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The role of shade tree pruning in cocoa agroforestry systems: agronomic and economic benefits

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Abstract Cocoa-based agroforests are promoted to replace monocultures for the provision of ecosystem services. However, shade tree pruning, an important tool to sustain cocoa yields, is not commonly implemented. This study investigates the effect of pruning on both agronomic and economic performance. In Bolivia, four famers' sites were divided in half, and shade trees pruned in one of the two plots. Pruning resulted in a significant increase in cocoa yield, from an average of 430 to 710 kg ha^{-1} by boosting flowering and pod production, but not reducing the proportion of damaged pods, and of those lost to cherelle wilt. Additionally, scenario calculations using international and organic premium cocoa prices were conducted to evaluate the economic feasibility of pruning. The minimum, mean and maximum yield of 22 local cocoa-based agroforestry farms were used as reference for 25, 50 and 75% yield increase scenarios. Offsetting the pruning costs highly depended on the initial yield levels. Using the minimum yield, all scenarios led to a lower net income compared with no pruning. For the mean yield level, the net income was equal to that obtained without pruning when the yield increase was above 51%. At the maximum yield level, all increase scenarios resulted in a higher net income. Our results prove the importance of pruning agroforestry trees to increase cocoa yields. However, with current farm-gate prices for cocoa, farmers alone cannot cover the extra management costs. The cocoa sector should discuss different strategies to support pruning for a broader adoption of agroforests.

Keywords Canopy closure · Flowering · Yield · Pest and disease · Income

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Introduction

Increasing awareness and knowledge of the environmental consequences of intensive agriculture are fueling a debate on sustainable production systems. In the case of cocoa (*Theobroma cacao* L.) the trade-offs between socio-economic and environmental factors of different production systems are increasingly investigated (Armengot et al. 2021). Full-sun monocultures usually have higher cocoa yields compared to traditional cultivation in forest understory or agroforestry systems (AFS) (Niether et al. 2020). But they are also associated with larger environmental impacts, such as biodiversity loss, reduced carbon stocks, and increased use of energy from non-renewable resources, as well as reduced energy efficiency (Jacobi et al. 2014; Blaser et al. 2018; Pérez-Neira et al. 2020; Bennett et al. 2021). The integration of shade trees in cocoa plantations is known to generate a variety of other considerable benefits for both farmers and the environment. Timber and fruit trees can provide diverse habitats and create a species-rich ecosystem for biodiversity conservation (Clough et al. 2011; Marconi and Armengot 2020). The biomass of these additional trees offers substantial carbon storage potential, thus contributing to carbon offset and climate change mitigation as compared to monocultures (Jacobi et al. 2014; Blaser et al. 2018; Schneidewind et al. 2019). Besides cocoa as cash crop, agroforestry tree products offer income security by providing additional income from fruit trees, bananas, spices and stored capital from timber trees (Tscharntke et al. 2011). This can reduce vulnerability to low prices and price volatility in the cocoa market that threaten the livelihoods of farmers, whose income largely depends on cocoa as the main cash crop (Voora et al. 2019).

Despite the potential benefits of AFS, their implementation and management are challenging. Previous approaches to promote and establish cocoa AFS have failed due to lack of adaptation to the local and socioeconomic context (FAO 2013; Jacobi et al. 2017). With smallholder farmers accounting for 95% of the global cocoa production, the success and sustainability of AFS require the establishment of resilient shaded cocoa plantations adapted to and capable of improving farmers' livelihoods. Higher workloads with increasing system complexity (Armengot et al. 2016), as well as inadequate designs, have led to farmers abandoning agroforestry plots (personal communication). Therefore, system objectives, management and labor requirements need to be well planned and adapted to the possibilities and constraints of farmers, sites and contexts. For instance, a study in cocoa AFS in Papua New Guinea reported that an improved pest and disease management system was not adopted by small holder farmers because the increase in cocoa yields did not compensate for the increased labor demand costs (Scudder et al. 2022). Studies and recommendations for improved management practices should therefore consider the required costs.

