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Rejuvenation of robusta coffee (*Coffea canephora* Pierre ex A. Froehner) plants under matured fruit trees reduces berry yield, increases land productivity and income

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Abstract: Sole coffee system is known to be efficient in utilizing scarce farmlands, while leaving the farmer with no income during the first two years after planting and during regeneration/rejuvenation. Therefore, it is critical to explore intercropping systems utilizing permanent fruit trees to improve the efficiency of land-use and buffer the farmer during vegetative growth phases of the coffee. In this study, Robusta coffee plants under mature sweet orange, avocado and coconut trees as well as coffee plants previously intercropped with pineapple and pawpaw were coppiced and monitored. The physiology, growth, and yield of the coffee plants and the intercrops, as well as the cost of management were evaluated. The results showed that the presence of fruit trees had adverse effects on coffee stem diameter, height, and lateral retention but not on its leaf chlorophyll content. Higher chlorophyll fluorescence was observed in coffee under avocado and coconut trees. Stomatal conductance of the coffee plants was moderated, especially by the presence of avocado trees, during adverse and optimal weather conditions. The fruit trees and the previous intercropping with pineapple and papaya led to significant reductions in clean coffee yield, ranging from 11 kg ha^{-1} (coffee+papaya) to 1,076 kg ha^{-1} (coffee+citrus) due to competition from citrus trees. However, the coffee+avocado and coffee+citrus systems increased the overall farm productivity ha^{-1}, leading to higher positive gross and net incomes. The cumulative net income from the coffee+avocado (US$8,432.07) and coffee+citrus (US$5,667.71) systems was higher than the income from the sole coffee system (US$5,426.28). The results, therefore, indicated that the coffee+avocado system was the most beneficial as it achieved higher productivity per unit land area with a higher cumulative net income increase of US$3,005.79 relative to the sole coffee system.

Keywords: Cropping systems; sustainability; agroforestry; livelihood; intercropping; resilience

Introduction

Coffee cultivation in Ghana and other West African countries is often done with limited or no overhead shade. This practice goes against one of the fundamental principles of traditional organic coffee growing systems (Beer et al., 1998). In situations where limited shade is provided, farmers tend to use crop species other than high-value crops. In other instances, farmers' choice of intercrops is mainly annuals or biennials that fade out by the third or fourth year after transplanting the coffee. The implications of this coffee farming system for farmer resources are profound. For instance, rapid weed regrowth associated with tropical agriculture demands up to 6 or more weed control operations within a single season (Opoku-Ameyaw et al., 2003; Van Asten et al., 2011). On the other hand, a failure in rainfall and other extreme environmental conditions can reduce yields, affecting the living standard of coffee growers. To mitigate fluctuations in farm income and enhance sustainability, it is essential to introduce high-value, long-term companion crops, primarily fruit trees, which can serve as a source of additional income for farmers. This approach can increase farm productivity and stabilize farmers' income during periods of low or poor yields of coffee crops (Muschler, 2001) while improving climate resilience.
The introduction of fruit trees into coffee plantations at the early growth stages provides shade effects, which have been demonstrated to protect coffee plants against environmental stresses such as excessive sunlight, high soil temperatures, and low relative humidity (Souza et al., 2024). Again, some of these fruit trees have been shown to create conducive

conditions for the survival and establishment of natural enemies for the management of pests and create hostile conditions for disease pathogens when used as intercrops (Beer et al., 1998; Adugna and Struik, 2011). Overhead shade also triggers changes in coffee's biochemical and physiological potentials, such as an improved rate of photosynthesis and the prevention of berry pre-maturation, which leads to better bean filling and larger bean size with higher volatile compounds relative to sun-grown coffee (Muschler, 2001; Bote and Struik, 2011). In addition, shade has also been reported to increase coffee yields in the long term (DaMatta, 2004), fitting the system into sustainable production modules. The incorporation of fruit trees into coffee brings in additional income from the fruits and the fuelwood when the prunings are sold (Adugna and Struik, 2011).

