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Shade versus intensification: Trade-off or synergy for profitability in coffee agroforestry systems?

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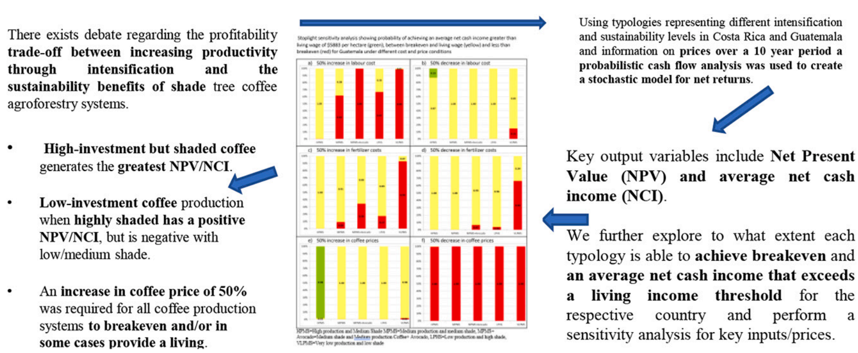
HIGHLIGHTS

- High-investment but shaded coffee generates the greatest NPV and net cash income under most cost scenarios.
- Low-investment coffee production when highly shaded has a positive NPV, but is negative with low/medium shade.
- Under normal price conditions only high-value diversification products increased NPV.
- Under very low coffee prices net cash losses were lower for low-investment high shade production.
- A 50% coffee price increase was needed for all coffee production systems to break-even and some to provide a living income.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Coffee agroforestry systems (shaded coffee) are considered less productive but more resilient than more intensive production systems. A persistent challenge for coffee farmers is the extreme fluctuations in coffee prices, leading to a loss of profitability and lower investment in production. There are contrasting conclusions regarding the profitability trade-off between increasing productivity through intensification and the sustainability benefits of shade tree coffee agroforestry systems.
OBJECTIVE: Using a typology of different intensification and sustainability coffee production strategies in Costa Rica and Guatemala, we assess the economic feasibility and sensitivity of those strategies under likely future scenarios of price and cost variability.
METHODS: Based on on-farm survey data from a large-scale survey of farmers with information on costs, prices and yields over ten years, a probabilistic cash flow analysis was used to create a stochastic model for net returns.
RESULTS AND CONCLUSIONS: Under future price scenarios, the Net Present Value (NPV) for coffee production was greatest for the high-productivity farms with high investment and moderate shade levels. The NPV of low-investment farms was greater (and positive) for highly shaded coffee production than for low shade coffee production (which, on average, had a negative NPV), despite the two having similar levels of investment. Diversification with bananas or avocados in association with coffee only improved NPV for high-value export

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avocado. Despite the substantially higher production costs for the high productivity systems, they generally maintained higher probabilities of achieving a positive net cash income or achieving a living income under most labour, fertilizer or coffee price scenarios, except a 50% fall in coffee prices. Diversification effects were as sensitive to changes in labour and input costs but in most cases reduced the probability of a more pronounced negative net cash income under low coffee price scenarios. We find an increase in coffee prices by 50% was needed to enable all farmers to achieve a positive net cash income; with an increased probability of achieving returns comparable with a living wage for higher productivity systems.

SIGNIFICANCE: We conclude that high-investment, high-productivity coffee production systems are compatible with shade-grown production; more likely to lead to economic success and achieve positive returns under most conditions, except large falls in coffee prices. For farmers with limited capacity to invest, high-shade production systems provide a positive cash return under a broader range of price conditions than low-shade systems.

1. Introduction

Coffee production is estimated to provide livelihoods for between 12.5 and 25 million farmers, and their families (ICO, 2019); of these, about 95% are smallholders with farms of <5 ha (Sachs et al., 2019)). While there is no significant trend of prices increasing nor decreasing over longer time frames (1970–2019) since the beginning of the 1990s, coffee prices have fluctuated considerably, varying between highs of US $ 3.00 per pound and lows of US$ 0.45 per pound (ICO, 2019). In 2018 prices dropped below US$ 1.00 per pound for the first time since the price crash of the early 2000s. Furthermore, production costs have increased sharply since 2010, thus reducing net returns for producers (Sachs et al., 2019), with coffee producers struggling to cover their operating costs from 2016 through 2019 due to rising input, compliance and transaction costs (ICO, 2019).

The main drivers of poor economic performance vary between countries. Kaitlin et al. (2021) found that the average coffee income was below a living income for all top ten coffee-producing countries except Brazil. Still, production costs were considerably higher in Latin America, Colombia, and Guatemala than in African or South-East Asian countries. Sachs et al. (2019) concluded that low prices and rising costs led to a concentration of production in highly intensified mechanized producers of Brazil. These producers were also best placed to meet future, increasing demand. The best option for the rest of the world was to focus on increasing productivity and quality of existing production.

At the same time here has been growing concern about the environmental impacts and sustainability of the intensification of coffee production and especially removal or simplification of the traditional shade trees under which coffee was grown (Harvey et al., 2021; Jha et al., 2014). While there is recognition that coffee farmers are suffering economically from low prices, there is also concern as to the environmental consequences of the loss of traditional complex shaded coffee production systems that host higher levels of biodiversity (Harvey et al., 2021; Philpott et al., 2008). Nevertheless, coffee production has been one of the leading commodities promoting sustainability, of which using coffee shade is a key element, with approximately 35% of global production now compliant with one of the private sustainability standards (Lernoud et al., 2018). This is not just to reduce negative environmental externalities but also shade is seen as providing a better microclimate for coffee production, improving soil fertility, and producing better quality coffee amongst other factors.

While conventional agronomic development has promoted increasing productivity to increase profitability, Jezeer et al. (2017), in a systematic review, concluded that lower-yielding shaded coffee systems were more profitable than more productive intensified systems. Jezeer et al. (2018), in a specific case study in Peru, similarly found that high-input (intensified) coffee production had lower profitability than lower-input shaded systems. If this is the case then the perceived trade-off between income and environmentally friendly production may not exist. Nevertheless, other studies of experimental production systems have found high-input, high-productivity systems to be more profitable than lower-input or organic production, irrespective of the use of shade (Noponen et al., 2013).

Previous research has explored the economics of agroforestry systems in the Latin America. Gobbi (2000) used Monte Carlo simulation to model the uncertainty of variations in coffee prices and yields. They found investment in biodiversity-friendly certification criteria is financially viable for most farmers, though incentives such as payment for environmental services and tax reliefs could make investment more attractive. Batz et al. (2005) modelled decision making of farmers managing shaded grown coffee under conditions of high volatility of prices, demonstrating how non-investment in plantation maintenance during periods of low prices leads to low productivity and low income even during periods of high prices. Haggar et al. (2017) compared farmers' net incomes under various certification schemes the promote shade grown production and matched them to conventional farms. They found that most certified farmers receive higher prices in recognition of improved environmental management, but only in a few cases was net revenue greater than that for matched farms. Bio-economic models have also been used recently (e.g., Hernandez-Aguilera et al., 2019), which have shown smallholders would have incentives to allocate more land to shade-grown coffee when they benefit from ecosystem services including natural pest control.

Particular gaps in the literature with respect to exploring the economics of coffee agroforestry systems have been the reliance on simulating net returns/net present value based on representative farms. Few studies have used large-scale survey data to develop/parameterize models. Furthermore, ranking options according to risk is seldom considered and/or yield and prices are rarely considered together as 'stochastic' in models. e.g. yield uncertainty was not considered by Batz et al. (2005) to simplify their model. Similarly, Gobbi (2000) also relied on mean yields over the past three years, which were used to account for annual variations in production.

Therefore, there is no consensus on the nature of the trade-off between profitability and environmental benefits with respect to intensified high productivity as opposed to more sustainable shade coffee systems. Moreover, the models used have not represented well how intensification and sustainability practices interact to affect profitability and their dependence on varying coffee prices, production costs and productivity as affected by climate and pests and diseases. Additionally, the inclusion of other products from the coffee agroforestry system are often discarded (e.g. the value of fruit, timber or firewood) and thus, the value of such by-products are not included in the calculation of net benefits of coffee agroforestry systems.

The objective of this paper is to assess the economic feasibility and sensitivity of different coffee production strategies that represent different levels of intensification and sustainability of production as identified by Haggar et al. (2021) under likely future scenarios (e.g. prices and input costs) using data from a survey of 180 farmers with information on prices/yields over ten years. Additionally, we will assess the economic contribution of other products, such as fruits, from the coffee production system when these are present.

2. Materials and methods

The study was conducted in Guatemala which is the tenth largest coffee exporter globally, and Costa Rica a smaller producer but with a reputation for high quality coffee. Costa Rica invested considerably in intensifying its coffee production in the 1980s and 1990s, although still largely maintaining use of shade trees, and had the highest productivity per hectare in the world in the 1990s (Samper, 1999). While in Guatemala traditional coffee agroforestry systems have been largely maintained and 98% of coffee production is shaded, although some farms have also invested in increasing productivity (ANACAFE, 2011). Thus, currently there is a mix of intensified and traditional coffee production systems with varying levels of shade tree inclusion in the plantations of the two countries.

2.1. Survey procedure

Coffee farms were surveyed in three of the main coffee regions in each country, covering a range of agro-environmental conditions, as described in Haggar et al. (2021). In Costa Rica, farms were selected from i) Turrialba-Orosi (low-medium altitude, high rainfall, standard commercial grade coffee), ii) Valle Occidental (mid-high altitude, seasonal climate with high-quality coffee), and iii) Los Santos Tarrazú (high altitude, seasonal climate, and coffee quality that is considered the best in the country) (Fig. 1a). In Guatemala, farms were selected from: West (departments of Quetzaltenango, Retalhuleu, and San Marcos) low-high altitude, high rainfall, commercial grade coffee; Mid (department of Solola) high altitude, medium rainfall, high-quality coffee; and East (departments of Guatemala, Sacatepequez and Chimaltenango) high altitude, low rainfall, and very high coffee quality (Fig. 1b).