Shade canopy management plays an important role in the productivity of AFS and helps sustain yields and balance trade-offs between yield and environmental benefits (Beer et al. 1998; Tscharntke et al. 2011; Blaser et al. 2018). Besides adequate planning of the canopy architecture and composition, the maintenance of a beneficial shade level through pruning of shade trees increases light transmittance and, consequently, the photosynthetic activity of cocoa trees, resulting in increased yields (Alvim 1977; Wessel 1985). Optimal shade levels are not universal and depend, among other factors, on farmers' objectives. Looking at cocoa yields only, Blaser et al. (2018) found no differences between AFS and full-sun monocultures at up to a 30% canopy cover. Pruning further alters the microclimate below the shade canopy, which is inherently connected to ecosystem processes and interactions that affect cocoa growth, and it contributes to nutrient cycling when pruning residues are left in the plantation (Beer et al. 1998; Niether et al. 2018; Schneidewind et al. 2019). Pruning of the AFS trees is also essential to ensure a good quality of the wood of the timber trees as well as for managing other associated trees such as fruit trees (Somarriba and Beer 2011; Schnabel et al. 2018). Nevertheless, carrying out pruning activities is resource and knowledge-intensive and partly requires specialized labor to ensure safety and appropriate implementation. It is therefore essential that the potential economic benefits of pruning offset the costs, at the very least. Despite the crucial role of pruning for the adoption and maintenance of AFS, up to now, the management of associated trees in traditional and successional AFS has been hardly studied (but see Riedel et al. 2019). This study investigates the effect of shade tree pruning on cocoa yield in diverse multistrata AFS in the region of Alto Beni, Bolivia. We expected that, after a pruning intervention, (i) cocoa yields would be higher than in unpruned plots. Apart from yields, we collected data on canopy closure, flowering, cherelle wilt and the incidence of pests and diseases to determine how they were affected by pruning and their influence to the final yields. Beyond the agronomic effects, we further considered economic aspects. We hypothesized that (ii) the additional income from increased cocoa yields would allow farmers to cover the costs of pruning. The study is aiming at providing relevant information to support the promotion and implementation of shade tree management, and expose the potentials and constraints to obtain economic benefits from it.

Material and methods

Trial site and experimental design

This study was conducted in the region of Alto Beni, Bolivia, as a participatory on-farm research trial within the SysCom project (www.systems-comparison.fibl.org). The region is characterized by a tropical winter dry climate with an average annual temperature and precipitation of, respectively, 25.2 °C and 1440 mm.

Four farmers' sites with highly diverse multi-strata cocoa-based AFS were selected. Farmers are associated with the farmer's cooperative El Ceibo, which provides services such as trading of cocoa and production of chocolates and organizes the organic certifications for the members. Farmers are mainly organic farmers by default, since the application of organic inputs such as compost or organic crop protection products is not common in the study region. The selected farmers established their cocoa AFS between 1995 and 2005 (Table 1). Most of the shade trees were intentionally planted after clearing the fields, but some already existing trees were left when the plantation was established and some new trees from the natural regrowth of the vegetation were kept in the system. Timber, fruit and medicinal trees were planted without a regular planting design at high density and diversity. A schematic diagram of the AFS evaluated and the most common tree species encountered in these systems are included in the supplementary material S1 and S2. Cocoa trees were regularly planted at a spacing of 4×4 m (625 trees ha^{-1}), following local standard practice.

There was only little or no variation regarding the management practices of shade trees among farmers, since farmers mostly let their trees grow uncontrolled, as the pruning of shade trees is not a common practice. Shade trees were not pruned for at least 10 years prior to the study. Cocoa tree varieties could not be fully identified and differed both between and, partly, within farms. At each site, a homogenous area of about 0.5 ha was selected and divided into two approximately same-sized plots, one of which was pruned, while the other was left unpruned as a control. All other management practices were kept equal, and no fertilizer and synthetic pesticides were used. Shade trees were pruned between December 2018 and January 2019. Pruning was carried out by choppers and arborists from the ECOTOP Foundation. The height and development of the trees required climbing equipment, and also expert knowledge on how to prune the trees according to their life cycle and canopy layer. Professional pruning of AFS trees is also important to minimize the damages to cocoa trees. Pruning intensity varied according to the density and age of the shade trees and involved the removal of all lateral branches to increase light incidence and aeration (supplementary material S3). When necessary due to high density, some trees were felled (Table 1). All pruning residues were shredded and distributed evenly across the pruned area or gathered in small piles. Pruning residuals did not change soil fertility parameters compared to the unpruned plots during the time frame of the study (data not shown).

