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Effects of pruning on flowering and yields of Cacao Nacional Boliviano

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Abstract Cacao Nacional Boliviano (CNB), the native cacao germplasm group in the Bolivian Amazon region, possesses distinct morphological, genetic, phenological and organoleptic characteristics. It is highly sought after in the global fine-flavour chocolate market, and has importance for conservation of cacao genetic diversity. However, CNB cultivation is minor and yield levels low. Aiming to develop profitable CNB cultivation practices adapted to its distinct phenology and genetic basis, we compared parameters on CNB flowering, yields, biomass and harvesting effort in three agricultural systems with and without pruning and varying management intensity: agroforestry with pruning (AF), underplanted secondary forest with (SFwP), and without pruning (SFnP). Repeated measures linear mixed models using Restricted Maximum Likelihood were applied for statistical analysis. While AF and SFnP yielded 127.6 ± 21.4 kg ha^{-1} and 212.4 ± 22.2 kg ha^{-1} on average, reaching > 300 kg ha^{-1} after 11 and 9 years, respectively, SFwP yields remained significantly lower than SFnP, with an average of 58.0 ± 9.5 kg ha^{-1} and maximum yield of 122.6 ± 36.5 kg ha^{-1}. This study demonstrates there may be a trade-off between pruning intensity and yield in AF and SFwP, as observed on young CNB trees' yield developments and yield increases during two years without pruning in mature trees. Based on preliminary results and CNB-specific phenology, we suggest a moderate pruning intervention early in July (allowing recovery time before start of flowering season in August), along with the need for validation of our findings and further investigation into management practices tailored to CNB.

Keywords Agroforestry · Management systems · Silvicultural treatments · Phenology · Productivity, *Theobroma cacao*

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Introduction

Cacao (*Theobroma cacao* L.), with a total global export value of 8.6 billion USD in 2017, is an important cash crop providing livelihoods to over 5 million smallholder farmer households in the world (Bermudez et al. 2022; Voora et al. 2019). While leading cacao exporting countries such as the Ivory Coast and Ghana primarily produce bulk-quality cacao, Latin America and in particular the Amazon region, being cacao's centre of origin and diversification, plays a prominent role in the production of high quality fine-flavour cacao, supplying about 80% of the global

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share (Ceccarelli et al. 2022; Tscharntke et al. 2023). Motamayor et al. (2008) identified 10 main genetic groups using molecular analyses, but various studies suggest that these do not yet represent the full range of cacao diversity (Arevalo-Gardini et al. 2019; Céspedes-Del Pozo et al. 2017; Thomas et al. 2012; Zhang et al. 2012). Preservation of these still understudied cacao groups is of utmost importance for the conservation of cacao genetic diversity.

One of these genetic groups is Cacao Nacional Boliviano (CNB). It is the native cacao present in the Amazon region of Bolivia, in wild populations and in abandoned plantations of unknown origin. CNB possesses its own distinct morphological and genetic characteristics, distinguishing it from other clusters in South and Central America (July Martinez 2016; Tscharntke et al. 2023). In the Alto Beni region, colonized by people from the Altiplano through a governmental program in the 1960's, international clones and hybrids were introduced and promoted, soon representing the largest share of productivity. Nevertheless, some cultivated CNB populations remained, along with the traditional practice of pod collection from wild or abandoned populations (Villegas and Astorga 2005; Zhang et al. 2012).

Lately, CNB has gained international attention in the fine-flavour cocoa sector due to its unique organoleptic qualities (FAO 2019), being regularly recognised in international competitions (Cacao of Excellence Awards, www.cacaoofexcellence.org). CNB may therefore represent an interesting diversification strategy for producers of introduced cacao, such as in the Alto Beni region, and a source of income for communities living in the Amazon and around protected forest areas.

CNB phenology patterns are distinctly different from the introduced international clones and hybrids cultivated in the region: peak flowering occurs in October and pods are harvested between January and April for CNB, while hybrids and international clones begin to flower in December and are harvested during May to August (Somarriba and Trujillo 2005). The resulting potential advantages and increased resilience of CNB in the Amazonian context should not be ignored:

Milz (1990) reported on CNB's lower susceptibility to diseases through better adaptation to the local climatic conditions. Its earlier fruit production allows CNB to better evade infections with black pod disease (*Phytophthora palmivora*), and remains less severely affected by the pest *Monalonion dissimulatum* ("chinche") and witches broom disease (*Crinipellis perniciosa*) (Villegas and Astorga 2005).

In 2023, the Alto Beni region experienced cold spells in June, the peak harvest season of most clones and local hybrids, leading to premature germination and lower quality beans. CNB, however, with its earlier production peak, remained unaffected (own observations and communication of local cacao cooperative El Ceibo).