A total of 180 farms (90 per country, 30 per region) were primarily selected from a list used in a previous study in 2009 comparing sustainably certified and uncertified farms (Soto et al., 2011); these were complemented by additional farms of similar characteristics (56 in total) where farms from the list were not available. Farms were selected to represent different shade types and cover and high, mid and low productivity in approximately equal representation.

Interviews of farm owners or managers were conducted between September 2019 and January 2020 to collect information on agronomic management and its costs. This was complemented by a second round of interviews between October 2020 and January 2021 to collect data on harvest costs, production level and income for the 2019/2020 production year (note this survey was delayed by 6 months due to COVID-19 restrictions). Ethical standards of prior consent and confidentiality were followed as appropriate for socioeconomic surveys, and farmers were at complete liberty to decline to participate (as a few did).

2.1.1. Variables and measurement

The interviews were conducted face-to-face with farmers to collect detailed information on farm characteristics, farmer and household characteristics, coffee area and yield, and details of coffee agronomic management, including all inputs used and labour invested. Information was mainly obtained through farmer recall of activities conducted during the previous year, assisted by farm records where available. Coffee production data and sale price was recorded for two harvests (the 2018/19 harvest and the 2019/20 harvest; agronomic pre-harvest costs were recorded for the 2019 production year that spans the period between these two harvests. Additionally, farmers were asked to report the highest and lowest yield, and highest and lowest coffee prices they have experienced during the previous decade. The yield, price and income from additional products from the coffee agroforestry system were also recorded, although in general farmers were only able to provide data for products that were sold and not those used for household consumption. Farmers were also asked to report any additional costs associated with the crops associated with the coffee agroforestry. Interviewers were limited to two people per country; people experienced and knowledgeable about coffee. Interviewers received training conducted trial interviews, and interview responses were reviewed periodically to ensure quality with feedback provided. All variables were quality checked in order to identify values out of acceptable or standardized ranges. All the values identified as outliers were reviewed or corrected with the producer in a second visit or phone call.

To evaluate the production costs, the following variables were considered: expenditures on labour (including family labour charged at the daily wage rate), transport and inputs and tools in fertilization, pest and disease control, shade management, weed control, coffee pruning, crop establishment soil conservation, harvest costs, and post-harvest processing (where undertaken). Fixed costs were estimated from the value of assets proportional to their usable life and administrative costs in terms of time invested or paid. Income was estimated as the product of quantity of coffee (or other product) produced and sales price (the very

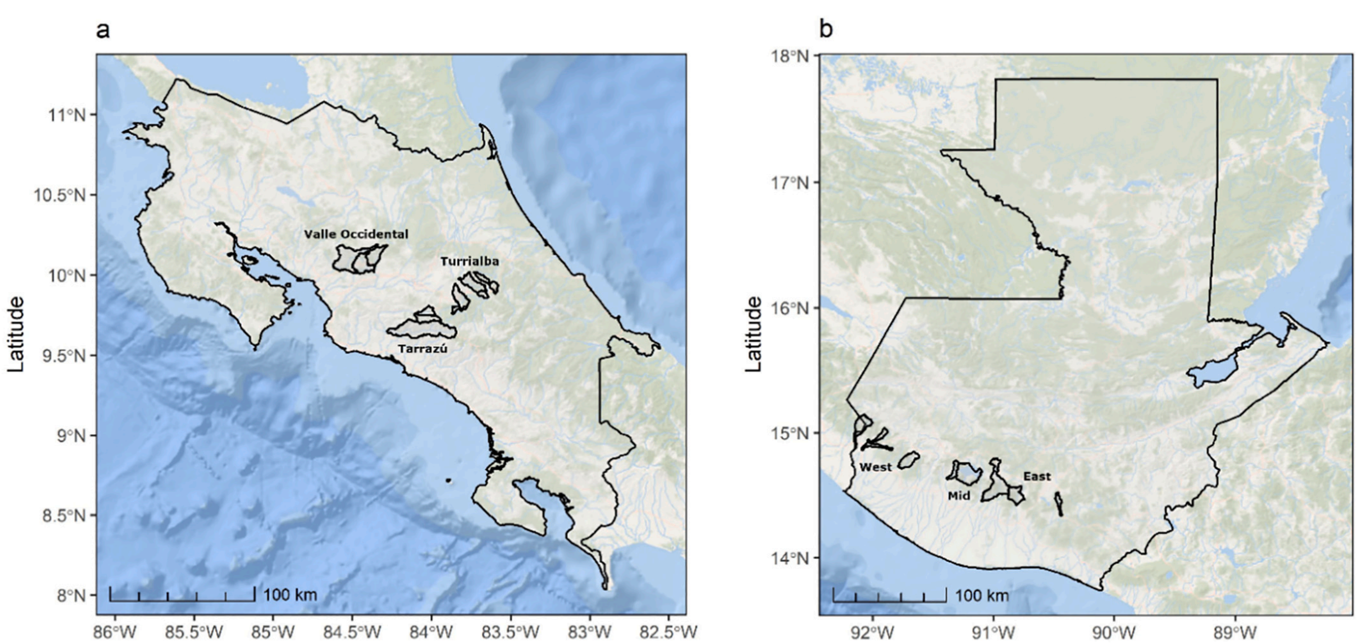

Fig. 1. Location of coffee growing regions sampled in a) Costa Rica, and b) Guatemala.

small amount of coffee consumed on farm was assigned the same price as that sold).

The percentage shade cover and leaf area index (LAI) of shade trees in all coffee plantations were measured using an analysis of hemispherical photographs described by Haggar et al. (2021). Shade was evaluated in three plots spaced at least 30 m apart across the range of shade conditions within a field or plantation typical or representative of the production strategy of the farm.

2.2. A typology of production strategies

A coffee plantation typology of production strategies was formed for each country using multivariate cluster analysis based on the shade LAI and coffee yield as indicators of sustainability and productivity outcomes of the management strategy of the plantation (Haggar et al., 2021). Cluster analysis of plantations per country was conducted using LAI and coffee productivity (kg/ha), previously standardized, using the Ward method with Euclidean distance. The resulting clusters represent the coffee plantation production strategies that reflects the strategy in terms of intensification and sustainability. Four production strategies were differentiated for each country representing high, medium, low and very low productivity plantations, with varying shade levels (Table 1). Production strategies significantly differed in the levels of agronomic investment, coffee yield, and shade levels, amongst other factors (Haggar et al., 2021), and can be summarised as follows.

High Productivity Medium Shade (HPMS), were high yielding plantations producing between 12 and 20 t of coffee cherries per hectare, with high investment in agronomic production over US$2000 per hectare. Most plantations had between 40 and 60% shade (LAI 0.5–1.1).

Medium Productivity Low/Medium Shade (MPLS/MS) plantations produced between 6 and 12 t (Costa Rica) and 4–12 t (Guatemala) of coffee cherries per hectare. Agronomic costs in Costa Rica were almost as high as HPMS systems, but only half of HPMS in Guatemala (about US$1100 per hectare). Shade levels in both countries were 20–60% (LAI 0.1–1.0), although on average higher in Guatemala.

Low Productivity High Shade (LPHS) were characterized by having high shade over 60% (LAI > 1.0), while productivity ranges from <1 t to 9 t of coffee cherries per hectare. Agronomic costs were on average half that of the Medium Productivity systems, US$1277 per hectare in Costa Rica and US$689 per hectare in Guatemala.

Very Low Productivity Low/Medium Shade (VLPLS/MS) systems had yields from <1 t up to 6 t of coffee cherries per hectare and shade levels <60% (LAI <1.0), although on average higher for Guatemala. Agronomic production costs were very similar to that for the LPHS system.

Contrary to expectations there was no simple trade-off between shade and productivity, with high productivity associated with medium shade levels in both countries (Haggar et al., 2021). While high shade levels were associated with low productivity, this was achieved for the same level of agronomic investment as the very low productivity farms, which were associated with low to medium levels of shade. While there was a large range in farm size across the sample (from 0.14 ha to 600 ha), farm size had no relationship with the production strategies, nor did other socioeconomic variables such as family size, number of family members working on the farm, educational level, or age of the farmer. Thus, the production strategies appear to be independent of the socio-economic status of the farmer, i.e. any of micro-producers (<0.5 ha of land), smallholders and larger estates might adopt any of the strategies.

While almost all the coffee plantations were shaded i.e. there were trees interplanted with the coffee bushes primarily to provide shade, on some farms some of these trees have a productive role, we refer to these as diversified coffee production systems. To assess their economic contribution some of the production strategies were sub-divided into those where coffee was the only commercial product and those with a secondary product in addition to coffee, avocados and bananas being the primary examples. While the farms that have diversified coffee production systems (i.e. with an associated crop) are classified as being from the same coffee production strategy there are some differences in coffee yield and production costs between the plantations with and without the associated crops (Table 2). These differences may be due to the presence of the associated crop e.g. a causing a reduction in coffee yield, or increasing production costs. However, in other cases they may be due other variations in the investment levels of the farms undertaking diversification. It should also be noted that the avocado production in Costa Rica was of the improved Hass variety and sold at three times the price of the local varieties produced in Guatemala (See Appendix Tables A2 and A10).

Table 1
Coffee production strategy according to productivity and shade level as assessed by LAI (Leaf Area Index) (N = number of farms in the group) (adapted from Haggar et al., 2021).

