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Long-term effects of shade and input levels on coffee yields in the Pacific region of Nicaragua

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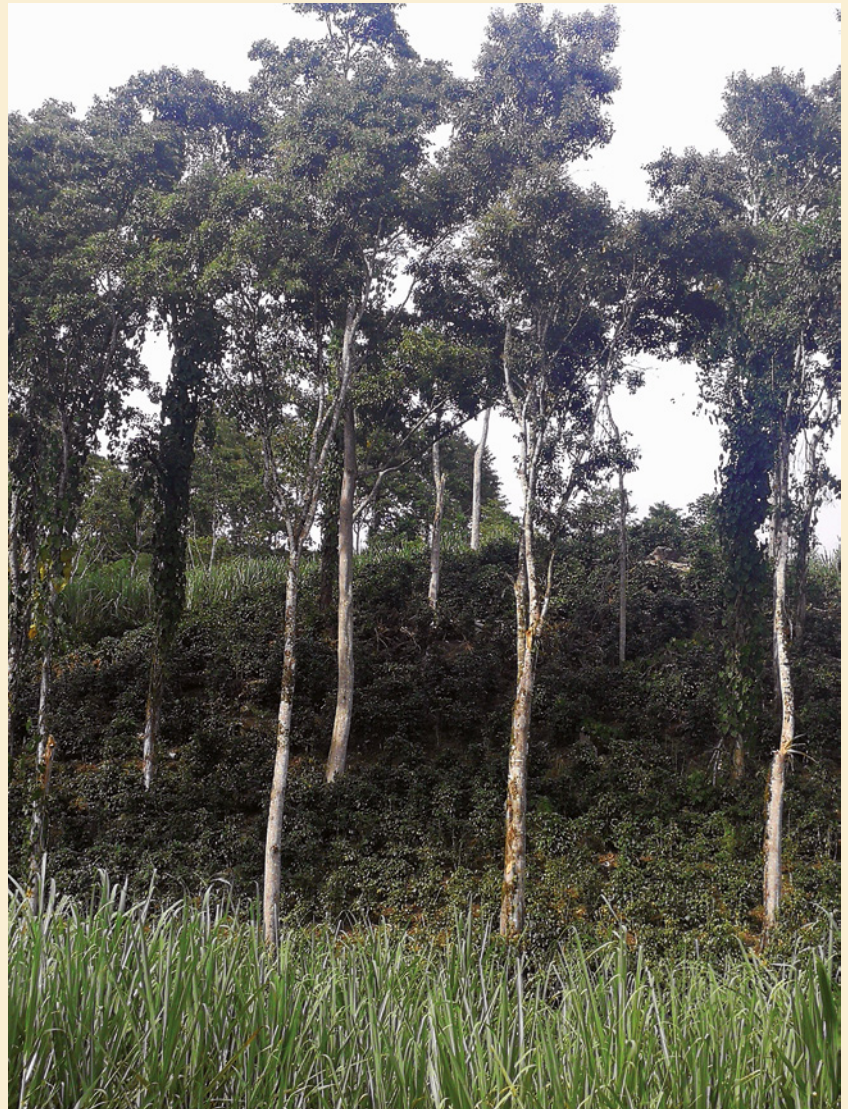Arlene LÓPEZ-SAMPSON –
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Photo 1.
Laurel (*Cordia alliodora*), a valuable timber species used as shade over Arabica coffee (*Coffea arabica* cv. Caturra), Turrialba, Costa Rica. Photo E. Somarriba.

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RÉSUMÉ

Effets à long terme de l'ombrage et des niveaux d'intrants sur les rendements de café dans la région Pacifique du Nicaragua

La pertinence et la rentabilité de la culture du café en Amérique centrale sont menacées par des infestations de ravageurs et des maladies, par la fluctuation des cours et par le changement climatique. La culture du café sous ombrage approprié serait une des pratiques les plus prometteuses dans une optique de développement durable et d'adaptation de la caféiculture en zone marginale. La présente étude vise à enregistrer et à comparer les rendements de cerises de café sur une période de 10 ans, sous l'ombrage d'essences fixatrices d'azote et d'essences à bois d'œuvre dans le cadre de différents systèmes d'agroforesterie (culture conventionnelle / culture biologique) sur site suboptimal. Pour certaines années de la période d'étude, des écarts de production significatifs sont constatés entre le système conventionnel et différentes combinaisons avec intrants biologiques sous différents types d'ombrage. Les systèmes de culture intensive en plein soleil sont les plus productifs en termes de rendement de café, suivis des systèmes sous ombrage d'essences à bois d'œuvre. Il est intéressant de noter que, quel que soit le système de gestion (conventionnel intensif ou biologique intensif), les systèmes de culture sous ombrage d'essences légumineuses (*Inga laurina* (Sw.) Willd. + *Simarouba glauca* DC.) sont les moins productifs en termes de rendement de café. Sur l'ensemble des placettes étudiées, les essences à bois d'œuvre *Simarouba glauca* et *Tabebuia rosea* (Bertol.) DC. montrent une bonne croissance, avec un accroissement moyen en diamètre de 2,5-3,3 cm/an (à 12 ans d'âge). Les systèmes d'agroforesterie en plein soleil et sous ombrage d'essences à bois d'œuvre génèrent les revenus bruts moyens les plus élevés. Globalement, les régimes intensifs sont les plus coûteux en gestion bien qu'ils aient les meilleures performances en termes de rendement de café.

Mots-clés : rendement de café, bois d'œuvre, système sous ombrage, *Inga laurina*, *Simarouba glauca, Tabebuia rosea*, conventionnel intensif, biologique intensif, agroforesterie, Nicaragua.

ABSTRACT

Long-term effects of shade and input levels on coffee yields in the Pacific region of Nicaragua

The suitability and profitability of coffee cultivation in Central America are at risk due to pest and disease outbreaks, price fluctuations and climate change. Proper shading is claimed to be one of the most promising practices to seek sustainability and better adapt coffee cultivation to climate change in marginal areas. This study recorded and compared coffee cherry yields over a ten-year period from shaded coffee (N-fixing-trees and timber trees) agroforestry systems under different management regimes (conventional vs. organic) in a suboptimal site. Significant differences in production were detected between conventional inputs vs. combination of organic inputs and shade types in some years of the evaluation period. Full-sun cultivation under intensive management was the most productive system for coffee yields, followed by shaded systems under timber trees. Interestingly, and regardless of management systems (intensive conventional or intensive organic) the worst combinations in terms of coffee yield were shaded systems under leguminous species (*Inga laurina* (Sw.) Willd. + *Simarouba glauca* DC.). Across all experimental plots, the timber species *Simarouba glauca* and *Tabebuia rosea* (Bertol.) DC. grew well, reaching a mean annual increment in diameter of 2.5-3.3 cm/year (age 12 years). Average gross revenues were higher in full-sun and timber-shaded agroforestry systems. Overall, intensive management regimes were the most expensive cultivation system to run but also the best in terms of coffee yield performance.