Data collection

As pruning was performed between the end of 2018 and the beginning of 2019 (see section 'Trial site and experimental design'), and some local farmers

Table 1 Description of the agroforestry systems evaluated

Farmers	Year of installation	Altitude m a.s.l	Pruned plot size m^2	Shade tree density trees ha^{-1}	Pruned trees trees ha^{-1}	Felled trees trees ha^{-1}
J. Ma	2005	491	1957	179	82	5
J. Mi	2003	420	2500	480	160	120
B. R	1996	450	2340	498	182	39
W. Y	1995	687	3028	439	116	50

reported harvest peaks occurring in March, no big effect on the cocoa yield was expected in the first harvest season after pruning. Therefore, data were not collected in 2019. However, farmers reported a substantial increase in cocoa yield in the pruned plots already in the harvest of 2019, but no accurate data are available. All data presented in this study were collected in 2020.

Canopy closure

To estimate the effect of pruning on the canopy closure, a GRS densitometer (Geographic Resource Solutions, USA) was used. Data were collected three times (March, June and October 2020) every two meters in between the cocoa rows (one meter before and after each cocoa tree), resulting in a sample size of 219 to 299 observations per plot for each sampling date. The hemispherical canopy projection was examined at an intermediate viewing angle and divided into four quadrants. According to the proportion of area within the quadrants filled with canopy above the cocoa trees, for each observation, the canopy closure was estimated at a scale of 0 (0%, no cover by AFS trees) to 4 (75–100%, all or most of the area covered by canopy). The canopy of cocoa trees was not considered. All observations were performed by the same person in order to avoid bias.

Yield and phenology

For the collection of yield and phenology data, 15 cocoa trees per plot were selected based on common criteria to ensure maximum possible homogeneity in age, habitus, and productivity. Cocoa pods were harvested approximately every two weeks between January and October, according to the harvest period of each site. For each sampling date and tree, the fresh weight of beans was recorded and converted into dry bean weight (DW) by multiplying it by the commonly used factor 0.33. Further, the total number of mature pods was recorded and classified into healthy pods, pods infected by frosty pod rot (*Moniliophthora roreri*), which was the predominant disease, and otherwise damaged or non-healthy pods due to other pests and diseases. The pods lost to cherelle wilt, i.e., the physiological thinning resulting in the wilting of young pods (Melnick 2016), were recorded as well. At each sampling date, wilted cherelles were counted and removed. Data on flowering and flushing were collected on the same sampling dates and ranged on a scale from 0 (no flowers/no new shoot growth) to 4 (almost all branches with a large number of flowers/shoots larger than 10 cm). Sampled trees that did not produce throughout the entire harvest season were removed from the data set for analyses (in total, 10 trees out of 120 sampled).

Pruning costs

The total pruning costs of 1600 Bs (232 USD) per plot (about 0.25 ha) comprise, on average, two full days of work for two arborists and two choppers, resulting in 6400 Bs ha^{-1} (929 USD ha^{-1}). Wages were paid by day of work (8 h), and the specialized work carried out by the arborists was remunerated at 300 Bs day^{-1} (43.5 USD day^{-1}), while the work performed by choppers was paid at 100 Bs day^{-1} (14.5 USD day^{-1}).

Scenario calculations

The profitability of pruning depends on whether the additional income of increased yields can cover the pruning costs. Therefore, the costs were subtracted from the farmer's income in pruned plots, hereinafter referred to as "net income", and compared with the income in unpruned plots. In order to have a larger sample size, the Bolivian farmers' cooperative El Ceibo provided yield data of cocoa produced in the unpruned AFS of 22 farmers in the Alto Beni region for three years. The average minimum (86.7 kg ha^{-1}), mean (287.4 kg ha^{-1}), and maximum (637.1 kg ha^{-1}) yields were registered.

Three levels of potential yield increase in relation to an unpruned plot were established: 25, 50, and 75%, which were considered plausible according to the field data collected (see section 'Canopy closure and cocoa yield formation'). In total, nine scenarios were obtained when applying each increase level to the minimum, mean, and maximum yield levels.

For the income calculations, the price of 21.89 Bs kg^{-1} (3.18 USD kg^{-1}), as paid for organic cocoa by the farmers' cooperative El Ceibo, was used, and additionally the 2019 average daily price of 2.34 USD kg^{-1} (16.13 Bs kg^{-1}), paid for cocoa in the international market (International Cocoa Organization 2019).

