult stages (>10 cm DBH) (Licona Vasquez et al., 2007). A study along a wide range of logging intensity in lowland Bolivia found that climate, more than soil and logging disturbance determined tree diversity and growth rates of tree species (Toledo et al., 2011a, 2011b). However, logging intensity and tree damage vary with the level of intervention and harvest method used, which may have implications for the future composition of a forest. Logging disturbance also affects species population size and distribution due to the withdrawal of reproductive trees and by producing changes on the availability of abiotic resources (Toledo et al., 2011a). Logging disturbance in the region can be as low as 5.5% (Guariguata et al., 2009) and as high as 10.6% of disturbed forest area (Soriano et al., 2012). Damage to the remnant vegetation has not been reported for the region, but may approximate to tree damage in transitional Amazonian - Chiquitano forests, which ranges from 5.5% (Shenkin et al., 2015) to 25% of trees >10 cm DBH (Jackson et al., 2002). In addition, selective logging may threaten the long-term persistence of many valuable timber species due to the extraction of only few high-value species (Schulze et al., 2008). Model simulations showed that only 21% of the timber volume removed is recovered after 25 years of the original basket of harvested commercial species at the average logging intensities occurring in the region (Dauber et al., 2005). Yet, the positive impact of logging intensity on the growth of the majority of valuable timber species may have positive implications on the percentage of timber volume recovered during the first cutting cycle. Recovery of timber volume could be optimized with additional silvicultural intervention and by switching the basket of species every other cutting cycle (Dauber et al., 2005; Fredericksen and Putz, 2003). Thus, reduced-impact logging (RIL), silvicultural intervention (Peña-Claros et al., 2008a; Schwartz et al., 2012), or small-scale logging operations on its own (Soriano et al., 2012), may not only reduce forest disturbance and tree damage but could potentially increase recruitment, survival and growth of timber species as well.

Research questions and hypotheses

The main objective of this thesis is to ***increase the understanding of the social, economic, and ecological factors driving the sustainable production of the most important MFM scheme in the Bolivian Amazon, and to determine the contribution of MFM to the well-being of community families and to the sustainable development of community forestry in this region***. To achieve this objective I asked the following research questions organized in three core research chapters as follows:

Chapter 2: In this chapter, we identify the socioeconomic and biophysical factors determining the income that community households in the Bolivian Amazon derive from forests (income from timber, non-timber forest products, and hunting), husbandry (income derived from agriculture, agroforestry and domestic animals), off-farm (income from salary, business and gifts) and from two keystone forest products separately: Amazon nut and timber. To this end, we ask the following questions:

- What is the contribution of forest products to the total income of community households?
- How do socioeconomic and biophysical factors determine forest, husbandry and off-farm income derived by community households?
- How do socioeconomic and biophysical factors determine the income that community households draw from Amazon nut and timber?

For the first question, we expect that the contribution of forest to the total income of community households will be greater than the contribution of other sources of income (i.e., husbandry and off-farm) due to the high economic dependency of community households on Amazon nut in the region (Duchelle et al., 2014; Zenteno et al., 2013). To answer the two last questions, we developed a conceptual framework (Fig. 1.3) built in hierarchical relationships indicating direct and indirect relationships among socioeconomic and biophysical household attributes (capital letters in the boxes of Fig. 1.3) and income sources of community households. For example, we expect that Amazon nut income will increase with residence time (Duchelle et al., 2014; Krishnakumar and Yanagida, 2014; Uma Shaanker et al., 2004), application of a larger number of management practices and proportion of *terra firme* forest (Coomes et al., 2004; Zenteno et al., 2013);

and we expect that it will decrease with distance to the nearest city (market) and off-farm income. The indirect effects of distance to the market and a household´s residence time will further increase Amazon nut income via the increase of the proportion of *terra firme* forest used by a community household (Fig. 1.3).

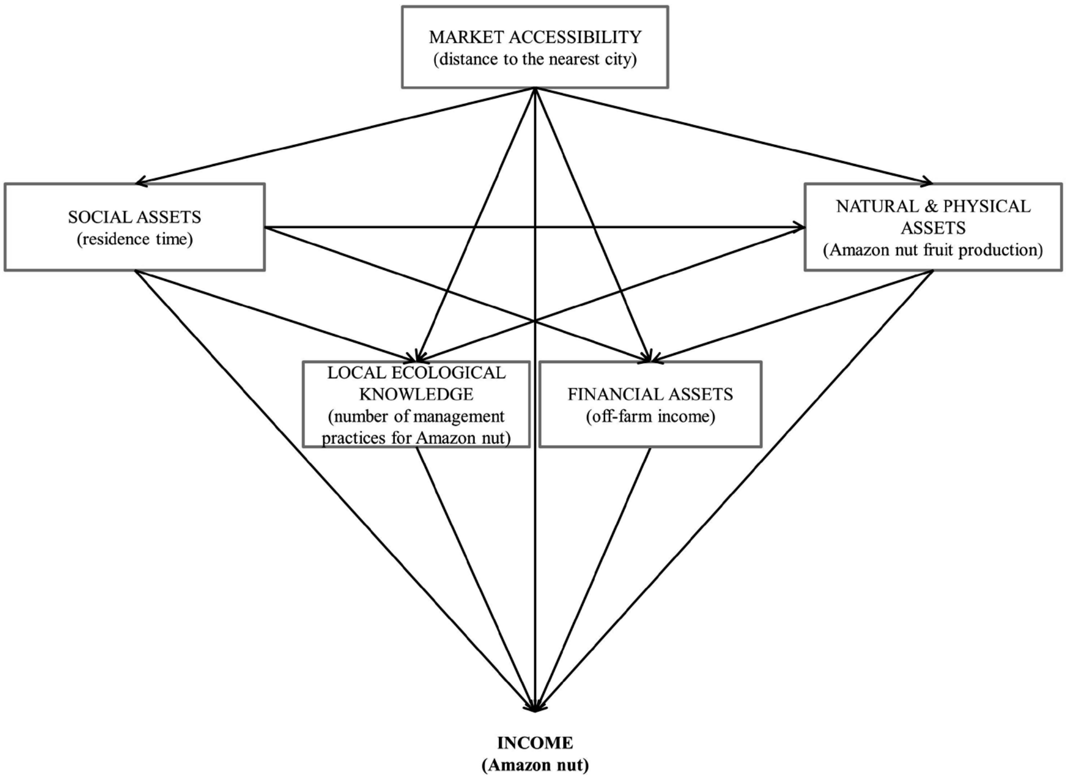

Figure 1.3. Conceptual framework showing the potential relationships of socioeconomic (i.e., social assets, local ecological knowledge, financial assets) and biophysical attributes (i.e., market accessibility, natural and physical assets) in relation to household income. Attributes can have direct (arrows linked directly to the box of income) and indirect (arrows linking socioeconomic and biophysical attributes) effects on the response variable. An example of these relationships is included within parentheses in each attribute box for Amazon nut income. Other variables used to characterize the different attributes are listed in Table 2.2. Selected variables are chosen based on an extensive literature review of the causal relationships between variables of the five household attributes.

Chapter 3: In this chapter we investigate *Bertholletia's* long-term population dynamics along a gradient of Amazon nut harvesting and timber logging intensity in a multiple-use forest management (MFM) scheme. We investigate this by addressing the following questions:

- What are the effects of Amazon nut harvesting, logging, and liana cutting intensities on *Bertholletia* survival, growth and fecundity rates?
- Under what Amazon nut harvesting and logging intensities can *Bertholletia* populations be sustained in the future, and does liana cutting contribute to it?

We expect that logging intensity will increase *Bertholletia* growth and recruitment rates due to increased light availability (Cotta et al., 2008; Soriano et al., 2012; Zuidema and Boot, 2002) created by logging (Soriano et al., 2012) but that it will decrease *Bertholletia* survival probability due to increased agouti predation of 1-year old recruits (D'Oliveira, 2000), and instability of large individuals due to logging of neighbouring timber trees. We do not expect that Amazon nut harvesting intensity will affect these vital rates because the harvest of nuts does not imply as much habitat disturbance as logging. With regards to *Bertholletia* fecundity, the cutting of lianas applied by collectors while they harvest the seeds will increase Amazon nut fruit production (Kainer et al., 2014); whereas, logging intensity will have no effect on *Bertholletia* reproduction rate due to low logging intensity rates inherent of the region (Guariguata et al., 2009; Rockwell et al., 2015). For the second question, we expect that *Bertholletia* populations will thrive when logging intensity is high and Amazon nut harvesting is low due to the positive impact of logging intensity on *Bertholletia* growth rates. Thus, the combined harvesting of these products will contribute more to *Bertholletia* transient population growth rate (λ_{100}; which is the population growth rate for 100 years, once a population has reached a stable size distribution; Caswell, 2001) than when only Amazon nut is harvested.

Chapter 4: Our main objective for this chapter is to compare tree density and timber volume of the eight most important commercial timber species harvested in the Bolivian Amazon among community forests, as well as, to investigate the impact of logging intensity on key ecological characteristics of species of the same genus. To achieve this, we ask the following questions:

- How commercial timber species differ in their density and timber volumes among community-owned forests in relation to logging intensity and time since logging?

- Given that congeneric species are often lumped for logging, we asked to what extent do commercial timber species of the same genus differ in their ecological characteristics and response to logging intensity.

To answer our first question, we hypothesized that density and timber volume will differ among community forests due to the rarity and localized distribution of many tropical tree species (Schulze et al., 2008). Species will also differ in the response of stem density and timber volume to timber logging intensity over time as the population recovers from logging disturbance (Duah-Gyamfi et al., 2014; Grogan et al., 2016). For the second question, we selected the following species: *Cedrela odorata, Cedrela fissilis, Hymenea courbaril* and *Hymenea parvifolia*. Species sharing the same genus are usually commercialized as if they correspond to the same species (namely *Cedrela odorata* or *Hymenaea courbaril*). We hypothesized that species belonging to the same genus will differ in density, timber volume, and growth and survival rates due to species-specific light requirements (Duah-Gyamfi et al., 2014; Grogan et al., 2016), differences in recruitment success (Harms et al., 2000), and on climate and soil requirements for their establishment (Gourlet-Fleury et al., 2011; Toledo et al., 2011b).

Thesis outline

This thesis consists of 5 chapters: a general introduction (this chapter), three research chapters (chapters 2 - 4) and a synthesis (chapter 5). In the first research chapter (chapter 2), we evaluate the socioeconomic and biophysical factors determining community household incomes, focusing on Amazon nut and timber incomes by using multi-model inference and hierarchical modelling techniques such as structural equation models (SEM). In chapter 3, we analyse the demography of Amazon nut under a set of combined Amazon nut harvesting and logging intensities, and at two levels of liana cutting intensities by using size-structured matrix models. In chapter 4, we look at differences in tree density and timber volume between communities for eight commercial timber species, and at the effect of logging intensity on the density, timber volume, and growth and survival rates of closely related species that are commercialized using the same genus name. Finally, in chapter 5, I synthesize the results obtained and analyse the enabling socioeconomic and ecological aspects of multiple-use forest management in the context of community forestry based on the three core research chapters.

Chapter 2

Socio-ecological costs of Amazon nut and timber production at community household forests in the Bolivian Amazon

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Abstract

The Bolivian Amazon holds a complex configuration of people and forested landscapes in which communities hold secure tenure rights over a rich ecosystem offering a range of livelihood income opportunities. A large share of this income is derived from Amazon nut (*Bertholletia excelsa*). Many communities also have long-standing experience with community timber management plans. However, livelihood needs and desires for better living conditions may continue to place these resources under considerable stress as income needs and opportunities intensify and diversify. We aim to identify the socioeconomic and biophysical factors determining the income from forests, husbandry, off-farm and two keystone forest products (i.e., Amazon nut and timber) in the Bolivian Amazon region. We used structural equation modelling tools to account for the complex inter-relationships between socioeconomic and biophysical factors in predicting each source of income. The potential exists to increase incomes from existing livelihood activities in ways that reduce dependency upon forest resources. For example, changes in off-farm income sources can act to increase or decrease forest incomes. Market accessibility, social, financial, and natural and physical assets determined the amount of income community households could derive from Amazon nut and timber. Factors related to community households' local ecological knowledge, such as the number of non-timber forest products harvested and the number of management practices applied to enhance Amazon nut production, defined the amount of income these households could derive from Amazon nut and timber, respectively. The (inter) relationships found among socioeconomic and biophysical factors over income shed light on ways to improve forest-dependent livelihoods in the Bolivian Amazon. We believe that our analysis could be applicable to other contexts throughout the tropics as well.

Keywords: Brazil nut; *Bertholletia excelsa*; structural equation modelling; non-timber forest products; logging intensity; Amazon nut harvesting intensity; community household income.

Introduction

The contribution of forests to rural livelihoods is well-acknowledged throughout the tropics (Belcher, 2005; Duchelle et al., 2014; Schure et al., 2014; Shackleton et al., 2007; Stanley et al., 2012; Zenteno et al., 2013). In particular, the local provision of, and the financial benefits from, timber and non-timber forest products (NTFPs) play an important role in improving rural livelihoods while also preventing forest degradation and deforestation (Porter-Bolland et al., 2012). Yet, high dependency on forest income can potentially 'trap' rural families in cycles of poverty due to low prices caused by insecure forest tenure and poor access to markets (Belcher et al., 2005; Coomes et al., 2004). Under improved socioeconomic and biophysical conditions, however, a greater value can be drawn from forest resources with the potential to increase the income and living conditions of rural families (Shackleton et al., 2007; Stanley et al., 2012). Recent studies show that income from the forest increases when rural families harvest a larger set of forest products (Stanley et al., 2012), and have improved organization (Quaedvlieg et al., 2014) and road infrastructure (Shackleton et al., 2007). The influence of these and other socioeconomic and biophysical factors on rural livelihoods have been examined in the context of changing rural economies. More specifically, we investigated how such factors are shaping the various sources of income derived by community households in the Bolivian Amazon, focusing on two keystone forest products: Amazon nut (a.k.a. Brazil nut, *Bertholletia excelsa*) and timber. We address these questions by combining socioeconomic information of community households and ecological information of household forests.

Changes in the demography of harvested species in response to socioeconomic factors have been examined by combining structured interviews at the household level with biological inventories at the community-level (Table S2.1; see Supporting Information). Uma Shaanker et al. (2004) pioneered this approach by differentiating three main socioeconomic attributes: i) extent of dependence, ii) local ecological knowledge and iii) market organization. Each attribute encompasses several socioeconomic variables for calculating the ecological costs of NTFP use in India. Contemporary researchers such as Brown et al. (2011), Mutenje et al. (2011) and Steele et al. (2014) adopted Uma Shaanker et al.'s approach to look at the ecological costs of firewood use in African countries (Table S2.1).

Their findings offer new insights to the understanding of the patterns of resource use and of changes in the availability of forest resources. In the Neotropics, only Zeidemann et al. (2013) have examined the socioeconomic factors governing Amazon nut harvesting intensity and found that access to the market increased fruit production of individual trees and the income derived from Amazon nut. Up to now, few studies have examined the potential socio-ecological costs of harvesting multiple forest products in relation to their impact on rural livelihoods. Furthermore, none of these studies addressed this topic at the household and household forest levels (Meilby et al., 2014). In the Bolivian Amazon region, we found an area that offers a unique opportunity to fulfil this knowledge gap.

The communities and households in the Bolivian Amazon are becoming more market-oriented due to the increasing accessibility of markets (Perz et al., 2013) and demands from growing human populations in recent years (Zenteno et al., 2014). The rise in market exchange and need for cash in communities themselves may also modify the use of available forest resources. For example, in 2009, these communities sold 71% more Amazon nut than in 1997 (2,821 vs. 4,811 boxes, i.e., a box containing 23 kg of unshelled nuts; Zenteno et al., 2014), an increase that may have been driven by increased international prices (Zenteno et al., 2013) and may have resulted from a higher harvesting intensity. However, concurring with demographic population studies, current harvesting levels of Amazon nut do not represent a threat to the long-term sustainability of this species (Kainer et al., 2014, Zuidema and Boot, 2002; cf. Peres et al., 2003, Scoles and Gribel, 2012). Indeed, human intervention, such as shifting cultivation (Cotta et al., 2008; Paiva et al., 2011), hereafter referred as agriculture, large disturbances created by logging (e.g. logging gaps and log landings; Soriano et al., 2012) and historic cultural practices, e.g. enrichment planting by past human inhabitants (Peres et al., 2003; Shepard Jr and Ramirez, 2011) may have a positive effect on Amazon nut populations due to the high light requirements this species needs for its regeneration (Soriano et al., 2012; Zuidema and Boot, 2002). The Amazon nut tree coexists with a large number of timber species, which has led community households to increasingly draw income from timber as well. A comprehensive study carried out at the national level on the forest response to selective logging projected a reduction of timber production in subsequent cutting cycles (Dauber et al., 2005), implying that current rates of timber harvesting are ecologically and economically unsustainable without the implementation of silviculture. These projections are of great concern, especially in view of the land redistribution process that occurred over the last couple of decades in the region; which have added pressure over these forests.

In this study, we aim to identify the socioeconomic and biophysical factors determining the income from forests (timber, NTFPs and hunting), husbandry (agriculture, agroforestry and livestock (mainly chicken and pigs)), off-farm (business, services and gifts) and two keystone forest products (Amazon nut and timber) derived by community households in the Bolivian Amazon region. To this end, we ask three questions. First, what is the contribution of forest to the total income of community households? We expect that the contribution of forest to the total income of community households will be greater than other sources of income (i.e., husbandry and off-farm) due to their high economic dependency on Amazon nut (Duchelle et al., 2014; Zenteno et al., 2013). Second, we asked, how do socioeconomic and biophysical factors determine forest, husbandry and off-farm incomes derived by community households? We developed a conceptual framework (Fig. 2.1) upon which we hypothesized the following relationships. We expect that mainly asset-based attributes will drive these incomes (Bebbington, 1999); e.g., natural and physical assets, see methods for more details. For example, the proportion of *terra firme* or upland forest – highly correlated with land (Angelsen et al., 2014; Jagger et al., 2014) and agricultural area (Angelsen et al., 2014) – will increase income from forest by comprising more Amazon nut producing trees. Husbandry income on the other hand, will be positively driven by a household's head residence time (Angelsen et al., 2014; Coomes et al., 2004), and negatively driven by the area of *terra firme* forest. Off-farm income will mainly depend on the value of material assets because households in businesses or with a paid job elsewhere will invest in acquiring more assets (Angelsen et al., 2014). Third, we asked more specifically, how do socioeconomic and biophysical factors determine the income that community households draw from Amazon nut and timber? We expect that Amazon nut income will increase with residence time, proportion of working household members (Duchelle et al., 2014; Krishnakumar et al., 2015; Uma Shaanker et al., 2004), application of a larger number of management practices to increase Amazon nut production, the proportion of *terra firme* forest (Coomes et al., 2004; Zenteno et al., 2013) and income from livestock; but will decrease with distance to the nearest city (market) and off-farm income (Fig. S2.1a, see in Supporting Information). Finally, we expect that the income from timber will decrease with distance to the market, and will increase as households carried more specialized tasks within the community timber management plan (CTMP) (Duchelle et al., 2014; Zenteno et al., 2013), comprised a larger proportion of working members, shared more times their timber benefits, and received greater financial support (Fig. S2.1b). Household forests further away from the market will comprise greater standing timber volume (Brown et al., 2011).

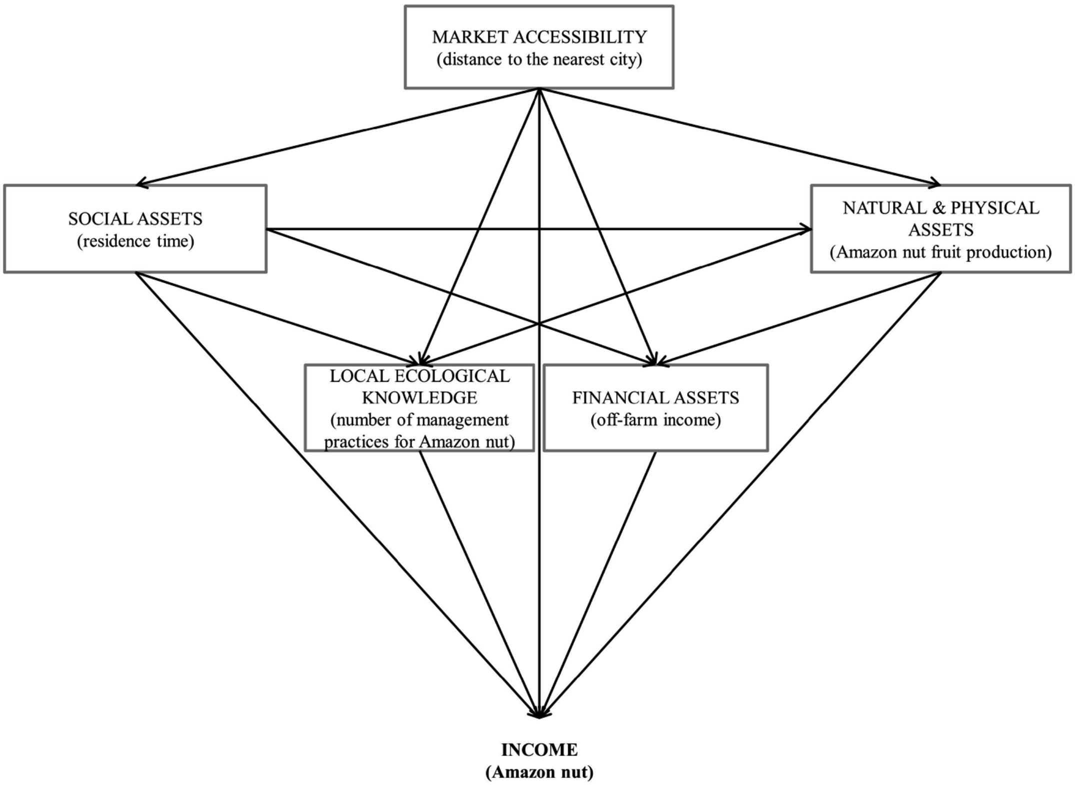

Figure 2.1. Conceptual framework showing the potential relationships of socioeconomic (i.e., social assets, local ecological knowledge, financial assets) and biophysical attributes (i.e., market accessibility, natural and physical assets) in relation to household income. Attributes can have direct and indirect effects on the response variable. An example of these relationships is included within parentheses in each attribute box. This conceptual framework is further developed for timber and Amazon nut income in the Supporting Information. Other variables used to characterize the different attributes are listed in Table 2.2.

Materials and methods

Research site

The Bolivian Amazon region encompasses the entire Department of Pando and the provinces of Vaca Díez of the Beni Department and Iturralde of the La Paz Department. Approximately 95% of the region is covered by forest (Marsik et al., 2011), and comprises 30% of Bolivia's timber production forests (8.8 out of 28.8 mill. ha; Hjortsø et al., 2006). Tree diversity ranges from 52 - 122 species ha^{-1} with a density between 544 - 627 trees ha^{-1} of trees ≥10 cm diameter at 1.3 m aboveground (DBH) (Mostacedo et al., 2006). The annual rainfall varies between 1,774 - 1,934 mm, while the mean annual temperature differs slightly between the two main regional cities: Cobija (25.4°C) and Riberalta (26.2 °C) (Zonisig, 1997). The region presents a relatively dry season from May through September with less than 60 mm of precipitation per month. Its topography varies from *terra firme* forests to seasonally flooded areas. *Terra firme* forests comprise over 50% of a forest area (Mostacedo et al., 2006), and grow on soils with low fertility (i.e., high aluminium toxicity), while seasonally-flooded areas have relatively high nutrient-rich soils due to the sediments carried by rivers originating in the Andes (Zonisig, 1997).

Historically, the economic development of the Bolivian Amazon has depended on NTFP exploitation such as rubber tapping during the late 1890s to early 1980s, and on Amazon nut gathering since the early 1990s (Bojanic, 2001). Timber harvesting has increasingly contributed to the regional economy since the 1960s (Bojanic, 2001). From around the 1970s, rights to log timber were granted through contracts to timber companies over a pre-determined timber volume (Peña-Claros et al., 2011), and after the enactment of the 1996 Forestry Law, through the granting or concession of a determined area. Contracts and concessions often overlapped with forests that were customarily used for NTFP extraction by rural settlements and indigenous communities (Pacheco, 2006) who only attained tenure rights in 2008 (Pacheco et al., 2009).

The adoption of community timber management plans for timber production (i.e., largely supported by local NGOs and governmental institutions) became an effective way to secure collective tenure rights by already established settlers and temporary Amazon nut gatherers. Despite secure tenure rights, most communities have not fully embraced the legal forestry framework for logging their timber through timber management plans. The implementation of these management plans challenged the capabilities of the newly formed communities in many ways (Benneker, 2005), ranging from lack of managerial skills to investments needed for defining the required management (Martinez Montaño, 2008). Furthermore, the lack of organizational and negotiation skills have constrained communities from maximizing their benefits from timber and NTFPs (Benneker, 2010; Quaedvlieg et al., 2014). Numerous subsequent amendments have been made to the forest management regulations in order to reduce communities' dependence on external agents and enhance the profits derived from the forest (Pacheco et al., 2010). These modifications created numerous pathways for small-scale timber operations to take place, the most dominant being logging for own use (1996 onwards) and logging of small volumes (2012 onwards). Amendments were also made for NTFPs management, including Amazon nut. As a consequence of these regional dynamics, national policies are currently directed towards integrated land and forest management, which urges forest owners to diversify their forest production to reduce pressure over forest products, but mainly over timber. The context of these management institutions potentially influences harvester decision-making and livelihood outcomes at the household level.

Bolivia's Amazonian forests have faced dramatic changes since the late 1990s after the implementation of the Forestry Law 1700 and the Agrarian Reform Law 3545 (Proyecto de Manejo Forestal Sostenible, 1997) as part of the land redistribution process. Timber concessions predominated throughout the Bolivian Amazon region after the enactment of these laws (Killeen et al., 2008), but shifted to a predominantly collective tenure system towards the end of the 2000s (Pacheco et al., 2009). Approximately 50% of the Bolivian Amazon is now under community ownership by indigenous and *campesino* communities (Pacheco et al., 2009). Indigenous communities have been able to secure vast tracks of indigenous territories; whereas, *campesino* communities could access land by forming a community with at least ten other families. In this way, each community member could gain access to ~500 ha of land (Proyecto de Manejo Forestal Sostenible, 1997). This 500 ha per household criteria was mainly based on the number of *estradas* (paths opened for rubber tapping) that a household is capable of tapping daily (L. Rojas, personal communication, June 6, 2015). We chose to work with *campesino* communities to reduce heterogeneity on the background, livelihood strategy and access to forest resources of community households (Stoian and Henkemans, 2000; Zenteno et al., 2013); and because these communities comprise the majority of the rural population in the region (58%; Pacheco et al., 2009) and have a relatively long tradition on using forest products.

Six *campesino* communities were selected for this study (Table 2.1). Studied communities were selected based on their long-standing engagement in formal timber management. These six communities represent 2.5 % of *campesino* communities of the Bolivian Amazon (out of 245; Pacheco et al., 2009), are 30 - 130 km distant from one of the two main regional cities, and together comprise an area of 80,711 hectares (Table 2.1). As in the majority of the *Campesino* communities, the forest is internally delimited by community households to enable household-level decision-making to harvest forest resources (Urapotina, 2011). However, collective decision-making is needed for logging timber; even in cases in which logging occurs at the household forest-level. The harvest of forest products at the household forest-level allowed us to account for households and their forest as our main sampling unit. We selected 24 households and their forests (2 - 5 households per community) representing a wide range of Amazon nut harvesting and logging intensities, equivalent to 3.7 - 36.4% of the household members forming these communities (Table 2.1). The large variation in the percentage of participating households is largely due to differences on the number of community households among studied communities (11 - 135; Table 2.1). Women as household heads represented 20.8% of the participating households. Selected households lived between 50 m and 20 km away from the forest from where they collect Amazon nut, timber and other NTFPs.

Data collection

To answer our research questions, we carried out socioeconomic assessments of selected households and biological assessments of the forest to which these households had *de facto* access. Both assessments took place during the first parts of 2014 and 2015. Out of the 24 selected household forests, only three were solely harvested for Amazon nut in a yearly basis, while 18 were logged once under the legal framework of the 1996 Forestry

Law over the last 10 years prior to data collection. In order to log timber under a CTMP, the legal framework requires forest users to carry a tree census of the area to be harvested, to plan a road infrastructure to extract trees, and to leave 20% of harvestable trees (i.e., trees > minimum diameter cutting (MDC) in the logging compartment as seed trees – MDC is ≥50 cm DBH for timber species of the Bolivian Amazonian forest (Ministerio de Desarrollo Sostenible y Medio Ambiente, 2000). During the two years of data collection, twelve household forests underwent some sort of small-scale logging operation, and some abandoned timber from a previous CTMP was extracted from only one household forest. We refer to these two sources of timber income as 'timber extra CTMP' in the rest of the manuscript. At the end of this section we describe how we organized the data to answer each one of our research questions, but before this, we describe how we obtained the socioeconomic and biophysical data separately.

Socioeconomic assessment

Survey questionnaires from the Poverty and Environment Network (PEN) were adapted into one comprehensive household-level questionnaire for the purpose of this research (Appendix S2.1, See Supporting Information). We collected socioeconomic information from 24 households (Tables 2.1 and 2.2). This research did not require approval from the Social Sciences Ethics Committee (SEC) at Wageningen UR because the survey questionnaire did not involve any political, medical or conflict sensitive issues; neither tried to obtain access to traditional knowledge or to other types of knowledge protected by international and national legislations. However, we accounted with the endorsement of the communities' associations at the regional level (*Federación Sindical Única de Trabajadores Campesinos de Pando* (FSTUCP) in Pando and *Federación Sindical Única de Trabajadores Campesinos Regional Vaca Diez* (FSUTCRVD) in the Vaca Díez province in Beni) and with a research collaboration agreement with each community (Appendix S2.2). Such agreement – signed by each community leader – enabled us to carry interviews to voluntary participants. An oral consent of the participating household heads in the survey questionnaires were also requested upon making the voluntary purpose of the survey clear. The questionnaires contained questions that recalled information of the last year (periods: 2013 - 2014 and 2014 - 2015), but also held questions that recalled information of the last 5 years (i.e., period 2009 - 2014). We assumed one-year recalling data

Table 2.1. Social and biophysical characteristics of selected *campesino* communities undertaking community timber management plans (CTMPs) in the Bolivian Amazon. FUG = forest user group.

Level	Social and biophysical characteristics	Community name					
		Primero de Mayo	**12 de Octubre**	**Limón**	**Loma Alta**	**Puerto Oro**	**San Antonio**
Community	Households (#)	19	79	20	135	18	11
	Sampled households	2	4	5	5	4	4
	Timber benefit sharing type*	Individual	Collective	Mostly Collective	Collective	Mostly Individual	Individual
	FUG members	10	29	17	84	17	0
	Nearest city (km)	110	42	122	29.5	72.9	73.6
	Community area (ha)	4,943	16,378	16,137	24,604	12,583	6,067
	Managed forest (ha)	4,942.8	2,281	1,6136.7	16,300	12,582.9	2,839.2
	Logging compartment (ha yr^{-1})	204	180 - 198	435 - 660	844 - 907	497 - 531	182 - 204
	Cutting Cycle (yrs.)	20	20	20	20	20	20
	First logging (yrs.)	2007	2000	2004	2006	2007	2004
	Logging events up to 2014 (#)	1	6	7	8	6	5
Household	*Terra firme* forest (ha)	385.0 ± 63.6	62.3 ± 26.0	394.9 ± 149.4	214.2 ± 150.6	498.8 ± 204.5	265.8 ± 205.9
	Proportion of *terra firme* forest (%)	78.2 ± 13.1	73.2 ± 29.3	87.5 ± 10.5	65.2 ± 31.8	83.1 ± 11.0	82.9 ± 12.5
	Reproductive Amazon nut trees (# ha^{-1})	1.3 ± 0.7	1.2 ± 0.5	0.9 ± 0.3	1.6 ± 0.7	1.4 ± 0.5	1.1 ± 0.6
	Amazon nut availability (Fruits ha^{-1})	160.3 ± 44.5	154.0 ± 91.9	233.3 ± 138.4	140.8 ± 92.5	146.4 ± 108.1	349.3 ± 221.3

* 'Timber benefit sharing type' indicate that timber benefits obtained from a household forest were: never shared with other community households (individual); once collectively shared, but not shared with other community households in most recent years (mostly individual); once individual, but collectively shared with other community households in most recent years (mostly collective); and always shared collectively with other community households (collective).

** A *barrica* is the common measurement unit for selling Amazon nut in the Bolivian Amazon. 1 barrica = 69 Kg. (3boxes).

Table 2.1. Continued.

Level	Social and biophysical characteristics	Community name					
		Primero de Mayo	**12 de Octubre**	**Limón**	**Loma Alta**	**Puerto Oro**	**San Antonio**
Household	Timber volume available (m^3 ha^{-1})	13.2 ± 5.4	8.2 ± 3.0	7.0 ± 5.0	6.7 ± 7.8	5.0 ± 3.3	5.4 ± 3.0
	Amazon nut harvesting intensity (% harvested fruits)	51.3 ± 0.4	64.2 ± 3.2	52.0 ± 30.1	43.7 ± 28.9	38.8 ± 22.0	64.5 ± 23.7
	Logged trees (# ha^{-1})	0.4 ± 0.6	2.7 ± 0.9	1.6 ± 0.6	1.7 ± 1.1	1.9 ± 1.8	1.2 ± 0.4
	Logged volume (m^3 ha^{-1})	0.7 ± 0.9	9.4 ± 1.8	4.4 ± 2.5	9.9 ± 8.3	4.3 ± 5.2	4.1 ± 2.7
	Amazon nut price in 2014 (USD *Barrica*$^{-1}$**)	60.7 ± 2.1	69.5 ± 2.8	59.9 ± 1.7	64.8 ± 9.7	63.9 ± 1.9	57.7 ± 1.7
	Agricultural area opened between 2010 - 2014 (ha)	2.0 ± 2.8	4.5 ± 1.3	2.6 ± 0.8	3.4 ± 2.1	4.8 ± 0.5	2.6 ± 1.8

as highly accurate given the seasonal allocation of the main production activities spanning a typical production calendar. The survey was conducted amongst the household heads, but often their wives/husbands were also actively involved. Survey questionnaires were carried out after the two weeks in which the vegetation sampling at each community was done. Survey questions were focused on obtaining information of household attributes: social assets, local ecological knowledge, market accessibility, financial assets, and natural and physical assets (Table 2.2). Variables related to market accessibility were calculated based on coordinates taken within the communities, and the house of the participating household member if outside of the community. Questions also gathered information on the income obtained from timber from the CTMP and from extra CTMP, Amazon nut, other NTFPs, hunting, fishing, agriculture, livestock, salary, business, and gifts. The price at which each household sold a *barrica* of Amazon nut was also recorded. To calculate the yearly timber income that a household obtained from the CTMP, we accounted for the times timber benefits were shared or were individually obtained. Yearly timber income was then deducted from projecting the income obtained so far by a household to the usual 20 years of the timber cutting cycle. For example: in a shared (collective) timber-benefit scenario, a household received three times USD 400 over a 5-year period since the start of the CTMP, thus its yearly timber income was USD 240 ((400 x 3)/5); whereas, in an individually shared timber-benefit scenario, in which a household derived income from timber once every 20 years (cutting cycle), we divided the amount received from timber over 20. We then separated incomes in three large groups: forest (timber, Amazon nut, other NTFPs and hunting), husbandry (agriculture, agroforestry and livestock) and off-farm income (salary, business and gifts). For all incomes, we calculated the net income as the gross income minus the production costs. Production costs included all monetary costs a household incurred during the production and/or harvest of a specific product (i.e., transport, extra labour, materials and food expenses). Our calculation of production costs does not account for the labour cost of family members. We discriminated subsistence from cash net income and values were converted to US Dollars at the exchange rate of Bs 1 = USD 0.148.

Table 2.2. Socioeconomic and biophysical variables potentially determining income from forests, husbandry, off-farm, Amazon nut and timber at community household forests that were collected in this study. Based on Uma Shaanker et al. (2004) and Duchelle et al. (2014). All variables are measured in a yearly basis, unless specified otherwise.

Attributes	Attribute indicators	Unit of measurement	Explanation
Social assets	Household head's education	Years	Years of formal education
	Residence time	Years	Number of years since a household is using the sampled area of forest
	# of working adults	Number of working adults	Proportion of economically active (working) members in a household
	Position in the community		Position or role occupied by a household head: 0. No role, 1. Secondary role in the community (including community founders), 2. Secondary role in a committee or organization, 3. Leading role (community or regional)
	Times timber benefits were shared	Proportion	Number of years timber benefits were shared collectively over the number of years that timber was logged under the community timber management plan (CTMP)
Local ecological knowledge	# of other NTFPs harvested	Number	Number of forest products harvested apart from Amazon nut and timber
	# of management practices for Amazon nut	number of management practices per year	Number of management practices carried to enhance Amazon nut production at the sampled forest (max. number of practices is 7): re-opening of nut collection paths, liana cutting, liberation of regeneration, burning of the understory around the tree to facilitate nut collection, wounding of the tree bark, on-purpose protection of regeneration and washing of nuts after harvest
	Degree of involvement in the CTMP		A household's degree of involvement in the community timber management plan (CTMP): 0. No member of the forest user group (FUG) – no involvement in the CTMP, 1. FUG member – involvement in a non-specialized task in the CTMP (e.g., opening of paths for tree inventory), 2. FUG member – involvement in a specialized task in the CTMP (e.g., sawyer)

Table 2.2. continued.