Costa Rica					Guatemala				
Production Strategy	N	Yield (kg/ha)	LAI	Agronomic cost US$ ha^{-1}	Production Strategy	N	Yield (kg/ha)	LAI	Agronomic cost US$ ha^{-1}
High productivity Medium shade (HPMS)	14	13,750 a	0.80 b	2117 a	High productivity Medium shade (HPMS)	8	16,298 a	0.54 b	2471 a
Medium productivity Low shade (MPLS)	24	9436 b	0.41 c	2012 a	Medium productivity Medium shade (MPMS)	26	6990 b	0.66 b	1137 a
Low Productivity High shade (LPHS)	26	5361 c	1.46 a	1277 b	Low-Productivity High shade (LPHS)	34	2879 c	1.71 a	689 b
Very low production Low shade (VLPLS)	25	3132 d	0.47 c	1377 b	Very low production Medium shade (VLPMS)	22	1699 d	0.63 b	625 b

Table 2
Comparison of productivity and production costs within production strategies with just coffee or coffee plus an associated crop (see legend Table 1 for production strategy codes).

	Costa Rica				Guatemala	
Production Strategy	MPLS	MPLS-Avocado	LPHS	LPHS-Banana	MPMS	MPMS-Avocado
Number of farms from which data collated	19	4	17	5	10	13
Coffee yield kg/ha	10,169	8894	6054	3493	6881	7102
Associated crop yield kg/ha		820		1127		585
Agronomic plus harvest costs US$/ha (coffee and associated crop)	4073	4016	2551	1579	2779	4121

2.3. Model description and financial criterion used

Similar to other models (e.g. Lalani et al., 2017), a probabilistic cash flow analysis was used to create a stochastic model for net returns (Richardson and Mapp Jr., 1976). Richardson et al. (2006) has previously explained the steps required for this type of economic model building. The first step requires that probability distributions for the risky variables (i.e. those that are stochastic such as prices and yields) must be defined and parameterized, which includes simulation and validation. Secondly, the stochastic values sampled from the probability distribution are used to calculate, for example, cash flows. Thirdly, using a random selection of values for the risky variables under study, the completed stochastic model is simulated many times (i.e. 500 iterations). The results of the 500 samples thus provide information which can be used to estimate true distributions of key output variables (KOVs) which were considered to be important financial criteria to evaluate the likelihood of project success.

Parameters for coffee production are estimated from actual production data reported by farmers allocated to the production strategies mentioned in section 2.2. An initial model was created based on one of the strategies, which was used as the template for the others with modifications where necessary similar to the approach taken by Richardson et al. (2014). As outlined above, the stochastic model for net returns developed was validated by comparing the stochastic means for coffee yields and coffee prices with their historic means using Student *t*-tests set at alpha 0.05. Each failed to reject the null hypothesis, signalling that the stochastic net returns assumed their original means and variability. Verification of the model was also done by entering survey data (e.g. by way of example total variable costs for each farmer and yields from the survey data) and comparing the deterministic results to the survey results of a key output variable such as net returns. An excel add-in, Simetar©, was then used to calculate the key output variable, in this case, Net Present Value (NPV) for the duration considered. NPV is a widely used financial criterion which reflects the overall returns to the business in today's dollars. If the net present value is positive, the farm's internal rate of return exceeds the discount rate, and the business is an economic success (i.e. NPV greater than zero). The NPV determines the present value of net benefits by discounting the benefits (B) and costs (C), that arise between the present and future time periods (T). The subscripts (t) denote a specific time period i.e. year and the discount rate is referred to as (r).

$$NPV = \sum_{t=1}^{T} \frac{B_t - C_t}{(1+r)^t} \quad (1)$$

Simetar uses Monte-Carlo simulation (500 iterations) to simulate the NPV, which does so by randomly drawing annual stochastic prices and yields from specific probability distributions (Richardson et al., 2014; Kadigi et al., 2020). Given farmers in our survey reported yields and prices over ten years (e.g. high, middle and low outcomes), these were used to provide the range for the respective probability distributions. Though historical data on actual prices and yields are highly variable in the short-term, recent analysis showed no historical trend can be found (ICO, 2019), and therefore yields and prices cannot be forecasted based on a long-term trend; future prices and costs were inflated using an annual stochastic inflation rate (See Section 2.4). Similar to Richardson et al. (2014), the economic model is simulated for 11 years, i.e. 2019 to 2029, including the base year 2019. This means that the ending cash position of the business in year 1 (2019) is, therefore, the beginning cash flow position for 2020 etc. The 11-year planning horizon is repeated 500 times (iterations) using different stochastic prices and production values for each year and for each coffee production strategy (random variables are independent across years). The statistics reported for the KOVs and their graphs are summary statistics for 500 iterations. They are not empirical distributions but 500 samples of the true distribution for the KOVs. The resulting 500 values for the key output variables (i.e. NPV/NCI) are used to calculate probabilities of financial and economic sustainability (Richardson et al., 2014). The economic variables such as receipts (production multiplied by price), cash expenses (variable costs and fixed costs, interest, taxes, and principal payments) are used to calculate the net cash income, ending cash reserves, and net worth for each of the years in the 11-year planning horizon and thereby NPV (Richardson et al., 2014). These are presented in United States Dollars (US$) for ease of international/regional comparisons.[1] Finally, a sensitivity analysis using the in-built function in Simetar (is available at www.simetar.com) was also conducted to examine the role of alterations to key parameters such as labour costs and coffee prices (See section 2.4).

2.4. Key assumptions

The base case scenario uses coffee yields for the 'base' year based on mean coffee yields for the past two years (survey data), and 2019 prices for variable costs and coffee prices. We modelled coffee yields (2020–2029) using the Uniform distribution (min, max) based on farmer reported minimum, average and maximum yields over the previous ten years. Initial simulations using the minimum and maximum values provided unrealistic estimates (e.g. yields that were too high or too low) so we opted to use the middle value between the minimum (lowest value) and the mean as the preferred minimum value (i.e. original minimum value plus mean/2) and the middle value between mean and maximum (highest value) as the preferred maximum value (mean plus original maximum value/2) which provided more realistic simulations.

A Gray, Richardson, Klose and Schumann (GRKS)[2] probability distribution (Richardson et al., 2006) was used to simulate coffee prices over the 2020–2029 period (i.e. based on min, average and maximum prices over the last ten years). Prices have also been inflated yearly based on stochastic annual inflation rates. Variable costs and fixed costs were yearly inflated by a reasonable inflation rate (2%) to account for an increase in costs over time. For strategies which included an associated crop (e.g. banana or avocado) the yields were simulated for the base year and for the period 2020–2029 using a GRKS distribution. The stochastic net returns for strategies with an associated crop are based on a joint probability of income from coffee production and the associated crop. On reflection the reported values for associated crops (i.e. estimation of yields over the last ten years) revealed some missing values, inconsistencies and/or extreme values and it was deemed more appropriate to simulate the base year and the future years (2020–2029) using the values from the survey data (i.e. based on min, average, maximum yields). However, associated crop prices were simulated using a GRKS distribution (i.e. minimum, average and maximum prices over the last ten years) for the base year and yearly inflated for 2020–2029. Base case scenarios are presented under a 10% discount rate and use output prices at harvest reported by farmers and checked by key informant interviews. (See Appendix A for key assumptions and the 'base case' budget used to simulate each production strategy).

2.4.1. Living wage comparison

Voorend et al. (2016, 2017) have estimated a living wage (i.e. calculates the cost of a simple but decent life, including a model diet that complies with WHO nutrition standards and a housing standard that meets minimum international standards for Costa Rica and Guatemala. Given these are based on a whole family/farm, we have adjusted for

[1] In the case of Costa Rica, the exchange rate used is 588.34 Colones. For Guatemala, the exchange rate used is 7.72 Quetzales

[2] The Gray, Richardson, Klose and Schumann (GRKS) distribution is at two-piece normal distribution with 50% of the weight below the middle value and 2.5% less than the minimum, and 50% above the middle value and 2.5% above themaximum. The distribution is used in place of a triangle distribution when one knows only minimum information about the random variable and the minimum and maximum are uncertain (Richardson et al., 2006).

farm size (based on the median farm size in both countries in our sample). Thus, for Costa Rica to achieve a living income of US$8892/year from a median of 2.9 ha would require an average cash income of US $3066/ha, and for Guatemala to achieve a living income of US$4308/ year from a median of 0.81 ha would require an average cash income of US$5318/ha. These were then inflated by a reasonable inflation rate for the simulation period (2%) similar to that used for the variable/fixed costs to account for an increase in living costs over time. The average living income was then used as the living income threshold i.e. US $3392/ha for Costa Rica and $5883/ha for Guatemala. Thus, alongside breakeven as an indicator of economic success, we will also use these estimates of living income as an 'indicator of success'.

2.5. Stoplight probability charts and sensitivity elasticity[3] analysis

Stoplight probability charts[4] were used to rank the various coffee strategies employed, which do not require knowing the exact risk preference of the decision maker and instead provide target probabilities for different risky alternatives. It calculates the probability, for instance, of scenarios falling below a lower target, exceeding an upper target and/or falling between the lower and upper target specified (See, e.g. Kadigi et al., 2020). The advantage of using the Stoplight chart for ranking risky alternatives is that it enables the decision maker to specify their lower and upper targets (e.g. achieving a minimum living wage as the upper target and breakeven as the lower target) and then allows them to decide which scenario is best using a simple graphic. There is, therefore, no need to specify a risk aversion coefficient or utility function which ultimately simplifies analysis and allows the decision makers to approach decisions according to the specific context and 'problem at hand' (Richardson and Outlaw, 2008).