Preliminary analyses showed that one year of harvest was not sufficient to cover the cost of pruning. Therefore, all scenarios were calculated with two-year data. The same percentage of yield increase in relation to the initial unpruned yield level was applied in both years, as well as the same price. Pruning costs that were not covered in the first year were subtracted from the income of the second year. Potential yield increases and income from by-crops, as well as the value of cut wood and biomass, are not considered in this study.

Statistical analysis

Yield (DW) and number of pods for the different categories registered on all harvesting dates in 2020 were accumulated per tree. Phenology data were converted into percentages of maximum possible flowering/flushing per tree over the harvest period. A linear mixed-effects model was used to test the effect of pruning on the following response variables: cocoa yield, number of mature pods (excluding those lost by cherelle wilt) and total fruit set (all mature pods in addition to pods lost by cherelle wilt), percentage of infested or infected pods, percentage of pods infected with *M. roreri*, and percentage of flowering and flushing. The analyses were conducted using R 3.6.1 software (R Core Team 2021) with the packages *lme4* (Bates et al. 2015) and *lmerTest* (Kuznetsova et al. 2017) for post-hoc analyses. Pruning was included in the model as a fixed effect, with random intercepts for the farmer's site. The significance level was set at $\alpha = 0.05$. Assumptions were tested visually with residual plots, and data were transformed when necessary. Results are presented as mean ± standard error of the four farmers' sites, and yield (DW) was converted into kg ha^{-1} using the tree density.

Results

Canopy closure and cocoa agronomic parameters

A higher canopy closure was observed in the unpruned compared with the pruned plots (supplementary material S4). Overall, the median canopy closure was 75% in the unpruned plots and 50% in the pruned plots. For example, in March, only 13% of all the observations had no canopy cover or very low levels (0 and 1 categories) in the unpruned plots (total number of observations: 1043) while it reached up to 30.6% of the sampling points in the pruned plots (number of observations: 1063). On the contrary, 53.3% of the observations were completely covered in the unpruned plots (category 4) while it was only 34.4% of the observations in the pruned plots.

As hypothesized, significantly higher cocoa yields were observed under pruned conditions ($p = 0.002$), ranging from a 27.8 to 81.5% increase in relation to unpruned plots. Without pruning of shade trees, the average annual yield at the farmers' sites was 430.8 ± 133.3 kg ha^{-1} (DW), compared with 707.6 ± 267.1 kg ha^{-1} (DW) two years after pruning (Fig. 1a, supplementary material S5).

Similarly, flowering increased from 15 to 19.2% ($p = 0.008$) in the pruned plots (Fig. 1b), and the total fruit set was on average 31.2% higher compared with that of the unpruned plots ($p = 0.003$, Fig. 1c, supplementary material S5). In both treatments, a similar percentage of fruit set was lost to cherelle wilt (51.4 ± 7.1% with pruning, 58.8 ± 8.8% without pruning, $p = 0.186$). Thus, on average, the number of mature pods harvested in the pruned plots was 0.73 times higher than in the unpruned control plots, increasing from 287.0 to 497.3 pods ha^{-1} ($p < 0.001$).

The share of healthy pods among mature pods did not differ significantly between treatments ($p = 0.425$, Fig. 1d): 63.3 ± 4.3 and 61.9 ± 5% in pruned and unpruned plots, respectively. The majority of non-healthy pods were infected with *M. roreri* in both treatments (25.7 ± 5.3% in pruned, and 25.6 ± 7.2% in unpruned plots, $p = 0.201$). Other minor damages were caused by black pod disease (*Phytophthora* spp.), cocoa mirid (*Monalonion dissimulatum*), or small mammals or birds.

Economic assessment and scenarios

The results from the trial and scenario calculations showed that the ability to cover pruning costs with income from additional yields in pruned cocoa-based AFS highly depends on initial yield levels, and on the degree of yield increase.

In the trial, two farmers achieved net incomes that were, respectively, 6.5 and 44.4% higher than those obtained without pruning when applying the organic premium price. Due to low yield and yield