Market accessibility	Distance to the nearest city	Km	Distance from the household house at the community to the nearest market or city
	Travel frequency to the nearest city	Number of times month-1	Number of times a household head travels to the nearest city per month
	Bargaining power to sell Amazon nut		Based on the possibility of (a) buyer (s) to offer a better price for Amazon nut (1 = lowest price, 3 = highest price): 1. Unknown; 2. Known dealer; 3. Direct processor
Natural and physical assets	Amazon nut fruit production	Fruits ha^{-1}	The number of fruits produced per hectare of a household forest
	Timber volume as of 2015	m^3 ha^{-1}	The volume of timber of standing trees > minimum diameter cutting (MDC) as of 2015 in a household forest
	Amazon nut harvesting intensity	Percentage	The average percentage of Amazon nut harvested from a household forest over the harvest seasons: 2013 - 2014 and 2014 - 2015
	Timber harvesting intensity	m^3 ha^{-1}	The amount of timber harvested from a household forest under the CTMP
	Proportion of terra firme forest	Proportional	Proportion of the area of terra firme (upland) forest in relation to the land area under household use
	Agricultural area	Hectare	Total area used for shifting cultivation over the last five years
	Value of material assets	USD	Value of all materials and equipment owned by a household
Financial assets	Financial support	USD	A household's total debt to formal institutions, as well as, to informal lenders
	Times external support was received	Number of times in the last 5 years	Number of times a household received support (either technical, in-cash, materials) from external sources over the period of 2009 – 2014
	Forest income	USD	Total income from forest (subsistence and cash): timber (CTMP and extra CTMP), Amazon nut, other NTFPs and hunting
	Husbandry income	USD	The sum of the net income (cash and subsistence) obtained from slash and burn agriculture, from agroforestry, and from raising domesticated animals (e.g., chicken, pigs, cows)
	Off-farm income	USD	Total income from salary and business earned by a household, in addition to the income from gifts or donations

Ecological assessment

We established three 40 m x 500 m (2 ha) transects within each household's *terra firme* forest to assess the density of Amazon nut trees and of the 17 most commonly harvested timber species (Table S2.2). Transects were placed at random distances from each other (varying between 500 - 1000 m) to comply with sampling independence, and at a random direction to account for the variability on species' population distribution (Fig. 2.2). All trees ≥10 cm DBH of studied species were inventoried, mapped and tagged in 2014, and re-measured in 2015.

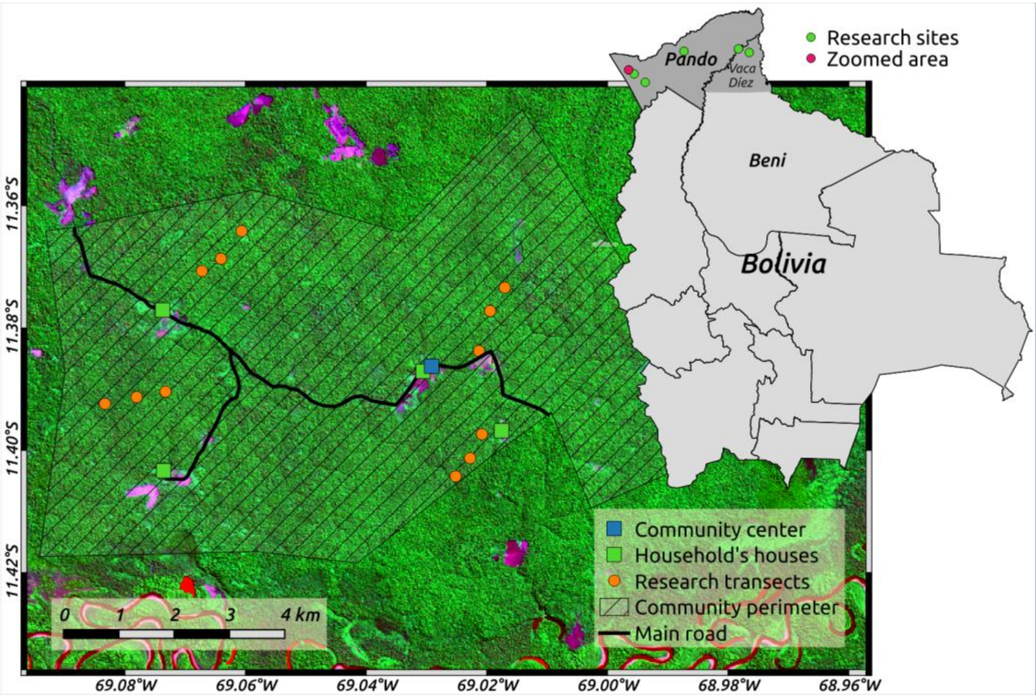

Figure 2.2. Study site and location of research transects within a community household in the Bolivian Amazon. Image from sentinel 2 satellite (band combination 11/8/2) acquired on August 25, 2016. Credit: Loïc Dutrieux.

With this information, we calculated timber availability as the volume of standing trees with a diameter >MDC per hectare accounting for species' differentiated MDC as specified in Bolivia's forestry rules (Ministerial Resolution 248/1998). We used an equation developed by Metcalf et al. (2009): Equation 1, to estimate the DBH of buttressed trees and of trees measured at a different measurement height than the standard 1.3 m DBH measurement height. This equation is the most reliable tapering approximation for tropical trees (Cushman et al., 2014).

$$D = \frac{d_h}{e^{b_i(h-1.3)}} \qquad \text{Eq. (2.1)}$$

Where, D is the diameter at 1.3 m height (cm), d is the diameter at height h (cm), h is the height of diameter measurement (m), and b_i is the taper parameter (average value of the posterior means calculated for 5 species = -0.04; Metcalf et al., 2009). Based on this equation, and for consistency in the formula used for calculating timber volume (i.e., Smalian's formula) of standing trees and logged trees, we calculated the stump diameter at 0.8 m aboveground (own estimation of stump height), and the crown base diameter of standing trees ≥MDC of the 17 study timber species. We discounted the stump height of the estimated commercial height of standing trees to estimate the trunk length necessary for calculating timber volume. We measured stump and crown base diameters, and trunk length (i.e., distance from the stump to the crown base) of logged trees found within the research transects to calculate timber volume of logged trees. We failed to account for the impact of small-scale logging operations because their incidence within the research transects were minimal; they occurred within few transects of three sampled household forests (12.5%), and disturbed only 0.06% of the total sampled area (144 ha).

At the end of two harvest seasons: 2013 - 2014 and 2014 - 2015, we counted all fallen Amazon nut fruits within the 30 m radius from the trunk of each producing tree (trees ≥40 cm DBH) found within the transects. Fallen fruits were classified in one of three categories: harvested by people (i.e., machete-opened fruits commonly found gathered near each tree), opened by agouties (*Dasyprocta* spp.) (i.e., the main seed disperser of *Bertholletia*), or unharvested/unopened (i.e., fruits not found by the collectors or the seed disperser). From Haugaasen et al. (2012) we calculated that 6.3% of fruits were removed by agouties beyond the 30 m from where fruits originally fell below a tree crown. This percentage was not considered in our calculations of fruits count because we assumed similar fruit removal rate in all sampled fruit producing trees and household forests. As the counting was done at the end of the harvest season, we believed that the percentage of non-counted fruits, i.e., apart from the 6.3% removed by agouties, was very small. The total number of fruits found within the three transects established at each household forest was averaged and divided by two to obtain the number of fruits produced ha^{-1} $year^{-1}$ at each household. Thus, the average number of fruits produced ha^{-1} from the two harvest seasons was used as a proxy for Amazon nut availability. We calculated the percentage of harvested fruits by people out of the total number of fruits produced per reproductive tree and used the average percentage of harvested fruits over the two years of this study as a proxy for Amazon nut harvesting intensity. We also calculated the density of reproductive (trees >40 cm DBH) Amazon nut trees per hectare using the data from the transects.

Data Analysis

We first ran a correlation analysis amongst the 26 predictor variables measured. Pairs of variables with a correlation coefficient greater than 0.68 were considered as covariates (Dormann et al., 2013), in which case only one variable was selected to avoid collinearity in subsequent analyses. In this way, we reduced our number of predictor variables to 23, 3 - 7 per socioeconomic and biophysical attribute associated to household forests (Table 2.2).

We built generalized linear models (GLMs) to derive the significant ($p < 0.1$), and otherwise, most important predictors from each of the five socioeconomic and biophysical attributes associated to income from forest, husbandry, off-farm, Amazon nut and timber (Table 2.3). We ran these analyses using the MuMIn package in R (R Development Core Team, 2015). By using the function “dredge” in the model statement, we could simultaneously deal with categorical and continuous predictors (explanatory variables). We also tested the influence of reproductive Amazon nut tree density on each source of income being tested, but this variable was not a significant predictor of any of the sources of income being tested, hence, it was removed from the models. Similarly, we incorporated Amazon nut price amongst the market accessibility attribute variables, but this variable did not have an effect on any of the sources of income being tested, and was also removed from the models. A total of nine structural equation (SEM) models resulted from interspersing the selected factors from the five attributes: one model for forest, three for husbandry, two for off-farm, two for Amazon nut, and one for timber income (Table 2.3). The number of models per response variable was determined by the number of significant variables in each attribute associated to the response

Table 2.3. Best predictors of income derived from forest, husbandry, off-farm, Amazon nut and timber. Values correspond to the weights of the Akaike Information Criteria (AIC) of all possible models in which each variable appears. Significance levels: ***p <0.01, **p <0.05, *p <0.1, ^p >0.1 (most important variable in the absence of a significant predictor per attribute). At least one variable was selected per attribute for each income source.

Attribute	Explanatory variable	Source of income				
		Forest	Husban-dry	Off-farm	Amazon nut	Timber
Social assets	Household head's education	0.15	0.15	0.2	0.34	0.16
	Residence time	0.28	0.28	0.22	0.75**	0.29^
	# of working adults	0.21	0.21	0.18	0.21	0.28
	Position in the community	0.17	0.17	0.75**	0.5	0.21
	Times timber benefits were shared	0.55^	0.55^	0.47	0.83**	0.25
Local ecological knowledge	# of other NTFPs harvested	0.1	0.91**	0.48	0.29^	0.18
	# of management practices for Amazon nut production	0.65*	0.33	0.65*	0.22	0.58^
	Degree of participation in the community timber management plan (CTMP)	0.2	0.18	0.18	0.2	0.09
Market accessibility	Distance to the nearest city	0.35	0.12	0.25^	0.92***	0.22
	Bargaining power to sell Amazon nut	0.62*	0.24	0.13	0.14	0.56^
	Travel frequency to the nearest city	0.14	0.26^	0.18	0.21	0.09
Natural and physical assets	Amazon nut availability	0.16	0.58***	0.18	0.58^	0.16
	Timber volume in 2015	0.69*	0.18	0.23	0.32	0.36^
	Amazon nut harvest intensity	0.17	1.00*	0.3	0.34	0.19
	Timber harvesting intensity	0.2	0.12	0.29	0.25	0.17
	Value of material assets	0.16	1.00***	0.64*	0.28	0.19
	Proportion of *terra firme* forest	0.27	0.17	0.15	0.3	0.28
	Agricultural area	0.16	0.25	0.64*	0.22	0.17
Financial assets	Financial support	0.22	0.23	0.16	0.21	0.16
	Times external support was received	0.17	0.28^	0.24^	0.36	0.17
	Forest income	n.a.	0.16	0.23	n.a.	n.a.
	Husbandry income	0.16	n.a.	0.19	0.13	0.22
	Off-farm income	0.23^	0.19	n.a.	0.42^	0.24^

variable because all possible combinations of variables needed to be tested in order to select the best model (Table 2.3). We used the lavaan and lavaan.survey packages in R (Rosseel, 2012) to run the SEM models.

SEM model construction

We limited the number of predictors in each model to five by selecting the significant or most important variables per attribute and type of income (Table 2.3) as this was required given our sample size of 24 households (Eisenhauer et al., 2015). From the models built per response variable, a single best model was selected under the following criteria. First, the model's p-value (Chi-square) must be greater than 0.05, which is an indicative of goodness of model fit (Bollen et al., 2014; Grace et al., 2010). Second, the best model was selected based on the highest Chi-square estimate of the main response variable involved in the model structure because the majority of the models presented a p-value (Chi-square) >0.05. Since our complete "hypothesized" model structure (Fig. 2.1) tested for the five income sources failed to meet the criteria of model fit under the Monte Carlo simulation probability (MCX2), i.e. needed because of our small sampling size (Grace et al., 2012), we decided to modify the hypothesized model structure 1) by removing three fixed pathways that were not significant in all models tested so far, and 2) by removing the three pathways with the lowest standardized coefficient. We opted for option 1 because the difference between both models was minimal in all cases (Table S2.3), and in order to balance the contribution of each attribute into the model.

Results

The contribution of forest to household net income

A community household in the Bolivian Amazon generates a yearly median net income of USD 9,388.51, equivalent to a daily median net income of USD 25.71. Amazon nut alone contributed 44% to a household's median net income (USD 2,811.26), while salary contributed 19% (USD 1,191.40), agriculture, 17% (USD 1,070.59), timber from the CTMP, 7% (USD 463.15), and timber extra CTMP, 2% (USD 125.80) (Fig. S2.2). The major contributors to a household's median cash net income were Amazon nut and salary (86.7% of total cash income); whereas, the majority of a household's median subsistence net income was derived from agriculture and livestock production (80.2% of total subsistence income; Fig. 2.3).

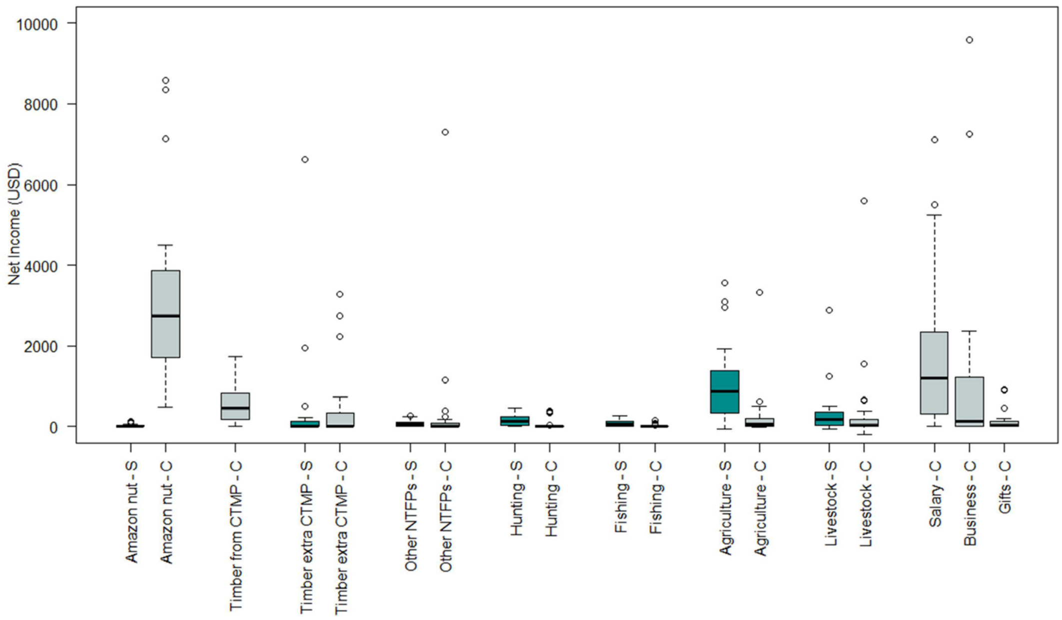

Figure 2.3. Income of community-based households from different sources by type of income (S) subsistence and (C) cash in the Bolivian Amazon. The upper and lower quartiles in the boxplots explain 25% of the variation in the median net income derived by participating households. Empty circles are the outliers. CTMP = Community timber management plan, NTFPs = Non-timber forest products.

Household heads who logged timber under the CTMP received twice as much timber income than households who did not log timber from their forest and who only benefited from the income shared from the CTMP. Half of the sampled households (n = 12) derived income from timber extra CTMP during the two years of our study, but its relative contribution to the total household income was small (on median 2%). Upon classifying the different sources of household income in three groups (forest, husbandry and off-farm), we found that the overall median contribution of forest reached 59% of a household's median net income (median = USD 4,034.00) (Fig. S2.3). Nevertheless, community households heavily relied on husbandry income for their subsistence (76%, median = USD 1,170.34) (Fig. 2.4).

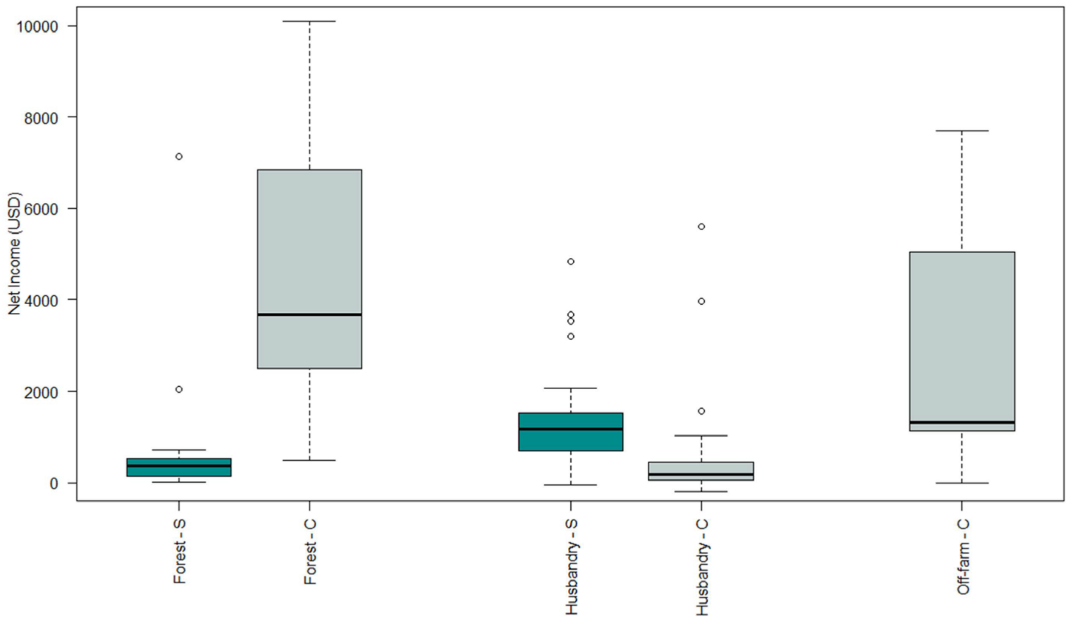

Figure 2.4. Contribution from forest (timber, Amazon nut, other NTFPs and hunting), husbandry (agriculture, agroforestry and livestock) and off-farm income (salary, business and gifts) incomes to the total net income of community households in the Bolivian Amazon by type of income: (S) subsistence and (C) cash. The upper and lower quartiles in the boxplots explain 25% of the variation in the median net income derived by participating households. Empty circles are the outliers.

Socioeconomic and biophysical factors driving incomes derived from forest, husbandry and off-farm by community households

Results of the SEM analysis indicate that the income that households obtained from the forest decreased as off-farm income (Std coefficient = -0.36) and the number of management practices applied to enhance Amazon nut production (Std coefficient = -0.36) increased (Fig. 2.5). The income derived from husbandry (i.e., agriculture, agroforestry and livestock production) increased with the number of NTFPs being harvested and the external support received by the household (Std coefficient = 0.35 and 0.35, respectively), but, it decreased with the intensity of Amazon nut harvesting and travel frequency of the household head to the nearest market (Std coefficient = -0.58 and -0.50, respectively) (Fig. 2.6). Household heads who travelled more often to the market also received greater external support (Std coefficient = 0.49), increasing further their income from husbandry. Off-farm income only increased as households capitalized on their material

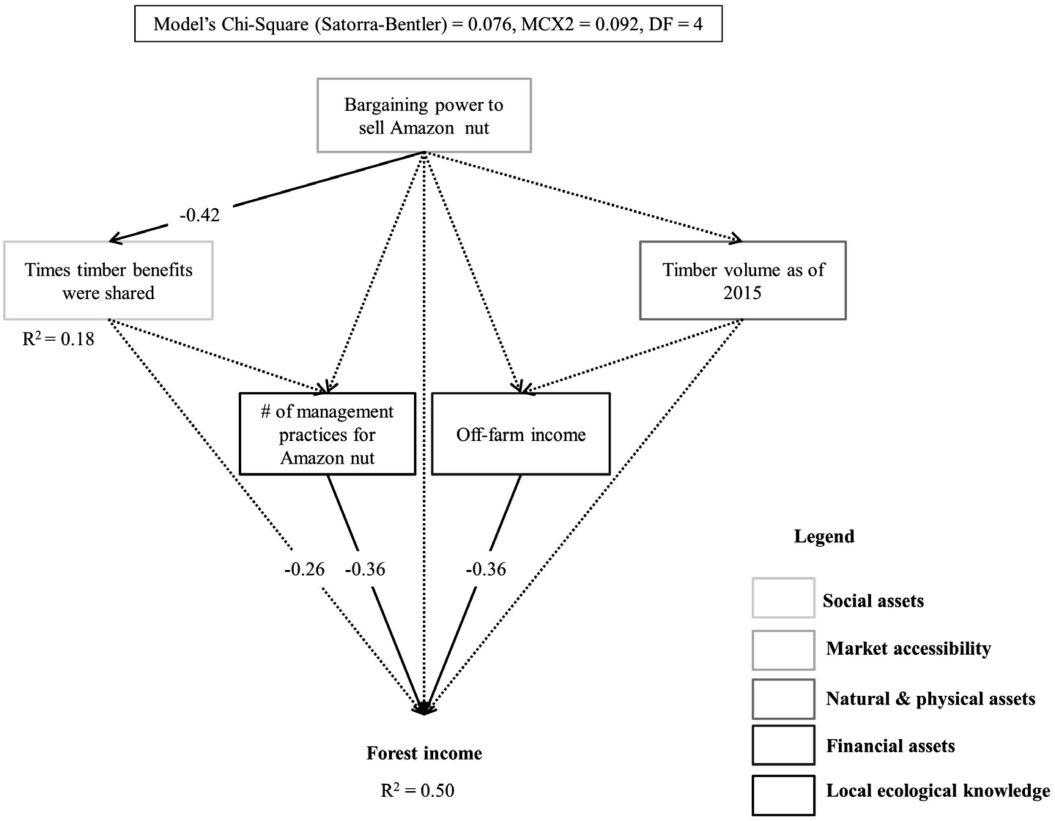

Figure 2.5. Socioeconomic and biophysical factors determining forest (timber, Amazon nut, other NTFPs and hunting) income of community households in the Bolivian Amazon. Solid arrows indicate significant effects of a variable on another, whereas, dotted arrows indicate non-significant effects. Standardized coefficient values are at the intersection of the arrows indicating the direction of the relationships. Values are only provided for significant relationships that resulted from the structural equation (SEM) models.

assets (Std coefficient = 0.40, Fig. 2.7). No other variable had a significant direct or indirect effect on off-farm income.

Socioeconomic and biophysical factors driving the income derived from Amazon nut and timber

The SEM analysis approach also allowed us to find the main socioeconomic determinants of Amazon nut and timber income. Only some of the socioeconomic and biophysical variables that we predicted to determine Amazon nut and timber income had indeed a significant effect on income derived from these forest products. Households further away from the market and with larger Amazon nut availability in their forests derived larger income from Amazon nut (Std coefficient = 0.47 and 0.25, respectively), while households residing for a shorter period of time in the community and relying less on off-farm income also derived a larger income from Amazon nut (Std coefficient = -0.36 and -0.42, respectively) (Fig. 2.8a). Households with a better bargaining power to sell their Amazon nut, those who relied more on off-farm income and applied more management practices to enhance Amazon nut production derived less income from timber (Std coefficient = -0.33, -0.41 and -0.32, respectively) (Fig. 2.8b). Households who resided longer in a community also applied more management practices to enhance Amazon nut production (Std coefficient = 0.39, Fig. 2.8b), decreasing further their income from timber.

Discussion

Amazon nut is central to community households' economy in the Bolivian Amazon

With a share of 44% of the total net income, the Amazon nut is clearly central to the economy of community households in the Bolivian Amazon (Fig. S2.2). This percentage is comparable to the 45% share of Amazon nut found by Duchelle et al. (2014) in 2006 - 2007, and it is double than the 22% found by Zenteno et al. (2013) in 2008 - 2009. The difference with Zenteno et al.'s study might be due to their focus on the broader regional context comprising the various community configurations as opposed to the more forest-dependent community households of our study. This difference in Amazon nut income may also be due to a higher density of Amazon nut producing trees and timber species at our studied communities who adopted a CTMP, and who also enjoy tenure rights over relatively large tracks of forest (Pacheco et al., 2009; Urapotina, 2011). Community households at our study site (2014 - 2015 survey) derived 59% of their income from the forest and 41% from non-forest related activities (i.e., husbandry and off-farm). Our calculated forest income is nearly double than the ~30% of forest income reliance found in two global comparative studies for community-owned forests (Angelsen et al., 2014; Jagger et al., 2014). The degree of dependence over forest, however, falls in between the dependency reported in two previous studies carried out in the region. For example, Duchelle et al. (2014) found that community households derived 64% of their overall income from the forest, whereas Zenteno et al. (2013) found that community households derived less income from forest (42%). Our findings are more comparable with Duchelle et al.'s in spite that half of their study communities were located inside a wildlife reserve in the Department of Pando where logging is not allowed; whereas, all of our study communities were located outside forest reserves. The close similarity of our results with those of Duchelle et al.'s indicates a strong dependency of *campesino* community households on forests. Given that Duchelle et al.'s study took place a decade earlier, the results of our study may be indicative of a slow decrease in forest income reliance over time, particularly among households who adopted the CTMP.

Income derived from the forest differed largely among studied households (Fig. S2.3). The largest observed variation among community households was in off-farm income (Fig. S2.3), which indicates that off-farm income, rather than forest income, is leading to greater income inequality among community households (Angelsen et al., 2014; Mutenje et al., 2011; Uma Shaanker et al., 2004). Alternatively, forest income dependency may be decreasing due to increasing pressure over forest resources as households become larger, there are more job/business opportunities within the communities, and market accessibility improves (Perz et al., 2013). Our calculated yearly household median net income turned out to be 36% higher than the livelihood strategy with the highest median net income found by Zenteno et al (2013), i.e., livestock = USD 6,000, implying that forest-based livelihoods outperforms livestock-based livelihoods with higher environmental footprint. The price of Amazon nut has doubled from 2009 (Zenteno et al., 2013) to 2015 (Cano et al., 2014), which may – to a large extent – explain the higher forest income obtained by our studied households. Additionally, the long-standing involvement of our studied communities in forest management (i.e., increased net timber income in recent years as a result of the improved legal (Cano et al., 2014) and structural (Perz et al., 2013) market accessibility) may explain the higher net income perceived by our studied households. In spite of the increasing total net income of our studied community households, their per capita daily median net income is nearly half of the national daily mean net income: USD 4.28 [a calculation of the daily household's median net income (USD 25.71)/the median number of household members (6)] vs. USD 8.5 [a calculation of the national gross domestic product for 2014 (USD 3,124.1)/365 days] (World Bank, 2016). We found thus sufficient evidence to affirm that Amazon nut plays a central role on the total income of community households, and that timber income could potentially place community households in a better-off position.

The role of socioeconomic and biophysical factors on different sources of income derived by community households in the Bolivian Amazon

Attribute indicators of local ecological knowledge and financial assets are the main driving factors of forest and husbandry income, whereas attribute indicators of natural and physical assets determined off-farm income, and to some extent, husbandry income as well (Figs. 2.6 and 2.7). We predicted that residence time would be the main driving factor of forest income.

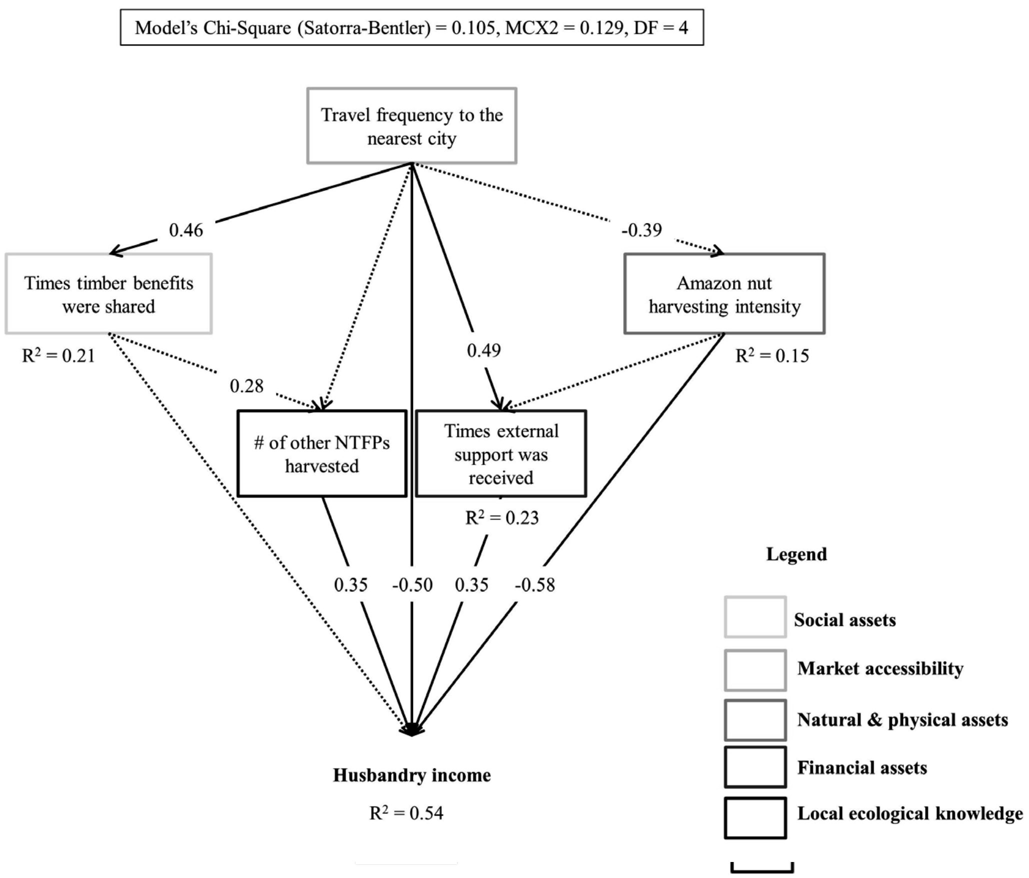

Figure 2.6. Socioeconomic and biophysical factors determining income derived from husbandry (agriculture, agroforestry and livestock) by community households in the Bolivian Amazon. Solid arrows indicate significant effects of a variable on another, whereas, dotted arrows indicate non-significant effects. Standardized coefficient values are at the intersection of the arrows indicating the direction of the relationships. Values are only provided for significant relationships that resulted from the structural equation (SEM) models.

However, the ability of a household to derive more income from the forest decreased as households applied more management practices to enhance Amazon nut production, which in turn, increased with residence time (Fig. 2.5). This finding is completely unexpected especially because Amazon nut was responsible for the majority of the income derived from the forest. A potential explanation to this might be that households who applied more management practices to increase the production of Amazon nut have less time or are less interested in drawing more income from other forest products such as timber or other commercial NTFPs, decreasing further their income from the forest.

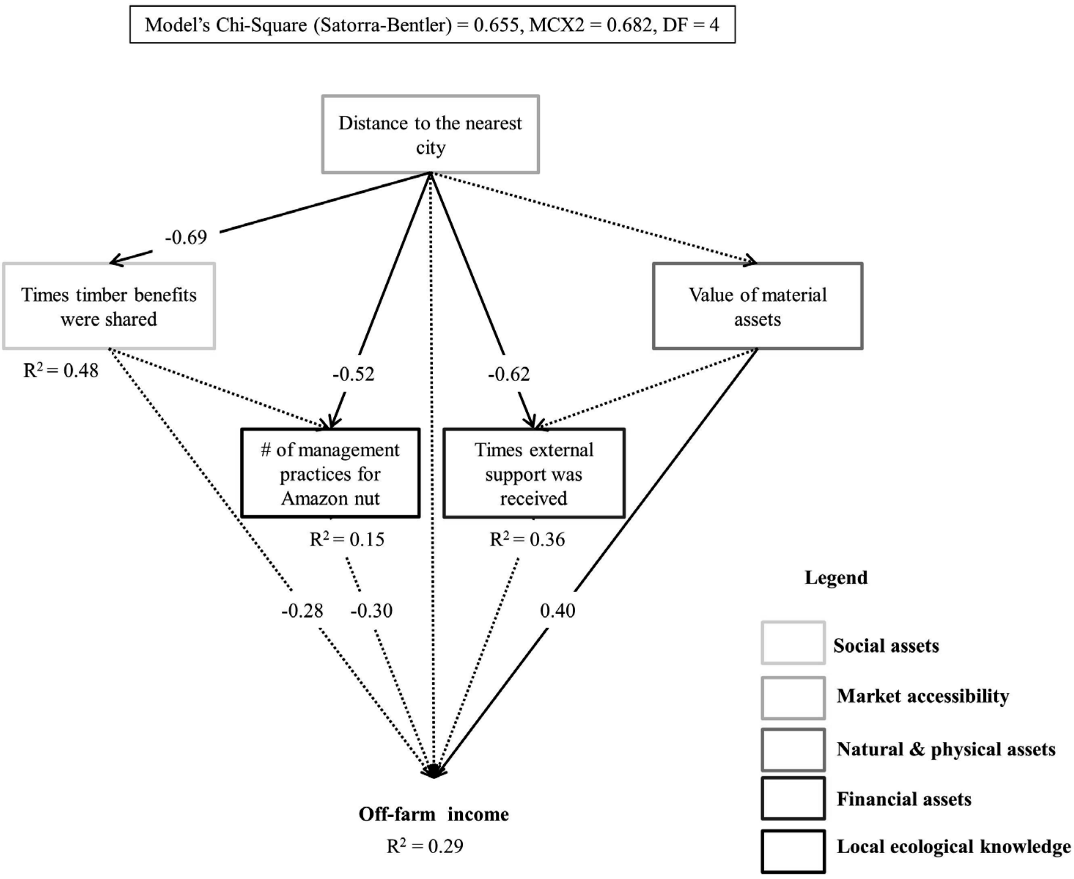

Figure 2.7. Socioeconomic and biophysical factors determining off-farm (salary, business and gifts) income of community households in the Bolivian Amazon. Solid arrows indicate significant effects of a variable on another, whereas, dotted arrows indicate non-significant effects. Standardized coefficient values are at the intersection of the arrows indicating the direction of the relationships. Values are only provided for significant relationships that resulted from the structural equation (SEM) models.

Forest income also decreased as households relied more on off-farm income rather than on husbandry. Off-farm income opportunities demand less work and are more opportunistic than husbandry, and could potentially offset forest income. This means that creating opportunities (e.g., a community forest enterprise or carpentry) for off-farm income among community households can reduce pressure on forests. However, the implementation of such opportunities needs to go hand in hand with *a priori* knowledge of the pressure these forests can withstand. Even though, market integration (travel frequency of the household head to the market) had a direct negative effect on husbandry income, it also had an indirect positive effect through the times a household received external support (Fig. 2.6). This indicates that households further away from the market are less likely to rely on husbandry income, probably because they base their diet on few agricultural products (i.e., such as manioc, rice and plantain) and go for game hunting instead of raising livestock. These households might also collect other NTFPs more intensively to supplement their diets. In line with our predictions, husbandry income decreased as households harvested Amazon nut more intensively. Farming activities likely keep community households busy, reducing thus the pressure they put on forest resources, mainly over Amazon nut. Our hypothesis that off-farm income will increase with the value of material assets owned by community households is also confirmed, implying that such value might be an indicative of the greater capability of households at obtaining greater off-farm income by investing in business or by undertaking paid jobs (Angelsen et al., 2014).

The role of socioeconomic and biophysical factors on the income derived from Amazon nut and timber by community households in the Bolivian Amazon

Our aim was to identify the socioeconomic and biophysical drivers of the use of Amazon nut and timber at the household level in the Bolivian Amazon. We found that few of the factors we predicted were actually driving Amazon nut income (i.e., off-farm income and Amazon nut availability), and none of our predicted (but other) factors had an effect on timber income. Some of our results contradicted our predictions, particularly when it comes to Amazon nut income (i.e., a positive rather than a negative influence of distance to the market; and a negative, rather than a positive influence of residence time). Such inconsistencies indicate that certain socioeconomic and biophysical factors determine household incomes in a specific context or scale. Our finding of a positive relationship between Amazon nut income and distance to the market also contradicts our predictions and those of other studies (Zenteno et al., 2013) that key forest resource face major pressure closer to the market allowing households to derive a larger income from those resources. The income that households derived from Amazon nut did not depend on their access to better prices (related to closeness to markets), which in turn, did not affect fruit production or the availability of reproductive trees. We also expected that residence time would have a positive influence on Amazon nut income because studies have found that older household heads may dedicate more time to NTFP extraction, yet, the opposite was true among our studied community households, and among community households in Peru and Brazil (Fig. 2.8a; Coomes et al., 2004 and Duchelle et al., 2014). The main reason explaining this finding might be that Amazon nut harvesting is rather labour demanding, e.g., it implies carrying approximately 70 kilos over long distances at once. In such case, older residents often give the responsibility of harvesting the Amazon nut from their forest to their offspring, without necessarily receiving a share from the harvesting. This was the case of two, out of the 24 studied households. In addition, and most commonly; sons (dependent and independent household members) living in the city would go to help their parents to harvest Amazon nut because the school holiday season coincides with the Amazon nut production season. These two factors may certainly be adding variation to the data, and are likely the main reasons why we did not find an effect of residence time on Amazon nut income as expected. Although, the number of management practices applied to increase Amazon nut production did not increase Amazon nut income as predicted, liana cutting (a common management practice) alone, could increase fruit production by 77% even 10 years after its application (Kainer et al., 2014).