A sensitivity elasticity analysis was conducted for the various strategies. Given NPV highlights a change in wealth/living income over the whole planning horizon, we have opted to use the average net cash income (NCI) (i.e. average net returns) over the planning horizon and have compared this to an indicator of success i.e. estimated living wage.

In this case, the key output variable is NCI. The sensitivity analysis quantifies the average percentage change in the NCI to a 1 % change in the exogenous variable (e.g. specific variable costs such as labour/fertilizer etc.) These results then informed the subsequent sensitivity analysis, which was also conducted in Simetar. We used +/− 50% and altered mean labour costs, fertilizer costs and coffee prices.

2.6. Modelling limitations

One limitation is the type of modelling employed and various assumptions. Whilst there were no significant differences between strategies for specific farm characteristics this does not discount the possibility of omitted variable bias/endogeneity. Moreover, other types of modelling may have been employed including estimating the effect of shade and/or diversification/different resource levels from year to year on profits in a profit function. For example, Flaten and Lien (2009). use a two-stage stochastic programming modelling framework with the objective function to maximize expected net income. Similarly, the use of panel data to account for differences across years/farms could also be employed. In this type of modelling exercise, we are also unable to model changes in coffee management the farmer would make in response to a change in price.

[3] Elasticity in this context is defined as the percentage change of the KOV to a 1 % change in an exogenous variable

[4] A Stoplight chart compares the target probabilities for one or more risky alternatives (e.g. different crop mixes). The user must specify two probability targets (Lower Target and an Upper Target) for the Stoplight and the alternative scenarios to compare. The Stoplight function calculates the probabilities of: (a) exceeding the upper target (green), (b) being less than the lower target (red), and (c) observing values between the targets (yellow). (Richardson et al., 2008)

3. Results

3.1. Production system NPV

The NPV of the different strategies in each country is presented over an 11-year planning horizon under the base-case scenario (Tables 3a and 3b). In both countries, the high-productivity medium shade systems have the highest average NPVs while the very low productive strategies with low/medium shade have, on average, a negative NPV. NPV for the medium productivity low/medium shade systems were very similar to the high productivity system in Costa Rica but considerably lower than the high productivity system in Guatemala. The low productivity high shade production system (LPHS) also has a mean positive NPV of about US$1600 per ha in Costa Rica and US$580 per ha in Guatemala (Tables 3a and 3b). Amongst the production systems with diversified products, only the MPLS+Avocado in Costa Rica had a higher NPV than MPLS with coffee alone (and was even slightly higher than the HPMS system). The other diversified options LPHS+Banana in Costa Rica and MPMS+Avocado in Guatemala had lower NPVs than their coffee only comparators.

3.2. Probabilities of breakeven and achieving a living income

Stoplight probabilities of achieving an average net cash income (NCI) over the 11-year planning horizon below breakeven, greater than breakeven and a living income from an average-sized smallholder farm (US$ 3392/ha for Costa Rica and US$ 5883/ha in Guatemala) are presented in Fig. 2a and c. Cumulative distribution functions (CDFs) of average net income are shown in Appendix B. The probabilities of achieving net income above breakeven were very high (96% and over) for high, medium and low production strategies, irrespective of shade intensity in both countries. None of the strategies were able to achieve a living income and there exists a low probability of not achieving breakeven for the low productivity high shade strategies (4–7%). In both countries, the very low productivity farms had a 96% (Costa Rica) and 80% (Guatemala) chance of not breaking even. The diversified production options LPHS+Banana in Costa Rica and MPMS+Avocado in Guatemala marginally increased the probability of not breaking even compared to the coffee only systems. Although the MPLS+Avocado diversified option in Costa Rica didn't pass the living income threshold it does show a higher probability of achieving net income greater than the medium or high productivity coffee only production strategies (Appendix B, Fig. B1.)

3.3. Sensitivity elasticity analysis

Figure 3a and b illustrate which variable costs have the greatest impact on the key output variable (i.e. average NCI). The larger the elasticity, the greater the sensitivity of the NCI to a change in the exogenous variable. In this case, for the high-production medium shade production strategy (Costa Rica), labour followed by chemical fertilizer and disease control have the highest elasticity of all the variable costs. The sensitivity elasticities show a percentage change for mean NCI for a 1% increase in each exogenous variable. The sensitivity elasticities are negative because the NCI is inversely related to an increase in costs. For example, if costs are decreased, the sensitivity elasticities would reflect percentage increases (Richardson et al., 2014). Thus, if labour costs were to decrease by 1%, the NCI would increase by 1.38%.

Similarly, if chemical fertilizer costs were to decrease by 1%, the NCI would increase by 0.39% (Fig. 3a). Similarly, labour costs have the highest elasticity for the high production medium shade system, followed by chemical fertilizer in Guatemala (Fig. 3b). Moreover, a 1% reduction in fertilizer cost for chemical fertilizer would only increase the NCI by 0.3% (Fig. 3b). Given the sensitivity of the NCI to chemical fertilizer, and labour costs, it was decided to alter these prices in the sensitivity analysis. Coffee prices were also included in the sensitivity analysis due to current events (an upward trend in coffee prices).

Table 3a
Mean NPV (US$/ha) and descriptive statistics (based on 500 iterations) for the coffee strategies in Costa Rica for the period 2019–2029.

	HPMS	MPLS	MPLS+Avocado	LPHS	LPHS+Banana	VLPLS
Mean	5644	4989	6170	1612	-110	-2263
SD	1419	1400	1081	1169	550	753
CV	25	28	18	73	-500	-33
Min	1689	1266	2922	-2407	-1788	-4547
Max	9627	8954	9803	4921	1457	170

SD: standard deviation, CV = coefficient of variation HPMS=High production and medium shade, MPLS = Medium production and low shade MPLS+Avocado = Medium production low shade Coffee + Avocado, LPHS = low production high shade, LPHS+Banana = Low production high shade Coffee+Banana, VLPLS=Very low production low shade. The same acronyms/labels were used in the subsequent tables and figures and the Appendix.

Table 3b
Mean NPV (US$/ha) and descriptive statistics (based on 500 iterations) for the Coffee strategies in Guatemala for the period 2019–2022.

	HPMS	MPMS	MPMS + Avocado	LPHS	VLPMS
Mean	12,339	2133	1481	568	−1557
SD	2300	1443	1577	1096	647
CV	19	68	106	193	−42
Min	6308	−1563	−2554	−2911	−3629
Max	19,177	6634	6176	4736	480

SD: standard deviation, CV = coefficient of variation HPMS=High production and Medium Shade, MPMS = Medium production and medium shade, MPMS+ Avocado = Medium shade and Medium production Coffee+ Avocado, LPHS = Low production and high shade, VLPMS=Very low production and medium shade. The same acronyms/labels were used in the subsequent tables and figures and the Appendix.

3.4. Sensitivity analysis

Increased labour costs led most strategies to an increased probability of strategies not breaking even (Figs. 4 & 5). The impact on the probability of not breaking even was substantially increased for low and very-low-productivity farms, becoming the most likely outcome. Conversely, lower labour costs led to a high probability of high (and in Costa Rica, medium) productivity farms achieving living income and low and very low productivity farms breaking even. Diversified strategies both with banana in Costa Rica (Fig. 4) and with avocado in Guatemala (Fig. 5) were more sensitive to increased labour costs than the pure coffee comparative systems. Increased fertilizer costs had similar effects reducing the probability of the low and very-low productivity farms breaking even, but not substantially changing the outcome of the high and medium productivity systems, except for medium-shade in Guatemala and especially when diversified with avocado when probability of not breaking even increased to 34%.

A 50% increase in coffee prices resulted in almost 100% probability of farms in all strategies breaking even and high productivity (and in Costa Rica, medium productivity) farms achieving a living income (Figs. 4 & 5). Conversely, a 50% reduction in price led to a 100% probability of farms in all strategies failing to breakeven. Cumulative distribution functions of average net income show substantial changes in the relative performance of production systems compared to higher coffee prices (Fig. 6). In Costa Rica under low coffee prices the high productivity medium shade strategy now generated the highest cash losses (e.g. approximately a 50% probability of achieving an average net income between –2750 and -2200US$ per hectare, while the diversified options with avocado or banana generated much lower cash losses (e.g. approximately a 50% probability of achieving an average net income between −1400 and − 850 US$ per hectare (Fig. 6).

In Guatemala however, the high production medium shade strategy was amongst the group generating the lowest losses (e.g. approximately a 50% probability of achieving an average net income between −1600 and -800US$ per hectare) alongside low production high shade and very low production medium shade (Fig. 6b). The greatest losses were generated by the medium productivity system diversified with avocado (e.g. approximately a 50% probability of achieving an average net income between −2750 and − 2100- US$ per hectare). Cumulative distribution functions under other scenarios didn't show relative differences between production strategies distinct from the base scenario (Appendix B, Fig. B1 and B2).

4. Discussion

4.1. Sensitivity of production strategies and investment to changes in costs and prices

High productivity, higher investment systems were no more sensitive to changes in costs than lower productivity lower inputs systems; indeed, they maintained a higher probability of breaking even across the different cost scenarios. As might be expected, changes in labour costs had more impact than changes in fertilizer costs as they represent a greater proportion of the costs of production (see Haggar et al., 2021). The approximate doubling of global fertilizer prices during 2021 (Hebebrand and Laborde, 2022) is greater than our 50% increase and would have a greater impact. There is a high dependency on fertilizer imports from Russia and Belarus for countries in the region; Costa Rica imports 38% of its fertilizer for domestic use from Belarus and Russia and Guatemala 25% (Hebebrand and Laborde, 2022). While during the first half of 2022, high coffee prices may have compensated for the high fertilizer prices, by the end of 2022, coffee prices had fallen by about 25% (https://www.ico.org/coffee_prices.asp) but fertilizer costs remained high, thus presenting a renewed cost of production challenge for coffee farmers. Even if high investment production remains the economically most productive option under high fertilizer prices, as our analysis suggests, many farmers are limited by access to credit to be able to afford the additional investment (Batz et al., 2005) and would be forced to move to less intensive but less economically productive strategies. Nevertheless, in terms of overall viability, the higher production systems would likely be able to best absorb an increase in costs of both fertilizer and labour costs.