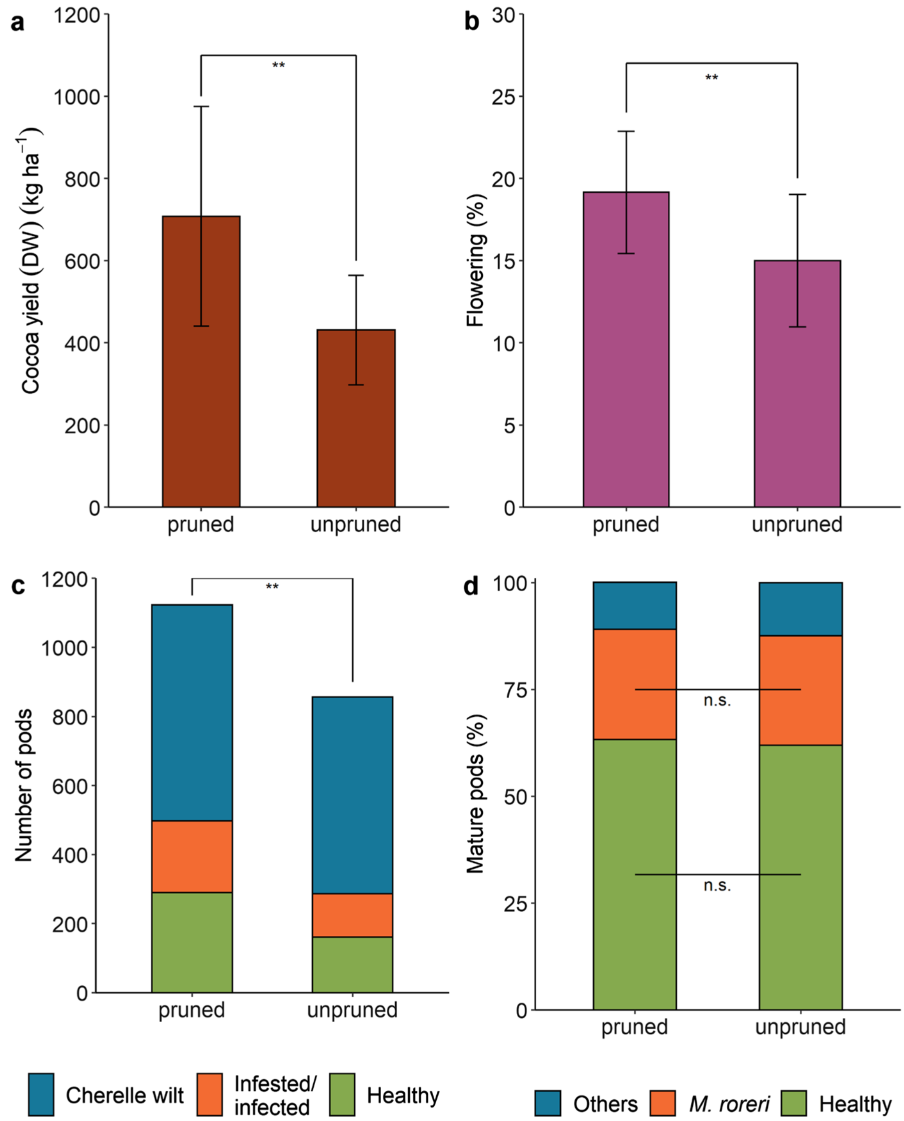

Fig. 1 Means and SE of dry cocoa yield in kilograms per hectare **a**; share of flowering **b**; number of fruit sets per plot, share of pods lost to cherelle wilt, infestation or infection, and healthy pods by the time of harvest **c**; share of healthy pods, pods infested by *M. roreri*, and other non-healthy pods in relation to mature pods **d**, in pruned and unpruned agroforestry systems. Asterisks indicate significance between the two systems, 0 = ***; 0.001 = **; 0.01 = *, n.s. = non-significant

increase levels, at the remaining two sites the income decreased by 57.6 and 159.6%, respectively.

In the scenario of a minimum yield of 86.7 kg ha^{-1}, yield and income need to increase by 168.6% during two consecutive years to compensate pruning costs if the organic premium price is paid. Both the 25% increase and the 50% increase scenarios resulted in a negative net income, which means that, in both, pruning costs were higher than the total income of two years (Fig. 2a). With an increase in yield of 75%, a net income was achieved, however, lower than the income of an unpruned site (94% decrease).

At the mean and maximum yield levels of 287.4 and 637.1 kg ha^{-1}, respectively, all scenarios led to a positive net income. However, for the mean yield level, a 25% increase resulted in a lower income compared with that of an unpruned site; in fact, the net income was higher only when the yield increase was above 50.9%. At the maximum yield level, all increase scenarios resulted in a higher net income, i.e., an increase of 22.9% was necessary to cover the pruning costs (Fig. 2a).