To our surprise, the degree of involvement in the CTMP was not a significant predictor of the income a household derived from timber, but rather, the number of management practices a household applied to increase Amazon nut production that negatively affected timber income (Fig. 2.8b). A potential explanation for this might be that households tend to carry more management practices to increase their Amazon nut income; and thus, rely less on timber income. We also found that households with better bargaining power to sell their Amazon nut also derived less income

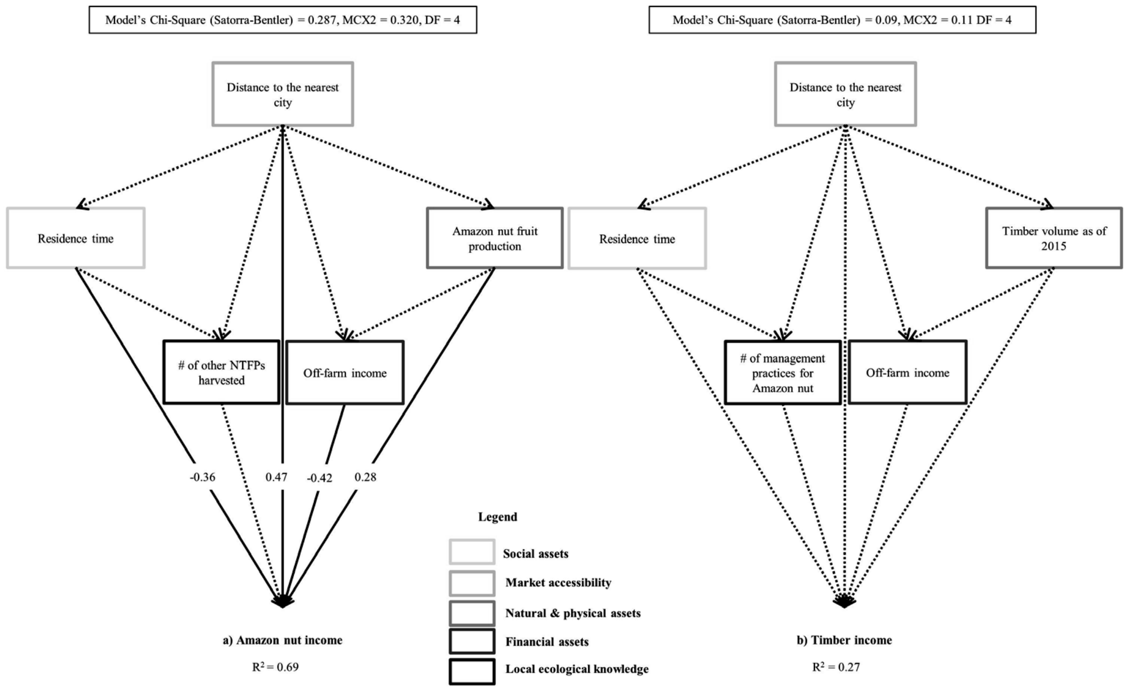

Figure 2.8. Socioeconomic and biophysical factors determining the income derived from (a) Amazon nut and (b) timber by community households in the Bolivian Amazon. Solid arrows indicate significant effects of a variable on another, whereas, dotted arrows indicate non-significant effects. Standardized coefficient values are at the intersection of the arrows indicating the direction of the relationships. Values are only provided for significant relationships that resulted from the structural equation (SEM) models.

from timber (Fig. 2.8b). Thus, we assert that households with greater bargaining power to sell their Amazon nut wait for better Amazon nut prices, and therefore, rely less on timber income. Households with greater bargaining power could potentially derive more income from timber too (Quaedvlieg et al., 2014). For example, we also observed that two studied households were able to increase their earnings by directly offering the sawn timber to a sawmill that offered the best price in the main regional city (Soriano, unpublished data). Chances for households to profit from timber have increased over most recent years with the enactment of the Bolivian Forest and Land Controlling Authority – ABT Directive Nº 02/2014 that allows the harvest of small-timber volumes for commercial purposes. This is particularly important because around 50% of the studied households could double their income from timber by also harvesting timber extra CTMP during the two year-study period, which was further increased when households harvested timber extra CTMP by themselves. However, we could not test the factors enabling households to incur in this activity because of the few participating households actually performing this activity (4 out of 24 households). We observed, however, that middle-aged household heads –particularly those who had worked at former timber enterprises – were the ones most likely to undertake this activity. Furthermore, off-farm income opportunities could potentially reduce pressure over timber as well because households perceiving greater off-farm income perceived less timber income, independently of the timber available in their forest (Fig. 2.8b). Similarly, high dependence on Amazon nut might decrease a household's chances of further profiting from timber by devoting more time to carry more management practices to increase Amazon nut production. Finally, some households may choose not to profit from timber yet as they may prefer to keep its timber trees for moments of hardship or sickness (de Jong et al., 2014).

Conclusions

Hierarchical models such as the SEM modelling approach used in this study helped us disentangle existing inter-relationships among socioeconomic and biophysical factors, which shed light on ways to increase the income derived by community households. Our findings offer insights on how community households can enhance their income, and simultaneously, reduce pressure over keystone forest resources. The modelling approach used for predicting income of *campesino* community households in this study, i.e., SEM models, could easily be replicated in other regions, and at varying temporal and spatial scales to come up with sound policy decisions to manage tropical forests accordingly. Even in communities with high degree of reliance on forest income like the communities in the present study, off-farm and husbandry income are complementary to their livelihoods, and can be targeted to improve their living conditions. Although pressure over forest can be overcome by husbandry income, one must be very cautious with the scale of the implementation of husbandry-related activities; particularly, when it turns to cattle ranching expansion (Gomes et al., 2012). Currently, the majority of the husbandry activities practiced by studied *campesino* communities in the Bolivian Amazon are based on shifting cultivation and raising small livestock (e.g., poultry and pigs). The contribution of cattle ranching is minimal (only four out of 24 households had between 1 - 17 cows in our sample). These generally “subsistence” driven activities currently practiced by *campesino* community households are certainly being outperformed by Amazon nut and timber production, which may be preventing them from obtaining further economic returns from other sources. For example, a most recent study in the Bolivian Amazon showed a relatively rapid increase of these activities amongst less forest-reliant communities (Zenteno et al., 2014).

Given Amazon nut’s importance to community household economies, its highly variable population structure (Peres et al., 2003), and the continual threat of deforestation (Peres et al., 2003) for other land uses; multiple-use forest management must be prioritized for the conservation of this rich ecosystem. Considerable external support and research may be required to simultaneously secure a natural resource base and to improve *campesino* community households’ livelihoods over the long run. External support needs to be directed towards capacity building on issues related to multiple-use forest management, and to empower negotiation and investment skills of community households; since these skills allowed them to draw greater income from timber (Fig. 2.8b). Skills they may apply to draw greater income from other forest products as well. Research needs to address the impact of logging and Amazon nut harvesting intensities on *Bertholletia* and timber species populations (Soriano et al., in preparation). Thus, we conclude that the socio-ecological costs of Amazon nut and timber production can be primarily tackled by increasing capacity building on forest management and negotiation and investment skills.

Acknowledgements

Our special thanks go to community leaders and hundreds of community participants, without whose collaboration our research goals would have not been met. Thanks also to a handful of collaborators who supported at various stages of this research: M. van der Sande, B. Shipley, L. Poorter, T. Caughlin, M. A. Albornoz, Canela, A. Romero-Seas, S. Hinojosa, H. Dumay, C. Barber Alvarez-Buylla, R. Banega, I. Paz Aguilera, Y. Gonzáles, J. C. Licona, L. Dominguez, S. Velasco and J. Jansen. We would like to thank to A. Duchelle, A. Almeyda Zambrano and two anonymous reviewers for their insightful comments on earlier drafts; and to L. Dutrieux for providing the map from our research sites.

Supporting Information

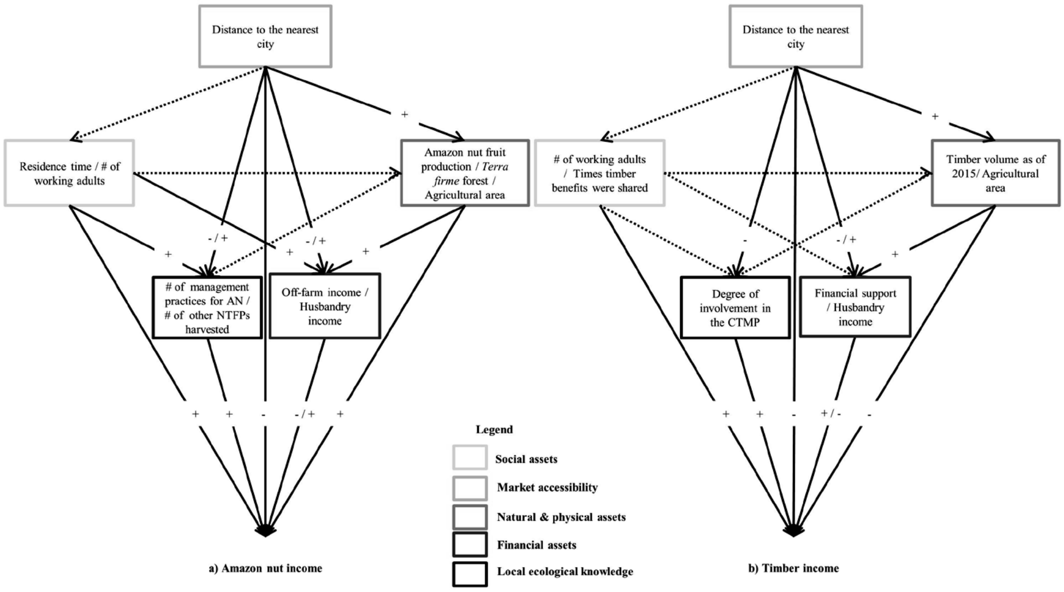

Figure S2.1. Hypothesized socioeconomic and biophysical factors determining the income derived from (a) Amazon nut and (b) timber by community households in the Bolivian Amazon. A description of the hypothesized factors of the different attributes can be found in Table 2.2. Solid arrows indicate significant effects of a variable on another, whereas, dotted arrows indicate non-significant effects. AN = Amazon nut, NTFPs = Non-timber forest products, CTMP = Community timber management plan.

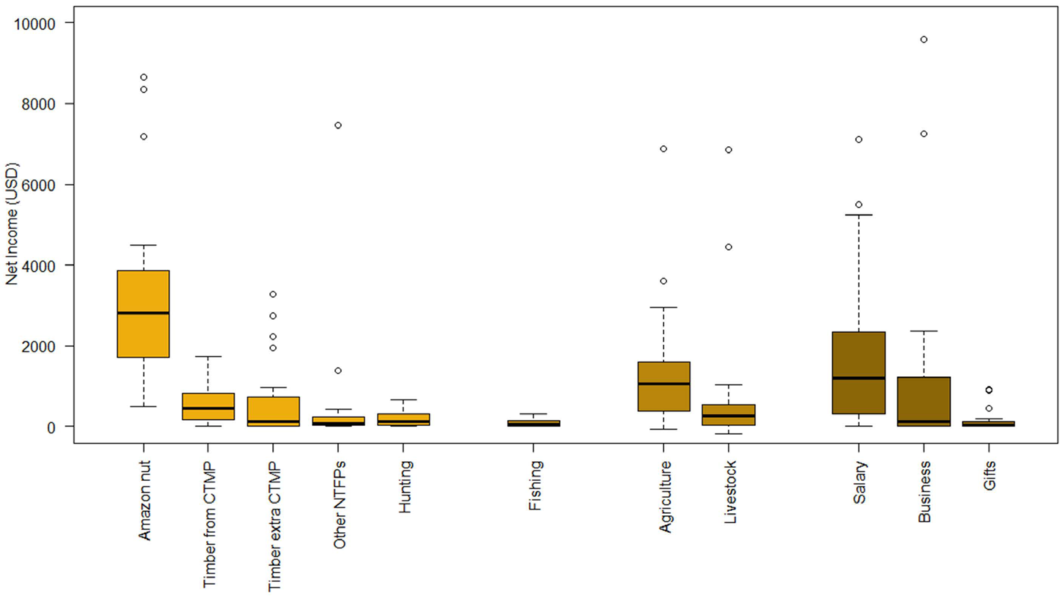

Figure S2.2. Median net income of the different sources of income derived by community households in the Bolivian Amazon. The upper and lower quartiles in the boxplots, each explain 25% of the variation in the median net income derived by participating households. Empty circles are the outliers.

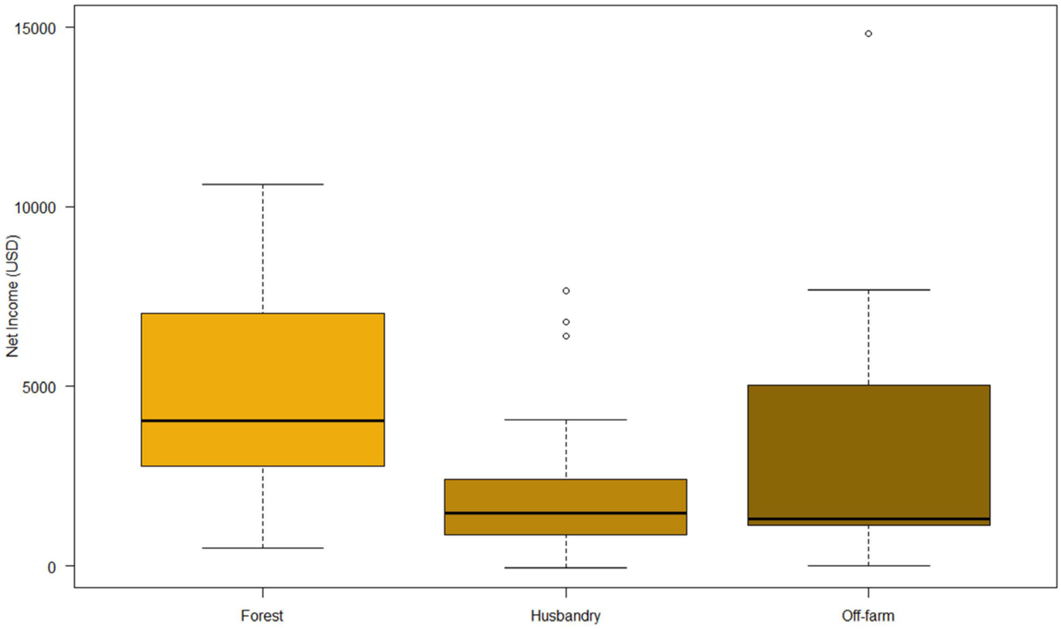

Figure S2.3. Contribution from forest (timber, Amazon nut, other NTFPs and hunting), husbandry (agriculture, agroforestry and livestock) and off-farm income (salary, business and gifts) incomes to the total net income of community households in the Bolivian Amazon. The upper and lower quartiles in the boxplots explain 25% of the variation in the median net income derived by participating households. Empty circles are the outliers.

Table S2.1. Studies that combine socioeconomic and biological surveys in their methodological approach to determine the socioeconomic and biophysical drivers of forest resources use.

Author	Geographical location	Forest products	Sampling methods		Analysis approach
			Socioeconomic survey	Biological survey	
Uma Shaanker et al. 2004 (Environmental conservation)	South India	NTFPs	Three sites: 207 households	Five radiating transects of 1200m at each site	Multiple linear regression
Brown et al. 2011 (PLoS One)	Ranomafana National Park, Madagascar	Firewood	Eight villages: 247 household questionnaires	Seven (40m x 40m) plots along transects: one in each village	Generalized Linear Models Regression trees
Mutenje et al. 2011 (Ecological Economics)	Gonarezhou National Park, Zimbabwe	Firewood	20 villages: 400 households (20 per village)	Five radiating transects of 10 km per village	Principal Component Analysis (PCA) Multiple regressions
Zeidemann et al. 2013 (Environmental conservation)	Central Amazonia, Brazil	Amazon nuts (ANs)	Three sites: 23 households	ANs trails of 6 landholdings, 2500m x 40m transects at non-harvested areas	Univariate models Generalized linear models
Steele et al. 2014 (Forest Policy and Economics)	South Africa	Firewood	8 rural villages: >30 households per village	Three radiating transects of varying lengths (1.8 - 4.7 km) per village	Principal Component Analysis (PCA) Multiple stepwise regression

Table S2.2. List of timber species sampled in 72 (2 ha) research transects established at community-based household forests in the Bolivian Amazon. These 17 species represent the 10 main timber species harvested in the region according to country-level forestry reports from 2002 to 2012 (Bolivia's Forest and Land Controlling Authority – ABT, Annual reports from 2002 - 2012). We ended up with 17 species because the reports only used genera names for several timber species (*Cedrela, Dipteryx, Hymenaea, Tabebuia and Terminalia)*.

Common Name	**Species Scientific Name**
Almendrillo amarillo	*Apuleia leiocarpa* (J. Vogel) J.F. Macbride
Almendrillo negro	*Dipteryx micrantha* Harms
Cedro fissilis	*Cedrela fissilis* Vell.
Cedro odorata	*Cedrela Odorata* L.
Cuta	*Astronium lecontei*
Mara	*Swietenia macrophylla* King
Mara macho	*Cedrelinga catenaeformis* (Ducke) Ducke
Marfil	*Aspidosperma macrocarpon* C. Martius
Morado	*Peltogyne* cf. *heterophylla*
Paquio	*Hymenaea courbaril* L.
Paquiocillo	*Hymenaea parvifolia* Huber
Roble	*Amburana cearensis* (Allemão) A. C. Smith
Serebo	*Schizolobium parahyba* (Vell. Conc.) S. F. Blake
Tajibo amarillo	*Tabebuia serratifolia* (Vahl) G. Nicholson
Tajibo colorado	*Tabebuia impetiginosa* (C. Martius ex A. DC.) Standley
Verdolago	*Terminalia* spp.
Verdolago amarillo	*Terminalia Oblonga* (Ruíz & Pavón) Steudel

Table S2.3. Results of the structural equation (SEM) models built for incomes of Amazon nut and timber at community-based household forests. DF = Degrees of freedom.

Income source	Model structure	DF	Model's p-value (Chi-square)	Monte Carlo Simulation probability	Main response R^2
Amazon nut	Model 1. Hypothesized complete model	1	0.243	0.000	0.65
	Model 2. Three fixed non-significant pathways removed	4	0.287	0.328	0.69
	Model 3. Three least significant pathways removed	3	0.418	0.251	0.63
Timber	Model 1. Hypothesized complete model	1	0.268	0.000	0.38
	Model 2. Three fixed non-significant pathways removed	4	0.063	0.077	0.41
	Model 3. Three least significant pathways removed	4	0.476	0.514	0.38
Forest	Model 1. Hypothesized complete model	1	0.240	0.000	0.50
	Model 2. Three fixed non-significant pathways removed	4	0.076	0.092	0.50
	Model 3. Three least significant pathways removed	4	0.332	365	0.51
Husbandry	Model 1. Hypothesized complete model	1	0.093	0.000	0.57
	Model 2. Three fixed non-significant pathways removed	4	0.105	0.129	0.54
	Model 3. Three least significant pathways removed	4	0.369	0.403	0.57
Off-farm	Model 1. Hypothesized complete model	1	0.526	0.000	0.32
	Model 2. Three fixed non-significant pathways removed	4	0.655	0.682	0.29
	Model 3. Three least significant pathways removed	3	0.836	0.665	0.32

* Best model structure for Amazon nut includes significant (z-value <0.05) predictors resulting from the regression model in addition to the hypothesized predictor variables in the absence of significant predictor.

Appendix S2.1. Annual household survey (modified from PEN Questionnaires): Socioeconomic determinants of household wealth and forest use in Bolivian Amazonian communities. Includes Spanish version, the original language in which the survey was carried out. This questionnaire was translated from Spanish for the thesis.

Task	**Date(s)**	**By who?**	**If not, give comments**
Interview			
Checking questionnaire			
Coding questionnaire			
Entering data			
Checking & approving data entry			

A. Household identification and general information

Item	**Name**	**Code**
Household		
Village		
Province		
Household head		
Position/role in the village or other social organization		
Country/region of origin		
Past occupation		
Current occupation		
Tenure type		
Year of forest access acquisition		
Year of tenure right acquisition		

B. Household composition

1. Who are the members of the household?

1. Personal Identification number (PID)	*** Name of household member**	**2. Relation to Household head 1)**	**3. Year born** *(yyyy)*	**4. Sex** *(0=male 1=female)*	**5. Education** *(number of years completed)*
1		Household head = 0			
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					

1) Codes: 0=household head; 1=spouse (legally married or cohabiting); 2=son/daughter; 3=son/daughter in law; 4=grandchild; 5=mother/father; 6=mother/father in law; 7=brother or sister; 8=brother/sister in law; 9=uncle/aunt; 10=nephew/niece; 11=step/foster child; 12=other family; 13=not related (e.g., servant).

C. Geographic location, accessibility and social relations

What is the distance from your house to the closest forest limit to which you have access and is utilizable for you?	1. … measured in terms of distance	*km*
	2. … measured in terms of time (by walk/motorcycle/car)	*Hrs.*
What is the main road or river to access to the community and to your house? Describe		

Since when there exist a road?		*año*
If only road, distance to the nearest commercial town/market	*Km*	Name the river, if there is one
If not, distance to the nearest road that connects with the nearest commercial town	*Km*	Indicate mean of transportation
Type of road (asphalted, gravelled, coarse, pathway)		Indicate road type: terciary, secondary, principal (km)
Transport cost in the dry season	*Bs$*	Price for 1 person
Transport cost in the rainy season	*Bs$*	Price for 1 person
Frequency		Times in a 3) year, 2) month, 1) week
Stay days in town (Days)	*Days/hours*	Rainy season
	Days/hours	Dry season
Could you name the institutions who have supported you over the past 5 years?		Indicate: institution Product Period Frequency
To what type of buyer did you sell your forest products?		Indicate: Product & Type of buyer: Relative Known intermediary Unknown intermediary Processing plants/sawmill

D. Land use

1. Please indicate the amount of land (in hectares) that you currently own and have rented in/out.
Note: See definitions of land categories in the Technical Guidelines.

Category	**1. Area** *(ha)*	**2. Ownership** *(code-tenure)*	**Main products grown/harvested in the past 12 months Max 3. If Brazil nut, indicate # of reproductive trees** *(code-product)*		
			3. Rank1	**4. Rank2**	**5. Rank3**
Forest:					
1. Natural forest (upland forest)					
2. Natural forest (seasonally flooded, flooded forest)					
3. Forest under some sort of use					
4. Managed forests					
5. Fallow					
6. Plantations					

Agricultural land:					
7. Cropland					
8. Pasture (natural or planted)					
9. Agroforestry					
10. Silvipasture					
11. Other vegetation types/land uses (residential, bush, grassland, wetland, etc.)					
12. Total land owned (1+2+3+...+9)					
13. Land rented out (**included** in 1-9)					
14. Land rented in (**not included** in 1-9)					

E. Assets and savings (household wealth)

1. Please indicate the type of house you have?

1. Do you have your own house? 1)	
2. What is the type of material of (most of) the walls? 2)	
3. What is the type of material of (most of) the roof ? 3)	
4. How many m^2 approx. is the house?	m^2

1) Codes: 0=no; 1=own the house on their own; 2=own the house together with other household(s); 3=renting the house alone; 4=renting the house with other household(s); 9=other, specify:
2) Codes: 1=mud/soil; 2=wooden (boards, trunks); 3=iron (or other metal) sheets; 4=bricks or concrete; 5=reeds/straw/grass/fibers/bamboo; 9=other, specify:
3) Codes: 1=thatch; 2=wooden (boards); 3=iron or other metal sheets; 4=tiles; 9=other, specify:

2. Please indicate the number and value of implements and other large household items that are owned by the household.

	1. No. of units owned	**2. Total value (current sales value of all units, not purchasing price)** (indicate with "0" if item is not owned)
1. Car/truck		
2. Tractor		
3. Motorcycle		
4. Bicycle		
5. Cellphone/phone		
6. TV		
7. Radio		
8. Cassette/CD/ VHS/VCD/DVD/ player		
9. Stove for cooking (gas or electric only)		
10. Refrigerator/freezer		
11. Fishing boat and boat engine		
12. Chainsaw		
13. Plough		
14. Scotch cart		
15. Shotgun/rifle		
16. Energy generator		
17. Wooden cart or wheelbarrow		
18. Water pump		
19. Solar panel		
20. TV antenna		

21.		
22. Others (worth more than approx. 50 USD purchasing price)		

3. Please indicate the savings and debt the household has.

1. How much savings does the household have in total?	***Bs$***
How much does the household have in savings in banks, credit associations or savings clubs?	*Bs$*
How much does the household have saved in loans to family, close relatives, friends?	*Bs$*
How much does the household have in savings in non-productive assets such as gold and jewellery?	*Bs$*
Other, specify (__________________________)	*Bs$*
2. How much does the household have in outstanding debt?	***Bs$***
To formal financing entities?	*Bs$*
To family, close relatives, and friends?	*Bs$*
To buyers, intermediaries, wholesalers?	*Bs$*
Other, specify (__________________________)	*Bs$*

F. Forest User Groups (FUG)

Note: The enumerator should first explain what is meant by a FUG, cf. the Technical Guidelines.

1. Are you or any member of your household a member of a Forest User Group (FUG)? *If 'no', go to 11.*		*(1-0)*
2. Does someone in your household normally/regularly attend the FUG meetings? *If 'no', go to 5.*		*(1-0)*
3. **If 'yes'**: in your household, who normally attends FUG meetings and participates in other FUG activities? *Codes: 1=only the wife; 2=both, but mainly the wife; 3=both participate about equally; 4=both, but mainly the husband; 5=only the husband; 6=mainly son(s); 7=mainly daughter(s); 8=mainly husband & son(s); 10=mainly wife & daughter(s); 9=other arrangements not described above.*		
4. How many person days (= full working days) did the household members spend in total on FUG activities (meetings, policing, joint work, etc) over the past 12 months?		*days*
5. Does your household make any cash payments/contributions to the FUG? *If 'no', go to 7.*		*(1-0)*
6. **If 'yes':** how much did you pay in the past 12 months?		*(Bs$)*
7. Did your household receive any cash payments from the FUG (e.g., share of sales) in the past 12 months? *If 'no', go to 9.*		*(1-0)*
8. **If 'yes':** how much did you receive in the past 12 months?		*(Bs$)*
9. What are your reasons for joining the FUG? *Please rank the most important reasons, max 3.*	**Reason**	**Rank 1-3**
	1. Increased access to forest products	
	2. Better forest management and more benefits in future	
	3. Access to other benefits, e.g., government support or donor programmes	
	4. My duty to protect the forest for the community and the future	
	5. Being respected and regarded as a responsible person in village	
	6. Social aspect (meeting people, working together, fear of exclusion, etc.)|	
	7. Forced by Government/chiefs/neighbours	
	8. Higher price for forest product	
	9. Receipt of direct payments	
	10. Makes harvest of forest products more efficient	
	11. Learn new skills/information	
	12. Reduce conflicts over resource	

	13. Participation (involvement) in management activities	
	14. Other, specify:	
10. Overall, how would you say the existence of the FUG has affected the benefits that the household gets from the forest? *Codes: 1=large negative effect; 2=small negative effect; 3=no effect; 4=small positive effect; 5=large positive effect.*		
11. **If you don't participate in FUG,** why? *Please rank the most important reasons, max. 3*	**Reason**	**Rank 1-3**
	1. No FUG exists in the village neither nearby	
	2. I'm new in the village/association	
	3. FUG members generally belong to other group(s) (ethnic, political party, religion, age, etc.) than I do	
	4. Cannot afford to contribute the time	
	5. Cannot afford to contribute the required cash payment	
	6. FUG membership will restrict my use of the forest, and I want to use the forest as I need it	
	7. I don't believe FUG is very effective in managing the forest	
	8. Lack of forest products	
	9. Not interested in the activities undertaken by existing FUGs	
	10. Corruption in FUG	
	11. Interested in joining but needs more information	
	12. FUG exists in village/nearby, but household is unaware of its presence	
	13. Other, specify:	

G. Crisis and unexpected expenditures

1. Has the household faced any major income shortfalls or unexpectedly large expenditures during the **past 12 months**?

Event	**How severe?**1)	**How did you cope with the income loss or costs?** *Rank max. 3*2)		
		2. Rank1	**3. Rank2**	**4. Rank3**
Significant drop of Brazil nut price				
Significant drop of benefits received from GUF				
Serious crop failure				
Serious illness in family (productive age-group adult unable to work for more than one month during past 12 months, due to illness, or to taking care of ill person; or high medical costs)				
Death of productive age-group adult				
Land loss (expropriation, etc.)				
Major livestock loss (theft, drought, etc.)				
Other major asset loss (fire, theft, flood, etc.)				
Lost wage employment				
Wedding or other costly social events				
Payment for sale of hh products arrive later than expected				
Other, specify:				

1) Codes severity: 0=no crisis; 1=yes, moderate crisis; 2=yes, severe crisis. See Technical Guidelines for definitions.

2) Codes coping: 1. Harvest more forest products; 2. Harvest more wild products not in the forest; 3. Harvest more agricultural products; 4. Spend cash savings; 5. Sell assets (land, livestock, etc.); 6. Do extra casual labour work; 7. Assistance from friends and relatives; 8. Assistance from NGO, community org., religious org. or similar; 9. Get loan from money lender, credit association, bank etc.; 10. Tried to reduce household spending; 11. did nothing in particular; 12. Spent savings / retirement money; 13. Reduced number of meals taken; 14. Borrowed against future earnings; 15. Sold food that would *otherwise be used for household consumption; 16. Rented out land; 17. Started new business; 18. Changed cropping patterns or types of crops planted; 19; 20. Harvested premature crops; Other, specify:*

H. Forest clearing

1. Did the household clear any forest during the **past 12 months**? *If 'no', go to 9.*		*(1-0)*		
If YES:	2. How much forest was cleared?	*ha*		
	3. What was the cleared forest (land) used for? *Codes: 1=cropping; 2=tree plantation; 3=pasture; 4=non-agric uses (Rank max 3)*	1.Rank1	2.Rank2	3.Rank3
	4. If used for crops (code '1' in question above), which principal crop was grown? *(code-product) Rank max 3*	1.Rank1	2.Rank2	3.Rank3
	5. What type of forest did you clear? *(code-forest)*			
	6. If secondary forest, what was the age of the forest?	*years*		
	7. What was the ownership status of the forest cleared? *(code tenure)*			
	8. How far from the house was the forest cleared located?	*km*		
9. Has the household over the last *5* years cleared forest? *If 'no', go to 11.*		*1-0*		
10. **If 'yes':** how much forest (approx.) has been cleared over the last 5 years? *Note: This should include the area reported in question 2.*		*Ha*		
11. How much land used by the household has over the last 5 years been abandoned (left to convert to natural re-vegetation)?		*Ha*		

I. Welfare perceptions and social capital

1. All things considered, how satisfied are you with your life over the **past 12 months**? *Codes: 1=very unsatisfied; 2=unsatisfied; 3=neither unsatisfied or satisfied; 4=satisfied; 5=very satisfied*		
2. Has the household's food production and income over the past 12 months been sufficient to cover what you consider to be the needs of the household? *Codes: 1=no; 2=reasonable (just about sufficient); 3=yes*		
3. Compared with other households in the village (or community), how well-off is your household? *Codes: 1=worse-off; 2=about average; 3=better-off*		
4. How well-off is your household today compared with the situation **5 years ago?** *Codes: 1=less well-off now; 2=about the same; 3=better off now If 1 or 3, go to 5. If 2, go to 6.*		
5. **If worse-** ***or*** **better-off:** what is the main reason for the change? *Please rank the most important responses, max 3.*	**Reason: Change in ...**	**Rank 1-3**
	1. off farm employment	
	2. land holding (e.g., bought/sold land, eviction)	
	3. forest resources	
	4. output prices (forest, agric,...)	
	5. outside support (govt., NGO,..)	
	6. remittances	
	7. cost of living (e.g., high inflation)	
	8. war, civil strife, unrest	
	9. conflicts in village (non-violent)	
	10. change in family situation (e.g. loss of family member/a major bread-winner)	
	11. illness	
	12. access (e.g. new road,...)	

	13. increased/reduced land area for agric. production	
	14. started a new business/lost or less business	
	15. livestock (gain or loss)	
	16. increased regulations	
	17. Joined cooperative	
	18. Forced to travel for family matters	
	19. other (specify):	
6. Do you consider your village (community) to be a good place to live? *Codes: 1=no; 2=partly; 3=yes*		
7. Do you **in general** trust people in the village (community)? *Codes: 1=no; 2=partly, trust some and not others; 3=yes*		
8. Can you get help from other people in the village (community) if you are in need, for example, if you need extra money because someone in your family is sick? *Codes: 1=no; 2= can sometimes get help, but not always; 3=yes*		

J. Direct forest income (income from unprocessed forest products)

1. What are the quantities and values of raw-material forest products the members of your household collected for both own use and sale over **the past month**?

Note: Income from plantations is defined as forest income, while agroforestry income is categorized as agric. income (H).

Note: The quantities of unprocessed forest products used as inputs in making processed forest products should only be reported in section C, table 2, and not in the table below.

1. Forest product *(code-product)*	**2. Collected by whom? 1)**	**Collected where?**		**5. Quantity collected (7+8)**	**6. Unit**	**7. Own use (incl. gifts)**	**8. Sold (incl. barter)**	**9. Price per unit**	**10. Type of market** *(code-market)*	**11. Gross value (5*9)**	**12. Transport/ marketing costs (total)**	**13. Purch. Inputs & hired labour**	**14. Net income (11-12-13)**
		3. Forest type *(code-land)*	**4. Ownership** *(code-tenure)*										
FRUITS													
Motacú													
Majo													
Asaí													
Palmito													
Chocolate													
Chonta													
Lúcuma													
SEEDS													
Castaña													
LEAVES													
Jatata													

BARK													
OLEO/LATEX													
Miel													
Copaibo													
Goma													
LIANAS													
Chamairo													
Uña de gato													
FIREWOOD													
Isigo													
Caricari													
Blanquillo													
Pacai													
TIMBER													
Aliso													
Almendrillo													
Cedro													
Cuta													
ANIMALS													
Mono					K								
Guaso					K								
Paca					K								
Jochi					K								
Chancho					K								
Taitetú					K								
Tatu					K								
Anta					K								
Pava					K								
					K								

Codes: 1=only/mainly by wife and adult female household members; 2=both adult males and adult females participate about equally; 3=only/mainly by the husband and adult male household members; 4=only/mainly by girls (<15 years); 5=only/mainly by boys (<15 years); 6=only/mainly by children (<15 years), and boys and girls participate about equally; 7=all members of household participate equally; 8=none of the above alternatives; 9=person employed by and living with the household.

2. Do you carry some extra activity to augment your Brazil nut production? If so, which activities do you carry of the list below?

1. Clearing of Brazil nut trails
2. Use of fire underneath reproductive trees to facilitate harvest
3. Enrichment planting

4. Clearing around seedlings and saplings
5. Purposefully protecting seedlings and saplings
6. Liana cutting
7. Washing nuts after harvest
8. Other

K. Forest-derived income (income from processed forest products)

1. What are the quantities and values of processed forest products that the members of your household produced during **the past 12 months?**

1. Product *(code-product)*	**2. Who in the household did the work?** [1)]	**3. Quantity produced (5+6)**	**4. Unit**	**5. Own use (incl. gifts)**	**6. Sold (incl. barter)**	**7. Price per unit**	**8. Type of market** *(code-market)*	**9. Gross value (3*7)**	**10. Purchased inputs & hired labour**	**11. Transport/marketing costs**	**12. Net income excl. costs of forest inputs (9-10-11)**

1) Codes: 1=only/mainly by wife and adult female household members; 2=both adult males and adult females participate about equally; 3=only/mainly by the husband and adult male household members; 4=only/mainly by girls (<15 years); 5=only/mainly by boys (<15 years); 6=only/mainly by children (<15 years), and boys and girls participate about equally; 7=all members of household participate equally; 8=none of the above alternatives.

L. Non-forest environmental income

1. In addition to forest products and fish included in the previous tables, how much of **other wild products** (e.g., from grasslands, fallows, etc.) did your household collect over **the past 12 months**?

1. Type of product *(code-product)*	**Collected where?**		**4. Quantity collected (6+7)**	**5. Unit**	**6. Own use (incl. gifts)**	**7. Sold (incl. barter)**	**8. Price per unit**	**9. Gross value (4*8)**	**10. Costs (inputs, hired labor, marketing, etc.)**	**11. Net income (9-10)**
	2. Land type *(code-land)*	**3. Owner-ship** *(code-tenure)*								

Note: Answers in columns 2 and 3 should be consistent with reported land categories.

LL. Wage income

1. Has any member of the household had paid work over **the past 12 months**?
Note: One person can be listed more than once for different jobs.

1. Household member (PID)	**2. Type of work** *(code-work)*	**3. Days worked past year**	**4. Daily wage rate**	**5. Total wage income (3*4)**

M. Income from own business (not forest or agriculture)

1. Are you involved in any type of business, and if so, what are the gross income and costs related to that business over **the past year?**

Note: If the household is involved in several different types of business, you should fill in one column for each business.

	1. Business 1	**2. Business 2**	**3. Business 3**
1. What is your type of business?[1)]			
2. Gross income (sales)			
Costs:			
3. Purchased inputs			
4. Own non-labour inputs (equivalent market value)			
5. Hired labour			
6. Transport and marketing cost			
7. Capital costs (repair, maintenance, etc.)			
8. Other costs			
9. Net income (2 - items 3-8)			
10. Current value of capital stock			

1) Codes: 1=shop/trade; 2=agric. processing; 3=handicraft; 4=carpentry; 5=other forest based; 6=other skilled labour; 7=transport (car, boat,…); 8=lodging/restaurant; 9=brewing; 10=brick making; 11=landlord/real estate; 12=herbalist/traditional healer/witch doctor; 13=quarrying; 14= contracted work (cleaning/maintenance); 15=renting out equipment; 19=other, specify:

N. Income from agriculture – crops

1. What are the quantities and values of crops that household has harvested during **the past 12 months**?

1. Crops *(code-product)*	**2. Area of production** (*m2)*	**3. Total production (5+6)**	**4. Unit (for production)**	**5.Own use (incl. gifts)**	**6. Sold (incl. barter)**	**7. Price per unit**	**8.Total value (3*7)**
Rice							
Maize							
Yucca							
Beans							
Plantain							
Banana							
Papaya							
Pineapple							
Watermelon							
Grapefruit							
Orange							
Lemon							

Lima							
Pacai							
Mango							
Coffee							
Coca							
Tropical potato							
Cane							
Copuazu							
Guajaba							
Sweet potato							
Cashew							
Advocado							
Onion							
Lettuce							
Tomato							
Parsley							
Spicy pepper							

2. What are the quantities and values of inputs used in crop production over **the past 12 months** (this refers to agricultural cash expenditures)?
Note: Take into account all the crops in the previous table.