Keywords: coffee yield, timber, shaded system, *Inga laurina, Simarouba glauca, Tabebuia rosea*, intensive conventional, intensive organic, agroforestry, Nicaragua.

RESUMEN

Efectos a largo plazo de la sombra y de las entradas en la producción de café en la región de Nicaragua del Pacífico

La adecuación y rentabilidad del cultivo de café en América Central están en riesgo debido a brotes de plagas y enfermedades, fluctuaciones en el precio y al cambio climático. La sombra adecuada se considera una de las prácticas más prometedoras en un enfoque sostenible y para una mejor adaptación del cultivo de cafetales al cambio climático en áreas marginales. Este estudio registró y comparó la producción de drupas de café durante un período de diez años para cafetos a la sombra de árboles fijadores de N y de árboles madereros, en sistemas agroforestales bajo diferentes regímenes de gestión (convencional o ecológico) en un lugar subóptimo. En determinados años del período de evaluación se detectaron diferencias significativas en la producción con entradas convencionales frente a las entradas ecológicas bajo determinados tipos de sombra. El cultivo intensivo a pleno sol era el sistema más productivo en términos de café, seguido por los sistemas de sombra bajo árboles madereros. Resulta interesante, independientemente de los sistemas de gestión (convencional intensivo o ecológico intensivo), que las peores combinaciones en términos de producción de café fueron el cultivo en sombra bajo especies leguminosas (*Inga laurina* (Sw.) Willd. + *Simarouba glauca* DC.). A través de todas las muestras experimentales, las especies madereras *Simarouba glauca* y *Tabebuia rosea* (Bertol.) DC. crecieron bien, alcanzando un incremento medio en diámetro de 2,5-3,3 cm/año (edad, 12 años). Los ingresos brutos fueron más elevados en los sistemas agroforestales a pleno sol y a la sombra de árboles madereros. En general, el sistema de cultivo de los regímenes de gestión intensiva era más caro, en cambio, proporcionó el mejor rendimiento en las cosechas de café.

Palabras clave: producción de café, madera, sistema a la sombra, *Inga laurina, Simarouba glauca, Tabebuia rosea*, cultivo convencional intensivo, cultivo ecológico intensivo, agroforestería, Nicaragua.

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Introduction

Climate change will negatively impact both the yield and quality of arabica coffee production in most of the growing regions world-wide (Vaast *et al.*, 2005; Ovalle-Rivera *et al.*, 2015). Climatic variability will also trigger pests and disease outbreaks and alter key ecological interactions within shaded coffee agroecosystems (Avelino *et al.*, 2015; Magrach and Ghazoul, 2015). In Nicaragua, it is projected that the climate will become hotter, dryer and with remarkable seasonality especially at lower altitudes which in turn will move upward the altitudinal range of suitable land to grow coffee (Laderach *et al.*, 2011). This scenario becomes worse for lowland areas (400-500 m above sea level -asl- in the Pacific region) where coffee is still grown (Padovan *et al.*, 2015). Nicaragua does not have available land at an altitude higher than 1,300 m asl to move coffee cultivation upwards, therefore designing and managing diversified and more resilient shaded coffee agroforestry systems to sustain farmers' livelihoods in the long term becomes a crucial action in marginal areas (Bouroncle *et al.*, 2017; Läderach *et al.*, 2017).

Across Mesoamerica, frequently used shade tree species for both coffee and cacao cultivation will also be affected by climate change (de Sousa *et al.*, 2017, 2019). For example, according to recent modelling of the suitability of common shade tree species, it is expected that the range of occurrence of 79% of the common shade tree species used for coffee, will grow in a narrower geographical belt and thus will be lest suitable to intercrop with coffee (Gay *et al.*, 2006; de Sousa *et al.*, 2019). The biggest losses in shade tree adaptability will be experienced in mid-altitudinal coffee-growing areas (400-700 m), especially by the most popular N-fixing, fruit, and timber shade trees. Climate change is already having significant adverse impacts on smallholder coffee and basic grain farmers across Central American, yet mitigation and adaptation measures are gradually taking place (Baca *et al.*, 2014; Harvey *et al.*, 2017).

Globally, coffee is cultivated under five main production systems defined by their vegetation composition, structural complexity, and management level. These coffee-production systems cover the spectrum from a very diverse "rustic" shaded-system to intensive monoculture either under a monospecific shade tree or in full-sun (see Moguel and Toledo, 1999 for an in-depth description of the systems). The extremes of this spectrum also represent the traditional management regimes with high diversity, which produce low coffee yields, and monocultures characterized by high coffee yields.

In Central America, coffee is produced mainly under the shade of trees (Jha *et al.*, 2014; Somarriba and López-Sampson, 2018). The contribution of companion trees has been largely recognized on soil health (Moço *et al.*, 2010; Thomazini *et al.*, 2015), coffee quality (Vaast *et al.*, 2005; Bosselmann *et al.*, 2009), and these trees support the livelihoods of coffee smallholders (Méndez *et al.*, 2009, 2010) while providing a buffer to counterbalance harsh conditions caused by climate variability in the long term (Mbow *et al.*, 2014). Proper management of companion trees can improve the growing conditions of the multi strata system reducing abiotic stress and facilitating the performance of understory crops (Beer *et al.*, 1998; Tscharntke *et al.*, 2011). Besides, farmers can benefit from agroforestry by its capacity to provide several ecological services, such as water conservation, nutrient cycling, carbon sequestration, pollination and regulation of pests and diseases (Jose, 2009; Vaast and Somarriba, 2014).

Most management regimes for coffee cultivation are mainly focused on increasing productivity and incomes with less attention given to crop resilience and sustainability. Jezeer *et al.* (2018), however, found similar economic performance between shade (low, medium and high) and input (high, medium and low) classes, but a reduced net income and benefit-cost ratio in the high-input class, confirming a win-win scenario of economic performance with more environmental-friendly production through agroforestry. Moreover, net income from organic coffee production systems was similar to conventional production systems (when excluding the cost of certification), even when the former had a 22% lower yield than their counterparts, mainly due to the premium price paid to organic farmers which compensated the lower yields (Lyngbæk *et al.*, 2001). Similarly, Rossi *et al.* (2011) evaluated the effect of management practices on coffee productivity in a long-term experiment in sub-optimal growing conditions and found that intermediate management intensity produces competitive coffee yields overtime.

In this research, we evaluated the performance of coffee yields over 10 years under different management regimes and shade canopy trees (N-fixing trees and timber trees) to determine the best possible shade tree combinations for coffee productivity. The following questions were addressed in this study: (1) Are there significant effects of shade composition and management regimes on coffee productivity? (2) In the timber-based agroforestry system (AFs), do the potential revenues from standing volume yields lead to higher total system revenues (sum of all marketable goods) compared to leguminous-based AFs?