Despite its economic potential and higher resilience in its native range, CNB cultivation in Bolivia is minor compared to the production of introduced cacao. Only 26% of the national surface area with cacao cultivation (8′635 ha) is dedicated to CNB, while around 11′544 ha of wild or abandoned CNB stands exist (Peralta et al. 2022), available for harvest. One reason for this low cultivation rate may lie in the low yields of cultivated CNB (average 230 kg ha^{-1}) relative to those of wild CNB stands (average 92 kg ha^{-1}; Bazoberry Chali and Salazar Carrasco 2008) and the national average cacao yield (569.3 kg ha^{-1} in 2021; FAO 2023), which may not pay off plot installation and management efforts.

In Alto Beni, cacao is predominantly cultivated under agroforestry systems. Pruning is a common practice to optimise tree development and yields. It is a technique to create a balanced tree architecture, support the tree's health by removing diseased branches and improving aeration and light availability minimising fungal infections, and stimulating shoot, flower and fruit development (Almestar-Montenegro et al. 2024; Carrillo Alvarado et al. 2014; Mata-Quirós and Cerda 2021; Vera Chang et al. 2021). To achieve the intended effects, however, it is important to carry out the pruning intervention in an appropriate manner, adequate to the seasonality and weather patterns of the location, development stage of the trees and the physiological characteristics as they may vary considerably depending on the variety cultivated (Gil Restrepo et al. 2017; Jaimez et al. 2008; Leiva-Rojas et al. 2019; Tosto et al. 2022; Vera Chang et al. 2021).

So far, management practices for CNB agroforestry systems adapted to its particular early flowering patterns have not been studied. This study is addressing this research gap. In the following, we investigated the effect of pruning on flowering, yield and harvesting effort of Cacao Nacional Boliviano.

In particular, we have evaluated the flowering intensity and flowering index (FI), as well as the number of pods harvested and dry bean weight of CNB in three agroforestry systems with and without pruning and varying management intensity, and compared the harvesting effort and harvesting efficiency in the three systems.

Materials and methods

Study site and cultivation systems

The trial was set up in 2012 in Sara Ana, Alto Beni in Bolivia (390 m a.s.l) in the scope of the SysCom project (www.systems-comparison.fibl.org). The site is characterised by a tropical humid climate with dry winters (mean annual rainfall: 1540 mm; average temperature: 26.6 °C). This study assesses the first 11 years of the trial, comparing three different production systems for CNB.

The first system is an agroforestry system (AF) installed after slashing and mulching of a secondary forest, accompanied by bananas, plantains, fruit and timber trees and an extensive management focusing on weeding and cacao tree pruning, as well as occasional shade tree pruning. "Classical" shape and maintenance pruning were applied to CNB trees. While the former removes suckers and low hanging branches, the latter focuses on height limitation (ca. 3–4 m), distance maintenance with neighbours (avoiding canopy intertwining) and vertical light distribution (removing unnecessary secondary branches within the crown). Maintenance pruning was done once yearly in July or August. However, as cacao yields were declining in two consecutive years (2018–2019), pruning was stopped from 2020 on, and resumed at reduced intensity in 2022. The AF gross plot measured 5616 m^2 and includes four subplots of 320 m^2 each, with 20 CNB trees per subplot.

In the second system, CNB was planted in the cleared understory of a young secondary forest, and the cacao trees were pruned similarly to those in AF. Analogous to the AF, CNB pruning was omitted from 2020 to 2022, and resumed again in 2023. The gross plot of this SFwP (secondary forest, with pruning) system measured 3888 m^2, with four subplots of 240 m^2 in size, 15 CNB trees per subplot.

The third system, SFnP (secondary forest, no pruning), was also planted in the understory of the same secondary forest, but the CNB trees were not pruned and left to grow. The gross plot measured 3024 m^2 and the four subplots with 15 CNB trees each measured 240 m^2. This system is imitating the local habit of collecting cocoa from wild CNB stands or abandoned plots.

None of the systems used fertilizers. Mechanical weeding and pest control (exclusively for *Atta vollenweideri*) were done when required in all systems. The implemented CNB tree density of 625 trees ha^{-1} corresponds to regional means of cultivated systems (Somarriba and Trujillo 2005). All CNB trees were grown from seeds of 6 trees from a plantation in the Communal Land of Origin Simay, ca. 60 km South-East of the trial.

Data collection

CNB trees began producing pods in 2015, and yield data collection at subplot level started in 2016. Cocoa pods were collected fortnightly, recording number of total pods, healthy pods and fresh bean weight per tree. A conversion factor of 0.33 was used to calculate dry bean weight. This conversion factor is in line with local studies done on CNB (Estivarez Copa and Maldonado Fuentes 2019; Marca Mamani 2018) and on-site on other varieties (Armengot et al. 2016, 2020, 2023). Yearly healthy pod count and yields were then calculated by summing all the harvests from one year. In SFnP, we harvested all pods up to the highest branches, which locals normally wouldn't collect from wild forest stands. This allowed us to compare the total yield potential of all systems.