1. Inputs	**2. Quantity**	**3. Unit**	**4. Price per unit**	**5. Total costs (2*4)**
1. Seeds				
2. Fertilizers				
3. Pesticides/herbicides				
4. Manure				
5. Draught power				
6. Hired labour				
7. Hired machinery				
8. Transport/marketing				
19. Other, specify:				
a. Bags				
b. Machete				
c. Ax				
d. Lime				
e. Emery				
f. Hoe				
g. Shovel				
h. Fossa				
i. Manual machine for seeding				
20. Payment for land rental				

O. Income from livestock

1. What is the number of ADULT animals your household has now, and how many have you sold, bought, slaughtered or lost during **the past 12 months**?

1. Livestock	2. Beginning number (1 year ago)	3. Sold (incl. barter), live or slaughtered	4.Slaughtered for own use (or gift given)	5. Lost (theft, died,..)	6. Bought or gift received	7. New from own stock	8. End number (now) (2-3-4-5+6+7)	9. Price per adult animal	10. Total end value (8*9)
1. Cattle									
Bull									
Dairy cow									
Beef cattle									
2. Buffalos									
3. Goats									
4. Sheep									
5. Pigs									
6. Donkeys									
7. Ducks									
8. Chicken									
9. Horses									
10. Rabbit									
19. Other, specify:									

2. What are the quantities and values of animal products and services that you have produced during **the past 12 months**?

1. Product/service	2. Production (4+5)	3. Unit	4. Own use (incl. gifts)	5. Sold (incl. barter)	6. Price per unit	7. Total value (2*6)
1. Meat [1)]						
2. Milk [2)]						
3. Butter						
4. Cheese						
5. Ghee						
6. Eggs						
7. Hides and skin						
8. Wool						
9. Manure						
10. Draught power						
11. Bee hives						
12. Honey						
19. Other, specify:						

1) Make sure this corresponds with the above table on sale and consumption of animals.
2) Only milk consumed or sold should be included. If used for making, for example, cheese it should not be reported (only the amount and value of cheese).

3. What are the quantities and values of inputs used in livestock production during **the past 12 months** (cash expenditures)?
Note: The key is to get total costs, rather than input units.

1. Inputs	2. Unit	3. Quantity	4. Price per unit	5. Total costs (3*4)
1. Feed/fodder				

Salt				
Vitamins				
Other:				
2. Rental of grazing land				
3. Medicines, vaccination and other veterinary services				
4. Costs of maintaining barns, enclosures, pens, etc.				
5. Hired labour				
6. Inputs from own farm				
9. Other, specify:				

4. Please indicate approx. share of fodder, either grazed by your animals or brought to the farm by household members.

Type of grazing land or source of fodder		**3. Approx. share** (%)
1. Land type *(Code-land)*	**2. Ownership** *(Code-tenure)*	
Total		100%

P. Other income sources

1. Please list any other income that the household has received during **the past 12 months**.

1. Type of income	**2. Total amount received past 12 months**
1. Remittances	
2. Support from government, NGO, organization or similar	
3. Gifts/support from friends and relatives	
4. Pension	
5. Payment for forest services	
6. Payment for renting out land (if in kind, state the equivalent in cash)	
7. Compensation from logging or mining company (or similar)	
8. Payments from FUG	
9. Other, specify:	

Q. Enumerator/researcher assessment of the household

Note: This is to be completed by the enumerator.

1. During the last interview, did the respondent smile or laugh? *Codes: (1) neither laughed nor smiled (somber); (2) only smiled; (3) smiled and laughed; (4) laughed openly and frequently.*	
2. Based on your impression and what you have seen (house, assets, etc.), how well-off do you consider this household to be compared with other households in the village? *Codes: 1=worse-off; 2=about average; 3=better-off*	
3. How reliable is the information **generally** provided by this household? *Codes: 1=poor; 2=reasonably reliable; 3=very reliable*	
4. How reliable is the information on **forest collection/use** provided by this household? *Codes: 1=poor; 2=reasonably reliable; 3=very reliable*	
5. If the forest information is not so reliable (code 1 above), do you think the information provided overestimate or underestimate the actual forest use? *Codes: 1=underestimate; 2=overestimate; 3= no systematic over- or underestimation; 4=don't know.*	

Appendix S2.2. Collaboration agreement signed between the researcher and community leader enabling to carry this research, and consent to interview participating households. This collaboration agreement was translated from Spanish for the thesis.

Collaboration agreement for the research "Quest for socio-economic and ecological sustainability of forest management in Bolivian Amazonian communities"

Background: Multiple use forest management constitutes the main activity among Bolivian Amazonian communities. The long postponed recognition of traditional forest use in national policies and of studies compatible with this use did not allow advances at improving community families' well-being. Due to the potential of the proposed research to contribute to the national policies and to facilitate the implementation of these policies by communities with a community timber management plan (CTMP, a CTMP requires the establishment of permanent research plots to monitor the response of the forest to management interventions), the community has found convenient to support the PhD research project proposed by the For. Eng. Marlene Soriano about the "**Quest for socio-economic and ecological sustainability of forest management in Bolivian Amazonian communities"**. This project seeks to provide reliable information about the state and functioning of community forests upon accounting for the socio-economic characteristics of community households, *campesino* communities and regional communities. This project is to be carried out under a participatory-action research approach.

Specific objectives of this collaboration agreement: To establish a participatory monitoring plan of research plots and to obtain reliable information of timber species and Amazon nut population recovery following a range of logging and Amazon nut harvest intensities.

After presenting the PhD research proposal at the *campesino* community of "______________________", on date:_________, we agree to collaborate in this research given the following conditions:

Obligations of the For. Eng. Marlene Soriano,

The for. Eng. Marlene Soriano guarantees to train selected community members on the fundamental principles of forest tree species growth and on the methods and tools used to carry the proposed research.

Deliver an oral and written report of the activities carried out in the community, together with a copy of the data collected at the end of each fieldwork season.

Consider authorship of the community or of a community representative in Spanish publications resulting of the proposed research.

Deliver two copies of any type of publication made based on the data coming from the community, and to return the results of the proposed research at a workshop addressed to community members.

Deliver a community photo frame reflecting the community's traditional uses one year after the signing of this collaboration agreement.

Obligations of the campesino community "________________",

The community guarantees the participation of community members to get trained as long as they receive a just salary that will allow them to bring the daily family income to their home.

The community will provide a camping space for the stay of the researcher and her research team, and will also provide a facility to carry the training of the selected community members.

The community commits to take care and to support the researcher to get further founding for creating a self-financing strategy for the continued monitoring of the permanent research plots.

The community consents the researcher to take photographs of the forest and of the people participating in data collection.

The present collaboration agreement is signed by the president of the community and the researcher in a way to make the commitments and obligations indicated in this document effective.

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Name:	For. Eng. Marlene Soriano
Position:	Research associate – IBIF
Community:	PhD candidate – WUR

Chapter 3

Fate of *Bertholletia excelsa* populations under multiple-use forest management

Marlene Soriano, Pieter A. Zuidema, Cristina Barber, Frits Mohren, Nataly Ascarrunz, Alejandra Romero-Seas, Juan Carlos Licona, Marielos Peña-Claros

Summary

1. Multiple-use forest management (MFM) is common practice among rural communities throughout the tropics, yet it is poorly known whether the exploitation of one resource limits that of other resources. The commercial harvest of Amazon or Brazil nut (*Bertholletia excelsa*) seeds and timber of other tree species is a typical case of MFM in South-western Amazon, with Amazon nut being the most important non-timber forest product (NTFP) in the Amazon basin. The species is under serious threat by deforestation and may also be affected by overharvesting. However, selective logging of other tree species coexisting with *Bertholletia* may positively affect *Bertholletia* populations, thus enabling a special case for MFM. For this research, we investigated the impact of the intensity of Amazon nut harvesting and timber logging on the future development of *Bertholletia* populations.

2. We collected demographic data in 24 community-based household forests located in the Bolivian Amazon. In these forests, we established 72 500 m x 40 m (2 ha) transects totalling a sampled area of 144 ha, varying in the intensity of nut collection (0 - 100%) and timber logging (0 - 15% of logging-disturbed forest area). In these transects, we measured growth, survival and recruitment of 702 *Bertholletia* individuals over 1 year. We then used population matrix models to calculate transient population growth rate for 100 years (λ_{100}) for varying intensities of nut and timber harvesting, and with low and high intensity application of liana cutting.

3. A positive effect of logging intensity on *Bertholletia* seedlings growth rate and of liana cutting on fruit production rate played a key role in the overall population growth rate of *Bertholletia*. Seedling growth rate increased with logging intensity ($p = 0.003$), but not after four years since logging ($p = 0.064$). Fruit production was higher in trees that had their lianas cut over the last five years ($p = 0.037$), and nut harvest intensity was higher in more productive trees ($p <0.001$). However, harvesters preference for harvesting high-producing trees over low-producing ones – evidenced by the fewer fruits of larger trees left unharvested in the forest – resulted in an overall decrease of *Bertholletia* fecundity rate under nut harvest intensity. Tree survival was not affected by nut harvesting, logging or liana cutting intensity.

4. Simulated *Bertholletia* population size increased with logging intensity, but decreased with Amazon nut harvesting intensity. *Bertholletia* populations were projected to grow at the average MFM harvest scenario tested: 57.4% of nut harvest, 5.3% of logging-disturbed area (λ_{100} = 1.011). From these simulations, up to 89% of Amazon nut seeds can be harvested – while sustaining a stable *Bertholletia* growth rate of at least 1 – in 15% of logging-disturbed area and with lianas cut from 90% of reproductive Amazon nut trees.

5. Synthesis and applications: Modest levels of timber logging and application of liana cutting may compensate for the negative effect of Amazon nut collection on *Bertholletia* populations for the next century. Our study demonstrates that Amazon nut and timber production could be managed sustainably under a MFM scheme, one that has the potential to increase the economic value of tropical forests. This is particularly relevant in view of the landscape-level management approach being widely implemented in tropical countries such as Bolivia, of which MFM is an important component.

Key-words: Amazon nut harvesting intensity, Bolivian Amazon, Brazil nut, growth rate, survival rate, fecundity rate, liana cutting, population matrix model, timber logging intensity

Introduction

Multiple-use forest management (MFM) has the potential to ensure the conservation of tropical forests in face of increasing demand for food, changing land access rights, and trends in markets (Cronkleton et al., 2012; Sabogal et al., 2013; Shanley et al., 2012). MFM entails the provision of multiple goods and services within a forest management unit area (García-Fernández et al., 2008; Sabogal et al., 2013). The harvest of multiple forest products can have synergic effects between species and effectively increase the provisioning services of a forest, and therefore, the income of forest-dependent people. Amazon or Brazil nut (*Bertholletia excelsa*) harvest and timber logging of other tree species is a common market-oriented multiple use practice among rural communities in a significant part of the Bolivian, Peruvian and Brazilian Amazon. The combined harvest of Amazon nut seeds and timber from other tree species may have synergic effects due to that the majority of these species require higher light levels at early stages of their life cycle like the ones created by logging disturbance (Myers et al., 2000; Schwartz et al., 2012; Silva et al., 1995; Soriano et al., 2012; Zuidema and Boot, 2002), and also because its harvest seasons are complementary to each other (Duchelle et al., 2012; Guariguata et al., 2009).Yet, the harvest of multiple forest products can turn conflicting at times. This may happen when the harvest of a multipurpose plant species requires killing the plant to extract one of its products, or when the harvest of a product disrupts the habitat of other provisioning species. Additionally, MFM encompass many (yet) unknown ecological feedbacks produced by the harvest of timber and non-timber species that need to be understood to guarantee the future availability of the products, and the income of rural families. In this research, we investigated the combined impact of Amazon nut harvesting and logging of commercial timber species on Amazon nut demographic rates with the aim to understand the nature of these ecological feedbacks around Amazon nut production.

Logging, as well as the harvest of many other forest products, alters the reproduction and regeneration of plant species (Hall & Bawa 2010). The extent of this effect depends on the harvest intensity applied, harvest method used, and size of harvested trees (Gourlet-Fleury et al., 2013; Rockwell et al., 2007; Shenkin et al., 2015). Logging disturbance, for instance, favours seedling establishment and growth rate of light-demanding species by increasing light availability in the understory (Van Rheenen et al., 2004) but can also contribute to the local extinction of low-density occurring species when the species is intensively logged (Rockwell et al., 2007; Schulze et al., 2008). Although NTFP harvest has been commonly considered as a benefitial or neutral activity, studies have shown that NTFP harvesting may negatively affect a plant's survival, growth or fecundity rate (Gaoue et al., 2011) due to the extraction of vital parts of a plant (e.g., fruits). In addition, liana cutting, i.e., a common management practice carried by nut collectors, enhances Amazon nut fruit production (Kainer et al., 2007), and may potentially improve *Bertholletia* population stability over the long-run by increasing growth rates (Peña-Claros et al., 2008a). Population stability is determined by lambda (λ), which is the population growth rate once a population has reached a stable size distribution (Caswell, 2001).

A considerable amount of research has focussed on studying the impact of harvesting on timber and NTFP species separately, but only few have assessed the effect of harvesting when multiple products are harvested from the same species (Herrero-Jáuregui et al., 2011; Klimas et al., 2012a) or from more species (Salick, Mejia & Anderson 1995; Guariguata et al., 2009; Soriano et al., 2012, Moll-Rocek et al., 2014) within a MFM scheme. Most of these studies focus on a specific life stage (e.g., seedlings) or on a specific part (e.g., fruits) of a plant. The increasing rate of Amazon nut harvesting and logging occurring in the Bolivian Amazon calls for studying the effects of Amazon nut harvest and logging intensities on *Bertholletia* long-term population dynamics under a MFM scheme. We investigated this by asking two questions. First, we asked what the effects of Amazon nut harvesting and logging intensities are on *Bertholletia* survival, growth and fecundity rates. We expect that logging intensity will increase *Bertholletia* growth and recruitment rates due to increased light availability (Cotta et al., 2008; Soriano et al., 2012; Zuidema and Boot, 2002) created by logging (Soriano et al., 2012). Additionally, we expect that logging intensity will decrease *Bertholletia* survival rate of small individuals due to increased agouti predation of 1-year old recruits (D'Oliveira, 2000) and of large individuals due to an increased susceptibility to windblown caused by the logging of neighbouring timber trees. Furthermore, we expect no effect of logging intensity on *Bertholletia* reproduction rate due to low logging intensity rates inherent of the region (Guariguata et al., 2009; Rockwell et al., 2015). Finally, we expect that Amazon nut harvesting intensity will not have an effect on growth or survival rates because the harvest of nuts does not imply as much habitat disturbance as logging. With regards to *Bertholletia* fecundity, *Bertholletia* reproduction rates will increase mainly due to the cutting of lianas applied by collectors during Amazon nut harvest (Kainer et al., 2014; Soriano et al., 2017). Then, we asked under what Amazon nut harvesting, logging and liana cutting intensities can *Bertholletia* populations be sustained in the future. We expect that the combined Amazon nut harvesting and logging of other timber species will contribute more to an increase of *Bertholletia* transient population growth rate (λ_{100}) than the harvest of only Amazon nut; whereas, liana cutting intensity will contribute to *Bertholletia* transient population growth rate by increasing fruit production rate.

Methods

Study site

This study was carried out in the Department of Pando, and the Vaca Díez province in the Beni Department of the Bolivian Amazon region. Approximately 95% of the region is covered by forest (Marsik et al., 2011), which comprises 30% of Bolivia's timber production forests (8.8 out of 28.8 mill. ha; Hjortsø et al., 2006). Tree diversity ranges from 52 - 122 species ha^{-1} with a density between 544 - 627 trees ha^{-1} of trees ≥10 cm diameter at 1.3 m aboveground (DBH) (Mostacedo et al., 2006). The annual rainfall varies between 1,774 - 1,934 mm, while the mean annual temperature differs slightly between the two main regional cities: Cobija (25.4ºC) and Riberalta (26.2ºC) (Zonisig, 1997). The region presents a relatively dry season from May through September with <60 mm of monthly rainfall. Its topography varies from *terra firme* (or upland) to seasonally flooded forests. *Terra firme* forests grow on soils with low fertility (i.e., high aluminium toxicity), while seasonally flooded areas have relatively high nutrient-rich soils due to the sediments carried by rivers originating in the Andes (Zonisig, 1997).

The region has a long history of NTFP exploitation but a more recent history of timber exploitation (Bojanic, 2001). Amazon nut is the most recent NTFP under exploitation and is the keystone of the regional economy. Whereas, timber is increasing in importance such that already 77% (189 communities out of 245; Pacheco et al., 2009) of *campesino* communities are engaged in timber management (Bolivia's Forest and Land Controlling Authority – ABT, unpublished data). For this study, we selected six *campesino* communities with a relatively long-standing engagement in timber management under a community forest management plan (CFMP) (Table 3.1). See Appendix S3.1 in Supporting Information for detailed information about the legal framework to log timber and harvest Amazon nut in *campesino* communities. The harvest of forest products at the household forest-level allowed us to account for households' forest as our main sampling unit. Thus, we selected 24 household forests that represented a wide range of Amazon nut harvesting and timber logging intensities occurring in the region. Among the 24 household forests, we made sure to select an unlogged (control) household forest in each community.

Species description

Bertholletia excelsa is a long-lived pioneer tree species that grows in the Amazonian upland or "*terra firme*" forest. As a light demanding species, *Bertholletia* needs disturbance for its germination and growth (Zuidema and Boot, 2002). *Bertholletia* regeneration density (individuals ≤10 cm DBH per hectare) ranges from 3 - 5 individuals in undisturbed forests (Kainer et al., 1998; Zuidema, 2003), 5.8 - 7.6 individuals in logged forests (Soriano et al., 2012), to 17 - 27 individuals in abandoned fallows (Cotta et al., 2008; Paiva et al., 2011). The agouti (*Dasyprocta* spp.), a rodent that scatters and buries *Bertholletia* seeds as food reserve, is the main seed disperser (Zuidema and Boot, 2002). Agouties disperse seeds within 15 - 30 m distance from the parent tree, reaching a maximum of 60 m (Haugaasen et al., 2012). Occasionally agouties forget buried seeds, which increases the chances of these seeds to germinate (Haugaasen et al., 2012; Zuidema and Boot, 2002). Seeds germinate within 1.5 years (Zuidema and Boot, 2002). *Bertholletia* survival is high compared to most tropical tree species, yet, increases with tree size (Zuidema and Boot, 2002). It can take *Bertholletia* individuals >100 years to reach the reproductive stage (Zuidema, 2003), whereas its reproductive stage can last over 150 years (Brienen and

Zuidema, 2006; Zuidema and Boot, 2002). Its clustered distribution is attributed to past human manipulation (Levis et al., 2017; Paiva et al., 2011; Shepard Jr and Ramirez, 2011).

Study design

In 2014, 72 transects were placed at the selected 24 household forests (three transects per household forest). Each transect had 500 m x 40 m (2 ha), totalling 144 ha of sampled area. Transects were established at random to account for the variability on *Bertholletia* populations across the Bolivian Amazon region. The distance between transects established at each household forest varied between 500 - 1000 m as to comply with sampling independence. Amazon nut was harvested from all selected household forests on a yearly basis, but only three household forests were solely harvested for Amazon nut seeds. Twenty-one household forests underwent timber logging at least once over the last 10 years prior to data collection: Eighteen were logged once under the legal framework of the 1996 Forestry Law, and 12 were logged once during the two years of data collection under the small-scale timber logging operation modality (ABT Directive Nº 001/2014). We did not account for the impact of small-scale timber logging operations in our analyses because its incidence within the research transects was minimal (disturbed 0.06% of the total sampled area).

Collection of demographic data

At the moment of plot establishment, all *Bertholletia* individuals ≥10 cm DBH were inventoried, mapped and tagged within the entire transect area; individuals ≤10 cm DBH were sampled from within a quarter of the transect area (the inner 10 x 500 m). Height of individual's ≤2.5 m was measured with a meter tape and height of larger individuals was estimated. DBH of individuals ≥1.5 m in height was measured with a diameter tape and DBH of individuals ≤5 cm was measured with a calliper. Categories of crown position (Dawkins and Field, 1978), crown form (Dawkins and Field, 1978), and degree of liana infestation were estimated for all trees. The reproductive status and evidence of liana cutting of trees ≥30 cm DBH were also recorded. A description of the variables measured can be found in Table S3.1, in Supporting Information. All individuals were re-measured in 2015, and new individuals were included. We corrected the DBH of trees measured at a different measurement height than the standard 1.3 m aboveground following the equation of Metcalf et al. (2009), the most reliable tapering approximation for tropical trees (Cushman et al., 2014), further explained in Soriano et al. (2017).

Amazon nut production and harvesting intensity

At the end of the 2013 - 2014 and 2014 - 2015 harvest seasons, we counted all fallen Amazon nut fruits within a radius of 30 m around the trunk of each producing tree (trees >30 cm DBH, the size at which trees started to produce fruits at our study sites) encountered within the transects. Fallen fruits were classified in one of three categories: harvested by people (i.e., machete-opened fruits commonly found gathered near each tree), opened by *Dasyprocta* spp. or unharvested/unopened (i.e., fruits not found by the collectors or the seed disperser). Harvested fruits and unopened fruits gathered next to a producing tree (clearly intended for harvesting too) were put together to calculate the percentage of fruits harvested per reproductive tree and per transect. The number of fruits left unharvested in the forest (unopened and agouti-opened fruits) was also used to investigate their role in the number of new recruits. We did not account for the 6.3% of fruits removed by agouties beyond the 30 m from where fruits originally fell below a tree crown (Haugaasen et al., 2012) in our calculations of fruits count because this percentage can be lower in the Bolivian Amazon due to that harvesters make frequent visits to the forest to harvest seeds, leaving fewer fruits for agouties dispersal. As the counting was done at the end of the harvest season, we assumed that the percentage of non-counted fruits was very small. Thus, the average number of fruits produced and the percentage of harvested fruits over the two-year period were used as proxies for Amazon nut production and harvesting intensity, respectively.

Timber logging intensity

We evaluated logging disturbance by measuring the areas of logging gaps, log landings, access roads and skid trails occurring within the transects. Following the protocol of Contreras et al. (2001), the area disturbed in logging gaps and log landings was estimated as described by Soriano et al. (2012). To calculate the area disturbed by access roads and skid trails, we measured the total length of those found inside the transects and measured their width at three randomly chosen points. The area disturbed was then calculated as the product of the length and the average width. The sum of all disturbed areas in each 2 ha transect was extrapolated to calculate the percentage of disturbed area per transect. We also obtained other logging intensity measures such as the number of harvested trees and harvested volume per hectare, and found that disturbed area is strongly correlated with both: number of logged trees (r = 0.70) and harvested volume (r = 0.63). Percentage of disturbed area was preferred over the other two logging intensity measures because percentage of disturbed area can be a better indicator of light availability to which survival, growth and recruitment responds more directly.

Relating vital rates to size, harvest intensities and liana cutting

We used backward regression analysis to determine the effects of variables related to tree size (e.g., diameter), tree condition (e.g., crown position), site-specific harvesting intensity (nut and timber) and management (liana cutting) on survival, growth and fecundity (see Table S3.1). Categorical variables (e.g., crown position) were included as dummy variables.

Given that the effect of our selected explanatory variables on growth and survival rates may differ throughout a plant's life cycle, we ran separate regression models for three broad size categories: ≤1 cm DBH (seedlings), 1 - 50 cm DBH (juveniles) and >50 cm DBH (adults) (see Table S3.2). Survival probability was predicted using a logistic regression model, using the glm function in R (R Development Core Team, 2015). However, juveniles and adults were combined to model survival rates because the initial size appeared to be the only predictor of survival. Three separate multiple linear regression models were ran to estimate *Bertholletia* growth rate because logging disturbance might be more important for the growth of seedlings (Soriano et al., 2012) and juveniles (Staudhammer et al., 2013) than for adults, whereas liana cutting might be more important for the growth of adults (Peña-Claros et al., 2008a; Villegas et al., 2009). We included time since logging among the predictors of seedling growth in spite of its slightly low significance level ($p < 0.1$) because logging intensity has a significant effect on seedling growth rate few years following logging (Schwartz et al., 2012; Silva et al., 1995). All analyses described in here were done in R (R Development Core Team, 2015).

Fecundity was calculated based on the probability of *Bertholletia* trees >30 cm DBH being reproductive, fruit production, and new recruits per unharvested fruits. The effect of size, size-squared, individual characteristics and harvesting intensity on the probability of *Bertholletia* being reproductive was predicted using logistic regression model under the glm function in R (R Development Core Team, 2015). We assumed a negative binomial distribution to predict *Bertholletia* fruit production due to the high variability found on fruit production among reproductive trees. For this, we used the glm.nb function developed under the MASS package (Ripley et al., 2016) in R (R Development Core Team, 2015). We used the lrm function developed under the rms package (Harrell, 2016) in R (R Development Core Team, 2015) to obtain the pseudo r^2 for our non-linear models of survival, reproduction probability and fruit production because these were not provided in the models' output.

Matrix construction

We classified *Bertholletia* individuals in 26 size-classes (see Table S3.2) to build two, 26 x 26 size-structured matrices, one matrix (Table S3.3) to account for the effects of logging disturbance on the growth rate of seedlings during the first 4 years following to logging, and another matrix (Table S3.4) to exclude this effect over the remaining 16 years of a timber cutting cycle. Such differentiation was not needed to incorporate the effect of Amazon nut harvesting intensity on any of *Bertholletia* vital rates because Amazon nut is harvested in a yearly basis, which is equivalent to the transition period of the matrix elements. We also incorporated the effect of a one-time application of liana cutting intensity into each matrix. Regression models for vital rates were used to calculate the matrix elements: progression, stasis and fecundity. Progression elements (G) represent the probability of an individual to grow from one size class (G_i) to the next: $G_i = C_i \cdot r_i$, where C_i is the probability that a surviving individual in size class i grows to the next class (i +1) and r_i is the annual survival probability in class i. $C_i = g_i / c_i$, where g_i is the height or DBH growth rate for class i, and c_i is the class width. Stasis elements (P) represent the probability that a surviving individual stays in the same size class: $P_i = r_i - G_i$. Fecundity elements (F) represent the production of new recruits per individual in a reproductive class: $F_i = r_i \cdot f_i$, where f_i is expressed as the new recruits produced by an individual in class i. $f_i = j_i \cdot k_i \cdot l_i$, where j_i is the probability of an individual in class i being reproductive, k_i is the number of unharvested fruits from an individual in class i, and l_i is the average number of observed new recruits per unharvested fruit. $k_i = ((Pk_i \cdot m_i)/100) \cdot (100 - h_i)/100))$, where Pk_i is the observed percentage of unharvested fruits in class i, m_i is the number of fruits obtained from the regression analysis (Table 3.1) in class i, and h_i is the percentage of harvested fruits (harvesting intensity). We could determine the overall effect of Amazon nut harvesting intensity on fruit production rate by incorporating the effect of harvesting intensity on the percentage of fruits left unharvested in the forest in function of tree size. We then built transition matrices in function of the effects of intensity of nut harvesting, logging and liana cutting of reproductive Amazon nut trees on *Bertholletia* vital rates, over which we calculated population growth rate, and simulated the population structure of different levels of exploitation and liana cutting.

A first matrix was multiplied four times to account for the initial effect of logging on seedling growth rate (Table 3.1). Then, the resulting matrix was multiplied by the matrix not accounting for the effect of logging until completing the 20-year rotation cycle, i.e., the minimum timber cutting cycle being used in the Bolivian Amazon (Proyecto de Manejo Forestal Sostenible, 1997). Based on this final matrix, we simulated the population growth rate and population structure after 100 years upon accounting for the initial population structure after each rotation cycle. Thus, we used a 20-year periodic matrix model (Caswell, 2001) for which we calculated elasticities for the average Amazon nut harvesting, logging, and liana cutting intensity following Zuidema and Boot's (2002) procedure.

We simulated the following management scenarios: the average observed combination of Amazon nut harvesting (57.4%) and timber logging intensities (5.3%), and all possible combinations of three Amazon nut harvesting intensities (0, 75, 100%) and 3 timber logging intensities (0, 10, 15%). Simulated harvesting intensities were limited by the observed ranges at our sampled household forests (Table 3.1). *Bertholletia* population growth rate values were obtained for each combination of harvest intensity under 21% (observed average percentage of trees with lianas cut) and 90% (hypothetical assumption) of reproductive trees with lianas cut. In addition, for each liana cutting intensity tested, we searched harvesting intensity thresholds at which *Bertholletia* populations are stable by increasing and decreasing the percentages of timber and Amazon nut harvesting intensities by one factor.

Results

Effects of Amazon nut harvesting and logging on *Bertholletia* vital rates

We found that the effect of Amazon nut harvesting, logging and liana cutting intensities on *Bertholletia* vital rates varied with *Bertholletia*'s size, especially when it comes to growth and reproduction (Table 3.1). Regarding survival, seedling survival probability ranged from 75 to 87% and was only, and positively affected by initial size ($r^2 = 0.11$, $p = 0.018$). Initial size also explained 40% of juvenile and adult survival ($p = 0.074$). We kept initial size in the model even at a probability of <0.1 because it was the single most important predictor.

Logging increased *Bertholletia* seedling growth during only the first four years following logging. In average, the growth rate of seedlings increased with logging intensity ($p = 0.003$) but decreased with time since logging ($p = 0.064$). These two variables together explained little of the variation in growth rate ($r^2 = 0.08$). In average, *Bertholletia* seedlings grew 1.7 cm year^{-1} more in height during the first four years after logging than during the subsequent 16 years of the timber cutting cycle (3.8 and 2.1cm year^{-1}, respectively). Initial DBH increased juveniles growth rate ($r^2 = 0.20$, $p < 0.001$), but decreased adults growth rate ($p = 0.002$). However, crown shape ($p = 0.039$, perfect crown) and crown position ($p = 0.013$, full light) counteracted the negative effect of initial DBH. All variables together explained 15% of the variation in adults DBH growth ($r^2 = 0.15$). DBH growth rate peaked in individuals between 40 - 50 cm DBH (1.3 cm year^{-1}). They grew 1 cm more than individuals >170 cm DBH (0.23 cm year^{-1}; Table S3.5).

Initial DBH was also the only main predictor of the probability of individuals >30 cm DBH being reproductive ($r^2 = 0.30$, $p < 0.001$). Trees between 30 - 40 cm DBH had 16% probability of being reproductive, whereas, trees >60 cm DBH had over 99% chance of being reproductive (Table S3.5). Initial DBH ($p < 0.001$), Amazon nut harvesting intensity ($p < 0.001$) and liana cutting ($p = 0.037$) determined fruit production ($r^2 = 0.55$, Table 3.1). Results of our logistic regression analysis showed an exponential increase in fruit production with tree size: without nut harvest and without liana cutting, trees >170 cm DBH produced 179 more fruits year^{-1} than trees between 30 - 40 cm DBH; 218 vs. 39 fruits year^{-1}, respectively. In contrast, the percentage of unharvested fruits per reproductive tree decreased with tree size. 100% of fruits produced by trees between 30 - 40 cm DBH, 51.3% by trees between 50 - 60 cm DBH, 9.4% by trees between 50 - 60 cm DBH, and 12.4% of trees >170 cm DBH were left unharvested (Table S3.5). The number of new individuals per reproductive trees increased with tree size: trees between 30 - 40 cm DBH produced 0.17 new recruits, whereas, trees >170 cm DBH produced 0.72 new recruits (Table S3.5).

Table 3.1. Models and corresponding significant predictors of *Bertholletia excelsa* vital rates. These regressions results are used to calculate the matrix elements. Significance levels are marked with asterisks: * p-value <0.05, ** p-value <0.01, *** p-value <0.001. DBH = diameter at 1.3 m aboveground.

<table>
<tr><th>Response</th><th>size class</th><th>R-square</th><th>significant predictors</th><th>Estimate</th><th>p-value</th></tr>
<tr><td rowspan="4">Survival</td><td rowspan="2"><1cm DBH</td><td rowspan="2">0.11</td><td>Intercept</td><td>0.617</td><td>0.145</td></tr>
<tr><td>Initial height (m)</td><td>1.921</td><td>0.018*</td></tr>
<tr><td rowspan="2">>1cm DBH</td><td rowspan="2">0.40</td><td>Intercept</td><td>13.687</td><td>0.021*</td></tr>
<tr><td>Initial DBH (cm)</td><td>-0.056</td><td>0.074</td></tr>
<tr><td rowspan="12">Growth</td><td rowspan="3"><1cm DBH</td><td rowspan="3">0.08</td><td>Intercept</td><td>0.054</td><td>0.046*</td></tr>
<tr><td>Percentage of area disturbed due to logging</td><td>0.011</td><td>0.003**</td></tr>
<tr><td>Years since last logging</td><td>-0.008</td><td>0.064</td></tr>
<tr><td rowspan="2">1 - 50 cm DBH</td><td rowspan="2">0.2</td><td>Intercept</td><td>0.282</td><td><0.001***</td></tr>
<tr><td>Initial DBH (cm)</td><td>0.022</td><td><0.001***</td></tr>
<tr><td rowspan="7">>50 cm DBH</td><td rowspan="7">0.15</td><td>Intercept</td><td>0.466</td><td>0.247</td></tr>
<tr><td>Initial DBH (cm)</td><td>-0.007</td><td>0.002**</td></tr>
<tr><td>Full light</td><td>0.601</td><td>0.013*</td></tr>
<tr><td>Vertical light</td><td>0.313</td><td>0.279</td></tr>
<tr><td>Perfect crown</td><td>0.614</td><td>0.039*</td></tr>
<tr><td>Good Crown</td><td>0.302</td><td>0.297</td></tr>
<tr><td>Fairly good crown</td><td>0.293</td><td>0.353</td></tr>
<tr><td rowspan="2">Probability of being reproductive</td><td rowspan="2">>30 cm DBH</td><td rowspan="2">0.30</td><td>Intercept</td><td>-9.43</td><td><0.001***</td></tr>
<tr><td>Initial DBH (cm)</td><td>0.222</td><td><0.001**</td></tr>
<tr><td rowspan="4">Fruit production</td><td rowspan="4">>30 cm DBH</td><td rowspan="4">0.55</td><td>Intercept</td><td>1.367</td><td>0.004**</td></tr>
<tr><td>Initial DBH (cm)</td><td>0.012</td><td><0.001***</td></tr>
<tr><td>Amazon nut harvesting intensity (% harvested fruits)</td><td>0.033</td><td><0.001***</td></tr>
<tr><td>Liana cutting</td><td>0.497</td><td>0.037*</td></tr>
</table>

Bertholletia populations under Amazon nut harvesting and timber logging intensities

Bertholletia's transient population growth rate (λ_{100}) appeared stable in most simulated scenarios with combined Amazon nut harvest and timber logging intensities (Fig. 3.1), but all simulated population

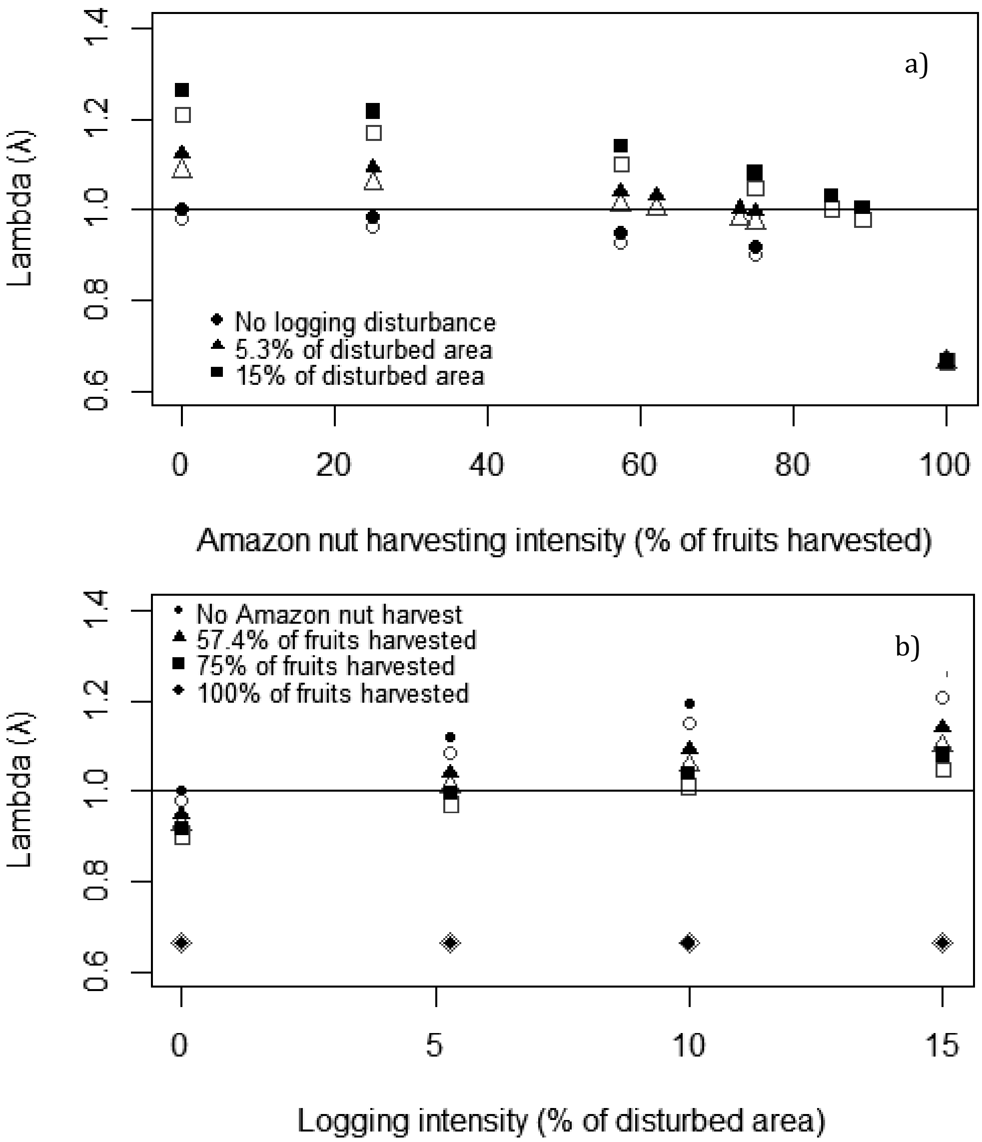

Figure 3.1. Impact of (a) Amazon nut (*Bertholletia excelsa*) harvesting and (b) logging intensity on *Bertholletia* transient population growth rate in the Bolivian Amazon. Empty and filled shapes are the population growth rate values for 100 years (λ_{100}) with lianas cut from 21% (average observed percentage from our studied populations) and 90% (hypothetical) of reproductive trees, respectively.

densities decreased from the initial population in the first logging rotation cycle (Fig. 3.2). Simulated population size increased at higher logging intensity, but decreased at higher Amazon nut harvesting intensity. Under the average observed percentage (21%) of reproductive Amazon nut trees with lianas cut, *Bertholletia* population growth rate was projected to be stable after 100 years under the average combination of Amazon nut harvesting and timber logging intensities (λ_{100} = 1.011, Fig. 3.1a), as opposed to an unstable unharvested scenario (λ_{100} = 0.979, Fig. 3.1a). However, after 100 years *Bertholletia*'s simulated population density was slightly lower in the scenario with average Amazon nut harvesting and timber logging intensities than at the unharvested one (10.4 and 12.8 ind. ha^{-1}, respectively, Fig. 3.2a). *Bertholletia*'s simulated population density increased by 31% under the average logging intensity and without Amazon nut harvest scenario (λ_{100} = 1.086, Fig. 3.1a; 16.8 ind. ha^{-1}, Fig. 3.2a), but decreased by 54% under the average Amazon nut harvesting intensity and without logging scenario (λ_{100} = 0.928, Fig. 3.1a; 8.3 ind. ha^{-1}, Fig. 3.2a) from the unharvested population. Thus, the population under the highest logging intensity (15% of disturbed area) and lowest Amazon nut harvesting intensity (0% of fruits harvested) tested presented the largest simulated population size (λ_{100} = 1.208, Fig. 3.1a; 25.4 ind. ha^{-1}, Fig. 3.2a) after 100 years.