A 50% decrease in coffee prices however had differential effects between the production systems, while all generated losses these were lower for diversified production systems in Costa Rica and low productivity high shade systems in both countries. High productivity high investment coffee generated the greatest losses in Costa Rica but was similar to other systems in Guatemala. Coffee prices 50% below the 2019/20 levels last occurred in 2001–2003 (https://www.ico.org/coffee_prices.asp) but for a crop with a minimum 20 year productive lifespan such prices would be within the experience of most coffee farmers, as would the consequences of bankruptcy and massive rural unemployment that resulted (Castro et al., 2004).

4.2. Economic and environmental sustainability

Our study finds a complex relationship between intensification, shade and income. Overall higher investment in production (intensification) leads to higher productivity and higher net cash income or NPV but this is compatible with coffee shaded up to 60% cover which would meet most standards of shade-grown production. Noponen et al. (2013)

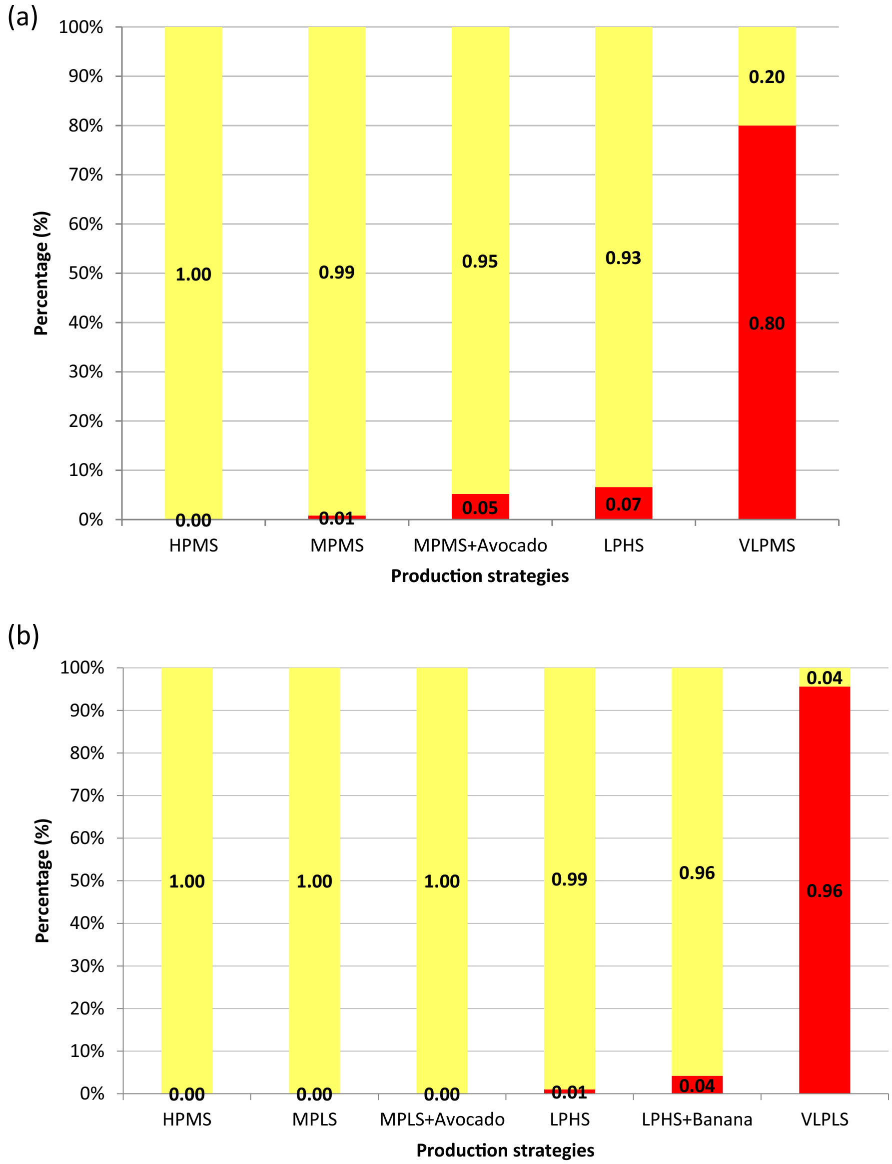

Fig. 2. a. Stoplight probability chart showing the probability of average net cash income below zero (red), between breakeven and the target income (yellow), and achieving an income greater than the target income (i.e. living income of $ 3392/ha) which would be shown in green if achieved for different strategies in Costa Rica. Production strategy codes are explained in Table 2A. b. Stoplight probability chart showing the probability of average net cash income below zero (red), between breakeven and the target income (yellow), and achieving an income greater than the target income (i.e. living income of $ 5883/ha) which would be shown in green if achieved for different strategies in Guatemala. Strategy codes are explained in Table 2B. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

likewise found that some shaded coffee agroforestry systems had similar profitability to full sun coffee under intensive management. While in our study we only had 3 full sun farms, there was a broad range of shade levels from zero to over 80%. Haggar et al. (2021) compared the response of coffee production to nitrogen fertilizer application rates under low (0–40%), moderate (40–60%) and high shade (>60%), and found no difference in the yield response between low or moderate shade. In this study low-shade farms (including full sun) were not associated with high use of inputs, high productivity nor high net cash income. On farms with low capacity to invest and lower productive potential, the farms with higher shade levels (over 60%) are more economically viable than those with low shade. Low capacity to invest is common to many smallholders in Latin America and may be why studies such as those by Jezeer et al. (2017 & 2018) found coffee was more profitable under shaded conditions.

The economic advantages of high-shade systems, as claimed by Gobbi (2000) and Hernandez-Aguilera et al. (2019) are dependent on additional ecosystem service payments. The only additional incentive available to farmers in our study was through certification under one of the sustainability standards (Rainforest Alliance, Organic and Fairtrade being the main options). Coffee produced under these standards has been found to receive higher prices in Central America (Soto et al., 2011; Haggar et al., 2017). Approximately a third of farms in the study were under one of these standards, with a slightly higher proportion of high-input moderate shade farms being certified than other production strategies, although organic farmers tended to be amongst the very low productivity strategy group (Haggar et al., 2021). It should be noted that all production strategies and almost all farms met the minimum shade standards of these certifications, and so is unlikely to have been an influential factor in their different shade strategies. Only the very localized and niche market Smithsonian Bird-friendly standard (https://nationalzoo.si.edu/migratory-birds/bird-friendly-farm-criteria)

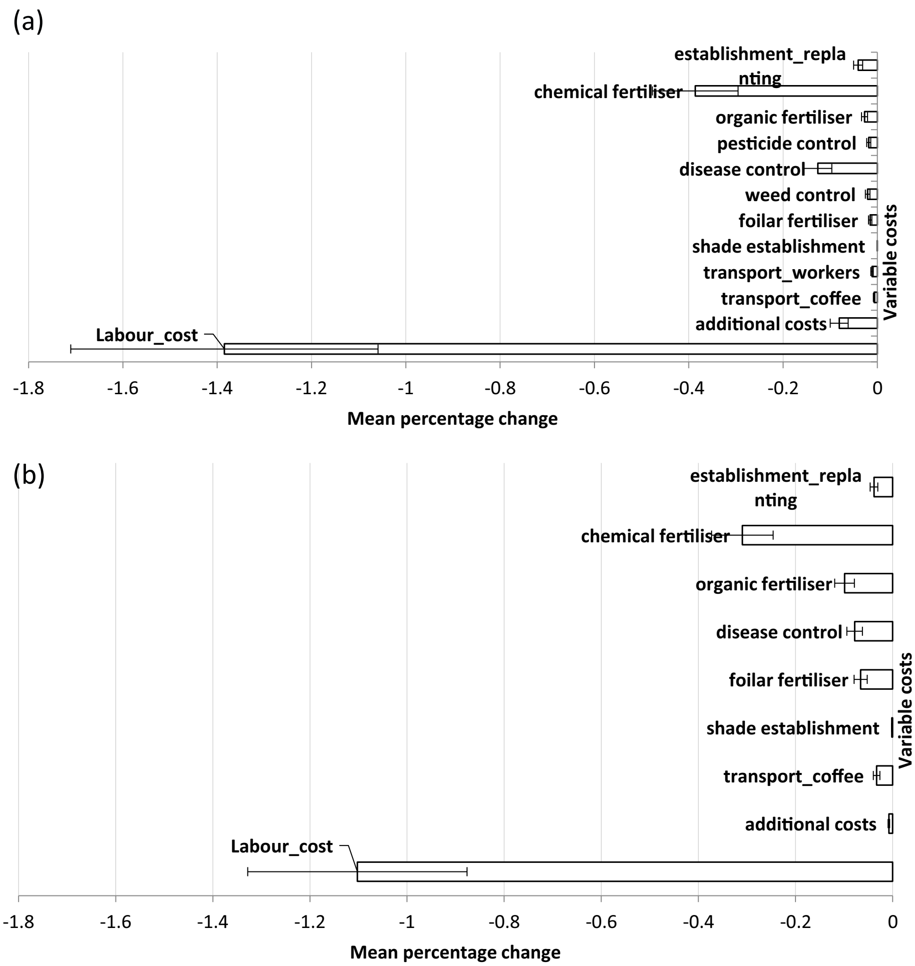

Fig. 3. a. Sensitivity elasticity analysis results showing the mean percentage change in the base case average NCI to a 1 % change in the exogenous variable (i.e. the different variable costs) High production medium shade (HPMS) in Costa Rica. (Error bars denote standard deviation). b. Sensitivity elasticity analysis results show the mean percentage change in the base case average NCI to a 1 % change in the exogenous variable (i.e. the different variable costs) for the High production medium shade (HPMS) (Guatemala) production system. (Error bars denote standard deviation).

requires high shade levels and high tree species diversity amongst other factors such as also being organic to maximize the potential for biodiversity.