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Methods

Study area and site description

This study was carried out from November 2001 to May 2014 in three experiment plots located at two different nearby sites in Masaya and Carazo, southern Nicaragua. The first two plots were established in a local Botanical Garden (11o 53' 54" N, 86 o08' 56" W) managed by the Tropical Agricultural Research and Higher Education Center (CATIE in Spanish), in partnership with the Agrarian National University (UNA), Federation of Cooperatives of Credit and Savings (CENECOOP-FEDECARUNA) and Nicaraguan Institute of Agrarian Technology (INTA). The third site was established in 2001 in the Campos Azules Experimental Center (CECA) handled by the INTA. The three sites are located at 455 m asl which is rather marginal for Arabica coffee cultivation. This region has a long history of coffee cultivation as the Central-Pacific Region of Nicaragua was the first region where coffee was introduced in late 1880 (Craipeau, 1992). Despite being classified as marginal land to grow coffee several farmers still rely on coffee cultivation as living income.

The experiment covers 3 ha. Details of experiment establishment were described by Haggar *et al.* (2011). The mean annual temperature was 27°C and mean annual rainfall of 1,470 mm (Haggar *et al.*, 2011). Most of the total annual precipitation falls over the wet season (May-November) while a pronounced seasonal drought occurs from late November to mid-May. Predominant soils in the study sites are originated from volcanic eruptions and classified as Andisols. These soils are commonly deep, well-drained, and have high organic matter content, low bulk density, high allophane content, and consequently a high phosphorus fixation capacity, high amorphous mineral content, and high-water retention capacity (Padovan *et al.*, 2015).

Experimental design

The five different coffee production systems under comparison included four agroforestry combinations (AFs) and a full sun plot as control, both under conventional (CONV) and organic (ORG) management (tables I and II). Fourteen combinations of shade trees, input levels, and management regimes were implemented. The combinations evaluated are described in table I. Three replicates were set at each site as a randomized block design with shade type as the main treatment and input levels as sub-treatments within shade types. Four different species were planted, managed, and combined with two different management regimes namely CONV and ORG, and input levels (moderate and intensive) (table II). The combination of tree species was selected depending on their morphological complementarity and their ability to provide, or not, certain products and services such as timber, firewood, or nitrogen fixation. Selected tree species were generally used by local coffee farmers in nearby localities (Bonilla and Somarriba, 2000; Cordero *et al.*, 2003).

Subplots sizes varied between 500 to 600 m² with an effective measurement area ranging from 225 to 300 m² and comprising a minimum of 24 shade trees and 100 coffee plants per plot. The final number of plots and treatments included in the experiment was limited by land availability and labor costs. Approximately 1,667 shade trees were initially planted across experimental plots, however, three thinning events were done at age 5, 8, and 12 years after planting to keep a final density of 272 shade trees/ha. Coffee plant density (*Coffea arabica* var *Pacas*) was 4,000 plants/ha. In this study, we only showed the results of coffee yields until the harvest season of 2011 given that in 2012 there was a drastic drop in coffee yields across all management regimes and shade combinations. Shade tree growing performance and management data were included until the year 2012 of evaluation.

Data collection

During the period 2002-2012, in each plot, coffee yield from 100 coffee plants was recorded annually. Coffee was manually harvested, depulped, fermented, washed and sun-dried. Yield per plot was then converted to kg/ha/year. As a part of regular maintenance, coffee plants were partially pruned every year, thus pruning intensity was registered from 2005 to 2012 as a proportion of planting density and accounted for coffee yield recordings. Tree dimensions and shade cover within plots were measured annually during the first year and then every two years. Shade cover (%) was measured at the center of each plot with a densiometer and taking four readings in each cardinal point. Shade cover from each measuring point was averaged and registered as the plot's annual value. Tree growth of each shade species (diameter in cm, total and commercial

Table I.
Shade tree (main plot) and input treatments (subplot) combinations.

Input treatments/ Shade combination	FS	SGTR	ILSG	SSTR	SSIL
CI	X	X			X
CM	X	X	X	X	X
OI		X	X	X	X
OM		X			X

IC: intensive conventional; MC: moderate conventional; IO: intensive organic; MO: moderate organic; FS: full sun; SGTR: *Simarouba glauca* DC. + *Tabebuia rosea* (Bertol.) DC.; ILSG: *Inga laurina* (Sw.) Willd. + *Simarouba glauca* DC.; SSTR: *Samanea saman* (Jacq.) Merr. + *Tabebuia rosea* (Bertol.) DC.; SSIL: *Inga laurina* (Sw.) Willd. + *Samanea saman* (Jacq.) Merr.

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height both in m and crown area in m²) was recorded every 6 months during the first five years and then annually until they reached the age of 14 years. Tree diameter and tree height were measured with diameter tape and clinometer, respectively. Between 20-24 shade trees were measured per plot and recorded tree attributes were averaged and coded per species.

Data management and statistical analysis

To evaluate the effect of shade tree species, input levels, and management regimes (grouped in a single variable named Treatment) on coffee yield (t/ha) a general linear mixed model was used (Di Rienzo *et al.*, 2011). In our model specification, the Treatment variable is considered as a random effect to account for the imbalance in the statistical design. The statement of the model was: Coffee yield ~ 1 + Treatment. The analysis was carried out by year due to the year variable was masking the "Treat-ment" effect when running treatment as a fixed effect and year and block as random effects. Fisher's Least Significant Difference (LSD) means comparisons were run among management regimes to evaluate statistical differences.

Annual total costs (coffee maintenance + harvest) were totaled, and gross revenues (incomes from coffee + firewood) was calculated per hectare and treatment. All the labor was hired. Gross revenues represent the earns from the sale of dried coffee and firewood sold in the local market at a particular year. The annual costs represent the actual cost incurred to maintain and run the experimental coffee plantation according to the management regime and input levels. Total Costs and Gross revenues are presented in US Dollars. Annual Increment in diameter (cm/year) and basal area (m²/ha/year) of timber and N-fixing trees are presented by shade type and input level combination. All statistical analyses were performed in InfoStat (Di Rienzo *et al.*, 2011).

Table II.
Description of coffee production systems compared in the pacific coast of Nicaragua (2002-2012).