Liana cutting intensity improves *Bertholletia* population growth rate

Simulation results showed a favourable impact of liana cutting on *Bertholletia* population growth rate. This impact however, decreased at higher nut harvest and logging intensity. Simulated liana cutting of 21 and 90% reproductive Amazon nut trees allowed for an increase of 15% (i.e., from 62 to 73% harvested fruits) to 4.5% (i.e., from 85 to 89% harvested fruits) of Amazon nut harvest intensity under the average 5.3% and 15% of logging disturbance intensities, respectively; provided population growth rates above 1 (Fig. 3.2).

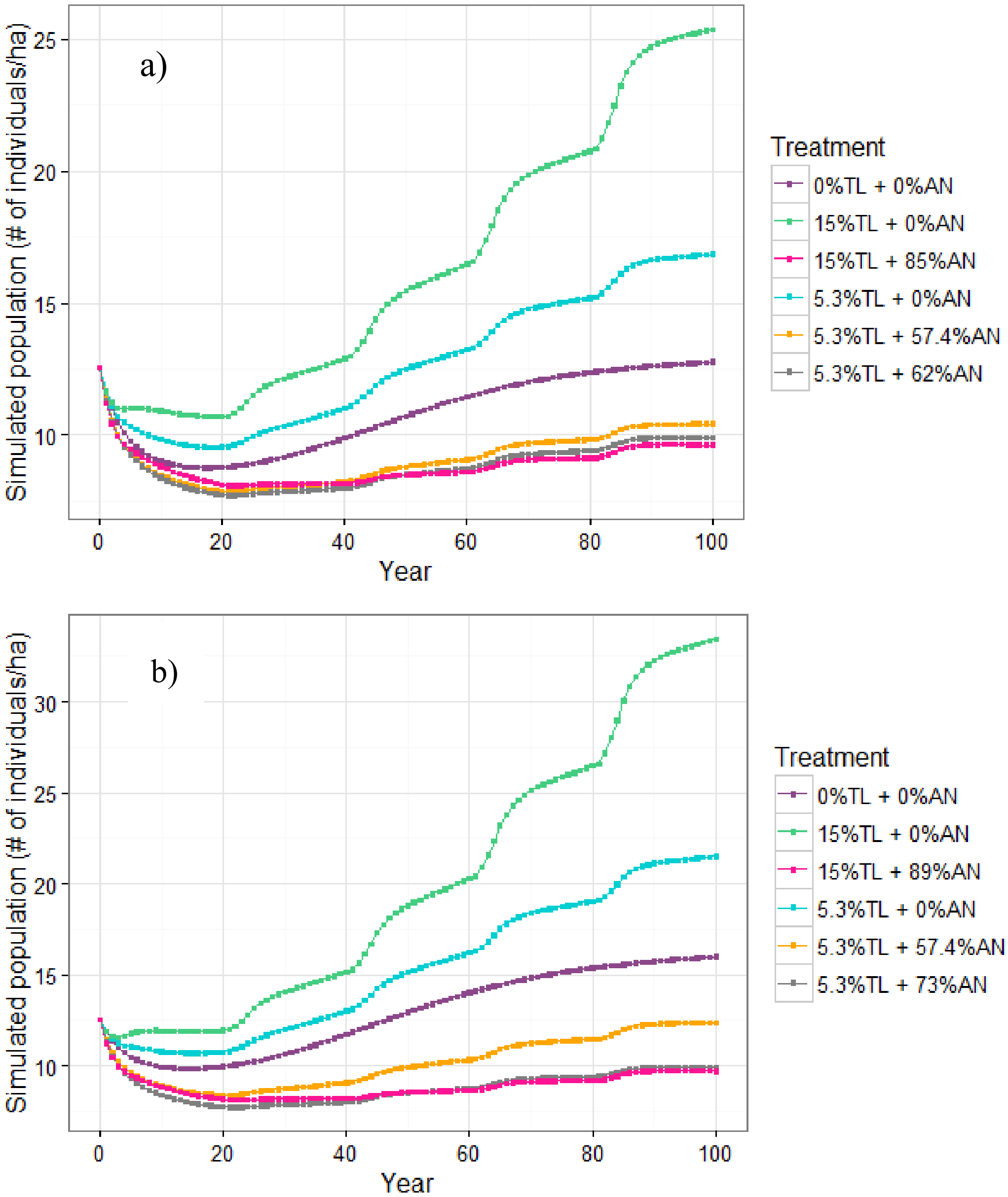

Figure 3.2. Simulated population densities of Amazon nut (*Bertholletia excelsa*) under several combinations of logging and Amazon nut harvesting intensities in which *Bertholletia* transient population growth rate was at least equal to 1 after 100 years (λ_{100} >1) compared to an unharvested (λ_{100} = 0.979) scenario (0% timber logging (TL) + 0% Amazon nut harvesting (AN) intensities). Scenarios of simulated populations are for liana cutting intensity of a) 21% (average) and b) 90% (hypothetical) of reproductive trees with lianas cut. Initial steep decrease of the simulated *Bertholletia* population is due to the initial population structure with an average Amazon nut harvesting and timber logging intensities.

Elasticity analyses for year 20 (end of the first cutting cycle) showed that the asymptotic population growth of *Bertholletia* was more sensitive to changes in the progression and growth matrix elements than to those in reproduction (Fig. 3.3).

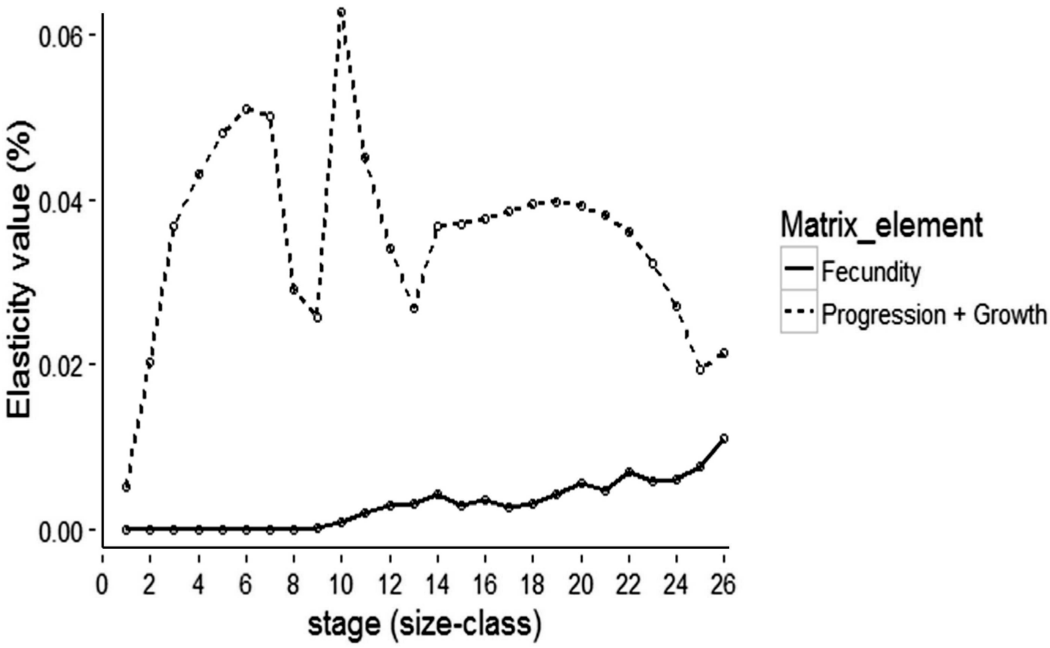

Figure 3.3. Elasticity values of *Bertholletia excelsa* populations under the average timber logging (5.3% of disturbed area) and Amazon nut harvesting (54.7% of harvested fruits) intensities, with lianas cut from 21% of reproductive trees. Stages 1 - 6 correspond to seedlings, stages 7 - 12 to juveniles, and stages 13 - 26 to adults.

Discussion

The positive effect of logging disturbance intensity on *Bertholletia* seedling growth rate and of liana cutting on fruit production rate played a key role on *Bertholletia* population growth rate after 100 years. This implies that Amazon nut can be harvested more intensively under higher timber logging intensity (up to 15% of disturbed area, the maximum logging intensity found in the study area) and when lianas are cut from a larger percentage of reproductive trees (up to 90% of trees).

Logging improves *Bertholletia* seedlings growth, but Amazon nut harvest decreases *Bertholletia* fecundity

We expected a positive effect of timber logging intensity on *Bertholletia* survival, growth and recruitment rates, but logging only affected seedling growth positively (Table 3.1). However, the effect of logging was not significant after four years. Four years after logging, our predicted growth rate ($Growth_{4\ yrs.}$ = 2.1) approximated to the average growth of two unlogged *Bertholletia* populations in the region ($\bar{x}$ = 2.40; Zuidema 2003). These findings are consistent with growth patterns of planted *Bertholletia* seedlings in logging gaps (D'Oliveira, 2000), and are related to the increase in light levels due to logging. Initial DBH was the only predictor of juvenile growth rate at our study sites, which differed from Staudhammer *et al.*'s (2013) study, who found that crown form and crown position are most critical for *Bertholletia* juvenile growth rate (5 - 50 cm DBH). However, these two variables, together with initial DBH, determined *Bertholletia* adult growth rate at our study sites (Table 3.1).We also expected that logging intensity may decrease *Bertholletia* survival, both of seedlings (D'Oliveira, 2000) and *Bertholletia* adult trees. We found, however, that the impact of logging intensity was not detectable on *Bertholletia* survival. Studies done in the Peruvian Amazon (Rockwell et al.(2015); Guariguata et al. 2009) have found that logging did not have an effect on *Bertholletia* fruiting and degree of damage to nut-producing trees due to low logging intensities. We believe that our lack of logging effects on *Bertholletia* survival may as well be due to the low logging intensities at our study sites.

Our estimated probability for *Bertholletia* trees of being reproductive was higher than the probabilities found by Zuidema and Boot (2002). They found that trees >40 cm DBH had 50% probability of being reproductive, whereas we found that trees of similar size had 63% probability of being reproductive. We attributed this variation on reproduction probability to the geographical focus of their study sites (two communities) and ours (six communities) implying that *Bertholletia´*s reproduction capacity varies even within the same region. Despite the positive effect of Amazon nut harvesting intensity on fruit production, and upon accounting for the positive relationship between tree size and percentage of unharvested fruits, Amazon nut harvesting intensity decreased *Bertholletia*'s overall fecundity rate. However, liana cutting increased *Bertholletia* fecundity rate by increasing fruit production as predicted (Table 3.1). In line with our expectations, logging had no effect on Amazon nut production, probably due to the low logging intensity found at our research site and to the fact that loggers avoid to damage large Amazon nut trees because those are easily recognizable (Guariguata et al., 2009).

Bertholletia excelsa population growth rate improves under multiple use forest management

Our population matrix analyses indicated a stable *Bertholletia* transient population growth rate at the average Amazon nut harvesting, logging and liana cutting intensities (Fig. 3.1). The positive effect of logging intensity on *Bertholletia* population growth rate is likely related to its positive effect on seedling growth during the first four years since logging. This demonstrates that gaps created by logging play a role, not only in improving *Bertholletia* regeneration density (Moll-Rocek et al., 2014; Soriano et al., 2012) but also in its long-term population stability. A higher logging (up to 15% disturbed area) and liana cutting intensity (up to 90% of reproductive trees with lianas cut) could potentially allow harvesting a large percentage (up to 89%) of Amazon nut seeds, and still ensure *Bertholletia* population stability. However, reported simulation results must be viewed and interpreted conservatively as those are projections and not predictions.

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Supporting Information

Appendix S3.1. Legal framework to harvest Amazon or Brazil nut (*Bertholletia excelsa*) and to log commercial timber species at community-managed forests in the Bolivian Amazon.

Timber logging under a community forest management plan (CFMP) in Bolivia is based on a general inventory of trees, and identification of logging compartments and of protection zones. To log timber from a logging compartment it is required to carry a pre-logging census of timber trees >40 cm diameter at 1.3 m aboveground (DBH), to plan a road infrastructure to extract trees, and to leave sufficient seed trees to guarantee natural regeneration by leaving timber species with low abundance and at least 20% of trees ≥ the minimum diameter cutting (MDC) of harvestable species (Proyecto de Manejo Forestal Sostenible, 1997). The MDC varies between 50 - 70 cm DBH, depending on the species (Ministerio de Desarrollo Sostenible y Medio Ambiente, 2000). A most recent modality for logging timber in the Bolivian Amazon is the small-timber volume logging operation, which allows each community household to log ~7 m^3 of timber six times a year following few management considerations in addition to timber being logged under the community forest management plan (CFMP), and prohibits the harvest of timber species listed in CITES Appendices I and II (Bolivia's Forest and Lands Controlling Authority – ABT Directive Nº 001/2014; Integral Management of Forests and Lands Plan in Bolivia - PGIBT, acronym in Spanish, *Plan de Gestión Integral de Bosques y Tierras*, ABT Administrative Resolution Nº 250/2013). Currently, national policies enable Integral Management of Forests and Lands (ABT Administrative Resolution Nº 250/2013), a landscape-level management approach that integrates the management of timber and non-timber forest products, and agriculture and pasture lands altogether. The legal framework for Amazon nut management requires to leave 10% of the area under management unharvested (ABT Administrative Resolution Nº 174/2008), and prohibits to make a re-entrance to harvest the remaining area under management (ABT Administrative Resolution Nº 250/2013).

Table S3.1. Variables used in the regression models to analyse the response of *Bertholletia excelsa* vital rates to timber logging and Amazon nut harvesting.

Response variables	**Survival rate:** trees that survived or died between 2014 and 2015. (0) Dead, (1) Alive
	Height growth rate: m that an individual grew between 2014 and 2015 (m $year^{-1}$)
	DBH growth rate: cm that an individual grew between 2014 and 2015 (cm $year^{-1}$)
	Probability of being reproductive: Chance of an individual to produce fruits.
	Fruit production: Average percentage of fruits produced between 2014 and 2015 per reproductive tree (# reproductive fruits $tree^{-1}$)
Explanatory variables	**Initial size:** Size of a tree measured at plot establishment.
	Logging intensity: Percentage of area disturbed due to logging (%)
	Years since last logging: Time that has passed since last logging to plot establishment in 2014. Unlogged sites have a value of zero.
	Amazon nut harvesting intensity: Percentage of harvested fruits (%)
	Liana cutting: (1) tree with lianas cut, (0) tree without lianas cut
	Liana cutting intensity: Proportion of reproductive trees with lianas cut in a transect
	Crown position: (1) crown receiving full light, (2) crown receiving only vertical light, (3) crown receiving some vertical light, (4) crown receiving only lateral light, (5) crown receiving some light or no direct light
	Crown form (1) perfect, (2) good, (3) fairly good
	Liana infestation: (1) lianas affecting growth, i.e., trees with lianas reaching the crown; (0) lianas not affecting growth, i.e., trees without lianas and with lianas around the trunk

Table S3.2. Classification used to build *Bertholletia excelsa* size-structured matrices (size-classes). Stages in bold are reproductive stages because trees larger than 30 cm diameter at 1.3 m aboveground (DBH) presented fruits at our studied sites.

Size groups for modelling vital rates	Stage	Height (m)
Individuals ≤3 m height but ≤ 1 cm DBH (Seedlings)	1	0.0 - 0.5
	2	0.5 - 1.0
	3	1.0-1.5
	4	1.5 - 2.0
	5	2.0 - 2.5
	6	2.5 - 3.0
		DBH (cm)
Individuals 1 - 50 cm DBH (Juveniles)	7	1 - 4
	8	4 - 7
	9	7 - 10
	10	10 - 20
	11	20 - 30
	12	**30 - 40**
	13	**40 - 50**
Individuals >50 cm DBH (Adults)	**14**	**50 - 60**
	15	**60 - 70**
	16	**70 - 80**
	17	**80 - 90**
	18	**90 - 100**
	19	**100 - 110**
	20	**110 - 120**
	21	**120 - 130**
	22	**130 - 140**
	23	**140 - 150**
	24	**150 - 160**
	25	**160 - 170**
	26	**>170**

Table S3.3. Output of the size-structured matrix with the effect of logging disturbance on *Bertholletia excelsa* population growth rate during the first four years following to logging.

Stage	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	0.603	0	0	0	0	0	0	0	0	0	0	0.080	0.151	0.307	0.084	0.202	0.093	0.089	0.111	0.209	0.093	0.216	0.157	0.143	0.275	0.335
2	0.146	0.714	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0.173	0.767	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0.186	0.790	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0.192	0.799	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0.194	0.803	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0.195	0.888	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0.112	0.874	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0.126	0.859	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0.141	0.939	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0.061	0.918	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0.082	0.896	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0.104	0.875	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0.125	0.912	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0.088	0.917	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.083	0.923	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.077	0.928	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.072	0.933	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.066	0.939	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.061	0.944	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.056	0.949	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.050	0.953	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.045	0.957	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.039	0.960	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.034	0.960	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.028	0.980
Total	0.750	0.887	0.953	0.982	0.993	0.997	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.999	0.999	0.998	0.996	0.993	0.988	0.980

Table S3.4. Output of the size-structured matrix without the effects of logging disturbance on *Bertholletia excelsa* population growth rate during 16 years out of the 20 years timber cutting cycle.

Stage	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	0.718	0	0	0	0	0	0	0	0	0	0	0.080	0.151	0.307	0.084	0.202	0.093	0.089	0.111	0.209	0.093	0.216	0.157	0.143	0.275	0.335
2	0.032	0.849	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0.038	0.913	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0.041	0.940	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0.042	0.951	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0.042	0.955	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0.042	0.888	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0.112	0.874	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0.126	0.859	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0.141	0.939	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0.061	0.918	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0.082	0.896	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0.104	0.875	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0.125	0.912	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0.088	0.917	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.083	0.923	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.077	0.928	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.072	0.933	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.066	0.939	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.061	0.944	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.056	0.949	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.050	0.953	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.045	0.957	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.039	0.960	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.034	0.960	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.028	0.980
Total	0.750	0.887	0.953	0.982	0.993	0.997	1.000	1.000	1.000	1.000	1.000	1.080	1.151	1.307	1.085	1.202	1.093	1.089	1.110	1.208	1.092	1.213	1.153	1.137	1.264	1.315

Table S3.5. Resulting matrix resembling *Bertholletia excelsa* population dynamics of the population 20 years following to timber logging and yearly Amazon nut harvest.

Stage	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	0.001	0.000	0.000	0.000	0.000	0.001	0.007	0.023	0.059	0.119	0.311	0.479	0.502	0.438	0.348	0.330	0.279	0.331	0.400	0.423	0.394	0.470	0.409	0.475	0.628	0.629
2	0.005	0.019	0.000	0.000	0.000	0.000	0.002	0.006	0.018	0.041	0.124	0.221	0.254	0.230	0.168	0.171	0.130	0.152	0.190	0.211	0.183	0.235	0.197	0.225	0.316	0.327
3	0.009	0.053	0.081	0.000	0.000	0.000	0.000	0.002	0.005	0.012	0.044	0.090	0.113	0.109	0.072	0.080	0.055	0.063	0.081	0.095	0.076	0.106	0.086	0.096	0.142	0.151
4	0.008	0.058	0.163	0.145	0.000	0.000	0.000	0.000	0.001	0.003	0.011	0.026	0.036	0.038	0.022	0.027	0.017	0.019	0.025	0.031	0.023	0.035	0.027	0.030	0.046	0.051
5	0.004	0.035	0.143	0.260	0.182	0.000	0.000	0.000	0.000	0.000	0.002	0.005	0.008	0.010	0.005	0.007	0.004	0.004	0.006	0.008	0.005	0.009	0.007	0.007	0.011	0.013
6	0.001	0.014	0.073	0.209	0.313	0.198	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.002	0.001	0.001	0.002	0.003
7	0.000	0.004	0.027	0.112	0.274	0.355	0.093	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.004	0.023	0.084	0.195	0.202	0.067	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	0.000	0.000	0.001	0.005	0.029	0.110	0.238	0.166	0.048	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.002	0.014	0.083	0.324	0.448	0.419	0.286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000	0.002	0.018	0.102	0.203	0.286	0.299	0.180	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.000	0.004	0.030	0.077	0.146	0.205	0.259	0.112	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	0.000	0.001	0.008	0.027	0.064	0.114	0.229	0.207	0.069	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.010	0.029	0.068	0.206	0.334	0.301	0.158	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.007	0.021	0.091	0.220	0.328	0.323	0.178	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.005	0.028	0.093	0.199	0.293	0.339	0.200	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.006	0.027	0.077	0.156	0.285	0.354	0.224	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.006	0.021	0.054	0.140	0.275	0.367	0.252	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.004	0.013	0.045	0.124	0.262	0.378	0.281	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.010	0.036	0.108	0.246	0.385	0.314	0.000	0.000	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.007	0.028	0.092	0.227	0.388	0.348	0.000	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.005	0.022	0.076	0.205	0.385	0.383	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.016	0.060	0.179	0.373	0.415	0.000	0.000	0.000
24	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.011	0.046	0.150	0.349	0.438	0.000	0.000
25	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.007	0.032	0.118	0.310	0.444	0.000
26	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.004	0.023	0.098	0.318	0.666
Total	0.028	0.184	0.492	0.755	0.898	0.965	1.009	1.031	1.083	1.175	1.492	1.821	1.915	1.827	1.615	1.614	1.482	1.563	1.690	1.749	1.648	1.798	1.633	1.680	1.909	1.840

Chapter 4

Ecological insights for sustainable timber production in Amazonian community-managed forests

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Abstract

Tropical forests are increasingly being exploited for timber in hand with the widespread promotion of forest management in tropical regions to boost economic development of forested regions while reducing tropical deforestation. Increasingly, local communities manage vast areas of Amazonian forests for timber production despite the limited existing knowledge on the fate of commercial timber species upon logging intervention. In Bolivia's highly-forested Amazon region, 77% of *campesino* communities have adopted community forest management plans (CFMPs) as of 2015. In this region, we investigated the response of the 17 most important commercial timber species to timber management in six *campesino* communities that started managing their forest for timber production between 2000 and 2007. All individuals of the 17 selected species were sampled at 72 (500 x 40 m) permanent research transects established at 24 household forests located in the selected communities. In this study, we investigated the extent of differences in species density and timber volume of the eight most abundant commercial timber species, out of the 17 studied species. Given that congeneric species are often lumped together for logging – a simplification that could have major impacts on species demographic rates – we also assessed differences in species density, timber volume, growth and survival rates between species of the same genus: two *Cedrela* (*Cedrela fissilis* and *Cedrela odorata*) and two *Hymenaea* (*Hymenaea courbaril* and *Hymenaea parvifolia*) species; and analysed the impact of logging intensity, time since logging and ecological tree characteristics on each species separately.

Nearly 17% of the studied species found at unlogged sites were not found at sites six years after logging (*Swietenia macrophylla, Tabebuia impetiginosa* and *Terminalia sp.*), while a larger percentage of the species (71%) in the harvestable category were not found at sites six years after logging. The total stem density of five of the eight commercial timber species investigated, differed significantly among community-owned forests after accounting for the effects of logging intensity and time since logging ; whereas, timber volume only differed among communities for three species. Our results indicate that logging intensity increased stem density and timber volume of *Apuleia leiocarpa*, *C. odorata* and *H. parvifolia*, and had no effect on the other five species investigated. Species of *Hymenaea* genus differed mainly in stem density and timber volume; whereas, species of the *Cedrela* genus differed mainly in growth and survival rates.

Diversification of the set of logged species and application of silvicultural practices to recover the population of commercial timber species should be prioritized in tropical regions rather than only calling for reducing logging intensity (i.e., already low in the Bolivian Amazon) given the large spatial heterogeneity of species occurrence and large variance in between-species responses to logging. In addition, careful identification of species requires immediate enforcement due to species' differential response to logging, even between species belonging to the same genus.

Keywords: tree density, timber volume, growth rate, survival rate, *Hymenaea*, *Cedrela*, logging intensity, time since logging

Introduction

The area of forest under communal property is becoming larger as communities claim devolution of land rights worldwide (Agrawal et al., 2008; Blaser et al., 2011). In the Bolivian Amazon alone, local communities have legal ownership of over 29% of the forested area (2 million hectares; Pacheco et al., 2009). Additionally, the proportion of communal forests set aside for timber production has as well increased over time. As of 2015, about 15% of the 2.8 million hectares of forests under forest management plans (FMPs) belonged to *campesino* communities (Bolivia´s Forest and Land Controlling Authority - ABT, unpublished data). Various adjustments made to the Bolivia's Forestry Law (1997) have facilitated community households' engagement in timber management at an unprecedented rate. The most recent adjustment to this law allows small-scale logging operations (ABT Directive 02/2013,), allowing each community household to log ~7 m^3 of timber six times a year following few management considerations in addition to timber being logged under the community forest management plan (CFMP). Under this rate of timber extraction the future availability of many commercial timber species may be threatened at community-owned forests (Soriano et al., 2012; Villegas, 2012). Thus, understanding the degree of variation in commercial timber stocks among community-owned forests, and of the response of commercial timber species to logging intensity is key to sustainably manage community-owned forests for timber production.

Timber recovery rate is highly variable in tropical regions, with most studies relying on coarse modelling approaches to estimate the amount of harvestable volume recovered after the first cutting cycle (Putz et al., 2012). In average, only about 54% of the commercial timber volume logged in the first cut would have been recovered in the forest for a second cut (Putz et al., 2012). This value decreases to 35% if one accounts for only the volume of the set of species harvested in the first cut (Putz et al., 2012). Silvicultural intervention could potentially improve the recovery of timber volume for a second cut. For example, two long-term studies in the Brazilian Amazon reported that even the lightest silvicultural intervention (e.g., reduced-impact logging, Vidal et al. 2016; and thinning, de Avila et al. 2017) can increase the recovery rate of timber volume beyond that of conventional logging. However, high intensity thinning intensity reduces the recovery rate of potentially harvestable commercial timber volume (de Avila et al., 2015). Such variation on recovery rates between sites and degree of silvicultural intervention calls for further investigation on the response of commercial timber species to logging intensity and silvicultural intervention at species-specific and site-specific levels.

In addition to the lack of information on the recovery of timber volume for the majority of tropical timber species (Putz et al., 2012), limited ecological knowledge of tropical tree species has led to identification mistakes during forest inventories and censuses, which may further decrease the recovery of timber volume for subsequent cuts. One such mistake is naming two or more congeneric species with the same common name whenever species are not immediately identifiable (Baraloto et al., 2007; Rockwell et al., 2007a; Zenteno et al., 2013). This lumping of species is often permitted in forest management reports under the assumption that species sharing similar characteristics (e.g., wood quality) may respond to logging in similar ways. Yet, subtle ecological differences in how species respond to logging could impact the population structure, demographic rates (growth, survival and fecundity), and the long-term timber availability of those species. The recovery capacity of many species may also be decimated by this common simplification in forest censuses due to a likely preference of one congeneric species over the other, resulting in the overestimation of pre-logging timber stocks of the preferred species. The correct identification of timber species appears even more important as selective logging is adopted throughout tropical regions (Escobal and Aldana, 2003).

We investigated the response of 17 commercial timber species to timber management practices in community household forests of the Bolivian Amazon. First, we asked how commercial timber species differ in stem density and timber volume among community-owned forests in relation to logging intensity and time since logging. We hypothesized that density and timber volume will differ between communities due to the rarity and localized distributions of many tropical tree species (Schulze et al., 2008). Species will also differ in stem density and timber volume with regards to logging intensity over time as the population recovers from logging disturbance (Duah-Gyamfi et al., 2014; Grogan et al., 2016). Second, we asked to what extent commercial timber species belonging to the same genus differ in their ecological characteristics and response to logging intensity.

For this part of the study, we selected two *Cedrela* species (*Cedrela odorata* and *Cedrela fissilis)* and two *Hymenea* species (*Hymenea courbaril* and *Hymenea parvifolia)* that are usually commercialized as belonging to the most preferred species (respectively, *C. odorata* or *H. courbaril*). We hypothesized that congeneric species will differ in stem density, timber volume, growth and survival rates due to species-specific requirements for light (Duah-Gyamfi et al., 2014; Grogan et al., 2016), climatic and soil requirements for their establishment (Gourlet-Fleury et al., 2011; Toledo et al., 2011a), and interspecific differences in recruitment success (Harms et al., 2000). Moreover, we expect that the species belonging to the same genus will also differ in density and volume depending on the rate of extraction of large trees (Gourlet-Fleury et al., 2013) and loggers' preference of one species over the other. Furthermore, we expect that the density of individuals ≤10 cm DBH of *Hymenaea* species will decrease or remain unchanged with logging intensity (Schwartz et al., 2012; Soriano et al., 2012) as these species are partially shade-tolerant and may not withstand the changes in abiotic conditions created by logging. Stem density and timber volume will increase with time since logging as forest recovers from timber extraction (Gourlet-Fleury et al., 2013), hence, we expect also an interaction between logging intensity and time since logging. Growth and survival rates of individuals ≤10 cm DBH of *Cedrela* species are expected to differ more with logging than of individuals of *Hymenaea* species as greater recruitment, growth and survival rates were observed for the *Cedrela* species at higher disturbance levels (D'Oliveira, 2000; Poorter and Hayashida-Oliver, 2000; Van Rheenen et al., 2004). Growth and survival of individuals from congeneric species will increase with logging intensity up to a few years after logging (Silva et al. 1995; Peña-Claros et al., 2008b; a; Villegas et al., 2009; Fortini, Cropper & Zarin 2015), and will become equal to growth rates found at unlogged forests in subsequent years as the forest recovers from logging disturbance (Schwartz et al., 2012; Silva et al., 1995).

Materials and methods

Research site

This study was carried out in the Bolivian Amazon, which encompasses the entire Department of Pando, and the provinces of Vaca Díez and Iturralde of the Beni and La Paz Departments in Bolivia, respectively. This research took place in the Department of Pando and Vaca Díez Province of the Beni Department only (Fig. 4.1) due to the similarities in terms of tenure and forest use arrangements of community families. Ninety-five percent of Pando is covered by forest (Marsik et al., 2011), which together with the Vaca Díez Province comprise 30% of Bolivia's production forests, i.e. 8.8 out of 28.8 million ha (Hjortsø et al., 2006). Diversity of trees ≥10 cm diameter at 1.3 m aboveground (DBH) ranges between 52 - 122 species ha^{-1} and total tree density between 544 - 627 trees ha^{-1} (Mostacedo et al., 2006). The annual rainfall varies between 1,774 - 1,934 mm, and the mean annual temperature differs slightly between the two main regional cities: Cobija (25.4ºC) and Riberalta (26.2ºC) (Zonisig, 1997). The region presents a relatively dry season from May through September with <60 mm of rainfall per month. Its topography varies from *terra firme* (or upland) to seasonally flooded lowland forests. *Terra firme* forests grow on soils with low fertility

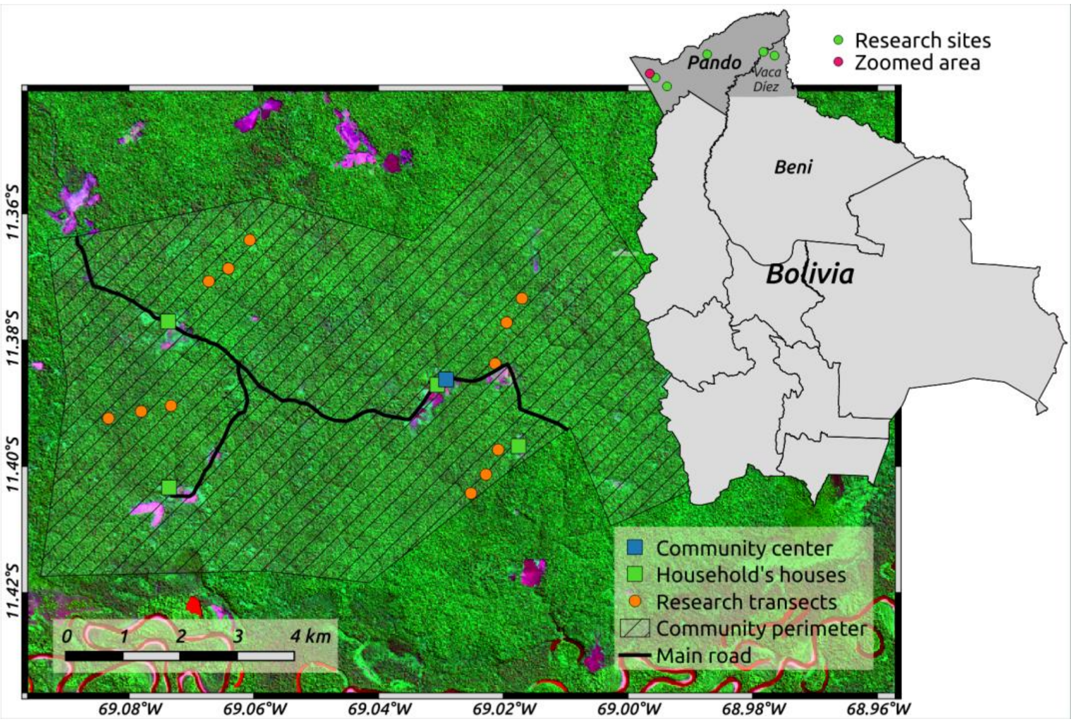

Figure 4.1. Location of study sites and of research transects within a community household forest in the Bolivian Amazon. Image from sentinel 2 satellite (band combination 11/8/2) acquired on August 25, 2016. Credit: Loïc Dutrieux.

relatively high nutrient-rich soils due to the sediments deposited by rivers originating in the Andes (Zonisig, 1997).

The region has fully decentralized tenure over forest, dominated by communal ownership. Communities extract multiple products from these forests, varying with the background of the community households and their main source of livelihood (Pacheco et al., 2009; Urapotina, 2011; Zenteno et al., 2013 and reference therein). Already 77% (n = 189 out of 245) of *campesino* communities residing in the Bolivian Amazon were engaged in timber management as of 2015 (ABT, unpublished data). For this study we selected six *campesino* communities with a relatively long-standing engagement in timber management (Fig. 4.1), in which 24 household forests representing a wide range of Amazon nut (*Bertholletia excelsa*) harvesting and timber logging intensities were selected. All selected household forests were annually harvested for Amazon nut between 2013 and 2015; in addition, 18 household forests were logged once for timber under the community forest management plan (CFMP). Logging under the CFMP often occurs at once over the entire *terra firme* forest area belonging to a given household as part of the communal annual operational plan (Soriano et al., 2012). The harvest of these forest products at the household forest-level allowed us to account for households' forest as our main sampling unit. In this paper, we limit our analysis to the impact of logging intensity on present and future timber stocks and assumed that Amazon nut harvesting has little impact on the logged forest.

Species description and identification

Commercial timber species in the Bolivian Amazon present low population densities of individuals ≤10 cm DBH, which ranges between 4 - 40 individuals per hectare (Soriano et al., 2012); whereas, individuals >10 cm DBH ranges between 0.5 - 5 individuals per hectare (Licona Vasquez et al., 2007). Selective logging predominates in the Bolivian Amazon,and has historically focused on a limited number of species such as mahogany (*Swietenia macrophylla*), amburana (*Amburana cearensis*) and Spanish cedar (*Cedrela* spp.) (Pattie et al., 1997). The Forestry Law (1997) urges forest users to diversify the number of logged species, but only a small number of species are logged, on average about nine species (Soriano et al., 2012). In total, we sampled 17 commercial tree species. Ten species were chosen from a list of commercial timber species with the highest timber volume permitted for logging by the Bolivian Forest and Land Controlling Authority (ABT, due to acronym in Spanish) between 2002 - 2012 (ABT, Annual Reports 2002-2012), plus two species of high commercial importance for two of our studied communities (Table 4.1). Five of the eight species selected with the highest timber volume permitted for logging by the ABT shared a genus name with another species and were commonly reported indistinctly to the ABT. Therefore, we chose to sample these tree species as well.