Obtaining economic benefits from pruning requires higher initial yield levels and yield and income increases when assessing scenarios using the international cocoa price as compared to the premium price (Fig. 2b). Under all pruning scenarios, the minimum yield level resulted in

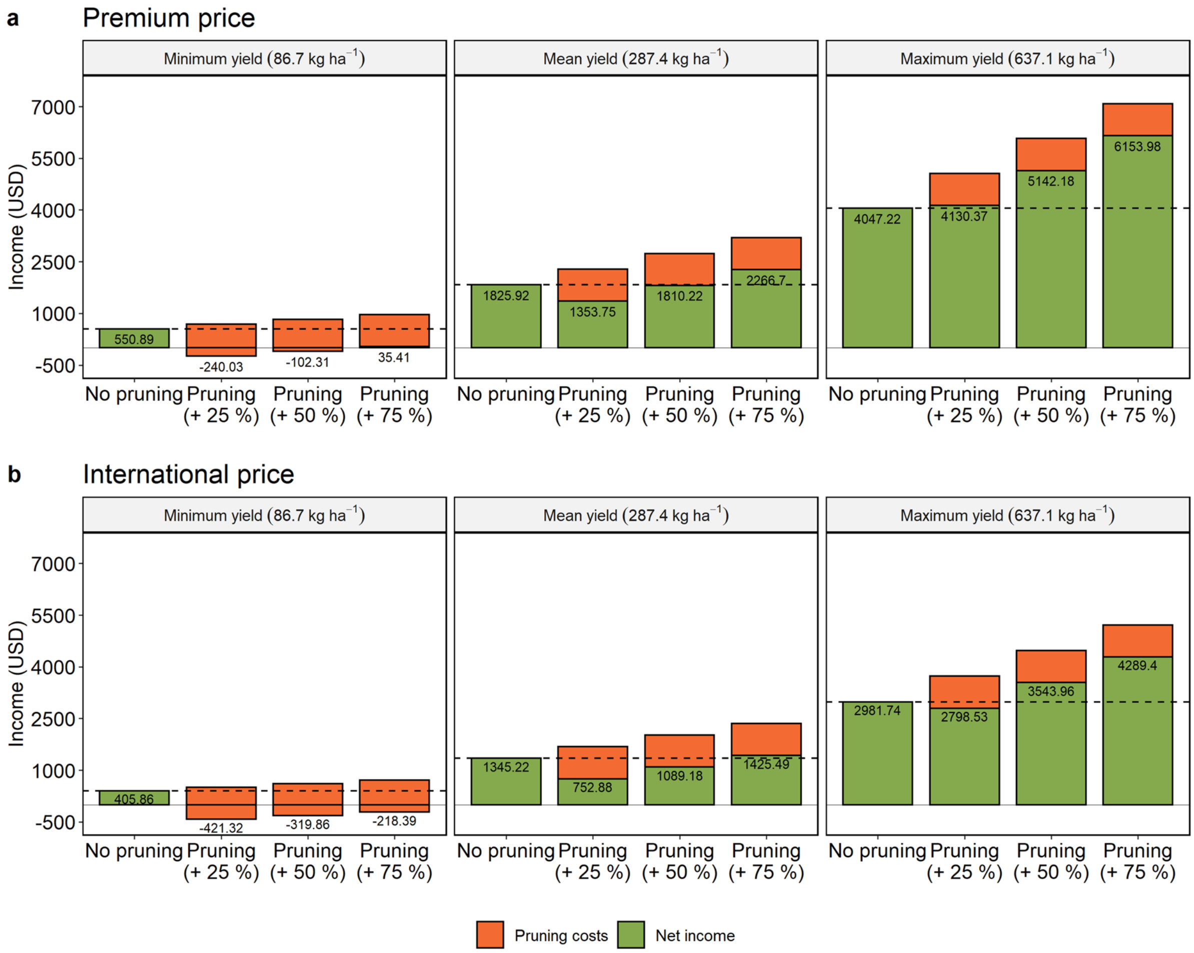

Fig. 2 Cocoa income (USD ha^{-1}) after two years for three yield levels (minimum, mean and maximum), without pruning (No pruning), and if pruning increases yields by 25, 50 or 75% in two consecutive years. Total bar height shows incomes according to premium **a** and international **b** cocoa prices. Green bar height (and values) indicates net income after subtraction of pruning costs (orange). At the minimum yield level, the income of both years did not cover pruning costs (in the case of 25 and 50% yield increases); therefore, the net income is negative. Dashed lines show incomes without pruning for each yield level

a negative net income, and an increase in yield of more than 2.29 times higher than without pruning over a period of two years was necessary to attain additional income. At a mean yield level, the same net income as in an unpruned site was reached only by an increase in yield of 69.0, and of 31.4% at the maximum yield level. In the latter case, economic benefits were achieved by all three scenario increases, ranging from a 0.02 times higher income in the 25% increase scenario to 0.27 and 0.52 times higher incomes for, respectively, the 50 and 75% increase scenarios.