It has been recognised that the shade trees in coffee agroforestry may provide a series of ecosystem services that support coffee production, especially under lower input conditions (Meylan et al., 2017). Although these services may be less critical under high input conditions farmers generally still maintained moderate levels of shade, and the diversity and density of trees was not different from production strategies with high shade levels (Haggar et al., 2021). Thus, even high-input farmers would seem to perceive benefits from shaded production, but an important subgroup of low input farmers maintained lower shade levels and tended to have lower tree diversity and density (Haggar et al., 2021). It is presumed this is because shade trees require investment of labour to adequately regulate shade levels and this was not compatible with their low-investment strategy. Thus, realization of the environmental benefits of shade trees and the economic benefits of coffee production are both limited by the capacity of farmers to invest. Higher coffee prices, such as through certification premiums, may help support such investment but also result in higher costs of production (Haggar et al., 2017).

4.3. Effects of diversified production systems on income and sensitivity

Diversification with bananas or avocados only improved the NPV compared to the coffee only strategies for Costa Rican farmers planted export quality Hass avocado. Guatemalan avocado production and bananas in Costa Rica were sold to the local market for lower prices that weren't able to compensate the additional investment. Furthermore, the diversified options were more sensitive to labour costs but did reduce losses under low coffee price scenarios in Costa Rica, but not Guatemala. The variable response to diversification indicates the challenge of identifying production options that are more economically productive than coffee. A previous study by Rice (2011) found that fruit production from coffee systems in Guatemala only accounted for about 10% of the income from shaded coffee systems, very similar to this study where avocado or banana production generated on average 14% of gross income. Although of limited economic importance Rice points out that these secondary products from shaded coffee can provide income when coffee is not in production as well as meeting some household needs.

4.4. Conditions for achieving a living income

As reported by ICO (2019) and Kaitlin et al. (2021), low coffee prices at the time of the study resulted in the vast majority of the smallholder coffee farmers surveyed in both countries not achieving a living income. According to our study a 50% increase in coffee prices would still enable only the more intensive and productive coffee farmers to reach a living income. Although much emphasis has been put on increased input and labour costs (Sachs et al. (2019)), a 50% reduction in these costs still

Fig. 4. Stoplight sensitivity analysis showing the probability (%) of achieving an average net cash income greater than a living wage of $3392 per hectare (green), between breakeven and living wage (yellow) and less than breakeven (red) for different production strategies in Costa Rica under different cost and price conditions (Note the baseline scenario is shown in Fig. 2 a, and production strategy codes under Table 2A). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

didn't generate a living income for the large majority of farmers. Only an increase in coffee prices of at least 50% enabled coffee production under all of the strategies to generate a positive cash income and some of them to achieve a living income.

Overall, the sensitivity analysis for all strategies shows a positive response to an increase in the price of coffee and a high sensitivity to a decrease in coffee prices, highlighting how central coffee prices are to the viability of these systems. Nevertheless, the 50% increase in price

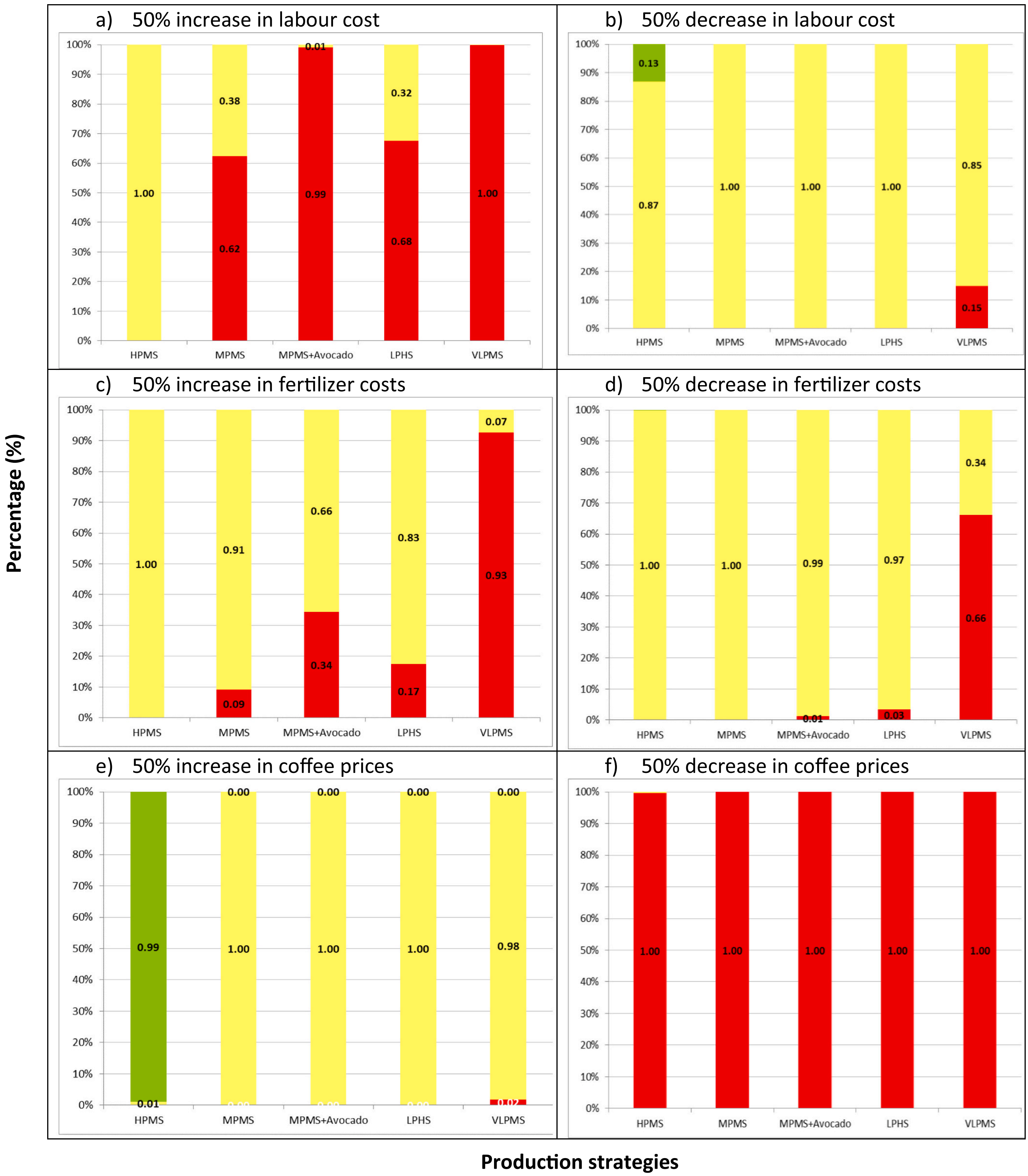

Fig. 5. Stoplight sensitivity analysis showing the probability (%) of achieving an average net cash income greater than a living wage of $5883 per hectare (green), between breakeven and living wage (yellow) and less than breakeven (red) for different production strategies in Guatemala under different cost and price conditions. (The baseline scenario is shown in Fig. 2 b, and production strategy codes are under Table 2b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

modelled is less than the doubling of coffee prices from 2019 (ICO monthly average composite price US$0.93 to US$1.17 per pound) to a monthly average price of between US$1.93 to US$2.10 per pound during the first six months of 2022 before falling back to about US$1.55 at the end of the year (https://www.ico.org/coffee_prices.asp).

Intensification of coffee production to increases the chances of achieving a living income but is limited by farmers lack of capacity to invest especially for smallholders (Batz et al., 2005). While many coffee smallholders are limited in their capacity to invest our analysis would indicate that as low-investment producers they have a greater likelihood