Flowering intensity of each cacao tree was assessed fortnightly since 2017 on a scale of 0–4 (0: none; 1: very few; 2: few; 3: average number; 4: many flowers; Armengot et al. 2023) and averaged per subplot. These averaged scores were summed per year (excluding January and February as data was missing in 2021) to obtain a yearly *flowering index* (FI). No FI was analysed for 2017, due to missing data between October and December.

Based on the fortnightly recorded flowering intensities, we identified the *beginning of the flowering season* in each year and system. We defined the beginning of the flowering season as the time point after the harvesting season (April), where the average flowering intensity was 0.7 or higher, and was at least double compared to the flowering intensity of the preceding survey. When the first criteria was met but not the second, the time point between both surveys was determined as the beginning of flowering season.

As a proxy for tree biomass, the trunk diameter was recorded in 2015, 2016, 2017 and 2020 for each tree within the subplots. Each trunk was measured with a calliper at 10 cm above ground. Two perpendicular measurements were taken and the averaged value calculated. If the tree was branching below 10 cm, the stem and branch were both measured.

Harvest labour time per subplot was recorded during the fortnightly harvests from 2016 on. The total yearly harvest labour time per subplot was converted to a common unit of working days ha^{-1} (1 working day = 8 h), which we refer to as *harvest effort*. The *harvesting efficiency* is defined as the ratio of number of healthy cocoa pods harvested ha^{-1} to the required *harvest effort*, in days ha $^{-1}$.

Data analysis

Data was prepared, aggregated and visualised using R Studio (R Core Team 2022; RStudio Team 2020). The effects of the agricultural system and year (directly linked to plantation age) on cacao FI, yield, tree diameter and harvesting effort and efficiency were analysed in XLSTAT (Addinsoft 2023) via repeated measures linear mixed models using Restricted Maximum Likelihood (REML) and pseudo-replicates (subplots) as nested random factor. Models included the interaction system * plantation age (2012 = year 1) and were followed by a post-hoc Benjamini–Hochberg test. When models could not converge (harvesting efficiency), data was log-transformed in order to reduce its heteroskedasticity. The relationship of FI and yield of a cycle was analysed separately per system via a linear regression and Pearson correlation coefficient. Statistical significance was set at $p < 0.05$.

Results

Flowering intensity and flowering index (FI)

The beginning of flowering season varied between years and systems, but largely fell into the month of August (Table 1). The earliest onset of flowering season occurred in SFnP in 2018 (17th July), the latest occurred in 2019 in AF (16th September). Each year, start of flowering season occurred synchronously in the three systems within 1 week of each other. The only exceptions are 2018 when SFnP was ahead of AF and SFwP by 3.5 weeks, and AF was ahead of SFnP and SFwP in 2021 by 2 weeks (Table 1). The pruning interventions were done before the flowering season, approximately 3–6 weeks, except in 2018 when pruning was done ca. 2 weeks after the beginning of flowering season (Fig. 1a, Table 1). Maximum flowering intensities occurred mostly in late September to October (Fig. 1a).

Year, system type and their interaction had significant effects on the flowering index FI (Table 2). No effect of pseudo-replicates was found, but were kept in the model. The FI was the highest in 2021. Considering the whole study period, FI was significantly higher in SFnP (6.76 ± 0.33) than in SFwP (4.27 ± 0.39), but AF (5.82 ± 0.53) could not be distinguished from both SFnP and SFwP.

The fortnightly flowering and pod production showed the synchronicity of these processes, regardless the type of system (Fig. 1a, c). The visual inspection of flowering intensity and production curves underlined that scores close to or under 1 did not seem to translate into significant pod production, especially for the pruned cacao systems (Fig. 1a, c). Yet, such a result would need to be further and specifically investigated. We found a significant linear relationship and strong positive correlation between FI and dry bean yield in the two pruned systems AF (R^2: 0.81; $p < 0.001$) and SFwP (R^2: 0.63; $p < 0.001$), but not in SFnP (R^2: 0.00026; $p = 0.95$) (Fig. 2).

Cocoa pod count and yield

Cacao production started between end of December to early January for all years. The peak of production occurred between February and March, while the end of the harvest appeared to be year-dependent (Fig. 1b, c). Year, and the system type x year interaction had significant effects on the cocoa yield (Table 2). No effect of pseudo-replicates was found, but were kept in the model. Average cocoa pod count and yields over all systems increased gradually year after year, except in 2018 and 2019. Overall cocoa pod count and yields were significantly higher in SFnP (13′939 ± 1585

Table 1 Dates of pruning intervention, beginning of flowering season, and number of days between pruning intervention and beginning of flowering season in three different Cacao Nacional Boliviano systems.