Description of practices	Management regimes			
	Moderate Organic (OM)	**Intensive Organic (OI)**	**Moderate Conventional (CM)**	**Intensive Conventional (CI)**
Soil amendments	Coffee pulp	Coffee pulp + chicken manure + phosphoric rock	Chemical fertilizers and micronutrients foliar sprays	Chemical fertilizers and micronutrients foliar sprays
Diseases control	None	Application of bio-fermented liquids	Regular application of commercial fungicides (Cu)	Regular application of commercial fungicides (Cu)
Insects/Pests control	Manually after the main harvest and scattered traps	Manually after the main harvest and scattered traps	Manually after the main harvest and scattered traps	Manually after the main harvest and scattered traps
Weed control	Manually (2-3 times a year)	Selective weeding 3-4 times a year	Selective weeding 3-4 times a year + herbicides application	Herbicides application (2-3 times a year) + weed control.
Fertilize inputs (Type, mean annual input overtime) and timing	Coffee pulp, 2.5 kg/plant (March-April)	Coffee pulp, 2.5 kg/plant (March-April) + chicken manure 3 kg/plant (July-August) and 1.75 kg/plant (September-November)	Mineral fertilizer: 18-6-12-4 kg/ha, 25 g/plant (June). 27-9-18, 17 g/plant (June). 12-30-10, 70 g/plant (September). Urea (46%), 20 g/plant (October). Potassium chloride, 5 g/plant (October). Foliar sprays, Urea-113 g + Zinc-25 g + Boro-30 g (November).	Mineral fertilizer: 18-6-12-4 kg/ha, 50 g/plant (June). 27-9-18, 33 g/plant (June). 12-30-10, 280 g/plant (September). Urea (46%), 40 g/plant (October). Potassium chloride, 10 g/plant (October). Foliar sprays, Urea-113 g + Zinc-25 g + Boro-30 g (November).
Shade cover (%)	50-60%	40-60%	30-50%	25-50%
Shade management and timing	Shade tree pruning, once a year	Shade tree pruning, once a year	Shade tree pruning, once a year	Shade tree pruning, once a year

Results

Coffee yield, management regimes and shade typology

Coffee yields varied between years, shade typology and management regimes (figures 1 and 2). There was a significant effect of shade combination and management regimes on coffee yield only in three out of ten years evaluated (table III). Fisher's LSD means comparisons among treatments did not show any pattern on yields performance in terms of best shade combinations and management regimes. For example, in 2002 all 14 fourteen combinations registered similar coffee cherry yields. However, in the second, fourth, sixth and seventh harvesting years, the full-sun coffee system under conventional-intensive management had the highest yields and was statically different from the other treatments. Intensive Organic (IO) management under the shade of timber trees combination (i.e. SSTR *Samanea saman* + *Tabebuia rosea*; and SGTR
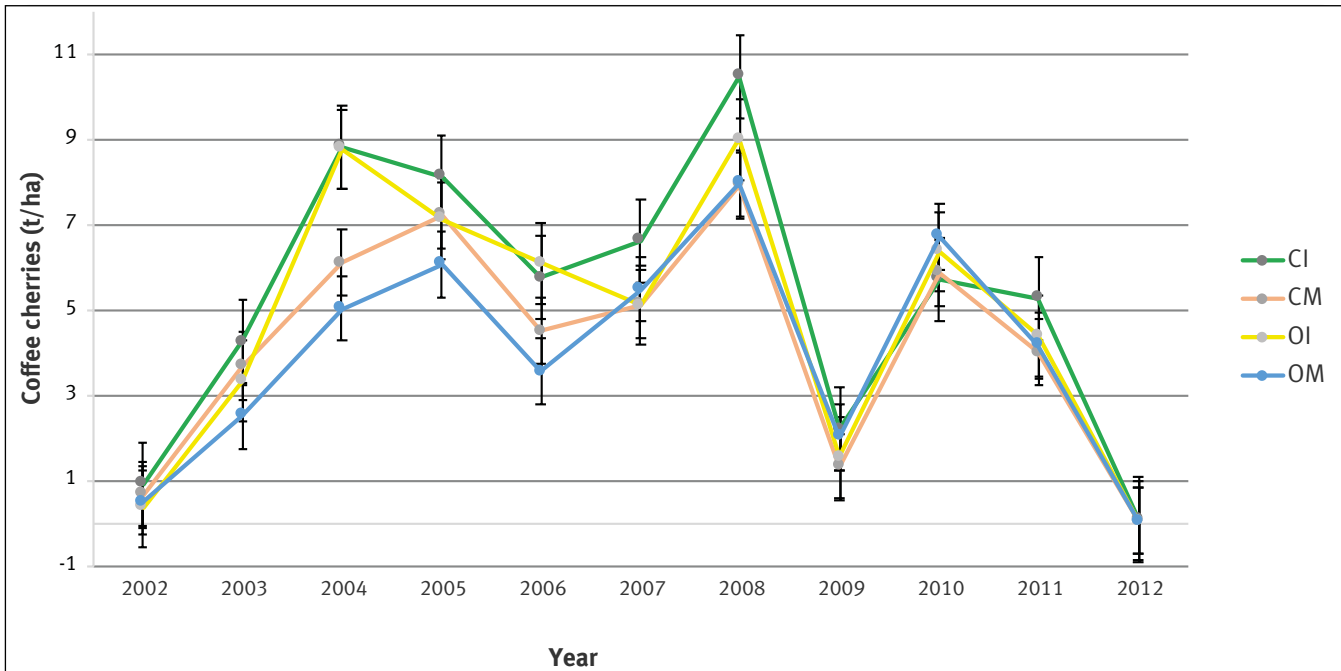