Discussion

Cocoa flowering, pod set and yield

The results show that the observed increase in cocoa yield after pruning of shade trees was due to a boost in flowering and fruit set, leading to a higher number of mature pods per tree compared with the unpruned plots.

Increased cocoa yields under reduced to no-shade conditions are frequently reported (Hurd and Cunningham 1961; Schneider et al. 2017; Blaser et al.

2018; Asante et al. 2021). Groeneveld et al. (2010) reported that the intensity of flowering and pollination was the main determinant of the final number of mature plods. Light plays a crucial role in the intensity of flowering in cocoa trees. For instance, Hurd and Cunningham (1961) already reported a higher number of flowers in unshaded than shaded systems, which is similar in our study for the pruned and unpruned plots. Further, wild cocoa trees in riparian forests start flowering when the deciduous trees have shed their leaves (personal communication). Pruning interventions also have the main goal of reducing shade. However, the physiological mechanisms of floral induction have not been fully investigated in cocoa trees.

The proportion of pods lost to cherelle wilt in our study was around 50–60% of the total fruit set, which is line with or a bit lower than the percentages found in previous studies (Groeneveld et al. 2010; Hurd and Cunningham 1961). Cherelle wilt is the physiological mechanism by which trees adapt the number of maturing pods to resource availability (Valle et. al. 1990). The proportion of cherelle wilt was similar regardless of the canopy closure, as found also by Hurd and Cunningham (1961), although Groeneveld et al. (2010) found a higher proportion of cherelle wilt in shaded compared to non-shade systems. Light intensity positively correlates with photosynthetic activity in cocoa leaves, with a depressing effect reported only at high solar radiation (Wessel 1985). The potential increase in assimilates allowed for a higher number of mature pods. However, this did not reduce the percentage of cherelle wilts because of the higher pod set (and flowers), pointing at the need to further investigate on wilt.

Pest and disease incidence

The relationship between shade intensity and the incidence of pests and diseases in AFS is complex and depends on many different management and microclimatic factors (Niether et al. 2020). Fungal infections are the major causes of yield losses in cocoa (ten Hoopen and Krauss 2016), and a higher incidence of black pod rot under increasingly shaded conditions has been reported (Beer et al. 1998). However, three-year data comparing full-sun monoculture and AFS show no differences in the incidence of black pod rot and frosty pod rot, and the overall incidence of non-healthy pods (Armengot et al. 2020). Furthermore, Melendez (1993) observed an increase in *M. roreri* spore count under shade trees, but no significant differences in the incidence of frosty pod rot disease, the major cause of damaged pods in our study (about a quarter of all mature pods). Our results support these previous studies since we did not observe differences between the pruned and unpruned AFS. The systematic phytosanitary control in both pruned and unpruned plots, i.e., the regular removal of infested pods, might also explain the lack of differences between the pruning treatments (Armengot et al. 2020).

Shade tree management

Pruning strongly reduced the canopy closure and this effect lasted until the end of the study (supplementary material S4). However, it is not clear how long this effect can last, and when a new pruning intervention will be necessary to maintain a higher yield level compared with that of unpruned plots. This should be addressed in further research. A continuation of the trial was not possible, as pruning was subsidized as part of a different project and farmers did not want to keep the unpruned plots. It should also be considered that the pruning intervention performed was quite strong since the AFS evaluated were not pruned for at least 10 years and they were highly diverse and dense. Another pruning intervention in the following years could be less intense and therefore less costly.

Next to the frequency of pruning, timing and intensity may further positively affect system performance if adapted to seasonal climatic changes (Niether et al. 2018). An earlier pruning intervention than implemented in our study may have a stronger effect on yield already during the first year after pruning, and therefore contribute to offsetting management costs earlier. Moreover, Tscharntke et al. (2011) suggest adapting pruning intensity to the age of cocoa trees to achieve optimum yields.