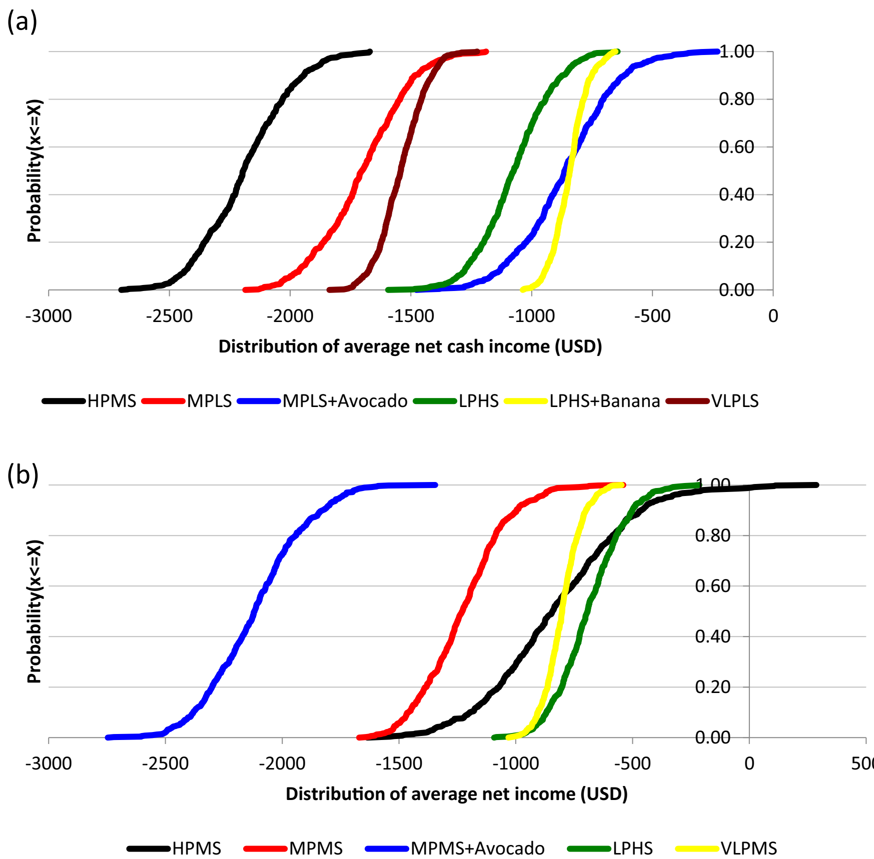

Fig. 6. a. Cumulative distribution function for average net cash income per hectare for each production strategy in Costa Rica under a scenario of 50% reduction in coffee prices. b. Cumulative distribution function for average net cash income per hectare for each production strategy in Guatemala under a scenario of 50% reduction in coffee prices.

of achieving a positive net cash income by adopting a high-shade production system. Key to enabling higher investment in production is increasing coffee prices, it was notable that the high-productivity farmers in this study tended to be concentrated in regions recognised for exceptionally high-quality coffee and thus commanding higher prices and presumably enabling them to invest more in production (Haggar et al., 2021).

5. Conclusion

In conclusion, we find that the interaction between intensification and shade production on economic performance is not a simple trade-off. There is compatibility between intensification of coffee production and the use of shade trees up to a certain level in systems that are likely to provide the greatest economic benefits. However, at least for Costa Rica they were vulnerable to generating large losses if coffee prices crash. The diversification products from shade trees were only found to make a significant positive contribution to the economics of production when they are products with a strong market demand, and in some cases buffer losses during low coffee prices. Nevertheless, for low investment farms higher shade levels have a positive influence on economic return and likelihood of breaking even or of minimizing losses when coffee prices are low, as well as maximising environmental benefits to society. Ultimately, both intensification and sustainability require investment to generate the economic and environmental outcomes desired, it is the capacity to invest that is limiting and not any trade-off between economic return and environmental sustainability.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Appendix

This Appendix displays the per hectare (ha) costs incurred by coffee farmers in Costa Rica and Guatemala for each production strategy simulated (variable costs by item and fixed costs). (See Tables A3- A8 and A11-A15). These are presented in United States Dollars (USD) for ease of international/ regional comparisons. In the case of Costa Rica, the exchange rate used is 588.34 Colones. For Guatemala, the exchange rate used is 7.72 Quetzales

A normal probability distribution was used to simulate stochastic/random production costs using the = NORM() function in Simetar (mean, standard deviation). The base case scenario uses coffee yields for the 'base' year based on mean coffee yields for the past two years (survey data) and 2019 prices for variable costs/coffee etc., and coffee yields (2020–2029) have been simulated using a UNIFORM (min, max) distribution using the middle value between the minimum and mean as the minimum value and middle value between mean and maximum as the maximum value from the survey data (i.e. based on farmers responses of the lowest, average, and highest yields over the last ten years). Prices have also been yearly inflated based on stochastic annual inflation rates (0–2.2%) using a uniform distribution for both countries. Variable costs and fixed costs were inflated using a reasonable inflation rate for both countries (2%). Associated crop prices were also yearly inflated and simulated using a GRKS distribution (i.e. minimum, average and maximum prices of the last ten years) for 2020–2029 and the base year. Associated crop yields were also simulated using a GRKS distribution for the base case year and for the period 2020–2029 using the values from the survey data (i.e. based on min, average, maximum yields).

Table A1 shows coffee and avocado yields used in the simulation of the base case scenario for each production system (production strategy) in Costa Rica.

A.1. Costa Rica

Table A1 Coffee and Avocado yields used in the simulation of the base case scenario by production strategy (kg/ha).

Production strategy	Base year (2019/2020)	Min value used	Max value used
HPMS	12,882	10,591	14,725
MPLS	10,169	8066	13,018
MPLS+avocado	8894	7659	9968
LHCR	6054	3251	8073
LHCR+Banana	3493	2500	4450
VLPLS	3600	2304	5557
Avocado yields	820	180	1200
Banana yields	1127	115	2400

Table A2 coffee, avocado and banana prices used in the simulation of the base case scenario and simulated using a GRKS distribution (minimum, middle and maximum values).

Table A2 Coffee and Avocado prices used in the simulation of the base case scenario ($/kg).

	Base year prices used (2019/2020)	Min	Mid	Max
Coffee prices	0.58	0.48	0.56	0.69
Avocado prices	(GRKS distribution used based on the min, mid max)	1.24	1.57	1.69
Banana prices	(GRKS distribution used based on the min, mid max)	0.02	0.04	0.07

Table A3 shows the variable costs by item and fixed costs (descriptive statistics) used in the simulation of the base case scenario for the HPMS (High production and medium shade) production strategy.

Table A3. Variable/fixed costs used in the simulation of the base case scenario for the HPMS (High production and medium shade) production strategy.[a]

	mean	std	min	max
Establishment costs	83	73	0	208
Chemical fertilizer	783	325	281	1207
Organic fertilizer	55	77	0	265
Pesticides	37	38	0	108
Diseases control	256	205	0	730
Weed control	42	49	3	186
Foliar fertilizer	31	42	0	136
Shade establishment	0	1	0	3
Transportation workers	23	68	0	243
Transportation of coffee	14	51	0	182
Additional costs per hectare	164	366	0	1214
Total_labour costs	2808	700	1442	3711
Total Fixed_costs (incl depreciation, interest+loan)	1829	2011	100	6077

[a] Items with zero/negligible have been deleted and figures have been rounded for ease of interpretation.

Table A4 shows the variable costs by item and fixed costs (descriptive statistics) used in the simulation of the base case scenario for the MPLS = Medium production and low shade production strategy.

Table A4. Variable/fixed costs used in the simulation ofthe base case scenario for the MPLS = Medium production and low shade production strategy.

	mean	std	min	max
Establishment costs	119	145	0	447
Chemical fertilizer	684	349	0	1443
Organic fertilizer	85	186	0	756
Pesticides	29	49	0	204
Diseases control	158	122	0	405
Weed control	26	35	0	140
Foliar fertilizer	239	769	0	3393
Shade establishment	1	2	0	10
Transportation workers	21	46	0	179
Transportation of coffee	66	138	0	500
Additional costs per hectare	30	45	0	162
Total_labour costs	2615	794	1262	4130
Total Fixed_costs (incl depreciation, interest+loan)	898	1138	37	4626

Table A5 shows the variable costs by item and fixed costs (descriptive statistics) used in the simulation of the base case scenario for the MPLS = Medium production and low shade (Coffee+ Avocado) production strategy.

Table A5. Variable/fixed costs used in the simulation of the base case scenario for the MPLS+Avocado = Medium production low shade Coffee + Avocado production strategy.

	mean	std	min	max
Establishment costs	90	62	23	171
Chemical fertilizer	673	189	526	935
Organic fertilizer	32	60	0	122
Pesticides	27	40	0	86
Diseases control	177	187	28	438
Weed control	9	6	4	17
Foliar fertilizer	43	70	0	147
Shade establishment	3	6	0	12
Additional costs per hectare	23	32	0	68
Establishment costs for associated crop	26	46	0	94
Total_labour costs	2913	531	2142	3297
Total Fixed_costs (incl depreciation, interest+loan)	381	186	109	532

Table A6 shows the variable costs by item and fixed costs (descriptive statistics) used in the simulation of the base case scenario for the LPHS = low production, high shade production strategy.

Table A6. Variable/fixed costs used in the simulation of the base case scenario for the LPHS = production strategy.

	mean	std	min	max
Establishment costs	67	114	0	402
Chemical fertilizer	365	285	0	994
Organic fertilizer	149	262	0	747
Pesticides	24	96	0	395
Diseases control	82	54	0	202
Weed control	11	11	0	33
Foliar fertilizer	30	39	0	138
Shade establishment	7	18	0	68
Transportation of coffee	7	29	0	121
Additional costs per hectare	9	17	0	54
Establishment costs for associated crop				
Total_labour costs	1800	1265	284	5989
Total Fixed_costs (incl depreciation, interest+loan)	374	301	46	1143

Table A7 shows the variable costs by item and fixed costs (descriptive statistics) used in the simulation of the base case scenario for the LPHS+Banana (Low production high shade Coffee+Banana production strategy).

Table A7. Variable/fixed costs used to calculate the base case scenario for the LPHS+Banana (Low production high shade Coffee+Banana production strategy).

	mean	std	min	max
Establishment costs	162	88	41	247
Chemical fertilizer	197	116	0	303
Organic fertilizer	53	35	0	91
Pesticides	2	4	0	9
Diseases control	74	66	20	181
Weed control	9	15	0	35
Foliar fertilizer	9	10	0	21

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(*continued*)

	mean	std	min	max
Shade establishment	1	1	0	3
Additional costs per hectare	2	2	0	5
Establishment costs for associated crop	31	30	0	72
Total_labour costs	1039	485	651	1856
Total Fixed_costs (incl depreciation, interest+loan)	432	252	135	787
production_average coffee (kg/ha) base case year	3494	1442	1508	5406

Table A8 shows the variable costs by item and fixed costs (descriptive statistics) used in the simulation of the base case scenario for the VLPLS (Vey low production low shade).