Figure 1.
Coffee cherries production (t/ha) by management regimes and year, Nicaragua 2002-2012. Vertical lines represent standard error. OI: organic intensive, CM: medium conventional, CI: intensive conventional.
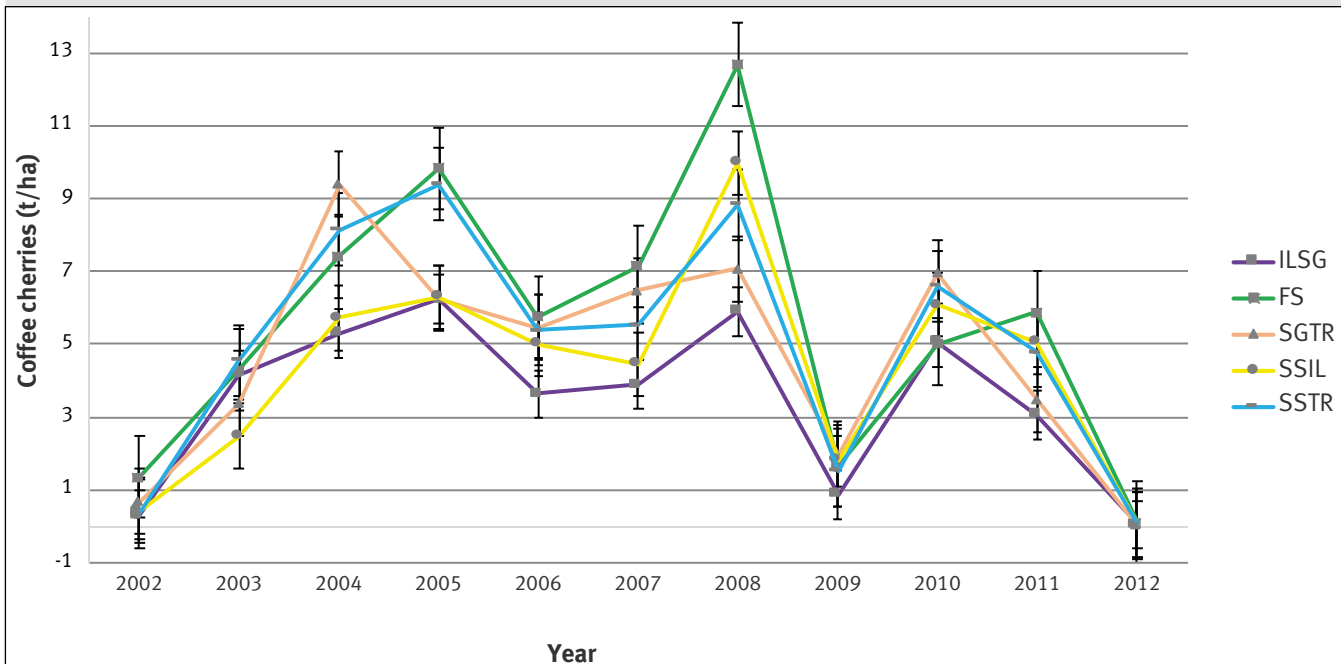

Figure 2.
Coffee cherries production (t/ha) by shade combination, full-sun and year, Nicaragua 2002-2012. Vertical lines represent standard error. ILSG: *Inga laurina* (Sw.) Willd. + *Simarouba glauca* DC.; SGTR: *Simarouba glauca* DC. + *Tabebuia rosea* DC.; SSIL: *Samanea saman* (Jacq.) Merr. + *Inga laurina* (Sw.) Willd.; SSTR: *Samanea saman* (Jacq.) Merr. + *Tabebuia rosea* DC.

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Table III.
P-values of the mixed model evaluating shade combination and management regimes (Treatment) in coffee agroforestry systems and full-sun coffee plantations in Nicaragua between 2002 and 2011.

Year	Parameter	p-value
2002	Treatment	0.0118
2003	Treatment	0.2763
2004	Treatment	0.0315
2005	Treatment	0.0182
2006	Treatment	0.7162
2007	Treatment	0.8021
2008	Treatment	0.3673
2009	Treatment	0.0948
2010	Treatment	0.8343
2011	Treatment	0.0948

Treatment refers to the 14 possible combinations of management regime and shade trees combination.

Simarouba glauca + Tabebuia rosea) ranked second or third best on the third, fourth and fifth harvesting season. Whereas, the shade combination with N-fixing trees, ILSG (*Inga laurina + Simarouba glauca*) and SSIL (*Inga laurina + Samanea saman*), under both management regime (IO or Moderate Conventional MC) coffee cherries consistently yielded poorly. On average in ten years of evaluation ILSG-MC and ILSG-IO treatments produced only 4 t/ha/ year coffee cherries. Similar values were registered for SSIL under different management regimes (table IV).

Until 2005, all tree shade combinations and management regimes showed an increase in coffee yield, although the intensive conventional (IC) and intensive organic (IO) management regimes showed better yields. However, during the period 2009 to 2011, there was a drop-in yields in all systems and it was in those bad years that coffee production under organic inputs regimes ranked better in terms of yield performance. Yet, lower coffee production was observed under ILSG at its two input levels (MC and IO). The *Inga-Simarouba* combination negatively influenced production regardless of whether the management regime was organic or conventional. ILSG performed better only when there was a drop-in production in the other treatments as a positive response to particular agronomic practices (i.e. pruning) or because of a stressful event (i.e. an extended dry period in a particular year of the evaluation). Better responses in terms of coffee yield were

Table IV.
Fisher's Least Significant Difference (LSD) means of coffee cherries (t/ha) from the combination of shade combination and input level (Treatment) and year.

Treatment	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
FS-CM	**1.47 a**	2.63 b	6.13 cd	**8.87 ab**	5.6 a	**6.01 ab**	**10.03 ab**	1.07 c	5.53 a	1.07 c
FS-CI	**1.36 a**	**5.97 a**	8.7 abcd	**10.8 a**	5.9 a	**7.5 a**	**15.33 a**	1.1 bc	4.47 a	1.1 bc
SGTR-CM	0.91 a	3.57 ab	9.33 abc	6.17 bc	5.03 a	4.83 b	7.33 b	1.73 abc	5.7 a	1.73 abc
SGTR-CI	0.81 a	**4.2 ab**	**12.33 a**	6.9 bc	6.33 a	5.16 ab	6.43 b	**2.05 a**	6.33 a	**2.05 a**
SGTR-OI	0.46 a	3.07 ab	9.47 abc	5.57 c	**7.07 a**	4.78 b	8.07 b	1.93 abc	7.1 a	1.93 abc
SGTR-OM	0.42 a	2.6 b	6.07 cd	6.4 bc	3.37 a	4.93 ab	6.5 b	1.38 abc	8.7 a	1.38 abc
SSTR-CM	0.4 a	**4.7 ab**	4.63 cd	8.1 ab	4.23 a	5.31 ab	7.9 b	1.08 c	6.23 a	1.08 c
SSTR-OI	0.3 a	**4.43 ab**	**11.67 ab**	10.7 a	**6.53 a**	4.99 ab	9.77 ab	1.61 abc	6.97 a	1.61 abc
SSIL-CM	0.59 a	2.53 b	6.33 cd	6.6 bc	4.03 a	5.12 ab	8.37 ab	1.98 ab	7.07 a	1.98 ab
SSIL-CI	0.55 a	2.57 b	5.47 cd	6.67 bc	5.03 a	5.91 ab	9.7 ab	1.89 abc	6.37 a	1.89 abc
SSIL-OM	0.43 a	2.43 b	4 c	5.73 c	3.73 a	4.88 b	9.47 ab	**2.12 a**	4.77 a	**2.12 a**
SSIL-OI	0.4 a	2.4 b	7.1 bc	6.17 bc	**7.2 a**	5.78 ab	**12.37 ab**	1.83 abc	6.13 a	1.83 abc
ILSG-CM	0.34 a	**4.93 ab**	3.73 d	6.4 bc	3.63 a	5.66 ab	6 b	**2.24 a**	4.83 a	**2.24 a**
ILSG-OI	0.29 a	3.4 ab	6.87 bcd	6.1 bc	3.63 a	5.65 ab	5.8 b	1.61 abc	5.27 a	1.61 abc