Desirable shade levels also depend on the farmer's objectives and, consequently, how trade-offs between environmental and economic costs and benefits are balanced (Steffan-Dewenter et al. 2007; Blaser et al. 2018; Somarriba et al. 2018). In the complex AFS studied here, the purpose was not to maximize the economic returns on cocoa, but to develop the best management practices for the well-functioning of the system while preserving its diversity. Especially under no-input conditions, the question arises on the extent of shade reduction at which nutrients replace light as a limiting factor for further yield increases (Wessel 1985). The above-mentioned pruning management strategies (frequency, timing, intensity) need to be further investigated and adapted to local conditions.

Economic assessment

Although pruning significantly increased cocoa yields, its implementation needs to be economically viable for farmers. Even a strong increase in yield does not result in a high additional income if the initial yield levels are low. The 550 kg ha^{-1} difference in cocoa yield between the minimum and maximum yields documented in the studied area shows that productivity varies strongly. This may be associated, among others, with the wide range of genetic material used by farmers; therefore, pruning cannot compensate for the gap in yield potential due to other management practices. The mean yield recorded in the study area was lower compared to the overall worldwide mean of about 550 kg ha^{-1} (including all types of production systems and external inputs), but the yields also vary strongly (minimum cacao yield: 31 kg ha^{-1}; median: 410 kg ha^{-1}; maximum: 3121 kg ha^{-1}) (FAOSTAT 2022).

Nevertheless, our results show that it is possible to cover pruning costs at higher yield levels with the increased yields obtained over two years. The economic calculations in this study were kept simple. For instance, we considered the same cocoa yield increase for both years. We based our assumption on the results of the canopy closure. We did not observe a strong increase in the canopy closure in the last sampling in comparison with the first one in March 2020. This indicated that the differences in the light incidence between the unpruned and the pruned plots in the second year could be similar to the first one and, therefore, we assumed a similar effect on the cocoa yield. However, this point needs to be further addressed in future medium- and long-term studies evaluating the relation between shade tree pruning and cacao yield. In addition, we focused only on cocoa yields and income, but the farmers' actual income may in fact be higher, as it includes the future value of timber trees and by-crops, such as fruit trees and bananas (See list of species in S2). Despite no data collection in this regard, we expect that by-crops too profited from higher light intensities and improved management after pruning, and an increase in yield is likely. Regardless of their use for either selling or self-consumption, a higher yield in by-crops may contribute to offsetting the pruning costs, and their value in connection to food and income diversification and security should not be neglected (Tscharntke et al. 2011; Cerda et al. 2014).

The comparison of pruning scenarios under the organic premium prices paid by the Bolivian farmers' cooperative El Ceibo and international cocoa prices shows the importance of a fair income for the sustainable management of cocoa AFS. At the lower international prices, higher yields are necessary to cover pruning costs. While AFS for cocoa production are promoted by different stakeholders for their contribution to climate change mitigation, carbon offsetting, and biodiversity conservation (Niether et al. 2020), there is a lack of definition and coordinated implementation, and the attempts are consequently failing to tap the potential of AFS (Sanial et al. 2020). Subsidies for pruning of shade trees or sourcing companies covering the costs are possible ways to ensure shade management. Furthermore, payment-for-ecosystem-service schemes, such as certifications for biodiversity conservation, or carbon-credit schemes, should be developed to compensate cocoa farmers for potential yield losses compared to full-sun monocultures and to cover the costs for the appropriate management of AFS (Steffan-Dewenter et al. 2007; Tscharntke et al. 2011; Waldron et al. 2015). The discussion on the promotion of shaded cocoa should not revolve only around economic losses but include incentives for farmers to adopt best management practices that support both shaded cocoa and resilient AFS.

Conclusions

Our results indicate that the promotion of cocoa AFS should not only include the design and planting of agroforestry trees, but should also be accompanied by a management plan involving different stakeholders. The increase in labour and cost due to the implementation of pruning activities cannot be solely covered by farmers under the current productivity and cocoa market prices. For a broader adoption of AFS, the cocoa sector should discuss the best way to support implementation of pruning as an integral part of the management of these systems, whether through subsidies that cover the cost of pruning, higher prices for cocoa sourced from AFS, or pruning costs covered by the sourcing companies. Frequency, intensity and timing of the pruning interventions should be further investigated and locally adapted. This is crucial for the farmers to know if these interventions are economically worthwhile in the long-term. Professional agroforestry tree pruning services and timber logging should be developed and be accessible for farmers.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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