To answer our first research question in which we test differences in stem density and timber volume between community-owned forests in relation to logging intensity and time since logging, we focused on eight species which had >75 individuals sampled in the 72 study transects and that occurred in all community-owned forests under study. To answer our second question, we focused on two pairs of species sharing the same genus name (two species of *Cedrela* and two of *Hymenaea* genera). These species are named after their most common-known commercial name (*C. odorata*), or the most commonly occurring species (*H. parvifolia*) in the documents presented to the ABT for obtaining logging permits, which adds more uncertainty to the correct identification of these species during the planning and execution of a forest management plan (C. Baraloto, personal communication, January 9, 2016). In terms of volume, *Cedrela* spp. and *Hymenaea* spp. occupy the fourth and sixth place, respectively, in the list of timber species allowed to be logged in forest management plans at the country level between 2000 - 2008 (Estado Plurinacional de Bolivia, 2010).

Species identification

At first sight, species belonging to the same genus have similar tree characteristics, e.g. tree form, bark and leaves (Toledo et al., 2008). These characteristics are however, only differentiable when examined closely. We used different criteria to identify seedlings and saplings (≤2.5 m height), and larger trees belonging to the same genus. For example, *C. fissilis* presented pubescent young leaves, whereas *C. odorata* did not (Toledo et al., 2008). The trunk of *C. odorata* presented buttresses up to 1.5 m high aboveground, and *C. fissilis* did not (Toledo et al., 2008). In both cases, we could corroborate our identification after observing the presence of fruits on the ground surrounding each tree, which are easily identifiable from both species: *C. fissilis* had bigger and more elongated fruits than *C. odorata* (Toledo et al., 2008). In the absence of fruits, a small cut to the tree revealed a stronger garlic-like smell in *C. odorata* than in *C. fissilis*. Because *Hymenaea* small individuals' leaves are identical (Toledo et al., 2008), we based our species identification for these species on the presence of fruits on the ground surrounding each tree. *Hymenaea courbaril* had larger fruits than *H. parvifolia*. We were then able to associate seedlings and saplings found near each tree to the nearest parent tree because these two species rarely occurred close to each other, and because most of its recruits are found within 20 m surrounding a parent tree (Soriano et al., 2012).

Experimental design

In 2014, 72 transects were placed at random within 24 community household forests, three transects per household forest. See Figure 4.1 for an example on the location of transects within the sampled household forests in a community. Each transect was 500 m long and 40 m wide (2 ha), totalling 144 ha of sampled area. Transects at each household forest were established at random to account for the variability on species populations across the Bolivian Amazon region. Within a household forest, distance between transects varied between 500 - 1000 m to ensure sampling independence. Twenty-one household forests underwent timber logging at least once over the last 10 years prior to data collection. Of these, three household forests were only logged under the small-scale logging operations, nine were logged once under the legal framework of the 1996 Forestry Law, and nine were logged under both schemes. Household forests logged under the small-scale timber logging operation modality were logged during the two years of data collection. We did not account for the impact of the small-scale logging operations because their incidence within the research transects were minimal. They occurred within the transects established at only three sampled household forests (12.5%), and only disturbed 0.06% of the total sampled area.

Data collection

Individuals <10 cm DBH were sampled within the 10 x 500 m centre strips of each transect, whereas, larger individuals were sampled within the entire transect. The following tree characteristics were measured as follows: total height of individuals ≤2.5 m height was measured with a meter tape, whereas, total height of larger individuals, and commercial height of individuals >10 cm DBH were visually estimated; DBH of individuals with 1.5 m total height but ≤5 cm DBH was measured with a calliper, whereas, DBH of individuals >5 cm DBH was measured with a diameter tape. Estimated height was calibrated by comparing visual estimations of 3 - 5 trees of different height with measurements of a laser range finder (Nikon forestry pro) at the beginning of each work day. Additionally, crown position and crown form were evaluated following Dawkins & Field's (1978) categories; whereas, categories of the degree of liana infestation was evaluated following Soriano et al.'s (2012) recommendations. A description of the variables measured can be found in Table S4.1, in Supporting Information. All individuals were re-measured in 2015, and all new individuals found were tagged and measured as indicated above.

We used Eq. 4.1 (Metcalf et al., 2009) to correct the DBH of trees measured at a different measurement height than the standard 1.3 m high aboveground. This equation is the most reliable tapering approximation for tropical trees (Cushman et al., 2014).

$$D = \frac{d_h}{e^{b_i(h-1.3)}} \qquad \text{Eq. (4.1)}$$

Where D is the diameter at 1.3 m height (cm), d_h is the diameter at height h (cm), h is the height of diameter measurement (m), and b_i is the taper parameter (average value of the posterior means calculated for 5 species = -0.04; Metcalf et al., 2009). We used Equation 1 to calculate the diameter at 0.8 m aboveground (which corresponds to the measured stump diameter in the field), and at the crown base (or estimated commercial height) of individuals >40 cm DBH. With this information, we estimated the standing timber volume of potentially harvestable (trees between 40 cm DBH and the minimum diameter cutting or MDC) and harvestable (trees >MDC) trees using Smalian's formula (Equation 4.2):

$$V = \frac{A_1 + A_2}{2} * L \qquad \text{Eq. (4.2)}$$

Where V is the tree volume expressed in m^3, A_1 is the area of the stump at 0.8 m aboveground (stump height), A_2 is the area of the trunk at the commercial height, and L is the estimated commercial height minus the 0.8 m stump height.

Logging intensity

We measured stump and crown base diameters, and trunk length (i.e., distance from the stump to the crown base) of logged trees found within the research transects to calculate the number of logged trees and harvested timber volume per hectare. We also evaluated logging disturbance by measuring the areas of logging gaps, log landings, access roads and skid trails occurring within the transects. The area disturbed in logging gaps and log landings was estimated in hectares as described by Soriano et al. (2012). To calculate the area disturbed by access roads and skid trails, we measured the total length of those found inside the transects and measured their width at three randomly chosen points. The area disturbed was then calculated as the product of the length and the average width. In all logging disturbance types, a disturbed area included the core zone disturbed by logging and the edge zone where woody debris was accumulated due to the manoeuvring of logging machinery and tree fall damage. We extrapolated the sum of all disturbed areas found within each 2 ha transect to the total area to calculate the percentage of disturbed area per transect (2 ha = 100%). From the three measures of logging intensity, we decided to use the number of logged trees in further analyses, because this measure is highly correlated with harvested timber volume in a household forest ($r = 0.76$), and therefore, can be easily translated into volume.

Data analyses

To answer our first research question on how commercial timber species differ in their stem density and timber volume among communities with respect to logging intensity and time since last logging, we selected eight commercial timber species, out of the 17 species sampled in the 72 transects. We used total stem density and two measures of timber volume commonly used in forest management planning: potentially harvestable (trees between 40 cm DBH and MDC) and harvestable (trees >MDC) timber volume as our response variables. Generalized linear and linear models were ran to determine whether stem density and timber volume differed among community forests, respectively; where community was set as factor, and logging intensity, time since last logging and their interaction were set as covariates. We modelled our stem density data using a negative binomial distribution, rather than Poisson distribution, due to the count nature of our data and to the high variability on total stem density of our study species among sites. We normalized our positively-skewed data distribution of timber volume per plot by adding one unit to the observed timber volume value before log transforming it. Thus, we were able to test whether timber volume data differed between community-owned forests in relation to logging intensity and time since last logging in a linear model. For analysing stem density, we used the glmer.nb function of the MASS package (Ripley et al., 2016); whereas for timber volume, we used the base R lm function (R. Development Core Team, 2015). We used the backward selection method to select the most significant predictors for each of the eight selected species. For stem density, we obtained p-values for each explanatory variable in the best selected model using the anova function in R (R Development Core Team, 2015), as no p-value was provided for community (as a covariate and not as a factor) by the glmer.nb function. Then, we used the lsmeans function in the lmerTest R package (Kuznetsova, 2016) to determine whether stem density and timber volume differed between pairs of communities after accounting for the variance attributed to logging intensity, time since last logging and/or the interaction between logging intensity and time since logging as specified in the best models of stem density and timber volume.

To answer our second question, we used mixed effects models (MEMs) to test for differences in density and timber volume, between species belonging to the same genus and to analyse the impact of logging intensity and time since logging on each species and for three size groups: individuals <10 cm DBH, individuals between 10 cm DBH and MDC, and trees >MDC, separately. To test whether individuals of *Cedrela* and *Hymenaea* species differed in stem density and timber volume between congeneric species, we specified "species" as a fixed effect and "community" as a random effect to account for spatial autocorrelation in species stem density. To address over-dispersion issues in stem density of individuals ≤10 cm DBH of *Cedrela* and *Hymenaea* species, we used a cut-off of 75 and 550 individuals per transect, respectively. Then, we used the backward selection method to determine the most significant predictors of stem density and timber volume for each of the four focus species (*C. odorata, C. fissilis, H. courbaril and H. parvifolia*), where "logging intensity" and "time since last logging" were specified as fixed effects, and "community" as random effect. For the analysis of stem density, we tested for both Poisson and negative binomial distribution of our data, and chose the model with the lowest AIC. For the analysis of timber volume, we normalized our positively skewed data distribution by adding one unit to the observed value before log transforming it. Models to compare and predict density and timber volume were tested under the glmer.nb, and lmer functions from the MASS (Ripley et al., 2016) and lme4 (Bates et al., 2015) R packages as suited.

We calculated the annual growth and survival rate of each individual of the four focal species using the two available measurements (2014 and 2015). As different factors may affect these rates at different stages of a plant's life cycle, we modelled growth and survival for two size classes: individuals ≤2 m high but ≤0.5 cm DBH (hereafter refered as individuals < 2m high), and of individuals >0.5 cm but >2 m high, separately (hereafter refered as individuals >0.5 cm DBH). We used only two size groups as there were not enough individuals to test differences in growth and survival rates among more size groups. We used linear models with backward selection to select the best predictors of growth out of the following explanatory variables: initial size, initial size-squared, logging intensity, standing timber volume of mature trees (trees >40 cm DBH), lianas affecting growth, crown position, and crown form. We used also generalized linear models to determine whether survival rate differs between congeneric species, with initial size, initial size-squared, logging intensity, standing timber volume of mature trees (trees >40 cm DBH) as explanatory variables. We included initial size-squared to test growth and survival of the studied species since some species might present an optimum growth and/or survival rates. We also included standing timber volume of mature trees because it can be an indicator of the successional stage of the forest and logging intensity (Gourlet-Fleury et al., 2013). The analysis was run at the genus and the species level. Heteroscedasticity of our growth models was tested by plotting the residuals of each model, whereas, survival models' heteroscedasticity was tested via an overdispersion test, which compared Chi-square residuals with degrees of freedom residuals. We used the McFadden pseudo R-squared to determine goodness of survival models' fit (Jackman et al., 2015).

Results

Eight (47%) of the 17 studied commercial timber species belong to the Fabaceae family, and 65% are considered long-lived pioneer species (11 out of 17, Table 4.1). In total, we found 8,154 individuals of the 17 studied species

Table 4.1. List of commercial species sampled in 24 hoursehold forests in the Bolivian Amazon. Rank and logging intensity are provided for the 10 species with the highest allowable volume in the Bolivian Amazon based on data from the Bolivian Forest and Land Controlling Authority (ABT), and for two species with economic importance for our six study communities. Five out of the 10 species are commonly lumped in the ABT reports, and therefore, are provided as such below. Logging intensity values provided come from sampled transects, and is also lumped for the same species because we were unable to identify their stumps in the field. Community families extract timber for commercial purposes using one of two mechanisms: through the design and implementation of a community forest management plan (CFMP) and through the logging under the small timber volumes logging operation modality in place since 2012. Empty cells indicate that data was not available for those species. MDC = minimum diameter cutting, LLP = long-lived pioneer, PST = partial shade tolerant.

Common name	Scientific name	Family name	MDC	Rank of timber species permitted for logging by the ABT		Regeneration strategy	Sampled individuals (all size classes)	Relative abundance (%)	Logging intensity		
				FMPs (2002 - 2012)	Small volumes (2012-2014)				Mean ± SE harvested trees per ha	Mean ± SE harvested basal area (m^2 ha^{-1})	Mean ± SE harvested volume (m^3 ha^{-1})
Almendrillo amarillo	*Apuleia leicocarpa*	Fabaceae	50	4	6	LLP	446	5.47	0.15 ± 0.05	0.09 ± 0.03	1.28 ± 0.46
Almendrillo negro	*Dipteryx michranta*	Fabaceae				PST	188	2.31			
Cedro "fissilis"	*Cedrela fissilis*	Meliaceae	60	1	4	LLP	310	3.8	0.12 ± 0.04	0.047 ± 0.2	0.70 ± 0.25
Cedro "odorata"	*Cedrela odorata*	Meliaceae				LLP	248	3.04			
Cuta	*Astronium lecontei*	Anacardiaceae	50		27	LLP	2,220	27.23	0.23 ± 0.10	0.084 ± 0.04	0.95 ± 0.45
Mara	*Swietenia macrophylla*	Meliaceae	70	9		PST	11	0.13	0	0	0
Mara macho	*Cedrelinga catenaeformis*	Fabaceae	50	6	37	LLP	137	1.68	0.44 ± 0.12	0.38 ± 0.11	4.11 ± 1.22
Marfil	*Aspidosperma macrocarpon*	Apocynaceae	50		3	LLP	23	0.28	0	0	0
Morado	*Peltogyne cf. heterophylla*	Fabaceae	50			PST	1,967	24.12	0	0	0
Paquio	*Hymenaea courbaril*	Fabaceae	50		32	PST	226	2.77	0.06 ± 0.03	0.04 ± 0.02	0.71 ± 0.38
Paquiocillo	*Hymenaea parvifolia*	Fabaceae				PST	2,147	26.33			
Roble	*Amburana cearensis*	Fabaceae	50	2	5	LLP	31	0.38	0.14 ± 0.06	0.05 ± 0.03	0.65 ± 0.3
Serebo	*Schizolobium parahyba*	Fabaceae	50	5		LLP	25	0.31	0	0	0
Tajibo amarillo	*Tabebuia serratifolia*	Bignoniaceae	50	3	17	LLP	79	0.97	0.04 ± 0.02	0.02 ± 0.01	0.33 ± 0.21
Tajibo colorado	*Tabebuia impetiginosa*	Bignoniaceae				LLP	55	0.67			
Verdolago	*Terminalia sp.*	Combretaceae	50	10	20	LLP	32	0.39	0	0	0
Verdolago amarillo	*Terminalia oblonga*	Combretaceae				PST	9	0.11			

in the 144 ha sampled. *Astronium lecontei* (n = 2,220) and *H. parvifolia* (n = 2,147) made up to 51% of the sampled population, with 27% and 24% relative abundances, respectively. Whereas, *S. macrophylla* (n = 11) and *Terminalia oblonga* (n = 9) were the least abundant species, representing only 0.13% and 0.11% of the total number of individuals found (Table 4.1). In the sampled household forests 0.93 ± 0.12 trees were logged per hectare, which corresponds to 0.60 ± 0.11 m^2 ha^{-1} of logged basal area, and 0.71 ± 1.21 m^3 ha^{-1} of logged timber volume. The two most logged species were *Cedrelinga catenaeformis* (0.44 ± 0.12 trees ha^{-1}) and *A. lecontei* (0.23 ± 0.10 trees ha^{-1}), whereas, the two least logged ones were *Hymenaea* spp. (0.06 ± 0.03 trees ha^{-1}) and *Tabebuia* spp. (0.04 ± 0.02 trees ha^{-1}, Table 4.1). We did not find stumps from *S. macrophylla*, *Aspidosperma macrocarpon*, *S. parahyba*, and *Terminalia spp.* (Table 4.1). The impact of logging on the studied species increased with the size of individuals sampled from these species. For example, 29% of the species in the size of individuals ≤10 cm DBH, and 62% of the species in the size of individuals >MDC found at unlogged sites were not found at sites six years after logging. We found as well that 17% of the species present at unlogged sites (*Swietenia macrophylla*, *Tabebuia impetiginosa* and *Terminalia* sp.) were not found at sites six years after logging.

Differences in stem density and timber volume of commercial timber species among communities

Our best models indicated that the density of seven out of the eight commercial timber species studied was determined by community, logging intensity and/or time since logging (Table 4.2). Community determines the density of *A. lecontei, C. fissilis, C. odorata, Dipteryx michranta, H. courbaril* and *Tabebuia serratifolia* (Table 4.2). Our best models also indicated that logging intensity increased total stem density of *Aspidosperma leiocarpa*, *C. odorata* and *H. parvifolia*; whereas time since last logging decreased stem density of *C. fissilis* but increased the density of *T. serratifolia* (Table S4.2). We also found that the interaction between logging intensity and time since logging decreased *C. odorata* and *H. parvifolia* stem density (Table S4.2).

The factors and covariables determining potentially harvestable and harvestable timber volume were not the same and varied even within a species (Table 4.3). The explanatory variables tested explained the potentially harvestable timber volume of only three species (*A. lecontei*, *C.*

Table 4.2. Results from generalized linear models used to determine differences in total stem density between six *campesino* communities for eight commercial timber species of the Bolivian Amazon. Logging intensity and time since last logging were included in the models as covariates. Models were selected using the backward selection procedure. The p-values of explanatory factors were calculated under the anova function of the best selected model. Communities with different letters differ from each other. Results from pairwise comparison tests based on our best models (Table S4.3). Significance levels are marked with asterisks: * p-value <0.05, **p-value <0.01, ***p-value <0.001. DBH = diameter at 1.3 m aboveground, MDC = minimum diameter cutting.

Species	Model's fit statistics			Community							Logging intensity (logged trees)	Time since logging (Years)	Logging intensity x time since logging
	# Obs.	p-value	pseudo r-squared	p-value	1	2	3	4	5	6	p-value	p-value	p-value
Apuleia leiocarpa	72	0.06	0.16	0.158	a	a	a	a	a	a	0.003**		
Astronium lecontei	72	<.001***	0.71	<.001***	a	b	bc	c	d	c			
Cedrela fissilis	70	<.001***	0.49	<.001**	a	b	a	a	a	b		0.011*	
Cedrela odorata	72	<.001***	0.57	<.001***	a	b	ab	b	b	b	0.002**	0.478	0.046*
Dipteryx micrantha	72	<.001***	0.34	<.001***	a	ab	b	ab	ab	ac			
Hymenaea courbaril	72	0.002**	0.25	0.009**	a	a	a	a	a	a			
Hymenaea parvifolia	72	0.022*	0.22	0.215	a	a	a	a	a	a	0.069	0.158	<.001***
Tabebuia serratifolia	72	<.001***	0.32	<.001***	a	ab	a	a	a	ac		0.012*	

odorata, and *T. serratifolia*), and the harvestable timber volume of four species (*A. leiocarpa*, *A. lecontei, H. parvifolia*, and *T. serratifolia*), with all r^2 being lower than 0.37 (Table 4.3). Pairwise comparison tests indicated that potentially harvestable timber volume of only *A. lecontei* and *C. odorata* differed between communities, whereas harvestable timber volume of only *A. leiocarpa*, *A. lecontei* and *T. serratifolia* differed between communities after taking logging intensity and time since last logging into account as indicated by the best models (Table 4.3). Logging intensity increased potentially harvestable timber volume of *D. micrantha*, but decreased that of *T. serratifolia*. Logging intensity also increased harvestable timber volume of *H.*

Table 4.3. Results from linear models used to determine differences in potentially harvestable (trees >40 cm DBH – MDC) and harvestable (trees >MDC) timber volume between six *campesino* communities for eight commercial timber species of the Bolivian Amazon. Logging intensity and time since last logging were included in the models as covariates. Models were selected using the backward selection procedure. Communities with different letters differ from each other: results from pairwise comparison tests based on our best models (Table S4.4). Significance levels are marked with asterisks: * p-value <0.05, **p-value <0.01, ***p-value <0.001. DBH = diameter at 1.3 m aboveground, MDC = minimum diameter cutting.

Species	Size groups of standing timber volume	Model's fit statistics				Community						Logging intensity (logged trees)	Time since logging (Years)	Logging intensity x time since logging
		# Obs.	p-value	r-squared	p-value	1	2	3	4	5	6	p-value	p-value	p-value
Apuleia leiocarpa	Potentially harvestable	72	0.338	0.1	0.565	a	a	a	a	a	a	0.086		
	Harvestable	72	0.003**	0.26	0.012*	a	a	ab	ac	ab	a		0.013*	
Astronium lecontei	Potentially harvestable	72	0.010*	0.2	0.010*	a	ab	b	ab	b	ab			
	Harvestable	72	<.001***	0.37	<.001***	a	b	b	b	b	b	0.775	0.231	0.018*
Cedrela fissilis	Potentially harvestable	72	0.266	0.09	0.266	a	a	a	a	a	a			
	Harvestable	72	0.27	0.09	0.27	a	a	a	a	a	a			
Cedrela odorata	Potentially harvestable	72	0.003**	0.23	0.003**	a	b	a	ab	ab	ab			
	Harvestable	72	0.064	0.14	0.064	a	a	a	a	a	a			
Dipteryx micrantha	Potentially harvestable	72	0.136	0.17	0.16	a	a	a	a	a	a	0.609	0.736	0.041*
	Harvestable	72	0.305	0.09	0.305	a	a	a	a	a	a			
Hymenaea courbaril	Potentially harvestable	72	0.592	0.05	0.592	a	a	a	a	a	a			
	Harvestable	72	0.2	0.1	0.2	a	a	a	a	a	a			
Hymenaea parvifolia	Potentially harvestable	72	0.342	0.08	0.342	a	a	a	a	a	a			
	Harvestable	72	0.043*	0.22	0.166	a	a	a	a	a	a	0.348	0.674	0.006**
Tabebuia serratifolia	Potentially harvestable	72	0.022*	0.2	0.198	a	a	a	a	a	a	0.005**		
	Harvestable	72	0.006**	0.21	0.006**	a	b	a	a	b	a			

parvifolia (Table S4.3), whereas, time since last logging only decreased potentially harvestable timber volume of *A. leiocarpa*. Finally, the interaction between logging intensity and time since logging only decreased potentially harvestable volume of *D. micrantha* and harvestable volume of *A. lecontei* and *H. parvifolia* (Table S4.3).

Differences in stem density and timber volume between commercial timber species logged under a shared genus name

Density of *Cedrela* did not differ between species in the two size groups tested (Table 4.4). Density of individuals ≤10 cm in DBH of both *Cedrela* species decreased with time since logging, while only *C. odorata* density was favoured by logging intensity (p = 0.004, Table S4.4). Thus, we observed an overall increase in the density of *C. fissilis* and an overall decrease in the density of *C. odorata* over time (Fig. 4.2a). Neither logging intensity nor time since logging affected *Cedrela* species density of trees between 10 cm DBH to MDC. Trees >MDC of *Cedrela* species were absent at our sampled sites.

Regarding the *Hymenea* genus, density of individuals differed between species in all three size groups tested (Table 4.4). We observed a positive interaction effect of logging intensity with time since logging on the density of individuals ≤10 cm DBH of both *Hymenaea* species (Table S4.4). Density of individuals ≤10 cm DBH of *H. courbaril* responded positively to this interaction (p = 0.007) but negatively to time since last logging (p = 0.014), whereas the density of individuals ≤10 cm DBH of *H. parvifolia* responded positively to logging intensity and to the interaction between logging intensity and time since last logging (p = 0.002 and 0.006, respectively, Table S4.4). Thus, the overall model showed a steady decrease of *H. parvifolia* stem density of individuals ≤10 cm DBH, and a slight increase of *H. courbaril* at increasing logging intensity (Fig. 4.2b). Neither logging intensity nor time since last logging affected *Hymenaea* species density of individuals between 10 cm DBH and MDC (Table S4.5). The effect of logging intensity and time since logging differed between species for the category of trees>MDC.

Logging intensity increased stem density of *H. courbaril* (p = 0.048) and *H. parvifolia (*p = 0.006) trees >MDC, whereas the interaction between logging intensity and time since last logging decreased only stem density of *H. parvifolia* trees >MDC (p = 0.009, Table S4.5). Thus, the overall model

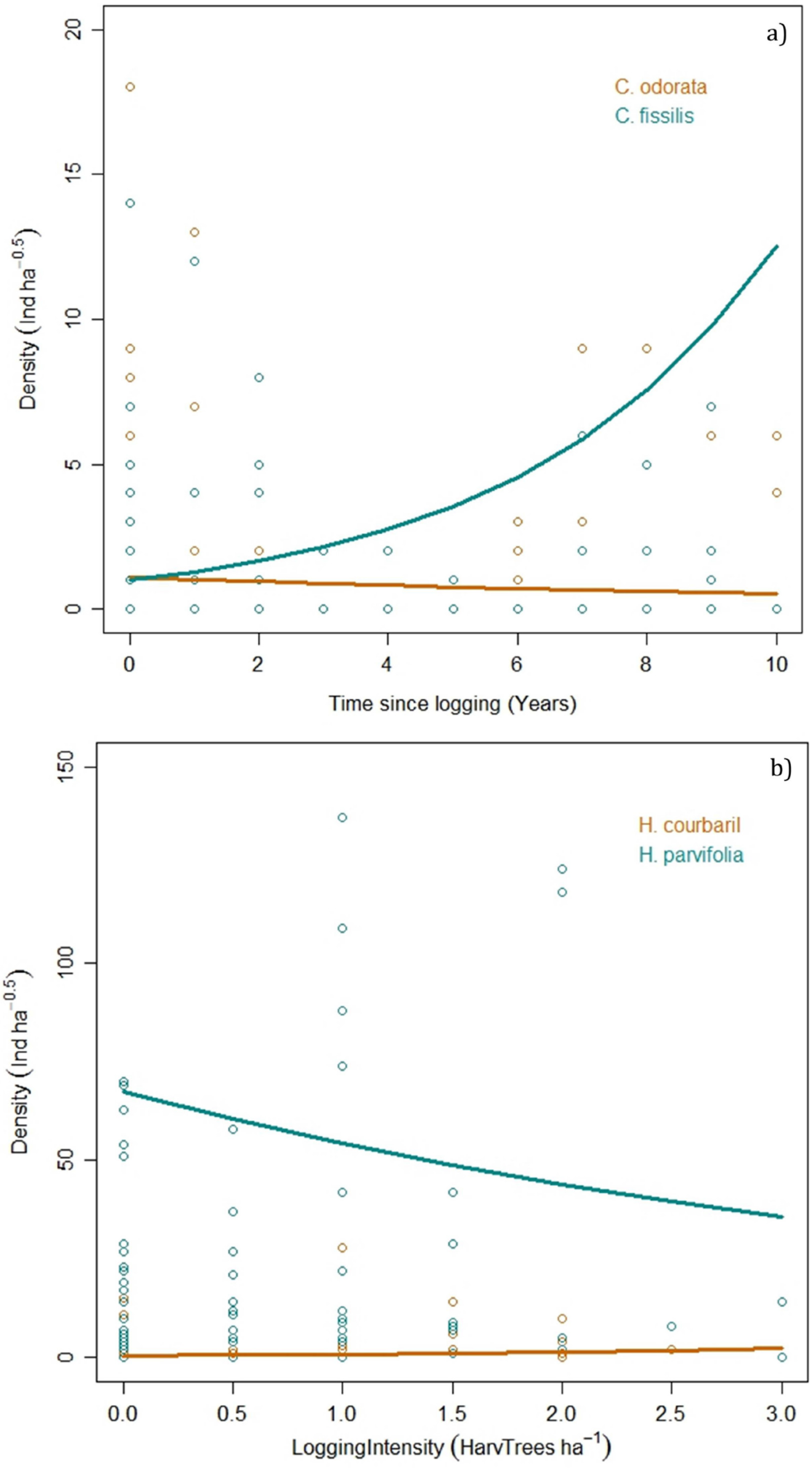

Figure 4.2. Impact of time since logging or logging intensity on the density of individuals ≤10 cm DBH of *Cedrela* (a) and *Hymenaea* (b) species at community household forests in the Bolivian Amazon. Points in the figure are observed densities per sampled transect. MDC for *Cedrela* is 60 cm at DBH and for *Hymenaea* species is 50 cm DBH. DBH = diameter at 1.3 m aboveground, MDC = minimum diameter cutting.

predicted a steady decrease of both *Hymenaea* species stem density with increasing logging intensity (Fig. 4.3).

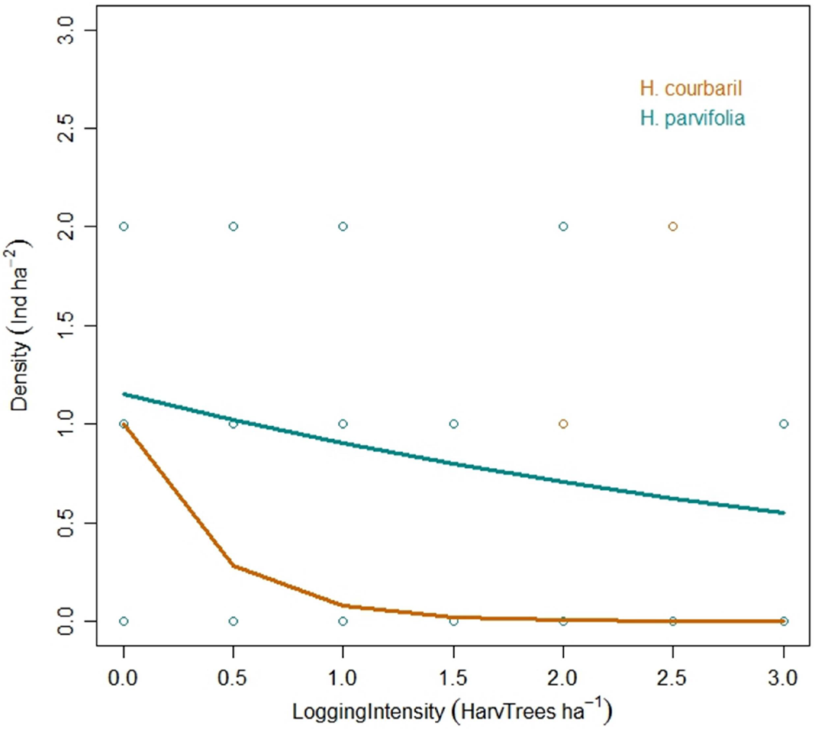

Figure 4.3. Impact of logging intensity on the density (Harvested trees ha^{-1}) of *Hymenaea* harvestable trees (trees > minimum diameter cutting; MDC)) at community household forests in the Bolivian Amazon. MDC for *Hymenaea* species is 50 cm DBH. Points in the figure are observed densities per sampled transect for the specified group size indicated above. DBH = Diameter at 1.3 m aboveground.

Standing timber volume of potentially harvestable trees differed between *Hymenaea* species ($p < 0.001$) but not between *Cedrela* species (Table 4.4). Harvestable timber volume also differed between *Hymenaea* species ($p = 0.005$), whereas, we did not find trees of harvestable size of *Cedrela* species to test for differences (Table 4.4). Only harvestable timber volume of *H. parvifolia* was affected by logging intensity and by the interaction between logging intensity and time since last logging: harvestable timber volume increased with logging intensity ($p = 0.012$), but decreased with the interaction of logging intensity and time since logging ($p = 0.009$, Table S4.5). This resulted in an overall decrease of *H. parvifolia* harvestable timber volume at increasing logging intensity (Fig. 4.3).

Table 4.4. Differences in stem density and timber volume between commercial timber species with a shared genus name. For stem density, we tested for both Poisson and negative binomial (NB) distributions of our data in a generalized linear mixed effect model (glmer), whereas for timber volume, we log-transformed timber volume to run linear mixed effect models (lmer). In both modelling procedures, we specified species as fixed factor and community as random effect. Theta and OverDispTest (overdispersion test) values further away from 1 means that residuals were over- or under-dispersed; R2c = conditional r^2 indicates the proportion of the variance explained by the fixed and random effects. Significance level was set at p-value <0.05 and significant values are marked with asterisks: **p-value <0.01, ***p-value <0.001. Empty cells indicate that individuals of a given group size of a species were absent in the sampled area. n.a. = parameter does not apply for a group size of a species given a chosen test, DBH = diameter at 1.3 m aboveground, MDC = minimum diameter cutting.

				Model's fit statistics				
Response	Species	Group size	Distr.	# Obs	Theta (NB test) / OverDispTest (Poisson test)	R2c	Slope	p value
Stem density	*Cedrela*	Individuals ≤10 cm DBH	NB	141	0.31	n.a.	-0.114	0.73
		Individuals 10 cm DBH - MDC	Poisson	143	<0.001	n.a.	0.216	0.134
	Hymenaea	Individuals ≤10 cm DBH	NB	144	0.41	n.a.	2.467	<.001***
		Individuals 10 cm DBH - MDC	Poisson	144	<0.001	n.a	2.467	<.001***
		Trees >MDC	Poisson	144	0.032	n.a.	1.581	<.001***
Standing timber volume	*Cedrela*	Potentially harvestable (trees >40 cm DBH - MDC)		144	n.a.	0.05	0.052	0.298
	Hymenaea	Potentially harvestable (trees >40 cm DBH - MDC)		144	n.a.	0.05	2.835	0.005**
		Harvestable (trees >MDC)		144	n.a	0.1	0.388	<.001***

Growth and survival rates of commercial timber species logged under a shared genus name

Height growth rate of individuals ≤2 m high but ≤0.5 cm DBH differed between *Cedrela* (p = 0.018) and *Hymenaea* (p = 0.031) species (Table 4.5). At the genus level the only factors determining *Cedrela* height growth rate were standing timber volume of mature trees (trees >40 cm DBH) and crown form determined (Table S4.6). However, if we differentiated height growth rate per species, then initial height was the only predictor of height growth rate of *C. fissilis* (r^2 = 0.13), while crown form was the only predictor of *C. odorata* height growth rate (r^2 = 0.24, Table S4.5). Regarding the genus *Hymenaea,* initial height (p <0.001), logging intensity (p <0.001), the interaction between logging intensity and time since logging (p = 0.010), and standing timber volume of mature trees (p = 0.013) determined its height growth rate (Table S4.6). The same variables, except for standing timber volume of mature trees, predicted height growth rate of *H. parvifolia*; whereas, only logging intensity and standing timber volume of mature trees determined height growth rate of *H. courbaril* (Table S4.6).

Table 4.5. Differences in growth and survival rates between commercial timber species with a shared genus name. Results from linear, and generalized linear mixed effects models for growth of individuals (in meters high and cm year^{-1}) and survival rates (probability to survive from one year to the next). Models were run for two size groups: individuals ≤2 m high (individuals ≤2 m high but ≤0.5 cm DBH) and individuals >0.5 cm DBH (individuals >0.5 cm DBH but >2 m high in cm). In both cases, species was set as fixed effect, and community as random effect. The Pseudo McFadden r-squared is an alternative measure of the model's goodness of fit for logistic models as it applies to survival. Significance level was set at p-value <0.05 and significant values are marked with asterisks: * p-value <0.05, **p-value <0.01, ***p-value <0.001. DBH = diameter at breast height (1.3 m high). DBH = diameter at breast height, AIC = Akaike's information criteria.

Size group	Growth				Survival				
	df	r^2	Species (fixed effect)		df	AIC	r^2 (Mc Fadden)	Species (fixed effect)	
			Slope	p-value				Slope	p-value
Cedrela									
Individuals ≤2 m high	92	0.059	0.131	0.018*	233	254.1	0.048	1.096	<0.001**
Individuals >0.5 cm DBH	195	0.033	0.284	0.011*	254	120.4	0.028	1.015	0.086
Hymenaea									
Individuals ≤2 m high	1135	0.004	0.035	0.031*	1841	1745.5	0.002	-0.426	0.102
Individuals >0.5 cm DBH	144	0.019	-0.236	0.101	198	48.41	0.05	1.558	0.097

DBH growth rate of individuals >2 m high but >0.5 cm DBH differed between *Cedrela* species ($p = 0.011$) but not between *Hymenaea* species ($p = 0.101$, Table 4.6). Regarding *Cedrela* as a genus, initial size ($p < 0.001$) and logging intensity ($p = 0.025$) increased growth rates of *Cedrela* ($r^2 = 0.11$, Table 4.5). The presence of lianas affecting growth decreased DBH growth rate of *C. odorata* (e.g., lianas on the crown, $p = 0.021$). Presence of lianas affecting growth, together with initial size and logging intensity, explained 23% of the variation in *C. odorata* DBH growth rate (Table S4.5). Regarding *Hymenaea*, initial DBH ($p = 0.001$) increased DBH growth of *Hymenaea* as genus, but DBH-squared ($p = 0.003$) decreased it (Table S4.6). These two variables together explained 52% of the variation in *H. courbaril* growth rate, whereas initial size ($p = 0.002$) alone explained only 8% of *H. parvifolia* growth rate (Table S4.6).

Individuals ≤2 m high of *Cedrela* species differed in their survival rates, but this was not the case for *Hymenaea* species (Table 4.5). Survival rate of *C. odorata* individuals was significantly greater than *C. fissilis* individuals but species explained little of the variation in survival rate (McFadden R-squared = 0.05, $p < 0.001$, Table 4.5). At the genus level, the survival rates of individuals ≤2 m high of *Cedrela* was explained by standing timber volume of mature trees, together with initial height and initial height-squared (McFadden test, Table S4.7). When *Cedrela* species were analysed separately, standing timber volume of mature trees did not have a significant effect on survival rates of individuals ≤2 m high (Table S4.7). Survival rates of individuals >2 m high did not differ between *Cedrela* species (McFadden $r^2 = 0.03$, $p = 0.086$). When *Cedrela* species were analysed separately, none of the tested variables influenced the survival rate of this size category. Regarding *Hymenaea*, initial height ($p < 0.001$), height-squared ($p < 0.001$), logging intensity ($p = 0.003$) and time since logging ($p < 0.001$) determined survival rates of *H. parvifolia* individuals ≤2 m high (McFadden $r^2 = 0.17$, Table S4.7); whereas, only initial height ($p < 0.001$) and height-squared ($p = 0.001$) determined survival rates of *H. courbaril* individuals ≤2 m high (McFadden $r^2 = 0.30$, Table S4.7). Survival rate of *Hymenaea* individuals >0.5 cm DBH did not differ between species (McFadden $r^2 = 0.05$, $p = 0.097$, Table 4.5), and neither logging intensity nor time since last logging determined survival rates of neither *Hymenaea* species (Table S4.7).