FS-CM: Full sun-moderate conventional; FS-CI: Full sun- intensive conventional; SGTR-CM: *Simarouba glauca* DC. + *Tabebuia rosea* DC. – moderate conventional; SGTR-CI: *Simarouba glauca* DC. + *Tabebuia rosea* DC. – intensive conventional; SGTR-OI: *Simarouba glauca* DC. + *Tabebuia rosea* DC. – intensive organic; SGTR-OM: *Simarouba glauca* DC. + *Tabebuia rosea* DC. – moderate organic; SSTR-CM: *Samanea saman* (Jacq.) Merr. + *Tabebuia rosea* DC. – conventional moderate; SSTR-OI: *Samanea saman* (Jacq.) Merr. + *Tabebuia rosea* DC. – intensive organic; SSIL-CM: *Samanea saman* (Jacq.) Merr. + *Inga laurina* (Sw.) Willd. – moderate conventional; SSIL-CI: *Samanea saman* (Jacq.) Merr. + *Inga laurina* (Sw.) Willd. – intensive conventional; SSIL-OM: *Samanea saman* (Jacq.) Merr. + *Inga laurina* (Sw.) Willd. – moderate organic; SSIL-OI: *Samanea saman* (Jacq.) Merr. + *Inga laurina* (Sw.) Willd. – intensive organic; ILSG-CM: *Inga laurina* (Sw.) Willd. + *Simarouba glauca* DC. – moderate conventional; ILSG-OI: *Inga laurina* (Sw.) Willd. + *Simarouba glauca* DC. – intensive organic. Means with common letters are not statically different (p › 0.05). Numbers in bold represent the "Treatment" that registered the highest coffee yields in a given year.

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observed under the shade of timber species (*S. glauca*, *T. rosea*, and *S. saman*). In some years, timber-based coffee system (SGTR and SSTR) performed similar to or better than the full-sun coffee system (p › 0.05). It seems that coffee yield is influenced by different levels of input, but when the system includes the shade of *I. laurina* there was no response on coffee yield along the evaluated period.

Performance of shade trees and silvicultural management

A 40% shade level threshold was intended to be maintained in all shaded coffee systems combinations through thinning and pruning. Three thinning events were performed during the cycle of evaluation, the first one was done in 2005 (two-three years after planting) with an intensity of 45-50% across treatments and management regimes, and the second one was performed in 2008 (5-6 years after planting) with an intensity of 25%. The last thinning event occurred in 2014 (12 years after planting, 25% intensity) which resulted in a final shade tree density across treatments ranging from 17 to 33 trees per plot (table V). However, an increase in the shade level above the attempted threshold was evidenced in 2014 and 2016 due to a lack of management of the companion trees pro-

bably because of the drop-in coffee yields. Regardless of the management regime, timber species grew better than leguminous shade tree species (table V). Mean Annual Increment in diameter (MAI-d) of *I. laurina* varied between 2.9 to 3.2 cm/year, for *S. glauca* MAI- ranged from 2.5 to 2.7 cm/year, for *T. rosea* MAI-d values were 2.8 to 3.3 cm/year and MAI-d values for *S. saman* ranked last with 1.3 to 1.9 cm/year (table VI).

Coffee production costs and revenues under different management regimes and shade type

The intensive organic system was the most expensive management regime to run per ha and year 1,474.2 USD/ha (± 122.9), with inputs representing most of the costs, irrespective of the shade typology. Followed by the full-sun coffee production system with expenses tallying 1,303.5 USD/ha (± 149.3). Moderate organic and moderate conventional registered the lowest costs across different shade typologies and full-sun systems (879.8 USD/ha ± 91). In terms of gross revenues, both full-sun systems and timber-based coffee agroforestry systems (SSTR and SGTR) were the treatments with better financial returns, even though gross incomes from the sale of timber trees were not considered (figure 3).

Table V.
Tree population remaining after the three thinning events performed in shaded coffee agroforestry systems in Nicaragua.

Tree species	Inga laurina (Sw.) Willd.				Simarouba glauca DC.				Samanea saman (Jacq.) Merr.				Tabebuia rosea DC.			
Shade Type	CI	CM	OI	OM	CI	CM	OI	OM	CI	CM	OI	OM	CI	CM	OI	OM
First thinning event (October 2005, 45-50% intensity across sites)																
ILSG		40	47			43	33									
SGTR					35	39	43	41					45	44	37	51
SSIL	49	44	45	58					79	82	72	66				
SSTR									79	69				83	80	
2nd thinning event (April 2008, 25% intensity across sites)																
ILSG		38	52			44	33									
SGTR					34	38	42	43					45	44	37	50
SSIL	41	39	45	52					74	76	66	60				
SSTR									74	66				42	41	
3rd thinning event (May 2014, 25% intensity across sites)																
ILSG		17	25			36	27									
SGTR					17	32	24	20					27	28	29	22
SSIL	33	26	31	33					18	26	23	19				
SSTR									25	15				28	30	

ILSG: *Inga laurina* (Sw.) Willd. + *Simarouba glauca* DC.; SGTR: *Simarouba glauca* + *Tabebuia rosea* DC.; SSIL: *Samanea saman* (Jacq.) Merr. + *Inga laurina*; SSTR: *Samanea saman* + *Tabebuia rosea*; Blank cells: tree species did not occur in that management regimes.

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Table VI.
Diameter and height mean annual increment values (cm/year) of four tree species growing in shaded coffee agroforestry systems in Nicaragua.

Tree Species Shade Combination/ Management regimes	Inga laurina (Sw.) Willd.		Samanea saman (Jacq.) Merr.		Simarouba glauca DC.		Tabebuia rosea DC.	
	MAI-d	MAI-h	MAI-d	MAI-h	MAI- d	MAI-h	MAI-d	MAI-h
ILSG-CM	3.0	1.2			2.5	1.2		
ILSG-OI	3.0	1.37			2.5	1.2		
SGTR-CI					2.5	1.2	2.8	1.2
SGTR-CM					2.8	1.2	3.3	1.3
SGTR-OI					2.6	1.2	3.2	1.3
SGTR-OM					2.7	1.2	3.2	1.3
SSIL-CI	3.2	1.2	1.3	0.6				
SSIL-CM	3.1	1.2	1.4	0.7				
SSIL-OI	2.9	1.1	1.7	0.8				
SSIL-OM	3.2	1.3	1.3	0.6				
SSTR-CM			1.9	0.8			2.8	1.1
SSTR-OI			1.9	0.9			3.1	1.2