Year	System	Pruning intervention	Beginning flowering season	Days between pruning and flowering season
2017	AF	11.07.2017	15.08.2017	35
2017	SFwP	12.07.2017	22.08.2017	41
2017	SFnP	-	22.08.2017	
2018	AF	24.08.2018	11.08.2018	-13
2018	SFwP	27.08.2018	11.08.2018	-16
2018	SFnP	-	17.07.2018	-
2019	AF	18.08.2019	16.09.2019	29
2019	SFwP	15.08.2019	09.09.2019	25
2019	SFnP	-	09.09.2019	-
2020	AF	-	31.08.2020	-
2020	SFwP	-	07.09.2020	-
2020	SFnP	-	31.08.2020	-
2021	AF	-	16.08.2021	-
2021	SFwP	-	30.08.2021	-
2021	SFnP	-	30.08.2021	-
2022	AF	22.07.2022	10.08.2022	19
2022	SFwP	-	10.08.2022	-
2022	SFnP	-	10.08.2022	-

AF: agroforestry system, where cocoa trees are pruned, *SFwP*: secondary forest with cleared understorey, where cocoa trees were planted and pruned; *SFnP*: secondary forest with cleared understorey, where cocoa trees were planted but not pruned.

pods ha^{-1}; 212.4 ± 212.2 kg ha^{-1}) than in SFwP (3′540 ± 707 pods ha^{-1}; 58.0 ± 9.5 kg ha^{-1}) and AF (7′241 ± 1498 pods ha^{-1}; 127.6 ± 21.4 kg ha^{-1}). However, in 2022, AF reached yields > 300 kg ha^{-1} for the first time, and with that caught up with SFnP yields and were higher than SFwP (Table 2).

Trunk diameter

Year, and the system type x year interaction had significant effects on the cacao trunk diameters (Table 2). No effect of pseudo-replicates was found, but were kept in the model. Diameters increased with the age of the trees in each system. In general, SFnP had significantly larger trunk diameters than SFwP and AF. Diameters in AF were significantly higher than in SFwP in 2020, showing that tree biomass between the two system types is gradually diverging (Table 2).

Harvest effort and harvesting efficiency

Year, and the system type x year interaction had significant effects on harvest effort and harvesting efficiency (Table 2). No effect of pseudo-replicates was found, but were kept in the model. As production was increasing year after year, harvest effort also increased with the age of the systems, being lowest in 2016, intermediate between 2017 and 2019 and highest between 2020 and 2022. From 2018 to 2022, SFnP demanded consistently higher harvest effort (11.6 ± 1.3 days ha^{-1}) compared to SFwP (2.7 ± 0.3 days ha^{-1}) and AF (4.8 ± 0.5 days ha^{-1}). Regarding harvesting efficiency, however, only the 2016 data showed significant differences between systems and to other years (2017, 2020 to 2022), with SFwP harvesting efficiency of 2016 being the lowest of all years and systems, followed by AF in 2016. In SFnP, the harvesting efficiency was significantly lower in 2016 compared to all other years. From 2017 on, no significant differences between systems could be detected (Table 2).