Discussion

Up to the maximum logging intensity (removal of 3 trees ha^{-1}) found at our research sites, at least 17% of commercial timber species logged at community-owned forests (3 species out of 17 most important) were lost to logging after six years. Logging intensity however, increased stem density of a subset of the eight most abundant species, and had no effect on the remaining species. Both findings denote the need for identifying the factors leading to temporal decay of some species over others, which could be due to overharvesting of species with regeneration limitations and slow growth rates. Preference of some species over others, particularly between congeneric species such as the ones studied in here, might also inadvertently lead to species loss.We discuss these aspects at length in the following two sections.

Variation in commercial timber species among communities, logging intensity, and time since last logging

In this section, we discuss about the variation in abundance of 17 commercial timber species, and in stem density and timber volume of eight commercial timber species among community-owned forests, logging intensity and time since last logging. The abundance of the 17 commerical timber species included in our study varied largely, from few individuals (*S.* macrophylla, *T. oblonga*) to very high numbers (*A. lecontei*, *H. parvifolia*; Table 4.1). This variation is probably partially due to natural local variation in abundance and distribution among species in the Bolivian Amazon (Picard et al. 2012). This is also supported by the differences in total stem density of six of the eight most abundant commercial timber species among communities (Table 4.2). This variation was also explained by logging intensity or time since logging in the case of five species (Table 4.2). Time since logging and/or when interacting with logging intensity decreased total stem density of *C. Fissilis*, *C. odorata* and *H. parvifolia* individuals (Table S4.3), suggesting slow recovery of stem density for these commercial timber species over time, which has also been found in other studies (Dauber et al., 2005; Gourlet-Fleury et al., 2013). Additionally, we found that only one (6%) and three (17%) species out of the 17 studied species were not found at sites two and six years after logging, respectively.

However, and in spite of differences in the set of studied species and/or to the large difference in logging intensities between ours and de Avila et al.'s study sites – 0.6 ± 0.1 vs. 4.6 ± 2.9 m^2 ha^{-1} of removed basal area, respectively – it is possible that species absent at our post-logged sites will reappear at logged sites over a longer period of time than we studied, also suggested by de Avila et al. (2015) who found a complete, and even surpassed recovery of species diversity 30 years after logging. Our findings on only positive effects (and generally no effects) of logging intensity on stem density of our studied species supports de Avila et al.´s findings that the creation of new habitats created by higher logging intensity increases species diversity in logged-over sites and is important for the regeneration of a large proportion of tropical timber species (de Avila et al., 2015; Schwartz et al., 2012; Silva et al., 1995; Soriano et al., 2012).

We also noted a temporal decay of harvestable trees of *C. fissilis* and *C. odorata* after comparing stem density between unlogged sites and sites six years after logging. Temporal decay of timber species with high commercial value is particularly common in selectively logged tropical forests (Richardson and Peres, 2016; Schulze et al., 2008). Species most affected by logging are rare ones such as *T. impetiginosa*, or overharvested species with regeneration limitations such as *S. macrophylla* (Schulze et al., 2008). A temporal decay of harvestable trees of *Cedrela* species was also evident due to the lack of harvestable trees in the 144 ha sampled, which is surprising given that *Cedrela* densities of 0.22 and 0.26 individuals ha^{-1} were reported at two community forest management plans of our study (ABT, unpublished data). An obvious explanation for this lack of harvestable *Cedrela* individuals might be the widespread selective logging of these species, occurring even within formally logged areas. Community families in the Bolivian Amazon face many limitations to sustainably log timber from their forests. One such limitation is the low standing timber volume of commercial timber species with well established national and international markets such as S*. macrophylla, Cedrela spp.*, and *Tabebuia* spp. These species were as well very rarely found in the 144 ha sampled across the Bolivian Amazon (Table 4.1), supporting the observations that community-owned forests have low density of the most precious timber species. Although standing timber volume differed between community-owned forests for five out of the eight commercial timber species studied (Table 4.3 and Table S4.4), the extent of these differences should not be accounted as the sole measure to manage tropical forests because stem density may turn more important to guarantee a widespread distribution of a species regeneration that will ultimately determine the degree of volume recovered in subsequent timber cutting cycles.

The small-volumes logging operation modality (Bolivia´s Forest and Land Controlling Authority - ABT Directive 001/2014) happens to formalize the re-logging of forests being managed under the community forest management plan (CFMP). This new form of logging will certainly increase pressure on a select number of commercial timber species even further in spite of its requirements for diversification of harvest species because it does not require an inventory or census prior to logging; neither it requires retention of seed trees or planning of roads and protection zones. Since our results come from forests logged under the CFMP, an increased focus on few timber species will most likely affect the species with low local abundance and those reported as not found at sites six years after logging.

Species sharing a genus differ in their response to logging intensity

Density and volume

Differences in density between *Hymenaea* species concur with differences in timber volume (Table 4.4), and indicate that *H. courbaril* has a naturally lower occurrence in the region than *H. parvifolia*. These results are consistent with pre-logging inventories done in the region that indicate that densities of *H. courbaril* only accounted for 8 - 13% of *H. parvifolia* densities (Proyecto de Manejo Forestal Sostenible, 2003). A significant decrease in stem density of individuals ≤10 cm DBH of *H. courbaril* over time since logging may be due to more intensive logging of this species during the past 10 years (Fig. 4.2b). Ten years ago, *H. courbaril* may have been more intensively logged than *H. parvifolia*, which may explain this negative effect (Estado Plurinacional de Bolivia, 2010). In contrast with *Hymenaea* species, stem density of ≤10 cm DBH and trees between 10 cm DBH and MDC of *Cedrela* species did not differ between species (Table 4.4). In Acre – Brazil, *C. odorata* presented 0.67 harvestable trees ha^{-1} (Rockwell et al., 2007a), whereas, in Pando – Bolivia stem density ranged between 0.21 - 0.30 individuals ha^{-1} (Proyecto de Manejo Forestal Sostenible, 1997). Such discrepancy in species density was also observed among our studied communities (Table 4.2). Density of individuals ≤10 cm DBH of *C. odorata* triplicated at logged-over sites compared to unlogged sites (Soriano et al., 2012), however, the negative influence of time since logging led to an overall decrease of its density over time (Fig. 4.2a) as light levels decreased. This decrease is yet very low and might not affect *C. odorata* overall population density due to an increased initial boost in recruitment produced by increasing canopy opening created by logging intensity (D'Oliveira, 2000; Poorter and Hayashida-Oliver, 2000; Van Rheenen et al., 2004).

Growth and survival

Differences found in the growth rate of individuals ≤2 m high between the two *Cedrela* and the two *Hymenaea* species (Table 4.5) might have important implications for the population growth rate of these species. Differences in growth rate deserve special attention, particularly because growth rate of the studied species were not always determined by the same predictors (Table S4.6). For example, presence of lianas affecting growth was more important for the DBH growth rate of individuals >0.5 cm DBH of *C. odorata* than of *C. fissilis* (Table S4.6). Concurring with Mostacedo et al. (2009), logging intensity was more important for the DBH growth rate of *Cedrela* than of *Hymenaea* species (Table S4.6). Differences found in survival rates of *Hymenaea* individuals ≤2 m high as genus might be related to the effects of logging intensity and time since logging on *H. parvifolia* and not on *H. courbaril* (Table S4.7). A lack of increase on *H. courbaril* survival rate with logging intensity might also be due to the low logging intensity at our study sites, because higher survival rate of this species and of *C. odorata* individuals were observed at larger disturbances created by logging ((Van Rheenen et al., 2004). We noted also that little of the variation in survival was explained by the significant differences found between species (up to only 6% of the variation), and argue that other factors (initial size, crown form or time since last logging, which explained most of the variation in stem density of the focus species) play a more important role than species in determining the survival rates of the species (Table S4.7).

Our results suggest that species-specific logging intensity – likely driven by loggers' preference over certain timber species – might be leading to a lack of harvestable sized *Cedrela* species, as well as of *H. courbaril* compared to its genus counterpart. The current legal framework prohibits the harvesting of both *Cedrela* species in the Bolivian Amazon (ABT Directive 02/2013) under the small timber volumes logging operation modality, which might count as a temporal solution to regain stem density of harvestable size for these species. However, more active management that incorporates pre- and post-logging silvicultural practices is required to regain stem density of harvestable size and to secure sufficient seed trees for these species.

Conclusions

We conclude that local and temporal variation of commercial timber species abundance and timber stocks are important factors to be accounted for managing tropical forests for timber production. To a large extent, such variation depends on species intrinsic characteristics and on species differential response to logging. We found both a positive and a negative impact of logging on the density of commercial timber species, but unfavourable impact over some species, indicating the need to learn more about the ecology and management requirements of individual commercial species. Our results also ask for a diversification of the set of logged species to spread the impact among many species. Our results also indicate the need to implement silvicultural treatments to recover the population of (endangered) commercial timber species. Silvicultural interventions need to be promoted instead of calling for reduced logging intensity (i.e., already low in the Bolivian Amazon). In addition, application of sivicultural practices, such as cutting of lianas, appears necessary to increase growth rate of commercial timber species, particularly of light-demanding species such as *C. odorata* (Table S4.6). These suggestions may be viewed more favourably in community-owned forests because communities are more interested in the long-term sustainability of commercially valuable species than the majority of timber companies whose focus is around maximizing timber profits (Shearman et al., 2012). Thus, financing post-logging silvicultural intervention will be necessary to increase sustainable timber yields and the environmental value of managed forests.

Addressing the abovementioned recommendations for commercial timber management require urgent action for two reasons. The first reason is that timber logging adds up value to the standing forest in a region driven by the

Amazon nut (*B. excelsa*) economy, a nut solely derived from mature forests to which timber logging is complementary (Soriano et al., 2017), which will also make local communities more resilient to changes in market preferences for forest products and market prices. Secondly, Amazon nut and timber production together, could potentially turn profitable enough to outcompete other production activities requiring forest clearing (Soriano et al., 2017). Urgent action is required to promote the management of these forests on the basis of species-specific response to logging and ecological knowledge, rather than harvesting timber without looking at the long-term consequences.

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Supporting information

Table S4.1. Variables used in the regression models to analyse the response of commercial timber species to logging intensity, time since logging and ecological tree characteristics.

Response variables	**Survival rate:** trees that survived or died between 2014 and 2015. (0) Dead, (1) Alive
	Height growth rate: m that an individual grew between 2014 and 2015 (m year^{-1})
	DBH growth rate: cm that an individual grew between 2014 and 2015 (cm·year^{-1})
Explanatory variables	**Initial size:** Size of a tree measured at plot establishment
	Initial size-squared: Initial size to the power of 2
	Logging intensity: Percentage of area disturbed due to logging (%)
	Time since logging: Time that has passed since last logging to plot establishment in 2014. Unlogged sites have a value of zero
	Standing timber volume of mature trees: timber volume of trees >40 cm DBH in a transect
	Liana infestation: (1) lianas affecting growth, i.e., trees with lianas reaching the crown; (0) lianas not affecting growth.
	Crown form (1) perfect, (2) good, (3) fairly good
	Crown position: (1) crown receiving full light, (2) crown receiving only vertical light, (3) crown receiving some vertical light, (4) crown receiving only lateral light, (5) crown receiving some light or no direct light

Table S4.2. Best generalized linear models determining the effect of community, logging intensity and time since last logging on total stem density of eight commercial timber species. We assumed a negative binomial distribution to run the models due to the high variability of our data. **S**ignificance level was set at p-value <0.05 and significant values are marked with asterisks: * p-value <0.05, **p-value <0.01, ***p-value <0.001. Empty cells indicate non-significant effect of a variable on total stem density of the specified species.

Species	Intercept		Community			Logging intensity (Logged trees)		Time since logging		Logging intensity x time since logging	
	Estimate	p-value	Community	Estimate	p value	Estimate	p-value	Estimate	p-value	Estimate	p-value
Apuleia leiocarpa (N = 72)	2.55	<0.001***	2	0.27	0.606	0.37	<0.001***				
Theta = 0.603			3	-0.96	0.061						
AIC = 574.8			4	0.83	0.226						
p-value = 0.06			5	-0.18	0.748						
Pseudo r-squared = 0.155			6	-0.15	0.779						
Astronium lecontei (N = 72)	6.21	<0.001***	2	-1.73	<0.001***						
Theta = 0.769			3	-2.26	<0.001***						
AIC = 683.6			4	-3.61	<0.001***						
p-value <0.001***			5	-5.36	<0.001***						
Pseudo r-squared = 0.71			6	-3.36	<0.001***						
Cedrela fissilis (N = 70)	2.86	<0.001***	2	-3.77	<0.001***			-0.16	0.014*		
Theta = 0.538			3	-0.11	0.841						
AIC = 347.6			4	0.72	0.311						
p-value <0.001***			5	0.02	0.971						
Pseudo r-squared = 0.49			6	-2.87	<0.001***						
Cedrela odorata (N = 72)	-2.94	0.004**	2	5.4	<0.001***	1.23	<0.001***	0.04	0.614	-0.12	0.020*
Theta = 0.495			3	-35.8	1						
AIC = 350.4			4	3.85	<0.001***						
p-value <0.001***			5	3.73	<0.001***						
Pseudo r-squared = 0.57			6	5.3	<0.001***						

Table S4.2. Continued.

Species		Intercept		Community			Logging intensity (Logged trees)		Time since logging		Logging intensity x time since logging	
		Estimate	p-value	Community	Estimate	p value	Estimate	p-value	Estimate	p-value	Estimate	p-value
Dipteryx micrantha (N = 72)		1.28	0.002**	2	0.4	0.471						
Theta	= 0.559			3	1.62	0.003**						
AIC	= 450.4			4	1.91	0.006**						
p-value	<0.001***			5	1.17	0.042*						
Pseudo r-squared	= 0.34			6	-0.3	0.619						
Hymenaea courbaril (N = 72)		2.84	<0.001***	2	-2.08	0.049*						
Theta	= 0.139			3	-0.1	0.924						
AIC	= 316			4	-22.14	0.995						
p-value	= 0.002**			5	-0.08	0.945						
Pseudo r-squared	= 0.25			6	-2.55	0.023*						
Hymenaea parvifolia (N = 72)		4.53	<0.001***	2	0.19	0.677	0.65	<0.001***	0.01	0.775	-0.12	<0.001***
Theta	= 0.831			3	-0.92	0.034*						
AIC	= 786.4			4	-0.96	0.105						
p-value	= 0.022*			5	-0.24	0.627						
Pseudo r-squared	= 0.22			6	0.26	0.597						
Tabebuia serratifolia (N = 72)		-0.43	0.508	2	-0.75	0.309			0.19	0.008**		
Theta	= 0.417			3	1.05	0.114						
AIC	= 273.4			4	-27.75	1						
p-value	<0.001***			5	0.58	0.453						
Pseudo r-squared	= 0.32			6	1.29	0.06						

Table S4.3. Best generalized linear models determining differences in standing timber volume of eight commercial timber species between communities, with logging intensity and time since logging as covariates. Standing timber volume was separated for potentially harvestable (trees >40 cm DBH – MDC) and harvestable (trees >MDC) trees. We log-transformed volume values per transect (N) to normalize the data distribution before carrying linear models. Significance level was set at p-value <0.05 and significant values are marked with asterisks: * p-value <0.05, **p-value <0.01, ***p-value <0.001. Empty cells indicate non-significant effect of a variable on standing timber volume of the specified species. DBH = diameter at 1.3 m aboveground, MDC = minimum diameter cutting.

Species	Standing timber volume	N	p value	r-squa-red	Intercept		Community			Logging intensity (Logged trees)		Time since logging (Years)		Logging intensity x time since logging	
					Estimate	p-value	Community	Estima-te	p-value	Estima-te	p-value	Estima-te	p-value	Estima-te	p-value
Apuleia leiocarpa	Potentially harvestable	72	0.338	0.10	0.07	0.173	2	-0.04	0.461	-0.02	0.086				
							3	0.06	0.335						
							4	-0.07	0.400						
							5	-0.05	0.400						
							6	0.02	0.734						
	Harvestable	72	0.003	0.26	1.06	0.001	2	0.36	0.311			-0.09	0.013*		
							3	-0.42	0.225						
							4	1.09	0.017*						
							5	-0.39	0.317						
							6	0.01	0.983						
Astronium lecontei	Potentially harvestable	72	0.010	0.20	0.389	0.000	2	-0.24	0.028*						
							3	-0.35	0.001**						
							4	-0.39	0.007**						
							5	-0.39	0.001**						
							6	-0.33	0.005**						
	Harvestable	72	0.000	0.37	1.26	0.000	2	-0.88	<0.001***	0.19	0.060	0.01	0.701	-0.04	0.018*
							3	-0.97	<0.001***						
							4	-1.27	<0.001***						
							5	-1.36	<0.001***						
							6	-0.95	<0.001***						

Table S4.3. Continued.

Species	Standing timber volume	N	p-value	r-squared	Intercept		Community			Logging intensity (Logged trees)		Time since logging (Years)		Logging intensity x time since logging	
					Estimate	p-value	Community	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
Cedrela fissilis	Potentially harvestable						2	-0.04	0.698						
							3	-0.01	0.944						
		72	0.266	0.09	0.072	0.292	4	-0.07	0.542						
							5	0.14	0.136						
							6	-0.07	0.455						
	Harvestable trees						2	0.18	0.324						
							3	0.08	0.647						
		72	0.270	0.09	0.00	1.000	4	0.53	0.027						
							5	0.09	0.631						
							6	0.00	1.000						
Cedrela odorata	Potentially harvestable						2	0.41	<0.001***						
							3	0.00	1.000						
		72	0.003	0.23	0.000	1.000	4	0.00	1.000						
							5	0.08	0.491						
							6	0.22	0.076						
	Harvestable trees						2	0.07	0.613						
							3	0.00	1.000						
		72	0.064	0.14	0.00	1.000	4	0.27	0.141						
							5	0.16	0.280						
							6	0.39	0.011*						
Dipteryx micrantha	Potentially harvestable						2	-0.02	0.700	0.04	0.045*	0.00	0.468	-0.01	0.041*
							3	0.08	0.071						
		72	0.136	0.17	-0.009	0.819	4	0.00	0.953						
							5	-0.02	0.737						
							6	-0.01	0.891						
	Harvestable trees						2	-0.15	0.440						
							3	0.21	0.271						
		72	0.305	0.09	0.15	0.301	4	0.19	0.431						
							5	0.00	0.990						
							6	-0.15	0.464						

Table S4.3. Continued.

Species	Standing timber volume	N	p value	r-squared	Intercept		Community			Logging intensity (Logged trees)		Time since logging (Years)		Logging intensity x time since logging	
					Estimate	p-value	Community	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
Hymenaea courbaril	Potentially harvestable	72	0.592	0.05	0.000	1.000	2	0.00	1.000						
							3	0.04	0.152						
							4	0.00	1.000						
							5	0.00	1.000						
							6	0.00	1.000						
	Harvestable trees	72	0.200	0.10	0.34	0.008	2	-0.34	0.047*						
							3	-0.34	0.047*						
							4	-0.34	0.122						
							5	-0.10	0.586						
							6	-0.34	0.059						
Hymenaea parvifolia	Potentially harvestable	72	0.342	0.08	0.095	0.176	2	-0.10	0.311						
							3	0.03	0.782						
							4	-0.10	0.432						
							5	0.04	0.721						
							6	0.10	0.315						
	Harvestable trees	72	0.043	0.22	0.09	0.702	2	0.38	0.140	0.31	0.005**	0.029	0.334	-0.05	0.006**
							3	0.06	0.796						
							4	0.12	0.724						
							5	0.41	0.146						
							6	0.46	0.093						
Tabebuia serratifolia	Potentially harvestable	72	0.022	0.20	0.169	0.002	2	-0.12	0.046	-0.04	0.005**				
							3	0.02	0.678						
							4	-0.16	0.049*						
							5	-0.14	0.035*						
							6	-0.13	0.042*						
	Harvestable trees	72	0.006	0.21	0.61	0.000	2	-0.61	0.001**						
							3	-0.34	0.059						
							4	-0.61	0.011*						
							5	-0.61	0.002**						
							6	-0.20	0.286						

Table S4.4. Predictors of stem density of species with a shared genus name, with logging intensity and times since logging as fixed effects and community as random effect in a mixed effects model. A fixed predictor with the lowest p-value was chosen in the absence of significant fixed predictors in a model in a backward selection of fixed effects. Values for the different fixed effects are given after controlling for the effects of the random factor on stem density. Values for stem density of *Cedrela* individuals >MDC are not shown in the table as no individual was found in the entire sampled area. The value of Theta and overDispTest are measures of goodness of fit for negative binomial (NB) and Poisson distributions, respectively. Values of Theta and OverDispTest closer to 1 means that the data's residuals were not over- or under-dispersed. **S**ignificance level was set at p-value <0.05 and significant values are marked with asterisks: * p-value <0.05, **p-value <0.01, ***p-value <0.001. Empty cells indicate non-significant effect of a given variable on total stem density of the specified species, DBH = diameter at 1.3 m aboveground, MDC = minimum diameter cutting.

Species	Size group	Distr.	N.	Theta	overDispTest	p-value of the intercept	Fixed predictors					
							Logging intensity (Logged trees)		Time since logging (Years)		Logging intensity* Time since logging	
							Slope	p-value	Slope	p-value	Slope	p-value
Cedrela fissilis	≤10 cm DBH	Poisson	70		<0.001	0.547			-0.1	0.002**		
	10 cm DBH - MDC	Poisson	72		0.108	0.071						
Cedrela odorata	≤10 cm DBH	Poisson	72		<0.001	0.673	0.45	0.004**	-0.07	0.007**		
	10 cm DBH - MDC	Poisson	72		0.602	0.123						
Hymenaea courbaril	≤10 cm DBH	NB	72	0.2		0.016	-1.66	0.056	-0.37	0.014*	0.52	0.007**
	10 cm DBH - MDC	Poisson	72		0.998	0.002						
	>MDC	Poisson	72		0.031	0	0.84	0.048*				
Hymenaea parvifolia	≤10 cm DBH	NB	72	0.84		<0.001	0.39	0.002**	0.06	0.984	0.08	0.006**
	10 cm DBH - MDC	Poisson	72		0.745	<0.001						
	>MDC	Poisson	72		0.81	0.002	0.43	0.006**	0.07	0.31	0.1	0.009**

Table S4.5. Mixed effects models (MEMs) output of the effects of logging intensity and times since logging on species potential and harvestable timber volumes following to logging, with community as random factor. Results from linear MEMs of log transformed timber volumes. Values for the fixed effect are given after controlling for the effects of the random factor on stem density. Values for **harvestable** (trees > MDC) timber volume of *Cedrela* individuals are not shown in the table as no individual was found in the entire sampled area. **Potentially harvestable** timber volume is set for trees between 40 cm DB and MDC. Significance level was set to p-value <0.05 and significant values are marked with asterisks: * p-value <0.05, **p-value <0.01, ***p-value <0.001. Empty cells indicate non-significant effect of a given variable on standing timber volume of the specified species. REML = convergence criteria, R2c = conditional r^2 explains the proportion of the variance explained by the fixed and random factors, DBH = diameter at 1.3 m high aboveground, MDC = minimum diameter cutting.

Species	Standing timber volume class (Size group)	#Obs.	REML-convergence	R2c	p-value of the intercept	p-values of the fixed effects					
						Logging intensity		Time since logging		Logging intensity x time since logging	
						Slope	p-value	Slope	p-value	Slope	p-value
Cedrela Fissilis	Potentially harvestable	72	25.1	0.027	0.352	0.058	0.168				
Cedrela odorata	Potentially harvestable	72	46.4	0.16	0.103	-0.36	0.72				
Hymenaea courbaril	Potentially harvestable	72	-91.7	<0.001	0.237	-0.206	0.838				
	Harvestable	72	98.9	0.003	0.518	1.396	0.167				
Hymenaea parvifolia	Potentially harvestable	72	28.2	0.002	0.01*	-0.35	0.727				
	Harvestable	72	156.6	0.11	0.02*	0.555	0.012*	0.026	0.379	-0.101	0.009**

Table S4.6. Best model indicating most significant predictors of growth rate of species with a shared genus name. Best models were chosen using the backward selection method and only significant variables were included in the model. Significance level was set at p-value <0.05 and significant values are marked with asterisks: * p-value <0.05, **p-value <0.01, ***p-value <0.001. Empty cells indicate non-significant effect of a given variable on standing timber volume of the specified species. DBH = diameter at at 1.3 m aboveground.

Size class	Species	df	p-value	r^2	p-values of explanatory predictors										
					Initial size	Initial size^2	Logging intensity	Time since logging	Logging intensity x Time since logging	Standing timber volume of mature trees (>40 cm DBH)	Perfect crown	Good crown	Not so good crown	Poor crown	Lianas affecting growth
Height growth rate of individuals ≤2 m high, but ≤0.5 cm DBH	*Cedrela*	88	0.003	0.18						0.035*	0.002**	0.001**	0.040*	0.001**	
	Cedrela fissilis	40	0.019	0.13	0.019*										
	Cedrela odorata	47	0.01	0.24							0.084	0.004**	0.065	0.005**	
	Hymenaea	1131	<0.001	0.04	<0.001***		<0.001***	0.127	0.010*	0.013*					
	Hymenaea courbaril	77	<0.001	0.23	.		0.008**	.	.	0.028*					
	Hymenaea parvifolia	1051	<0.001	0.03	0.002**		<0.001***	0.864	0.003**	.					
DBH growth rate of individuals >0.5 cm DBH, but >2 m high	*Cedrela*	194	<0.001	0.11	<0.001***		0.025*								
	Cedrela fissilis	193	<0.001	0.14	<0.001***	0.014*	0.009**								
	Cedrela odorata	93	<0.001	0.23	<0.001***		0.024*								0.021*
	Hymenaea	143	<0.001	0.11	0.001**	0.003**									
	Hymenaea courbaril	15	0.004	0.52	0.001**	0.003**									
	Hymenaea parvifolia	126	0.002	0.08	0.002**										

Table S4.7. Results from logistic regression models indicating the impact of logging intensity and ecological tree characteristics on survival rate of species sharing the same genus. Best models were chosen using the backward selection method and only significant variables were included in the model. Over-dispersion test values closer to 1 means the model's residuals were not over- or under-dispersed. The Pseudo McFadden r-squared is an alternative to measure the model's goodness of fit for generalized linear models as it applies to survival. Significance level was set to p-value <0.05 and significant effects are marked with asterisks: * p-value <0.05, **p-value <0.01, ***p-value <0.001. DBH = diameter at breast height.

Size class	Species	DF	AIC	Over-dispersion test	r^2 (Mc Fadden)	p-values of explanatory predictors									
						Initial size		Initial size²		Logging intensity		Time since logging		Timber volume >40 cm DBH	
						Slope	p-value	Slope	p-value	Slope	p-value	Slope	p-value	Slope	p-value
Height survival rate of individuals ≤2 m high, but ≤0.5 cm DBH	*Cedrela*	155	185.91	1.03	0.32	5.225	<0.001***	-2.844	0.003**					-0.095	0.002**
	Cedrela fissilis	80	103.69	1.04	0.32	6.618	0.001**	-3.141	0.012*						
	Cedrela odorata	73	85.48	1.1	0.25	5.561	0.039*	-3.386	0.066						
	Hymenaea	1472	1471	1.26	0.16	2.888	<0.001***			0.389	<0.001***	-0.066	0.002**		
	Hymenaea courbaril	97	80.93	0.94	0.3	11.993	<0.001***	-5.296	0.001**						
	Hymenaea parvifolia	1371	1373.9	1.07	0.17	5.551	<0.001***	-2.329	<0.001***	-0.066	<0.001***	0.389	0.003**		
DBH survival of individuals >0.5 cm DBH, but >2 m high	*Cedrela*	254	120.07	0.98	0.03	-0.624	0.054								
	Cedrela fissilis	135	83.37	1	0.02					-0.539	0.167				
	Cedrela odorata	101	36.78	1.11	0.06	-0.023	0.287								
	Hymenaea	156	46.84	0.99	0.08	-0.018	0.196								
	Hymenaea courbaril	24	17.13	0.87	0.07									0.155	0.434
	Hymenaea parvifolia	172	32.69	1.24	0.05					-0.89	0.197				

Chapter 5

Synthesis

Marlene Soriano Candia

Introduction

Rural families throughout tropical regions derive an important share of their livelihood from a variety of forest products (Agrawal et al., 2008; Jagger et al., 2014), ranging from non-timber to timber forest products. A large proportion of these products are harvested and commercialized in local, regional, national and international markets, which further enhances rural livelihoods (Stanley et al., 2012). The management of multiple forest products, and of non-timber forest products (NTFPs) in particular, have also played an important role in protecting large tracks of tropical forests from conversion to other less environmentally-friendly land uses such as pastures for cattle-ranching (Duchelle et al., 2011). Thus, research on the socioeconomic and ecological viability of timber and non-timber production in a multiple-use forest management (MFM) scheme appears crucial for guaranteeing the sustainable management of the species being harvested, but it is also challenging because it requires disentangling complex socio-ecological interrelationships from a multidisciplinary perspective (García-Fernández et al., 2008; Ticktin, 2004).

MFM is defined as the production of multiple forest products and services from within a single management unit (Sabogal et al., 2013). Accordingly, from this point onwards, I refer to MFM as the production of timber and non-timber forest products derived from tree species within the same management unit. The harvest of timber and non-timber products from a forest unit encompasses many (yet) unknown ecological and social feedbacks affecting the future availability of the species from which these products are harvested and the income that community families derive from these forests. Consequently, to guarantee the sustainable timber and non-timber production in a MFM scheme, we need to understand the role of socioeconomic and biophysical factors (e.g., local ecological knowledge; Uma Shaanker et al., 2004), on household income, as well as the role of ecological factors on recovery rates of valuable tree species following harvesting. In this thesis, I aimed to ***increase the understanding of the social, economic, and ecological factors driving the sustainable production of an important MFM scheme in the Bolivian Amazon, and to determine the contribution of* this *MFM to the well-being of community families and to the sustainable development of community forestry in this region***.

In the Bolivian Amazon, Amazon nut (*Bertholletia excelsa*, also known as 'Brazil nut') is the most important non-timber forest product (NTFP) used for its fruits, followed by timber production (Cronkleton et al., 2012; Soriano et al., 2012). This study encompassed 24 community households located in six communities distributed throughout the Bolivian Amazon (Fig. 1.1). To evaluate the socioeconomic and biophysical aspects of community households, I carried out survey questionnaires with the heads of 24 community households. To evaluate ecological aspects contributing to recovery rates of Amazon nut and 17 most important commercial timber species, I established 72 permanent research transects (three transects per community household, with total area of 144 ha) that were monitored for two consecutive years in 2014 and 2015.

We first looked at the impact of socio-ecological factors on the income derived from Amazon nut and timber by community households (chapter 2). Second, we determined the impact of logging and Amazon nut harvesting intensity on the Amazon nut population growth rate (chapter 3). And last, we determined whether density and timber volume of important commercial timber species differed among communities in relation to logging intensity and time since last logging, and given that congeneric species are often lumped together for logging – a simplification that could have major impacts on species demographic rates – we also assessed whether density, timber volume, and growth and survival rates differed between congeneric species in relation to logging intensity and time since logging (chapter 4). In this last chapter (chapter 5), I aim to first denote the contribution of our findings (chapters 2, 3 and 4) to current discussions on forests and livelihoods, multiple-use forest management, community forestry, and socio-ecological systems. Then I discuss the implications of these findings for the implementation of MFM in the Bolivian Amazon, from which I will draw on some policy and management recommendations and directions for future research in this area.

Multiple-use forests and forest livelihoods

The contribution of forest to household income in our study communities was nearly double (59% of the total household net income, Fig. 2.4) than the 30% contribution of forest to total household income reported in two global comparative studies (Angelsen et al., 2014; Jagger et al., 2014). Region-wise, the contribution of forest to household income in our studied communities is comparable with the forest income of community households residing within and outside a forest reserve with restricted access to timber (64%; Duchelle et al., 2014), and higher than the mean income of all community types residing in the region (42%; Zenteno et al., 2013). Amazon nut and timber alone made up to 92% of the income that community households derived from forest in our study sites (Fig. 2.3), creating an important opportunity to investigate the relationships between multiple-use forest management and livelihoods. The identification of factors leading to increased income from main rural livelihood sources, particularly cash generating sources such as timber and Amazon nut, may help increase household income and reduce the increasing migration rate of community households to regional cities (de Jong et al., 2014; Zenteno et al., 2014) as well as promote the sustainable use of the forest resource.

Numerous research approaches have been developed to understand the links between forests and livelihoods. Advances have been made towards understanding the driving factors of household wealth, forest conditions, governance, and tropical deforestation using bivariate statistical analysis approaches (Andersson et al., 2014; Duchelle et al., 2014; Gibson et al., 2005; Humphries et al., 2012; Ostrom and Nagendra, 2006; Zeidemann et al., 2013; Zenteno et al., 2013). Relationships among these factors are, however, generally complex and call for novel approaches to integrate existing knowledge (Agrawal et al., 2008; Liu et al., 2007; Ostrom, 2012). By using multi-model inference we could narrow the numerous socioeconomic and biophysical factors influencing the different sources of household income down to the most significant ones. Their subsequent incorporation in a hierarchical model such as structural equation model (SEM) allowed predicting the overall impact of these factors on the different sources of household income, focusing on Amazon nut and timber income (Fig. 2.8).

Results of the SEM analysis carried out in chapter 2 showed that off-farm income (e.g., business within the community) decreased the income generated and harvesting intensity of Amazon nut and timber simultaneously (Fig. 2.8), and that households with better bargaining power to sell their Amazon nut and who applied more management practices to increase Amazon nut production derived less income from timber (Fig. 2.8b). These findings indicate complementarity between Amazon nut, timber and off-farm incomes at the household level, where increased livelihood opportunities generated by off-farm income – facilitated by improved market connectivity – could potentially help reduce migration and pressure over forest resources. Furthermore, better bargaining power can potentially increase income derived from forest products without necessarily increasing harvesting intensity.

The findings above indicate the path for community households to improve their livelihoods through multiple-use forest management involving Amazon nut and timber production. The contribution of Amazon nut to the higher per capita income of *campesino* families in the Bolivian Amazon is remarkable and calls for a better understanding of this MFN scheme. However, the high dependency of local communities on forests for their livelihoods is criticized because it traps community families into cycles of poverty (Coomes et al., 2004; but see Shackleton et al., 2007), and therefore, special consideration should be paid to the power dynamics within communities. In the Bolivian Amazon, community families get trapped into poverty in two ways: 1) by incurring in a patronage-like system under wealthier families – who can access larger forest areas – to extract forest products, and 2) by lacking financial means and skills to bargain better prices for their forest products. The second way to get trapped into poverty could be overcome by the fact that communities organize themselves – largely supported by external agencies – by creating a community forest enterprise (CFE) to maximize profits from forests (mainly timber) through the development of a community forest management plan (CFMP), and by selling certified timber (Antinori and Bray, 2005; Humphries et al., 2012). Among our studied communities, 75% of the interviewed households indicated that the CFMP increased their total income (M. Soriano, unpublished data). Given that households with higher bargaining power to sell Amazon nut increased their income derived from Amazon nut, it appears that negotiation skills can potentially increase income from other NTFPs as well. Promoting CFEs or cooperatives for managing commercially valuable NTFPs (currently rare, probably even non-existent in tropical regions; Antinori and Bray 2005) and building capacities on managerial and negotiation skills are some of the immediate interventions needed to reduce poverty and lift the education of people in these communities.

Another important livelihood gain of CFMPs is the increased technical and negotiation skills of community people, which have helped them improve their livelihoods and allocate further benefits to their communities. In the Bolivian Amazon, one such learning outcome is the application of management practices to increase Amazon nut production and the negotiation for better Amazon nut prices by which families could reduce pressure over timber by decreasing their income from this resource (chapter 2).

Ecological insights for multiple-use forest management

The Bolivian Amazon offers a promising case to study the compatibility of timber and Amazon nut production in a MFM scheme due to the relatively long history of exploitation of these products and fully decentralized and stable tenure system. The study of complex ecological interactions such as the ones resulting from harvesting multiple forest products in a MFM scheme requires carefully designed experiments to avoid making too many assumptions and to thoroughly understand the feedbacks on the life cycle of the harvested species. The few studies on MFM in tropical regions focused on understanding the ecological sustainability of harvesting two products from the same tree species (Gaoue and Ticktin, 2008; Herrero-Jáuregui et al., 2011; Klimas et al., 2012a). This is the first time that the ecological sustainability of timber and NTFPs harvested from separate tree species in the same area is investigated at the population level (chapters 3 and 4).

In chapter 3, we disentangled the impact of Amazon nut harvesting, logging of other tree species and liana cutting (i.e., from producing *Bertholletia* trees) on *Bertholletia* demographic rates (i.e. growth, survival and fecundity) and on *Bertholletia* population dynamics using size-structured matrix models. A positive effect of logging intensity on *Bertholletia* seedlings growth rate, and of liana cutting on fruit production rate played key roles on *Bertholletia* overall population growth rate (Table 3.1, Fig. 3.3b), and counteracted the negative impact of nut harvesting intensity on the number of *Bertholletia* new recruits. Thus, compatibility between

Amazon nut and timber logging in a MFM scheme is determined by a trade-off between Amazon nut harvesting intensity (up to 85% of nut harvest on a yearly basis) and logging intensity (up to 15% of forest area disturbance every 20 years) when 21% of *Bertholletia* reproductive trees are liberated from lianas (average application of liana cutting intensity) every 20 years (Fig. 3.1).

After looking at the impact of logging intensity on various ecological tree characteristics of the 17 most important commercial tree species for the region (chapter 4), we found that 17% of the species present at unlogged sites (*Swietenia macrophylla, Tabebuia impetiginosa* and *Terminalia* sp.) were not present at sites six years after logging. Moreover, no harvestable tree > the minimum diameter cutting (MDC) from 71% of the species found at unlogged sites were present at sites six years after logging, e.g., the two *Cedrela* species. Total stem density of five of the eight most abundant commercial timber species investigated (*Astronium lecontei, Cedrela fissilis, Cedrela odorata*, *Dipteryx micrantha* and *T. impetiginosa*) differed between community-owned forests after accounting for the effects of logging intensity and time since logging; whereas, potentially harvestable (trees between 40 cm DBH and MDC) and harvestable timber volume of only two (*A. lecontei* and *C. odorata*,) and three (*Apuleia leiocarpa, A. lecontei,* and *T. impetiginosa*) species differed between communities, respectively. Best models indicated that logging intensity increased total stem density of *A. leiocarpa, C. odorata* and *Hymenaea parvifolia*; and timber volume of *D. micrantha* and *H. parvifolia*, and only decreased potentially harvestable timber volume of *T. impetiginosa*. When looking at differences between species of the same genus in response to logging, we found that species of *Hymenaea* genus differed mainly in density and timber volume; whereas, *Cedrela* genus differed mainly in growth and survival rates. The impact of logging intensity was favourable for the growth rate of *C. odorata* individuals >0.5 cm DBH but >2 m high, but unfavourable for *Hymenaea courbaril* (Table S4.6), and favoured survival rate of *H. parvifolia* individuals ≤2 m high but ≤0.5 cm DBH (Table S4.7). Given the high variability in the population density of commercial timber species between communities and in response to logging, management on a species basis is required to sustain timber yields of the investigated species for future harvest rotations.