ILSG-CM: *Inga laurina* (Sw.) Willd. + *Simarouba glauca* DC. – moderate conventional;
ILSG-OI: *Inga laurina* (Sw.) Willd. + *Simarouba glauca* DC. – intensive organic;
SGTR-CI: *Simarouba glauca* DC. + *Tabebuia rosea* DC. – intensive conventional;
SGTR-CM: *Simarouba glauca* DC. + *Tabebuia rosea* DC. – moderate conventional;
SGTR-OI: *Simarouba glauca* DC. + *Tabebuia rosea* DC. – intensive organic;
SGTR-OM: *Simarouba glauca* DC. + *Tabebuia rosea* DC. – moderate organic;
SSIL-CI: *Samanea saman* (Jacq.) Merr. + *Inga laurina* (Sw.) Willd. – intensive conventional;
SSIL-CM: *Samanea saman* (Jacq.) Merr. + *Inga laurina* (Sw.) Willd. – moderate conventional;
SSIL-OI: *Samanea saman* (Jacq.) Merr. + *Inga laurina* (Sw.) Willd. – intensive organic;
SSIL-OM: *Samanea saman* (Jacq.) Merr. + *Inga laurina* (Sw.) Willd. – moderate organic;
SSTR-CM: *Samanea saman* + *Tabebuia rosea* DC. – moderate conventional;
SSTR-OI: *Samanea saman* + *Tabebuia rosea* DC. – intensive organic; blank cells: tree species did not occur in that management regimes; MAI-d: diameter mean annual increments; MAI-h: total height means annual increments.

Discussion

Coffee production: Interaction between shade typology and management regime

Full sun and conventional management have been largely promoted as an avenue to intensify coffee cultivation in producing countries (Perfecto *et al.*, 2005; Guhl, 2008). It estimated that 41% of the coffee area worldwide is produced without the shade of trees (Jha *et al.*, 2014). Although coffee intensification leads to an increase in yields, achieved by the high use of external inputs such as fertilizers, pesticides, and fungicides, it also has an increasing environmental footprint (Lyngbæk *et al.*, 2001; DaMatta, 2004). In our study, full sun production under intensive management performed better in most of the years of evaluation. While cof-fee yields of organic systems are usually lower than conventional ones (Lyngbæk *et al.*, 2001; Van Der Vossen, 2005), this study demonstrated that coffee yields under intensive organic management regimes were similar to those obtained under intensive conventional management yet some significant differences were evident overtime (figure 2, table II).

The best coffee yields came from the combination of full-sun and intensive conventional management, followed by timber tress (SSTR and SGTR) under intensive organic systems. This demonstrates that the use of high-level inputs and moderate shade had a strong influence on coffee yields. Contrary to expectations, the ILSG combination (leguminous shade tree) had the worst coffee yield performance, mainly due to negative effect of *I. laurina* on coffee plants, as this species had a dense canopy thus increasing the shade level of the plot.

Haggar *et al.* (2011) also pointed out that the shade cast by *I. laurina* prevented a better response of coffee production even when conventional inputs and intensive organic is provided. Similarly, Siles *et al.* (2009) found lower coffee yield under agroforestry systems due to the lack of pruning and thinning of the companion trees. Therefore, there is a need to efficiently manage (frequency and intensity of events) shade cover according to the characteristics of the companion species (size of the trees, crown shade and canopy density) (Somarriba and Calvo, 1998; Somarriba and Beer, 2010) as there is a direct negative effect between the increase in planting density of shade trees, shade cover (%) and expected coffee production (Jezeer *et al.*, 2018).

The advantage of shading in coffee yields is only realized if a judicious evaluation and management plan of the companion trees is done and matched with local agro-ecological characteristics when designing coffee agroforestry systems (Beer *et al.*, 1998; DaMatta, 2004; Bosselmann *et al.*,

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2009). In general terms, the benefit of tree cover increases when the agro-environment is less favourable for sustainable coffee production (DaMatta, 2004; Carr and Lockwood, 2011). For example, shade provided by trees acts as a buffer for sub-optimal environments such as extreme temperatures and prolonged droughts (Siles *et al.*, 2009; Padovan *et al.*, 2015). In addition, van Kanten and Vaast (2006) reported that for coffee grown in suboptimal low-altitude sites, *Euca-*

lyptus deglupta cast the most beneficial shade as it maintained a more constant shade level throughout the year thus better protecting coffee plants in comparison to *Terminalia ivorensis* and *Erythrina poeppigiana* which underwent complete defoliation during the dry period.