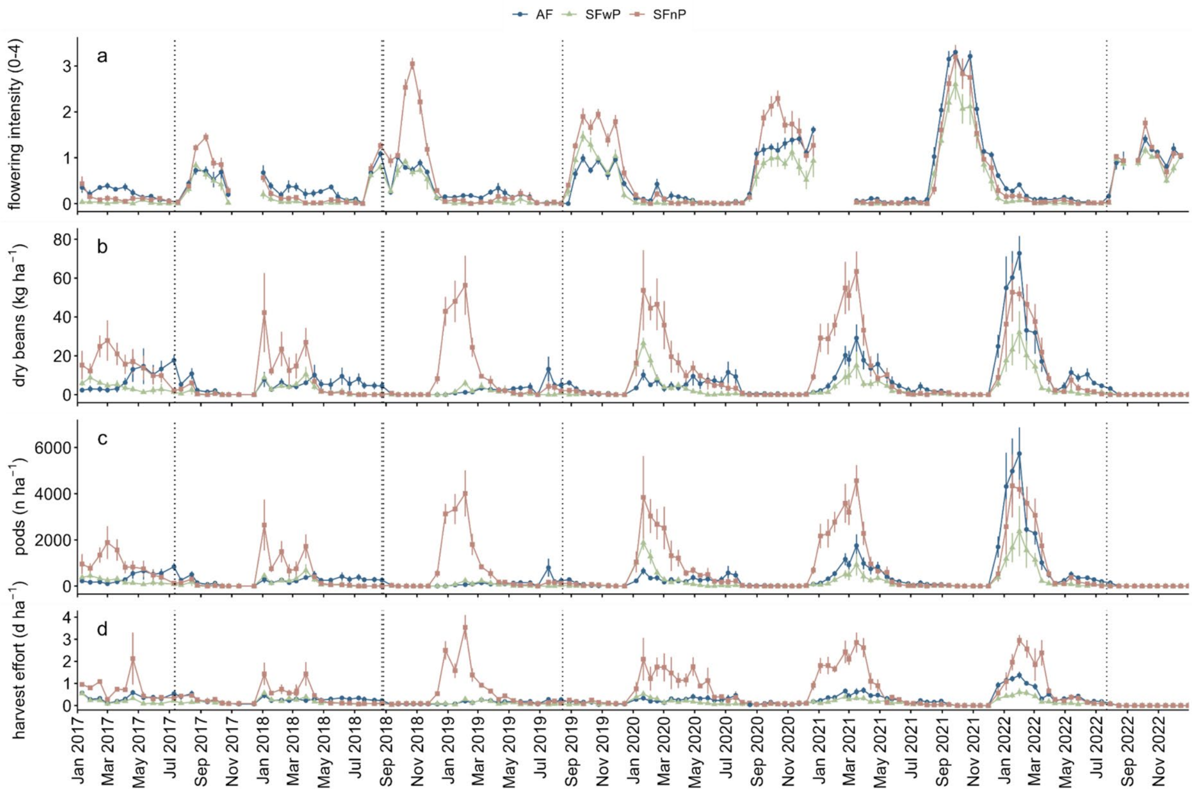

Fig. 1 Temporal evolution of (**a**) flowering intensity, **b** dry bean yield, **c** number of pods harvested, and **d** harvesting effort in three different Cacao Nacional Boliviano systems. *AF*: agroforestry system, where cocoa trees are pruned, *SFwP*: secondary forest with cleared understorey, where cocoa trees were planted and pruned; *SFnP*: secondary forest with cleared understorey, where cocoa trees were planted but not pruned. Dotted vertical lines indicate the pruning events.

Discussion

Our results confirm CNB trees' late initiation of pod production and low yield level compared to introduced international varieties. They also show CNB's distinct seasonality of flowering and fruit setting, underlining its genetic basis (Somarriba and Trujillo 2005; Villegas and Astorga 2005). While this seasonality appeared synchronous for all systems, the annual data analysed (FI, yield, trunk diameter, harvest effort) showed significant differences between systems with pruned and unpruned cacao in different years. The distinct yield dynamics can be discussed under various interrelated aspects, such as the maturity and size or biomass of the trees, light availability, intensity and timing of the pruning treatment, and other factors such as pest and disease pressure, or nutrient input from shade trees.

FI and translation into yield

We found highly significant linear relationships and correlation coefficients between FI and dry bean weight in AF and SFwP, but not in SFnP (Fig. 2). One line of explanation is a potential methodological limitation in the way the phenology survey was carried out in SFnP. The visual inspection and scoring of flowering intensity from ground level is a suitable method for pruned trees with maximum heights of 3–4 m. However, it becomes increasingly difficult to accurately determine flowering intensity in taller trees. On the other hand, there may be other physiological and ecological factors at play, such as higher incidence of cherelle wilt or diseases in the unpruned system, differing distinctly from the pruned systems. Since the pruning of shade trees and cacao trees alter the microclimate, such as through reduction of relative humidity (Niether et al. 2018), it may affect

Table 2 Results from the repeated mixed-model (F-values) and yearly means of the studied variables in three different Cacao Nacional Boliviano systems.

		Flowering index	Number of pods (n ha^{-1})	Bean dry weight (kg ha^{-1})	Trunk diameter at 10 cm (cm)	Harvest effort (day ha^{-1})	Harvesting efficiency (pods day^{-1})
	Year	21.77 ***	31.00 ***	28.69 ***	162.26 ***	43.37 ***	29.02 ***
	System	23.32 ***	61.53 ***	61.38 ***	49.28 ***	190.32 ***	6.10 **
	Year vs. system	3.46 **	5.46 **	4.83 ***	3.39 **	11.65 ***	2.71 **
Year	**System**						
2015	**AF**	na	na	na	3.7 G	na	na
	SFwP	na	na	na	3.7 G	na	na
	SFnP	na	na	na	4.7 FG	na	na
2016	**AF**	na	63 F	1.6 G	5.5 EF	0.19 G	272 C
	SFwP	na	10 F	0.1 G	4.9 FG	0.11 G	57 D
	SFnP	na	208 F	4.8 G	7.2 D	0.33 G	421 BC
2017	**AF**	na	5164 DEF	111.7 DEFG	7.8 D	4.57 DEF	1062 A
	SFwP	na	2688 EF	49.4 FG	6.7 DE	2.32 FG	1106 A
	SFnP	na	10031 DE	181.2 BCDE	9.3 BC	7.03 CDE	1566 A
2018	**AF**	4.12 DEFG	3922 DEF	90.3 DEFG	na	4.73 DEF	770 AB
	SFwP	2.85 G	2354 EF	45.0 G	na	3.62 EFG	650 ABC
	SFnP	6.87 BCD	12104 BCD	197.2 BCD	na	10.20 C	1165 A
2019	**AF**	3.64 FG	2734 EF	60.4 EFG	na	3.46 EFG	741 AB
	SFwP	3.64 FG	1094 F	23.7 G	na	2.31 FG	458 ABC
	SFnP	6.27 BCDEF	11677 CD	170.6 CDEF	na	10.99 C	1058 A
2020	**AF**	5.90 BCDEF	5078 DEF	105.4 DEFG	10.3 B	5.25 DEF	952 A
	SFwP	3.87 EFG	5865 DEF	89.1 DEFG	8.0 CD	3.85 EFG	1494 A
	SFnP	7.26 ABC	19052 ABC	302.8 AB	12.1 A	18.25 AB	1028 A
2021	**AF**	10.04 A	10367 CDE	191.8 BCD	na	7.05 CDE	1463 A
	SFwP	6.66 BCDE	4156 DEF	76.0 DEFG	na	3.34 EFG	1174 A
	SFnP	8.23 AB	23792 A	353.1 A	na	19.06 A	1234 A
2022	**AF**	5.40 BCDEFG	23359 A	332.1 A	na	8.35 CD	2782 A
	SFwP	4.33 DEFG	8615 DEF	122.6 DEFG	na	3.61 EFG	2175 A
	SFnP	5.18 CDEFG	20708 AB	277.0 ABC	na	15.06 B	1424 A