Our findings above indicate that logging intensities as carried out at *campesino* community-owned forests in the Bolivian Amazon (with up to 15% of logging-disturbed area, with 3 logged trees ha^{-1}) are beneficial for the population growth rate of *Bertholletia* (Fig. 3.1b) and for the density of at least three of the eight studied commercial timber species (*A. leiocarpa*, *C. odorata* and *H. parvifolia*; Tables 4.2 and 4.S3). Logging intensity also benefitted *Bertholletia* growth rate and the two species of *Hymenaea* genus (Table S4.6). The beneficial effect of logging intensity on *Bertholletia* (chapter 3) is in accordance with the hypothesis that *Bertholletia* populations benefit from unintended human-caused forest disturbance (Scoles and Gribel 2012, 2015, Rockwell et al., 2017) and management (Levis et al., 2017a; Ribeiro et al., 2014). Commercial timber species such as the least abundant ones (*Aspidosperma macrocarpon, Amburana cearensis* and *Schizolobium parahyba*) and those not found at sites six years after logging (*S. macrophylla, T. impetiginosa* and *Terminalia* sp.) may need to be logged less intensively, rather than logged at a lower degree of logging disturbance, to avoid temporal decay and unexpected local extinction (Tables 4.2 and 4.S2; Richardson and Peres 2016, Schulze et al., 2008). However, the favourable influence timber logging intensity on *Bertholletia* and commercial timber species populations is only relevant when sufficient seed trees are retained for a continued regeneration. Retention of seed trees needs to be based on the species local abundance prior to logging, determined by its reproductive biology (e.g., frequency of reproduction), regeneration requirements (Fredericksen et al., 2003).

In contrast to privately-owned forest and forest concessions, timber extraction in community managed forests may face greater pressure on timber due to the share of revenues with a larger number of stakeholders and to the new logging modality in place since 2014, which enables community households to log small-volumes of timber from their forest even from areas assigned to the CFMP (Bolivian Forest and Land Controlling Authority - ABT Directive Nº 001/2014). Under this new logging modality a community household can log up to 42 m^3 of timber per year from its forest in six small-scale timber logging operations. Timber logged can be of any species, except for *S. macrophylla, Cedrela* spp., and *Amburana cearensis.* This form of logging is expected to increase pressure on a select number of commercial timber species even further (N. Ascarrunz, personal communication, September 22, 2016). Such rate of extraction may affect mainly species with low local abundance and those reported as not found at sites six years after logging because the new logging modality does not require an inventory or census of trees, retention of seed trees or planning of roads and protection zones prior to logging.

Liana cutting from reproductive Amazon nut trees is commonly practiced by harvesters during visits to the forest in Amazonian community-owned forests (chapter 2; Kainer et al., 2014). Other practices include liana cutting of saplings and juveniles from Amazon nut and other valuable tree species, and protection of regeneration (chapter 2; Kainer et al., 2014). As mentioned earlier, liana cutting increases *Bertholletia* population growth rate by increasing fruit production (chapter 2; Kainer et al., 2014). The application of liana cutting and other silvicultural treatments could also significantly increase growth and recruitment rates of commercial timber species (Peña-Claros et al., 2008a, 2008c; Villegas et al., 2009). Although we did not test for the effect of liana cutting on commercial timber species, the presence of lianas affecting the crown appeared to negatively affect the growth rate of *C. odorata* (Table S4.6). Thus, diversification of the set of commercial timber species and the application of liana cutting may lead to a faster recovery of timber volume of low-density commercial timber species.

Where does multiple-use management stand in community forestry?

The potential of community forestry to reduce poverty and effectively retain forest conservation value has been the main reason for governments and international donors to direct efforts towards facilitating the adoption of CFMPs throughout the tropics. Despite the important gains of community forestry in terms of empowerment, increased economic returns and skills developed, community forestry has not yet fully met its most important development goal, which is reducing poverty (Sunderlin et al., 2005). In order to reduce poverty, communities have slowly engaged in profit maximization-driven timber production by opting for developing community forest management plans (CFMPs). However, communities' self-modes of organization, traditional ecological knowledge to manage their resources, and limited financial means to better position themselves to negotiate for a good price for their products were often ignored under the profit maximization-driven formal forest management. This may have also counteracted community forestry's efforts to reduce poverty.

So far, important insights were revealed about the factors leading to the success of community forestry in tropical regions. Among those are clear tenure rights, proven self-control of forest resources use, and creation of internal organizations focused on the production of a specific product (Andersson et al., 2014; Coomes et al., 2004; Toledo et al., 2003). Few of these studies, however, investigated a particular forest production system in relation to socio-ecological aspects of community households (see Coomes et al., 2004; Duchelle et al., 2014; Uma Shaanker et al., 2004; Zenteno et al., 2013). The methods used in these studies were, however, largely based in extensive semi-structured interviews and community workshops with little regard to the ecological component, in other words without much information about the forest the communities were managing. The socio-ecological analysis used in this thesis to investigate the viability of a particular MFM scheme among community households is an initial step to measure and identify the factors leading to the success (or failure) of community forestry in Bolivia and elsewhere.

Studies on the cultural and natural access to common pool resources by members of a social group or community have contributed substantially to the understanding of the factors leading to the success of community forestry (Agrawal, 2014; Andersson et al., 2014; Ostrom and Nagendra, 2006). These studies show that in the short-term, forest-dependent families may be better off at managing common pool resources individually rather than collectively, whereas, common pool resources management has more long-term benefits for the community if managed collectively (Ostrom, 2012). Common pool resource management also provides short-term benefits for the further development of community families in terms of infrastructure, social capital homogeneity, equity and leadership in the long run (Pacheco et al., 2008). It has also increased the technical skills of community members and improved community households' production systems (Humphries et al., 2012). This is also the case of the MFM system studied in this thesis. An important learning outcome was the need for better negotiation skills of community families to obtain better Amazon nut prices that can also be promoted locally to reduce pressure on timber.

Improved skills also contributes to community families´ total income when resource use and/or negotiation takes place collectively because communities get better empowered to obtain better prices for their products (chapter 2). For example, in one of our communities, community households had nearly doubled their income from timber by only having better negotiation skills (unpublished data). Gains by obtaining a better price for a given forest product could also help reduce pressure over other forest products, not only of timber (Fig. 2.8b). Additionally, community households could also increase their income from timber over the long run by sharing their income from timber with other community household members (chapter 2).

Due to the importance of timber as one of the main commodity forest products in many tropical regions (Sabogal et al., 2013), and given that more than half of the most commercially important timber species in the Bolivian Amazon are locally and temporally absent or at very low densities at *campesino* community-owned forests (Table 4.2), transformation of timber to elaborated products needs more promotion and support to reduce pressure over timber while maximizing profits. The implementation of transformation industries will require improved governance and control systems to avoid mismanagement of economic resources. Diversification of income through the incorporation of other commercially valuable NTFPs within a MFM scheme with timber production can initially compensate for the high costs and burden of implementing processing plants, e.g., for fruit pulp. In this sense, MFM involving timber and non-timber production must be viewed as an important avenue for diversifying community households´ income from the forest, and at the same time for avoiding forest conversion to other land uses and for promoting equity in terms of the allocation of forest resources to community families.

Silvicultural intervention is also key to enhance timber yields and Amazon nut fruit production (chapter 3). The application of silvicultural treatments may also have greater adoption among communities than among timber concession holders because community people are more interested in the long-term sustainability of their forests than the majority of timber companies which focus is around maximizing timber profits (Shearman et al., 2012). Communities also have a great potential to sell certified products, which has already generated significant social benefits to communities

(Burivalova et al., 2017). Certification of forest products, however, needs to bring better returns by easing the burden of certification costs, and by improving market access and prices for forest products derived from sustainably managed forests owned by local communities. In this way, income from community-managed MFM products can compete with environmentally-unfriendly land uses. We have demonstrated that timber management is compatible with Amazon nut production (chapter 3), and that it may also be compatible with the production of many other valuable NTFPs commonly harvested within communities. The opportunities to maximize profits from MFM production explained above show the path for community forestry to meet communities' development goals, and to achieve sustainable forest management goals at the same time.

Multiple-use forest management as a socio-ecological system

A multidisciplinary approach such as the one used in this study is crucial to disentangle coupled human-nature relationships in a socio-ecological system such as MFM. Comprehensive data from the social as well as ecological sides are essential to capture the dynamics of MFM systems under production, and to understand the socio-ecological feedbacks driving the production of forest products. Data is, however, sparse, discipline focused, and therefore, still immature for many socio-ecological systems. In this study, we found that MFM entailing Amazon nut harvest and logging of commercial timber species is socially, economically and ecologically compatible in the Bolivian Amazon due to existing socioeconomic complementarity of both activities, and to the positive impact of logging intensity levels as practiced in the region on Amazon nut and commercial timber species. Customary practices such as the management measures undertaken by community households to improve Amazon nut fruit production (i.e., by cutting lianas from reproductive trees), and the positive impact of logging on *Bertholletia* population growth rate are two ways to simultaneously improve returns from forests and to enhance ecological sustainability (Figs 2.8b, Table 3.1). Therefore, the combination of the approaches used in this thesis to reach these findings – from basic to complex modelling techniques, and from analytical such as the structural equation models (SEM) to process-based analyses such as the matrix models – proved effective for disentangling and combining causal relationships of the factors involved. However, the compatibility found of the MFM system under study is confined to changing socioeconomic factors that are likely to result from changing policies, markets as well as to changing ecological factors due to for example climate change. To this end, other analyses can be taken from related disciplines (e.g., game - theory), and can be incorporated for a better understanding of these systems' adaptive capability under different scenarios of socioeconomic and ecological changes. These research approaches could potentially be replicated in other socio-ecological systems with similar characteristics.

The path to sustainable multiple-use forest management in face of socio-environmental constraints

The Bolivian Amazon shares similar forest and livelihood dependency with neighbouring Peruvian (Madre de Dios) and Brazilian (Acre) states, forming the South-western Amazon region, also known as the MAP region. In this region the degree of dependency on forest and other income sources are influenced by these countries' development of social contests over tenure rights and policies in place to manage forest resources (Duchelle et al., 2014). The region is currently facing unprecedented pressure over timber, which calls for bottom-up approaches to manage forest resources from a MFM perspective. The vast diversity of valuable NTFPs and timber species in the Bolivian Amazon offers unique opportunities to successfully manage these forests as MFM units.

In recent years, Bolivia has put in place a technical directive for integral management of forests and lands, the Integral Management of Forest and Land Plan (PGIBT due to acronym in Spanish; ABT Administrative Resolution Nº 250/2013) to formalize the management of multiple forest resources in combination with other land uses such as shifting cultivation by community families in the Bolivian Amazon. As of 2016, already 24 *campesino* communities (out of 245; Pacheco et al., 2009) in this region accounted with a PGIBT (ABT 2016, unpublished data). A PGIBT entails the participatory decision-making for allocating forest and land for multiple uses on the basis of the livelihood systems upon which community members rely. The PGIBT demands communities to accordingly manage their main production systems. As we found in chapter 2 the main production systems of the campesino community families in the Bolivian Amazon are: Amazon nut production, agriculture, agroforestry, timber production and off-farm activities (Fig. 2.3). Bolivian Amazonian forests are remarkable for their high density of reproductive Amazon nut trees. The production of Amazon nut hardly requires any investment, placing this activity as the most profitable one for a large proportion of community families in the region. Timber extraction is, and will continue to be for a while, the second most important cash income source derived from forest after Amazon nut, and is often used as natural insurance when Amazon nut production and price drop (Cano et al., 2013), and/or to make important investments such as the purchase of a motorcycle (unpublished data). Therefore, MFM entailing the management of timber and non-timber forest products comes as an important component of PGBITs (Villegas, 2012).

With regards to timber, communities only need to follow already established rules for logging timber established by the Forestry Law. In order to secure the regeneration of threatened species, the PGIBT also prohibits logging timber species listed in CITES Appendices I and II. Species listed in the CITES Appendix II are only to be logged upon demonstrating sufficient local abundance of a species. With regards to Amazon nut, the PGIBT prohibits re-entering the forest to harvest nuts or to hunt seed dispersers and requires the application of liana cutting to reproductive trees. These legal requirements are, however, largely based on general information about tropical silviculture and limited knowledge specific to a region and to the species being harvested (Fredericksen et al., 2001). Results of this thesis aim to contribute to filling this gap of scientific knowledge regarding existing opportunities for the sustainable production of Amazon nut and timber in a MFM scheme. Based on our population projection models, logging intensity impacting up to 15% of a logged area every 20 years may allow harvesting Amazon nut more intensively (up to 85% of nut harvest intensity in a yearly basis) within a MFM scheme than a system in which only Amazon nut is solely harvested (chapter 3). Since logging intensity levels as practiced at our study communities increases stem density and timber volume for at least 60% of the currently most important and abundant commercial timber species in the region (Table S4.4), species favoured by logging could potentially be logged using low logging intensities (up to 3 trees ha^{-1}) and cutting cycles of 20-year cutting cycles without being significantly affected by logging (chapter 4).

Communities in the Bolivian Amazon have effectively established their own internal rules to allow its members to access forest resources (Zenteno et al., 2014). Hence, the PGIBT does well in recognizing communities' effectiveness at self-regulating the compliance of rules for achieving the sustainable production of Amazon nut and timber in a MFM scheme. Moreover, such effectiveness, together with high Amazon nut prices has led communities to retain the high forest cover of the region (Duchelle et al., 2013). To maximize profits from forest products, social organizations in the Bolivian Amazon have prompted the Bolivian government to implement fruit processing industries to produce pulp from non-timber forest products, such as from acai berry (*Euterpe* spp.). Knowledge about the potential of community forests to feed these fruit-processing industries is, however, still limited. The potential exists for expanding our research to study the potential and the consequences of harvesting other timber and non-timber species. Continued generation of the ecological information generated from these transects established in this thesis and of semi-structured questionnaires aimed at obtaining information about rural livelihoods sources and indicators of community households´ well-being could bring further light for the holistic understanding of this socio-ecological system.

Policy implications and management recommendations

In this thesis, I demonstrated that Amazon nut and timber production are socially, economically (chapter 2) and ecologically (chapters 3 and 4) compatible when harvested in a MFM scheme under certain conditions. Our results suggest that emphasis should be put into capacity building programs to facilitate technical, negotiation and managerial skills among community households. It also suggests that the promotion of off-farm activities such as entrepreneurship and jobs in the community is a priority as they may help reducing pressure over forest resources (chapter 2). Careful implementation of these recommendations will require drawing policies that allows equal access to forest resources, promotes incentives and capacity building programs to communities and community households, and especially to the poorest household members or communites that depend the most on forest resources.

The enhancement of short-term benefits from sustainable forest management need to be prioritized to avoid that management does not come at the cost of the environmental benefits generated by these forests to present and future generations of people living inside and outside of these forests. This recommendation comes as a priority since Bolivia's timber sector is currently in a crisis due to the high costs attached to Bolivia's timber exports in its landlocked condition, and Africa's recent massive incursion in timber production (Shearman et al., 2012) that has put timber prices down, outcompeting Bolivia's timber from international markets. Thus, a better price for timber and Amazon nut produced in a MFM scheme would have immediate positive outcomes for the development of the fairly neglected South-western Amazon region, as well as for the continued conservation status of this socio-ecological system.

In agro-extractive communities of the Brazilian Amazon, community households rely on forest to mitigate subsistence agricultural risks, but cattle is considered a safer risk mitigation strategy than forests (Gomes et al., 2012; Pattanayak and Sills, 2001). Among Bolivian *campesino* communities, subsistence agriculture plays a similar role as cattle in Brazil, in other words it is used for mitigating fluctuations in the price of forest products. However, 21% of studied community households did not practice subsistence agriculture during the two study years (chapter 2, unpublished data), either because they preferred to work as independent chainsaw operators or pick any other temporal job outside the Amazon nut production season. Community household forests run the risk of conversion to detrimental land uses such as commercial agriculture and cattle ranching if the promotion of off-farm and subsistence agriculture activities is not promptly and adequately addressed. A more direct way to avoid conversion of forest to other land uses is by facilitating access to formal credit to forest owners to harvest Amazon nut and log timber (up to 15% of logging-disturbed forest area) in a MFM scheme. This can provide local insurance to offset the local opportunity costs of other land uses (Pattanayak and Sills, 2001).

The generally "subsistence" driven husbandry income (i.e., derived from shifting cultivation, agroforestry and raising of small livestock such as poultry and pigs), long-time practiced by *campesino* community households in the Bolivian Amazon are currently outperformed by income from Amazon nut and timber production, which may be preventing community households from incurring in commercial agriculture and cattle-ranching expansion (Cronkleton et al., 2012; Duchelle et al., 2014). The significant greater income derived from Amazon nut and timber under a MFM scheme is certainly the main motivation for communities to plan the PGBITs. The socio-ecological relationships revealed in chapter 2 of this thesis should contribute to the implementation of PGIBTs because we also provide insights about the drivers of household income. For example, although households travelling less frequently to the nearest city perceived less income from husbandry activities, they could harvest more NTFPs and received external support more times. We also found that households perceiving greater income from husbandry activities harvested Amazon nut less intensively. Based on these relationships, communities and community households poor in Amazon nut or timber can direct their activities to husbandry activities and/or to the extraction of other NTFPs, for which external support of governmental and municipal programs and local NGOs needed.

Commercial timber species respond differently to logging even when in the case of species belonging to the same genus (chapter 4). Given that loggers prefer to harvest some species over others, there is an obvious need for species-level management. In addition, proper identification of species at the species level, and not at the genus level as it is commonplace during management interventions in the tropics should be prioritized (chapter 4). The implementation of these management recommendations may come at a higher cost than the already prohibited costs of current management requirements. Thus, forest management in tropical regions need to revalorize local ecological knowledge, and adapt to technological change, such as developing management tools based on hyperspectral multidimensional imagery, in order to cheapen management costs.

Concluding remarks and the way ahead for multiple-use forest management research

Compatibility between Amazon nut harvest and logging of commercial timber species in a MFM scheme is largely due to existing socioeconomic complementarity of both activities and to the positive impact of logging intensity levels as practiced in the region on Amazon nut and on most commercial timber species. Community families' better negotiation skills to obtain better prices for Amazon nut, and increased implementation of management practices to increase Amazon nut production (e.g., liana cutting) helped them not only increase their income, but also decrease pressure on timber. Replication of this work in different contexts and ecological constraints, and at different spatial scales, with more observations and over a longer period of time, will allow identifying unknown direct and indirect relations among socioeconomic and ecological factors. Such studies are needed to address sustainability issues of socio-ecological systems in face of changing populations, policies, markets and climate. It will also be important to investigate the economic returns generated by a MFM scheme involving more NTFPs to sustain increasing economic and livelihood needs. This will imply exploring the commercial potential and socio-ecological viability of other forest products, such as the numerous NTFP species harvested throughout the Amazon Basin (Cámara-Leret et al., 2014), e,g., acai berry (*Euterpe* spp.). Embedding results of this research with traditional ecological knowledge to produce Amazon nut and timber in a MFM scheme is thus crucial for a sustainable and efficient use of forests resources, and for improving rural livelihoods and the environment. The absence of evidence-based policies specific to the management of timber and non-timber forest products has hindered the identification of the overall benefits of logging disturbance, and likely of many unknown traditional forest management practices, on the population of many commercial tree species. Hence, understanding the complexities that MFM entails seems necessary for a continued provision of forest products with long-lasting benefits for forest communities.

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Summary

Community families throughout tropical regions derive an important share of their income from multiple forest products, with generally positive outcomes on their livelihoods. The production of these products in a multiple-use forest management scheme (MFM, the production of multiple forest products within a single management unit) encompasses many (yet) unknown socioeconomic and ecological feedbacks. In particular, MFM entailing timber and non-timber production may be affecting the future availability of valuable timber and non-timber tree species due to the extraction of vital plant components, which may have undesired outcomes on the income that community families derive from forests. In this thesis, I evaluated the social, economic, and ecological viability of an important MFM scheme widely practiced by community households in the Bolivian Amazon: the production of Amazon or Brazil nut (*Bertholletia excelsa*) and timber from other tree species. Data was obtained from a two-year (2014 and 2015) survey questionnaires of 24 community households in six *campesino* communities with community forest management plans (CFMPs) and from ecological surveys of 72 2 ha permanent research transects (three transects per household forest) harvested at varying Amazon nut and logging intensities. A CFMP entails the planning and execution of logging activities in compliance with formal rules intended to secure the long-term provision of timber at community-owned forest. Household-level decisions to harvest Amazon nut and to log timber allowed us to account for household forest as our sampling unit. We used multi-model inference and structural equation modelling techniques to determine the impact of socio-ecological factors on the income that community families derived from Amazon nut and timber (chapter 2), and regression and matrix modelling techniques to determine the impact of Amazon nut harvest and logging intensity on *Bertholletia* (chapter 3) and commercial timber species (chapter 4).

In general, we found that few socioeconomic and biophysical factors of community households, together with a general positive response of studied species to timber logging and customary silvicultural intervention, make the production of Amazon nut and timber production of other tree species viable in a MFM scheme. In chapter 2, we found that community households could reduce their dependency on forest resources by increasing income opportunities from other existing livelihood activities. Amazon nut represented the largest source of household income (44% of the total household net income); and off-farm (salary, business and gifts; 21%), husbandry (generally subsistence agriculture, animal rising, and agroforestry; 21%), and timber (9%) incomes were complementary to their livelihood. Increased skills and ecological knowledge of community households enhanced household income derived from forest products. For example, an increase in the number of management practices reduced the need for timber income by increasing Amazon nut production; decreasing further pressure on timber of other tree species.

In chapter 3, logging intensity was found to increase *Bertholletia*'s seedlings and saplings growth rate, and liana cutting was found to increase Amazon nut production rate. Both, logging and liana cutting intensities played a key role on *Bertholletia* population growth rate. Increased logging and liana cutting intensities counteracted the negative impact of Amazon nut harvesting intensity on the number of new recruits (i.e., due to nut harvest), indicating a trade-off between logging, liana cutting and Amazon nut harvesting intensities.

Considering the overall stem density of commercial timber species (chapter 4), we found that 17% of the species present at unlogged sites (3 species out of 17: *Swietenia macrophylla*, *Tabebuia impetiginosa* and *Terminalia* sp.) were not present at sites six years after logging; and a larger percentage (71%) of the species present at unlogged sites in the harvestable size (trees>minimum diameter cutting – MDC) were not present at sites six years after logging, e.g., *Cedrela* spp. Stem density and timber volume of five of the eight most abundant commercial timber species under study differed among community-owned forests, after accounting for the effects of logging intensity and time since logging as indicated by our best models; whereas, potentially harvestable and harvestable timber volume differed between communities for only two and three species, respectively. Best models indicated that logging intensity increased either stem density or timber volume of *Apuleia leiocarpa*, *Cedrela odorata*, *Dipteryx micrantha* and *Hymenaea parvifolia*, decreased potentially harvestable timber volume of *T. serratifolia*, and had no effect on the other three species investigated. We also investigated the impact of logging intensity on congeneric species given that lumping congeneric species for logging is a common simplification during forest inventories and censuses, and is accepted in CFMPs assuming that closely related species respond to timber logging in a similar way. However, logging intensity had a differentiated effect on congeneric species. Logging intensity favoured growth rate of *C. odorata* trees >10 cm DBH and had no effects on *Cedrela fissilis*. Regarding *Hymenaea* congeneric species, logging intensity favoured *H. parvifolia* survival of individuals <10 cm DBH, but decreased growth rates of *H. courbaril* trees >10 cm DBH.

In conclusion, Amazon nut harvest and timber logging of other tree species are compatible under certain socioeconomic and biophysical conditions, and as long as commercial timber species differential response to harvesting are accounted for in managing these species in a MFM scheme. This compatibility is due to existing socioeconomic complementarity of both activities and to the positive impact of logging intensity levels as practiced in the region on Amazon nut production and on most commercial timber species. Community families' better negotiation skills to obtain better prices for Amazon nut, and increased implementation of management practices to increase Amazon nut production (e.g., liana cutting) helped families to increase their income and also decrease pressure on timber. These results highlight the need to look at both socioeconomic and ecological aspects when assessing the long-term sustainability of MFM schemes.

Results of this research have important implications for policy to support the sustainable development of community forestry in the Bolivian Amazon. The compatibility found between Amazon nut and timber production calls for the investigation of the compatibility of timber production with other valuable NTFPs commonly harvested by community families throughout the tropics. We argue that management needs to be done at species-specific level, rather than at the level of products or at the level of species groups. This may result prohibitively expensive for communities and smallholders. Thus, we urge governments and the international community to revalorize local ecological knowledge of community people to manage their forests, while supporting the development of technologies, such as the ones based on hyperspectral LiDAR technology, to develop tools that could help reduce management costs of tropical forests at the required level. Such policies need to be accompanied by capacity building programs on different management tasks and negotiation skills to enhance the income obtained from MFM schemes. The research approaches used here could be used in other contexts and scales involving natural resources management to get a better understanding of the systems.

Resumen (Summary in Spanish)

Las familias de comunidades que habitan regiones tropicales, reciben una parte importante de sus ingresos de varios productos forestales con resultados generalmente positivos en sus medios de vida. El aprovechamiento de estos productos bajo un esquema de manejo múltiple de bosques (MMB, aprovechamiento de varios productos forestales dentro de un área de manejo) comprende distintos procesos de retroalimentación entre los que inciden factores socioeconómicos y ecológicos aún desconocidos. En particular, el aprovechamiento de productos maderables y no-maderables bajo un esquema de MMB, pudiera afectar la disponibilidad de especies maderables y no-maderables en el futuro debido a la extracción de partes vitales de las plantas, con impacto negativo en los ingresos que las familias obtienen del bosque. En esta tesis, evalué la viabilidad social, económica y ecológica de un esquema de MMB: la producción de castaña amazónica (*Bertholletia excelsa*) y madera de otras especies arbóreas, extensamente practicado por las familias de comunidades en la Amazonía Boliviana. Los datos fueron obtenidos de cuestionarios de 24 familias que viven en seis comunidades campesinas con planes de manejo forestal comunitario (PMFC), y de un muestreo ecológico de 72 transectos de investigación permanentes de 2 ha c/u (3 transectos por bosque familiar) que fueron aprovechados bajo diferentes intensidades de aprovechamiento de castaña y madera. Un PMFC comprende la planificación y ejecución de actividades de aprovechamiento en cumplimiento con normas legalmente establecidas para asegurar la provisión de madera en bosques comunales en el largo plazo. La toma de decisiones a nivel familiar acerca del aprovechamiento de castaña y madera nos permitió considerar el bosque familiar como nuestra unidad de muestreo. Utilizamos modelos múltiples inferenciales y de ecuaciones estructurales para determinar el impacto de factores socio-ecológicos en los ingresos que las familias comunales obtienen de la castaña y de la madera (capítulo 1), y modelos de regresión y de matrices para determinar el impacto de las intensidades de aprovechamiento de castaña y madera en las poblaciones de *Bertholletia* (capítulo 3) y de especies maderables comerciales (capítulo 4).

En general, encontramos que pocos factores socioeconómicos y biofísicos de las familias comunales- al igual que la una respuesta positiva de las especies estudiadas al aprovechamiento de madera y a intervenciones silviculturales tradicionales- hicieron que la producción de castaña y madera de otras especies maderables sea viable bajo un esquema de MMB. En el capítulo 2, encontramos que las familias comunales logran reducir su dependencia sobre recursos forestales al incrementar las oportunidades de ingresos de otras actividades existentes. La castaña representó la mayor fuente de los ingresos familiares (44% del total de los ingresos); y las actividades fuera de la parcela (salarios, negocios y regalos, 21%), cultivos agrícolas, sistemas agroforestales y cría de animales, y madera son complementarios al sistema de vida de las familias. Un aumento en las capacidades técnicas y en el conocimiento ecológico de las familias mejoraron los ingresos de productos forestales. Por ejemplo, un aumento en el número de mejores prácticas de manejo, redujo los ingresos de madera al aumentar la producción de castaña; reduciendo aún más la presión sobre el aprovechamiento de madera de otras especies arbóreas.

En el capítulo 3, se encontró que la intensidad de aprovechamiento de madera aumentó la tasa de crecimiento de plántulas y brinzales de *Bertholletia*, y la corta de bejucos disminuyó la tasa de producción de frutos de castaña. Ambos, la intensidad de aprovechamiento de madera e intensidad de corta de bejucos, tuvieron un rol importante en el crecimiento poblacional de *Bertholletia*. Mayores intensidades de aprovechamiento de madera y de corta de bejucos redujeron el impacto negativo de la intensidad de aprovechamiento de castaña en la cantidad de reposición de plántulas (ej. debido a la extracción de semillas), indicando un compromiso entre las intensidades de aprovechamiento de madera, corta de bejucos y castaña.

Luego de tomar en cuenta la densidad total de especies maderables comerciales (capítulo 4), encontramos que tres (*Swietenia macrophylla*, *Tabebuia impetiginosa* and *Terminalia sp.*) de 17 especies presentes en bosques sin aprovechamiento de madera, estuvieron ausentes en bosques que fueron aprovechados seis años antes del muestreo para este estudio, y un porcentaje mayor (71%) de las especies presentes en sitios sin aprovechamiento de madera de tamaño aprovechable (árboles > diámetro mínimo de corta - DMC) no se encontraron en bosques aprovechados seis años antes del muestreo, ej. *Cedrela spp*. La densidad de palos y volumen maderable de cinco de las ocho especies comerciales más abundantes de las especies estudiadas, varió entre comunidades después de tomar en cuenta el efecto de la intensidad de aprovechamiento y tiempo desde el aprovechamiento como lo indican nuestros mejores modelos; en tanto, los volúmenes de madera potencialmente aprovechables y aprovechables difirieron entre comunidades de sólo dos y tres especies, respectivamente. Los mejores modelos indicaron que la intensidad de aprovechamiento incrementó tanto la densidad como el volumen maderable de *Apuleia leiocarpa*, *Cedrela odorata*, *Dipteryx micrantha* e *Hymenaea parvifolia*; disminuyó el volumen potencialmente aprovechable de *T. serratifolia*; y no tuvo ningún efecto en las demás especies investigadas. También investigamos el impacto de la intensidad de aprovechamiento en especies comúnmente aprovechadas bajo el mismo nombre, una simplificación de los inventarios y censos de especies comerciales maderables en los planes de manejo forestal comunitario (PMFC) bajo el supuesto de que las especies del mismo género responden de manera similar al aprovechamiento de madera. No obstante, el impacto de la intensidad de aprovechamiento de madera difirió entre especies aprovechadas bajo el mismo nombre. La intensidad de aprovechamiento de madera favoreció la tasa de crecimiento de árboles > 10 cm DAP de *C. odorata* y no tuvo ningún impacto en *Cedrela fissilis*. Respecto a las especies de *Hymenaea*, la intensidad de aprovechamiento de madera favoreció la tasa de sobrevivencia de individuos <10 cm DAP de *H. parvifolia* pero disminuyó la tasa de crecimiento de árboles > 10 cm DAP de *H. courbaril*.

En conclusión, el aprovechamiento de castaña y madera de otras especies arbóreas es compatible bajo ciertas condiciones socioeconómicas y biofísicas, y en tanto se tome en cuenta la respuesta diferenciada de las especies comerciales al aprovechamiento bajo un esquema de uso múltiple. Esta compatibilidad se debe a la complementariedad de ambas actividades y al impacto positivo de los niveles de intensidad de aprovechamiento practicados en la región en la producción de castaña y en la mayoría de las especies maderables comerciales. La capacidad de negociación para obtener un mejor precio por la castaña, y el aumento en la aplicación de una mayor cantidad de prácticas de manejo para aumentar la producción de castaña (ej., corta de bejucos) ayudó a las familias a mejorar sus ingresos y a disminuir la presión sobre la madera. Estos resultados resaltan la necesidad de considerar ambos aspectos: socioeconómicos y ecológicos al momento de evaluar la sostenibilidad de los esquemas de MMB.

Los resultados de esta investigación tienen implicaciones importantes en el ámbito político para apoyar el desarrollo sostenible del manejo forestal comunitario en la Amazonía Boliviana. La compatibilidad entre la producción de castaña y madera llama a seguir investigando la compatibilidad de la producción de madera con otras especies forestales no-maderables valiosas comúnmente aprovechadas por las familias de comunidades forestales a lo largo de los trópicos. Argumentamos que es necesario manejar el bosque sobre la base de cada especie, y no tanto sobre la base de productos (ej. madera) o de un grupo determinado de especies. Entendemos que esto podría resultar bastante caro para las comunidades y pequeños productores forestales, por tanto, convocamos a los gobiernos y a la comunidad internacional a revalorizar el conocimiento ecológico local de las comunidades para manejar sus bosques, mientras apoyen el desarrollo de tecnologías, tales como la tecnología basada en imágenes hyper-espectrales LiDAR, para desarrollar herramientas que pudieran reducir los costos de manejo de bosques tropicales en los niveles que estos requieren. Dichas políticas necesitarían estar acompañadas de programas de capacitación en diferentes actividades de manejo y habilidades de negociación para mejorar los ingresos generados bajo esquemas de MMB. Los enfoques de investigación aplicados en este estudio pueden ser utilizados en otros contextos y escalas que consideren el manejo de recursos naturales para un mejor entendimiento de los sistemas de vida tropicales.

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Short Biography

Marlene Soriano Candia was born on September 22, 1980 in Omereque, Cochabamba, Bolivia. She is the last of four siblings born to Walter Soriano Jiménez and Cornelia Candia Gonzáles. She obtained her High School diploma from the Colegio Gabriel René Moreno "Fé y Alegría" in Comarapa, Santa Cruz, Bolivia. Her enjoyment of the surrounding wilderness around her mother´s agricultural field in the outskirts of the Amboró National Park - where she used to spend her school holidays - and her amusement with the biological processes explained at her biology class played a key role in Marlene´s decision to pursue a career in Forestry at the university Gabriel René Moreno in Santa Cruz de la Sierra, Bolivia. She did her Bachelor thesis with the Instituto Boliviano de Investigación Forestal – IBIF on the reproductive capacity of commercial timber species in the Chiquitano Dry Forest. The following day after defending her BSc thesis in December 2005, she was hired as a research assistant at IBIF. After working for 2.5 years, she decided to pursue her masters in the School of Forest Resources and Conservation, with a concentration in Tropical Conservation and Development at University of Florida. Marlene´s main motivations to pursue a post-graduate education were to gain knowledge and to learn skills to carry participatory research to support community forestry in her country. Her MSc thesis was on "The growing dilemma of logging in Brazil nut rich, community forests in Northern Bolivia: Effects on natural regeneration and forest disturbance". After obtaining her Master degree, she returned to work at IBIF by the end of 2010 and started to put into practice what she has learned at University of Florida. Again, it was time to go deep and search more qualification to continue her work, and two years later, she decided to do her PhD in the Forest Ecology and Forest Management Group at WUR. Marlene is now working at IBIF, writing grant proposals to continue investigating multiple-use forest management (MFM) involving other non-timber forest products (NTFPs) and timber production in the Bolivian Amazon and at other socio-ecological systems in Bolivia.

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Soriano, M., P. A. Zuidema, C. Barber, F. Mohren, N. Ascarrunz, A. Romero-Seas, J. C. Licona & M. Peña-Claros (in preparation). Fate of Bertholletia excelsa populations under multiple use forest management.

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PE&RC training and Education Statement

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (5 ECTS)

- Where does multiple-use forest management stand in sustainability, development and conservation?

Writing of project proposal (4.5 ECTS)

- Quest for the socio-economic and ecological sustainability of forest management in Bolivian Amazonian communities

Post-graduate courses (7.5 ECTS)

- Practices, power and knowledge in participatory forest management; The Forest and Nature Conservation Policy Group (FNP) WUR & Program for Law and Environment Getúlio Vargas Foundation (PDMA/FGV) (2012)
- Multivariate analysis; PE&RC (2012)
- Ecological modelling in R; PE&RC (2012)
- Structural equation modelling; PE&RC (2015)

Invited review of (unpublished) journal manuscript (2 ECTS)

- Society and Natural Resources: is certification associated with better forest management and socioeconomic benefits? (2012)

- Forests: tropical forest-cover gain and interactions amongst agents of forest change (2015)

Competence strengthening / skills courses (2.9 ECTS)

- Communication in interdisciplinary research; WGS (2012)
- Project and time management; WGS (2012)
- Competence assessment; WGS (2012)

PE&RC Annual meetings, seminars and the PE&RC weekend (2.7 ECTS)

- PE&RC PhD Weekends first, mid-term, last years (2012, 2014, 2015)
- PE&RC Days (2012, 2014)

Discussion groups / local seminars / other scientific meetings (4.2 ECTS)

- Ecological theory and application (2012-2016)
- Ciclo de Conferencias en investigación de recursos naturales (2013-2015)

International symposia, workshops and conferences (4.7 ECTS)

- ATBC-OTS 50th Anniversary meeting; co-organizer of symposia; Costa Rica (2013)
- ATBC 2016 Meeting; oral presentation; Montpellier, France (2016)
- FLARE 2016 Annual meeting; oral presentation; Edinburgh, Scotland (2016)

Lecturing / supervision of practicals / tutorials (1.2 ECTS)

- Resource dynamics and sustainable utilization (2014)
- Resource dynamics and sustainable utilization (2016)

Supervision of MSc students

- Population dynamics of *Bertholletia excelsa*: response to logging and Brazil nuts harvesting

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