In our study, it seems that the type and combination of trees influenced coffee yield performance. Cordero *et al.* (2003) reported that *S. glauca*, an evergreen species, is
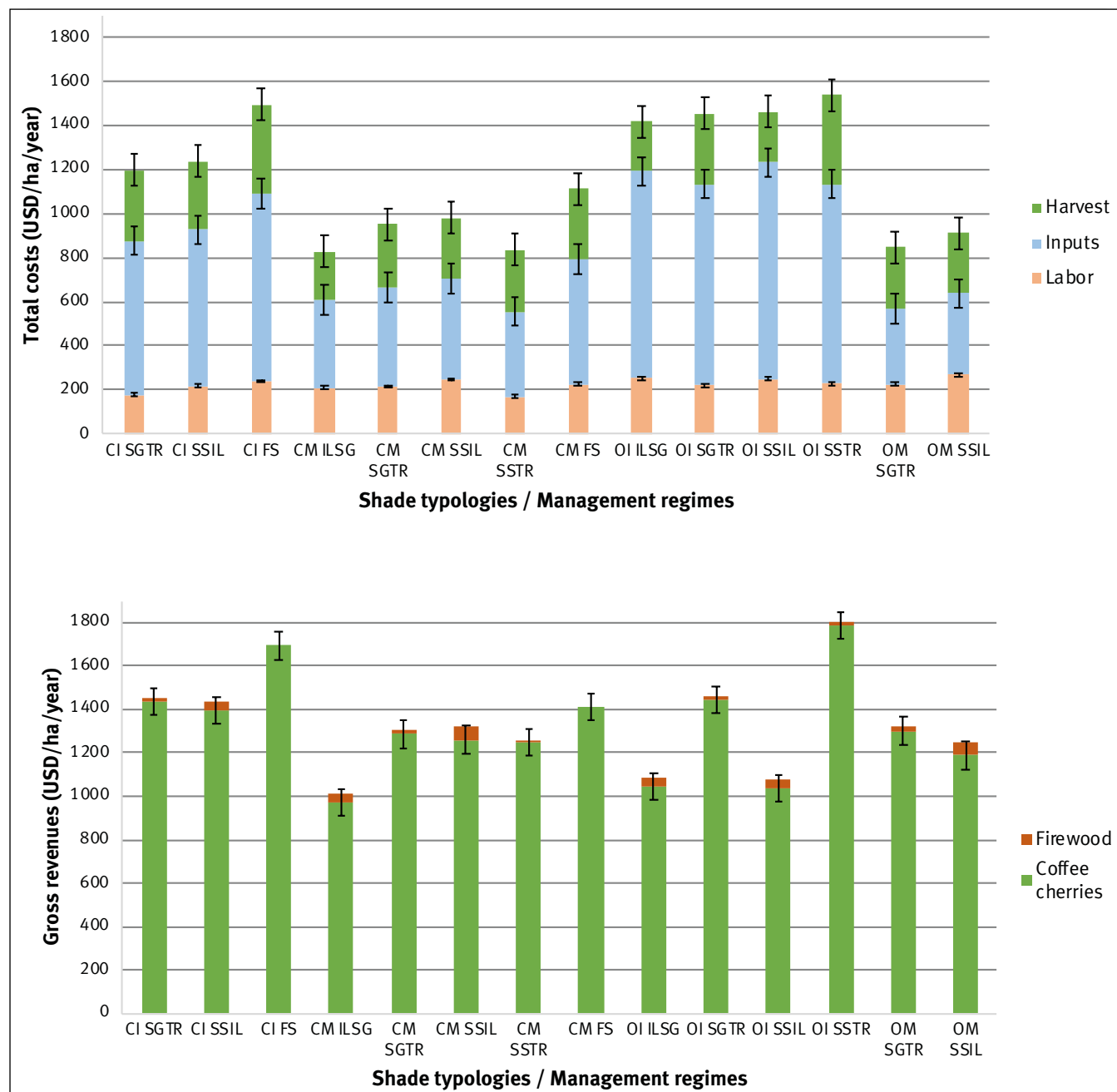
Figure 3.
Average total production costs (a) and gross revenue (b) of coffee under different shade combination, full-sun and management regimes. Vertical lines represent standard error. SGTR-CI: *Simarouba glauca* DC. + *Tabebuia rosea* DC. – intensive conventional; SSIL-CI: *Samanea saman* (Jacq.) Merr. + *Inga laurina* (Sw.) Willd. – intensive conventional; FS-CI: full sun – intensive conventional; ILSG-CM: *Inga laurina* (Sw.) Willd. + *Simarouba glauca* DC. – moderate conventional; SGTR-CM: *Simarouba glauca* DC. + *Tabebuia rosea* DC. – moderate conventional; SSIL-CM: *Samanea saman* (Jacq.) Merr. + *Inga laurina* (S.w.) Willd. – moderate conventional; SSTR-CM: *Samanea saman* (Jacq.) Merr. + *Tabebuia rosea* DC. – conventional moderate; FS-CM: full sun – moderate conventional; ILSG-OI: *Inga laurina* (Sw.) Willd. + *Simarouba glauca* DC. – intensive organic; SGTR-OI: *Simarouba glauca* DC. + *Tabebuia rosea* DC. – intensive organic; SSIL-OI: *Samanea saman* (Jacq.) Merr. + *Inga laurina* (Sw.) Willd. – intensive organic; SSTR-OI: *Samanea saman* (Jacq.) Merr. + *Tabebuia rosea* DC. – intensive organic; SGTR-OM: *Simarouba glauca* DC. + *Tabebuia rosea* DC. – moderate organic; SSIL-OM: *Samanea saman* (Jacq.) Merr. + *Inga laurina* (Sw.) Willd. – moderate organic.

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widely used as a shade to protect coffee plants during the 6 months-long dry seasons in the south Pacific of Nicaragua. Padovan *et al.* (2015) studied root distribution and water use in the same experimental plot and found a root niche differentiation for optimal exploitation of resources in shaded coffee agroforestry systems. However, there were differences between shade tree species, *S. glauca* exhibited a denser root system in deep soil layers compared to *T. rosea*, indicating complementarity with coffee root growth. The shaded coffee system used more water and at a greater rate at the beginning of the two dry seasons evaluated, explained by a better exploration of the roots of shade trees in the soil profile. Yet, when the shaded coffee system faced a severe dry season the advantage of better exploration was inexistent as it seems that underground water from the systems was no longer available for the crops and the shade trees (Motisi *et al.*, 2019).

Costs and gross revenues under different shade typologies and management regimes

In this study, the costs of running intensive organic and intensive conventional management systems for coffee production had similar figures with the highest costs represented by inputs (fertilizers, pest, and diseases control, weeding) and exceeded the conventional moderate and moderate organic management systems in 28%-37% and 33%-40% of the costs, respectively. Other studies reported coffee yield under conventional management exceeding in more than 20% of the costs spent in comparison with organic management regimes (Lyngbæk *et al.*, 2001). Likewise, Jezeer *et al.* (2018) found for conventional coffee cultivation, higher yields associated with higher costs, mainly due chemical inputs and hired labour. In our study higher yields were obtained in both intensive management systems, however large variation in coffee yields was recorded between years (table IV). Full-sun systems and timber-based coffee agroforestry systems had the best average gross revenues as compared to leguminous based-coffee systems.

Timber trees are a conspicuous element in shaded coffee agroforestry systems (López *et al.*, 2003; Peeters *et al.*, 2003; Méndez *et al.*, 2009). In our study of coffee yield performance under timber, trees were similar to that of full-sun cultivation systems. Regardless of the management regime, timber species grew better than leguminous shade tree species (table VI). Timber tree growth rates in shaded coffee systems were in the range of tree growth reported for other timber trees in multistrata-agroforestry systems elsewhere (López *et al.*, 2003; López-Sánchez and Musálem, 2007; Méndez *et al.*, 2009). Even in our analysis, we did not consider the potential income from harvesting timber trees in the gross revenue estimates, selling timber could add on average 400 USD/ha (std 307 USD/ha) to the overall gross income of timber-based coffee systems. Several authors support the argument that both firewood and timber generate considerable revenues for coffee growers which helps cope with fluctuation of coffee prices and pest and diseases outbreaks (Peeters *et al.*, 2003; Rice, 2008; Noponen *et al.*, 2013; Ehrenbergerová *et al.*, 2018, 2019).

Conclusion

Coffee productivity was influenced by levels of inputs and management systems (conventional and organic) and shade typologies. Overall, in this study, intensive organic production was found to be equally productive as conventional production regime. Intensive full sun-conventional coffee systems had the highest productivity, followed by the combination of timber *Samanea saman* + *Tabebuia rosea* organic intensive, which showed the positive effect of shade typology and intensive organic inputs on coffee yields. Costs of running conventional inputs vs intensive organic inputs were similar, however the use of intensive organic inputs lowers the net profitability of the systems due to their high maintenance costs. Moderate organic treatments showed a better performance when combined with timber trees as they could provide an increase in the total income by selling standing timber stock. The economic potential value of *Tabebuia rosea* and *Simarouba glauca*, in the long term is around 800 USD/ha and 400 USD/ha, respectively. This is a clear indication that coffee cultivation under shade helps to maximize the benefits of diversification while minimizing competition between companion trees and coffee plants.

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