*: $p<0.05$; **: $p<0.01$; ***: $p<0.001$. *AF*: agroforestry system, where cocoa trees are pruned, *SFwP*: secondary forest with cleared understorey, where cocoa trees were planted and pruned, *SFnP*: secondary forest with cleared understorey, where cocoa trees were planted but not pruned. *na* data not available. Letters after the mean show significant differences across years.

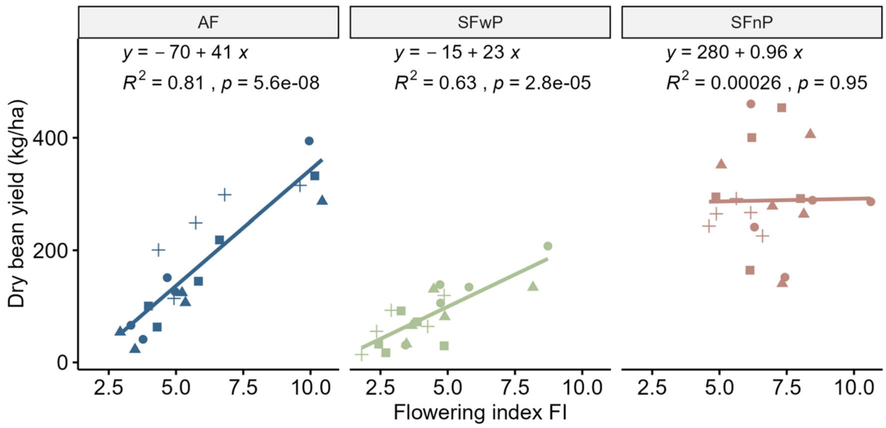

Fig. 2 Linear relationship between flowering index (FI) and dry bean yields in the same cycle for the three different CNB systems. *AF*: agroforestry system, where cocoa trees are pruned; *SFwP*: secondary forest with cleared understorey, where cocoa trees were planted and pruned; *SFnP*: secondary forest with cleared understorey, where cocoa trees were planted but not pruned. Different shapes are used for data points of the different subplots per system.

disease incidence in cacao. This is a topic to be further explored in our CNB trial.

Cacao tree biomass

Pruning not only alters the microclimate under the canopy, but also leaf area and with it the photosynthetic capacity of the tree, as well as tree biomass and the available carbohydrates stored in the hardened wood, essential for pod production (Lass 2001). In our trial, CNB architecture developed distinctly in the pruned and unpruned secondary forest systems, differing in trunk diameters, height and resulting surface area (only trunk diameter measured; see Appendix for visual comparison). Higher cacao tree biomass (+33% in trunk diameter by 2020), associated with a bigger surface available for flower cushions and greater carbohydrate reserves, may explain the consistently better yields in SFnP compared to SFwP. This also applies for SFnP's quicker yield increase in young years, and is supported by Tosto et al. (2022) who found higher yields when small cacao trees were left unpruned.

Light availability

While CNB trees in AF and SFwP initially had the same biomass, AF trees developed faster as seen in the trunk diameter data (Table 2). This is likely related to differences in light availability. At trial establishment, CNB in AF and SF systems likely were not submitted to the same light conditions (data not measured, but see Appendix for visual comparison). SF systems were subjected to shade from a higher canopy from the existing secondary forest. AF were shaded by planted plantain, banana and young AF trees. Nevertheless, cacao production started the same year, with comparable levels between SFwP and AF until 2021. This result supports the idea that in young systems with small trees, pruning was a more important factor affecting (limiting) CNB productivity (Tosto et al. 2022) than the positive effect of light availability (Almeida and Valle 2007).

As the systems were maturing, SF systems' canopy gradually closed, further limiting light penetration. Meanwhile in AF, companion and CNB trees where managed and pruned, maintaining lower overall canopy cover. AF yields surpassing SFnP in 2022 indicate that the difference in light availability might start to play a stronger role in cacao productivity, while illustrating that AF are able to reach equivalent yields as in unpruned systems.