Table A8. Variable/fixed costs used to calculate the base case scenario for the VLPLS (Very low production low shade production strategy).

	mean	std	min	max
Establishment costs	95	109	0	367
Chemical fertilizer	283	229	0	870
Organic fertilizer	64	144	0	641
Pesticides	6	20	0	97
Diseases control	66	79	0	306
Weed control	41	114	0	568
Foliar fertilizer	48	103	0	493
Shade establishment	89	437	0	2141
Transportation of coffee	9	28	0	121
Additional costs per hectare	10	17	0	81
Total_labour costs	1636	1042	452	3580
Total Fixed_costs (incl depreciation, interest+loan)	318	325	20	955

A.2. Guatemala

Table A9 shows coffee and avocado yields used in the simulation of the base case scenario for each production system (production strategy) in Guatemala.

Table A9. Coffee and Avocado yields used in the simulation of the base case scenario by production strategy (kg/ha).

Production strategy	Base year	Min over the past ten years	Max, over the past ten years
HPMS	14, 868	11,491	18,497
MPMS	6881	4494	9742
MPMS+Avocado	7102	5310	11,103
LHCR	2154	1315	6344
VLPLS	1716	930	3.646
Avocado yields	585	340	810

Table A10 Coffee and Avocado prices used in the simulation of the base case scenario and simulated using a GRKS distribution (minimum, middle and maximum values).

Table A10. Coffee and Avocado prices used ($/kg) and key assumptions in the simulation of the base case scenario.

	Bae case prices used (2019/2020)	Min	Mid	Max
Coffee prices	0.51	0.39	0.5	0.72
Avocado prices	(GRKS distribution used based on the min, mid max)	0.42	0.81	1.68

Table A11 shows the variable costs by item and fixed costs (descriptive statistics) used in the simulation of the base case scenario for the HPMS (High production and medium shade) production strategy.

Table A11. Variable/fixed costs used in the simulation ofthe base case scenario for the HPMS (High production and medium shade) production strategy.

	Mean	std	min	max
Establishment costs	107	166	0	455
Chemical fertilizer	861	1392	0	4145
Organic fertilizer	276	458	0	1087
Diseases control	218	378	0	979
Weed control	17	34	0	92
Foliar fertilizer	183	435	0	1244
Shade establishment	5	12	0	35
Transportation workers	79	192	0	551
Transportation of coffee	92	134	0	345

(*continued on next page*)

(*continued*)

	Mean	std	min	max
Additional costs per hectare	22	47	0	135
Establishment costs for associated crop				
Total_labour costs	3069	1765	1050	5804
Total Fixed_costs (incl depreciation, interest+loan)	325	315	27	784

Table A12 shows the variable costs by item and fixed costs (descriptive statistics) used in the simulation of the base case scenario for the MPMS (Medium production and medium shade) production strategy.

Table A12. Variable/fixed costs used in the simulation of the base case scenario for the MPMS (Medium production medium shade) production strategy (USD).

	Mean	std	min	max
Establishment costs	202	272	0	772
Chemical fertilizer	638	453	0	1466
Organic fertilizer	74	101	0	246
Pesticides	0	1	0	5
Diseases control	78	69	0	172
Weed control	11	27	0	86
Shade establishment	10	27	0	86
Transportation workers	33	76	0	240
Transportation of coffee	91	138	0	459
Additional costs per hectare	8	13	0	36
Total_labour costs	1634	1122	313	4043
Total Fixed_costs (incl depreciation, interest+loan)	459	617	21	1964

Table A13 shows the variable costs by item and fixed costs (descriptive statistics) used in the simulation of the base case scenario for the MPMS (Medium production and medium shade Coffee + Avocado) production strategy.

Table A13. Variable/fixed costs used in the simulation of the base case scenario for the MPMS+ Avocado (Medium shade and Medium production Coffee+ Avocado) production strategy.

	mean	std	min	max
Establishment costs	229	358	0	1149
Chemical fertilizer	408	355	0	956
Organic fertilizer	223	398	0	1268
Diseases control	51	57	0	168
Foliar fertilizer	4	11	0	40
Shade establishment	9	25	0	90
Transportation workers	4	15	0	54
Transportation of coffee	79	67	0	193
Additional costs per hectare	12	17	0	57
Establishment costs for associated crop	54	119	0	377
Total_labour costs	3048	2960	1249	10,851
Total Fixed_costs (incl depreciation, interest+loan)	387	684	14	2546

Table A14 shows the variable costs by item and fixed costs (descriptive statistics) used in the simulation of the base case scenario for the LPHS (Low production and low shade Coffee + Avocado) production strategy.

Table A14. Variable/fixed costs used in the simulation of the base case scenario for the LPHS (low production, high shade) production strategy.

	Mean	std	min	max
Establishment costs	153	204	0	705
Chemical fertilizer	234	259	0	1136
Organic fertilizer	36	66	0	264
Pesticides	8	36	0	185
Diseases control	45	66	0	223
Weed control	1	4	0	14
Foliar fertilizer	29	120	0	600
Shade establishment	6	16	0	68
Transportation workers	1	3	0	16
Transportation of coffee	27	42	0	191
Additional costs per hectare	19	27	0	121
Total_labour costs	978	606	21	2536
Total Fixed_costs (incl depreciation, interest+loan)	163	236	11	921

Table A15 shows the variable costs by item and fixed costs (descriptive statistics) used in the simulation of the base case scenario for the VLPMS (Medium production and medium shade) production strategy.

Table A15. Variable/fixed costs used in the simulation of the base case scenario for the VLPMS (Very low production and medium shade) production strategy.

	mean	std	min	max
Establishment costs	118	165	0	549
Chemical fertilizer	158	265	0	743
Organic fertilizer	196	642	0	2737
Pesticides	6	19	0	74
Diseases control	34	65	0	215
Shade establishment	3	10	0	42
Transportation workers	9	36	0	153
Transportation of coffee	24	63	0	269
Additional costs per hectare	11	20	0	72
Total_labour costs	577	256	262	1309
Total Fixed_costs (incl depreciation, interest+loan)	254	424	9	1833

Appendix B. Cumulative distribution functions of average net cash income

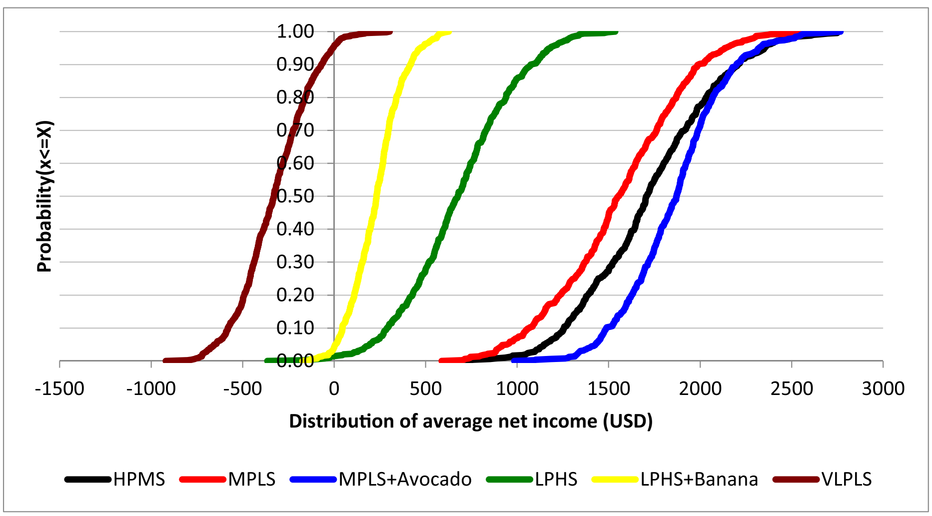

Fig. B1. Cumulative distribution function for average net cash income for each production strategy in Costa Rica under a base case scenario.

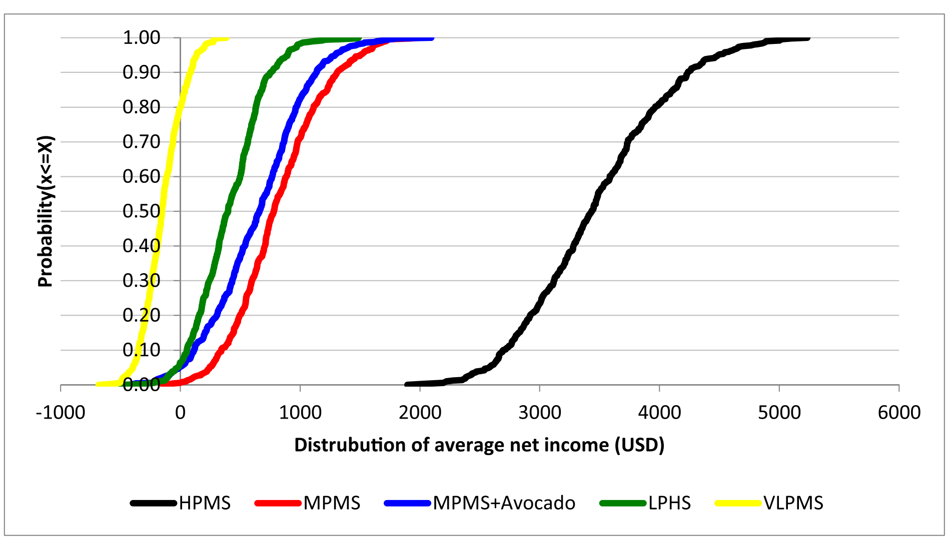

Fig. B2. Cumulative distribution function for average net cash income for each production strategy in Guatemala under a base case scenario.

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