Nutrient input

When talking about light availability, nutrient input must be addressed as well—two factors whose effects on cacao yield are interrelated, as discussed by Wessel (2001): When nutrients are limited, e.g. on poor soils without fertiliser application, best cacao yields are achieved under shade, but when sufficient nutrients are available, cocoa with little to no shade yields higher. Since no fertilizer was applied in our trial, differences in organic matter inputs from within the plots ought to be considered. In the initial years, size and maturity of accompanying trees were an important factor differing between AF and SF systems. While shade trees of an existing secondary forest in SF systems likely will have provided nutrients through leaf litter to the young CNB trees, the nutrient contribution of the smaller, young accompanying trees in AF were supposedly lower. With increasing age of the AF system's trees, this difference in nutrient input may have reduced and contributed to AF's yield increases, although a targeted study is needed to verify this hypothesis.

Pruning intensity and yield

Various studies investigated the effect of different pruning strategies on (non-CNB) cacao yield in mature trees, where moderate pruning treatments led to better yields than strong pruning (Engracia Manobanda 2018; Leiva-Rojas et al. 2019; Meneses-Buitrago et al. 2019). When compared against non-pruned controls, however, Vera Chang et al. (2021) and Engracia Manobanda (2018) found no statistically significant effect on yield. Tosto et al. (2022) relates the pruning effect to tree size, concluding that large trees under high competition profited from pruning (+150%), while small trees under low competition had reduced yields (−58%) when pruned.

The fact that unpruned cacao in SFnP showed earlier yield increase and higher yields, while AF yields started to increase after a period of non-pruning (2020–2021), suggests that cacao pruning may have limited yields. This could be owed to too high intensity of pruning, reducing leaf area and/or carbohydrate reserves under a certain level impeding pod production. In the earlier years, linked to the small tree sizes in a young plantation, this effect might have been aggravated.

In summary, AF's yield recovery in 2022 is thought to be owed to a combination of tree maturation, better light availability, assumed assimilation of nutrient inputs from shade tree litter and reduced pruning. Further studies will be needed to disentangle these effects and isolate the effect of different pruning intensities on mature CNB trees.

Timing of pruning intervention

Another potential factor to consider is timing of pruning adequate to CNB-specific phenology. Pruning in 2018 was done 2 weeks after the start of flowering period, and resulted in reduced yields in 2019. In other years, pruning was done 3 to 6 weeks before the start of the flowering period, allowing trees to optimally invest in vegetative and reproductive growth and resulting in gradually increasing yields. The beginning of flowering season fluctuated between early August and mid-September in different years (Fig. 1, Table 1). Considering our data, we suggest early July as a suitable time for CNB pruning, which is after the harvesting season and few weeks before the beginning of flowering season. Further studies are recommended to confirm the suggested practice.

Harvesting efficiency

While no statistically significant difference in harvesting efficiency was found between systems in 2017 to 2022, it may still be interesting to compare the absolute values from a cocoa producer's perspective. In 2022, the highest yielding year for AF (332.1 ± 22.8 kg ha^{-1}), with comparable yields to SFnP (277.0 ± 6.9 kg ha^{-1}), the mean harvesting efficiency in AF was nearly double of SFnP's (2782 ± 352 vs. 1424 ± 189 pods day^{-1}), also reflected in the significantly higher harvest effort in SFnP (Table 2). In 2020, when AF yields were around one third of SFnP yields, the harvesting efficiency of both systems was very similar (952 ± 35 vs. 1028 ± 95 pods day^{-1}). This suggests that there may be a yield threshold above which the implementation of an AF system may become economically interesting compared to SFnP, mimicking CNB collection from wild or abandoned tree stands. (It is important to note here that the yields of SFnP represent the total yield potential of the system. It is higher than the yield local collectors would get from wild stands, who harvest only pods that are in reach without the use of climbing equipment or ladders.) However, such a hypothesis needs to be tested in further studies with a comprehensive dataset on labour requirement for the management of a CNB AF system and revenues from CNB and other by-crops.

Need for selection for profitable CNB systems

Regardless of the system, CNB yield levels are still low. Further efforts in tree selection are indispensable in order to improve the profitability and to increase attractiveness of CNB cultivation in Bolivia. With increasing international attention on CNB, selection processes of genetic material were initiated in the region (Estivarez Copa and Maldonado Fuentes 2019), and advances in this area are to be expected.

Conclusion

The distinct yield dynamics in the three different CNB systems studied are owed to the interplay of various factors discussed (tree maturation, light and nutrient availability, intensity and timing of pruning intervention, disease pressure), whose effects could not be fully isolated in this study. However, our results suggest that pruning cacao under unmanaged secondary forest canopy does not represent an interesting option for CNB. Yield results of 2022 illustrate that CNB-based agroforestry systems can reach yields equivalent to those of completely unmanaged systems, though needing to be confirmed in the continuation of the trial. Further improvement of CNB-tailored management practices are required, considering the development stage of the tree, especially with regard to pruning timing and intensity. Our harvest effort data suggests there may be a yield threshold above which the implementation of a CNB-based AF could be a profitable alternative to collection from wild populations, encouraging a more in-depth and comprehensive analysis on economic parameters in the future. Long-term studies like the present one are crucial to evaluate economic viability of perennial production systems.

Finally, insights from this study lay the basis for further investigation both at tree-level and plot-level on factors that may play a crucial role in CNB fruit production, including CNB and shade tree management related to light availability, nutrient dynamics, and biomass / architectural factors, as well as on the design of economically viable CNB agroforestry systems.

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Data availability The data that support the findings of this study are available from the authors upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Appendix

See Table 3.

See Fig. 3, 4, 5

Table 3 Yearly means of the studied variables (bold) and standard errors (normal) in three different Cacao Nacional Boliviano systems.

Year	System	Flowering index	Number of pods (n ha^{-1})	Bean dry weight (kg ha^{-1})	Trunk diameter at 10 cm (cm)	Harvest effort (day ha^{-1})	Harvesting efficiency (pods day^{-1})
2015	**AF**	na	na	na	**3.7** 0.5	na	na
	SFwP	na	na	na	**3.7** 0.2	na	na
	SFnP	na	na	na	**4.7** 0.5	na	na
2016	**AF**	na	**63** 29	**1.6** 0.9	**5.5** 0.4	**0.19** 0.05	**272** 117
	SFwP	na	**10** 10	**0.1** 0.1	**4.9** 0.1	**0.11** 0.02	**57** 57
	SFnP	na	**208** 117	**4.8** 3.1	**7.2** 0.4	**0.33** 0.13	**421** 180
2017	**AF**	na	**5164** 1520	**111.7** 36.1	**7.8** 0.4	**4.57** 0.64	**1062** 187
	SFwP	na	**2688** 882	**49.4** 15.7	**6.7** 0.2	**2.32** 0.22	**1106** 281
	SFnP	na	**10031** 543	**181.2** 11.5	**9.3** 0.3	**7.03** 1.11	**1566** 328
2018	**AF**	**4.12** 0.32	**3922** 1144	**90.3** 31.1	na	**4.73** 0.70	**770** 142
	SFwP	**2.85** 0.39	**2354** 671	**45.0** 9.9	na	**3.62** 0.08	**650** 183
	SFnP	**6.88** 0.31	**12104** 2150	**197.2** 33.2	na	**10.20** 0.94	**1165** 130
2019	**AF**	**3.64** 0.32	**2734** 928	**60.4** 19.7	na	**3.46** 0.33	**741** 196
	SFwP	**3.64** 0.40	**1094** 240	**23.7** 4.8	na	**2.31** 0.18	**458** 74
	SFnP	**6.27** 0.27	**11677** 1271	**170.6** 18.9	na	**10.99** 0.74	**1058** 61
2020	**AF**	**5.90** 0.47	**5078** 1279	**105.4** 33.2	**10.3** 0.3	**5.25** 1.21	**952** 35
	SFwP	**3.87** 0.87	**5865** 921	**89.1** 8.4	**8.0** 0.4	**3.85** 0.31	**1494** 139
	SFnP	**7.26** 0.83	**19052** 3072	**302.8** 34.2	**12.1** 0.2	**18.25** 1.67	**1028** 95
2021	**AF**	**10.04** 0.17	**10367** 1770	**191.8** 41.8	na	**7.05** 1.08	**1463** 71
	SFwP	**6.66** 1.04	**4156** 1393	**76.0** 21.8	na	**3.34** 0.61	**1174** 206
	SFnP	**8.23** 0.92	**23792** 3681	**353.1** 45.5	na	**19.06** 1.94	**1234** 82
2022	**AF**	**5.40** 0.26	**23359** 3418	**332.1** 22.8	na	**8.35** 0.30	**2782** 352
	SFwP	**4.33** 0.18	**8615** 3172	**122.6** 36.5	na	**3.61** 0.59	**2175** 490
	SFnP	**5.18** 0.34	**20708** 1309	**277.0** 6.9	na	**15.06** 1.52	**1424** 189

AF = agroforestry system, where cocoa trees are pruned; SFwP = secondary forest with cleared understorey, where cocoa trees were planted and pruned; SFnP = secondary forest with cleared understorey, where cocoa trees were planted but not pruned. na = data not available.

Fig. 3 Agroforestry system with pruning (AF) in 2016 (top) and 2023 (bottom)

Fig. 4 Secondary forest with cleared understorey, where cocoa trees were planted and pruned (SFwP) in 2016 (top), 2020 (middle) and 2023 (bottom)

Fig. 5 Secondary forest with cleared understorey, where cocoa trees were planted but not pruned (SFnP) in 2016 (top), 2020 (middle) and 2023 (bottom)

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