Organic and shade coffee production systems have recently gained global momentum (Van der Vossen, 2005). For the coffee farmer, the need to increase productivity and income per unit of land area, and to stabilise farm income during periods of coffee rejuvenation is of paramount. The provision of overhead shade through the introduction of shade trees reduces and stabilizes the soil temperature by reducing the radiant flux reaching the soil and modifying the temperature amplitude at the soil surface (Siebert, 2002; Campanha et al., 2005; Morais et al., 2006; Adugna and Struik, 2011, de Souza et al., 2012). Coffee plants grown in direct sunlight with higher air temperatures above 25 °C often suffer a significant reduction in the rate of CO_2 assimilation (Sethar et al., 2002; Adugna and Struik, 2011). Adugna and Struick (2011) reported a non-significant reduction in the yield of shade-grown coffee compared to coffee grown in the full sun. Contrary to their reports, yield reductions ranging from 18% to 36% (Costa Rica), 28% (Central America), and 50% (Brazil) have been reported (Campanha et al., 2005; Siles et al., 2009; and Haggar et al., 2011). However, a small reduction in yield that supports long-term plant health and yield is more sustainable for the farmer and the environment.

At the end of growth (9 years) or yield (7 years) cycle of Robusta coffee, the plants are often cut 30 cm to 45 cm above ground level at an angle of 45 degrees. This process, which is known as rejuvenation, allows new, stronger, and more productive plants to grow. This is well understood and practiced in sole and lightly shaded coffee systems. This study addresses the currently unknown effects of fruit trees, introduced as intercrops at planting, on coffee growth during the rejuvenation period. It is therefore important to understand the effects of this shade on coffee yield and how fruit trees can be used to compensate for these yield reductions, improve sustainability, and support biodiversity and environmental protection. However, this, requires research on the effects of fruit trees on the growth, yield and quality of the coffee beans. More importantly, the research should address the sustainability and income stability of such systems. In this trial, we evaluated the growth, physiology and yield performance of rejuvenated Robusta coffee under citrus, avocado, and coconut trees, and addressed the sustainability and income stability of Robusta coffee-fruit tree intercropping systems.

Results

Baseline soil characteristics of the study site

The results of soil chemical characterization generally showed that the surface soil layer (0 cm to 15 cm) had higher values than the subsurface soil layer (15 cm to 30 cm). The average soil pH in the surface layer was 5.5, while that of the subsurface layer was 4.9 (Table 1). Soil organic carbon (SOC) content in the surface layer (1.29%) was higher than in the subsurface layer (0.62%). The highest available phosphorus (AP) content was found in the surface layer. The surface layer contained higher exchangeable K, Ca, and Mg (Table 1) than the subsurface layer.

Table 1. Baseline soil chemical properties of the study site.

Soil depth (cm)	pH	OC	TN	AP	K	Ca	Mg
		(%)		(mg kg^{-1})	(cmol$_c$ kg^{-1} soil)		
0 – 15	5.5	1.29	0.15	10.4	0.09	1.31	0.92
15 – 30	4.9	0.62	0.10	3.16	0.07	1.15	0.45
†Critical minimum	*5.5*	*1*	*0.002*	*60*	*0.75*	*1.60*	*3.00*

†Critical minimum = minimum soil nutrient required for coffee cultivation (Winston et al., 2005). OC-organic matter, TN-Total nitrogen, K-potassium, Ca-Calcium, Mg-Magnesium

Rainfall and temperature

Total annual rainfall ranged from 1,416.2 mm in 2022 to 1,665.7 mm in 2023. Generally, the trial site experienced precipitation in most of the months from January 2020 to December 2023 (Fig. 1A). The bimodal rainfall in each year peaked in May-June (major season) and October (minor season). The periods during which no monthly precipitation was received were August 2020, and December 2021 and December 2022. The lowest and highest monthly rainfall values were 2.7 mm in January 2020 and 370 mm in June 2022 (Fig. 1A). The average maximum temperature ranged from 26.2 °C in August 2022 to 47.2 °C in February 2022 (Fig. 1B).

Relative chlorophyll content and stomatal conductance of coffee plants

Cropping systems significantly ($p < 0.05$) affected Fv/Fm and stomatal conductance of coffee plants during 2022/2023 season (Fig. 2). Generally, the chlorophyll content for the cropping systems in the 2022/2023 season was higher than that of the 2023/2024 season (Fig. 2). Robusta coffee plants in the coffee+avocado system had high chlorophyll content during 2022/2023 growing season (Fig. 2a). The influence of the avocado and coconut trees on the Fv/Fm of the robusta coffee in the 2022/2023 season was statistically similar ($p > 0.05$), and significantly higher ($p < 0.05$) than those of the other cropping systems (Fig. 2b).

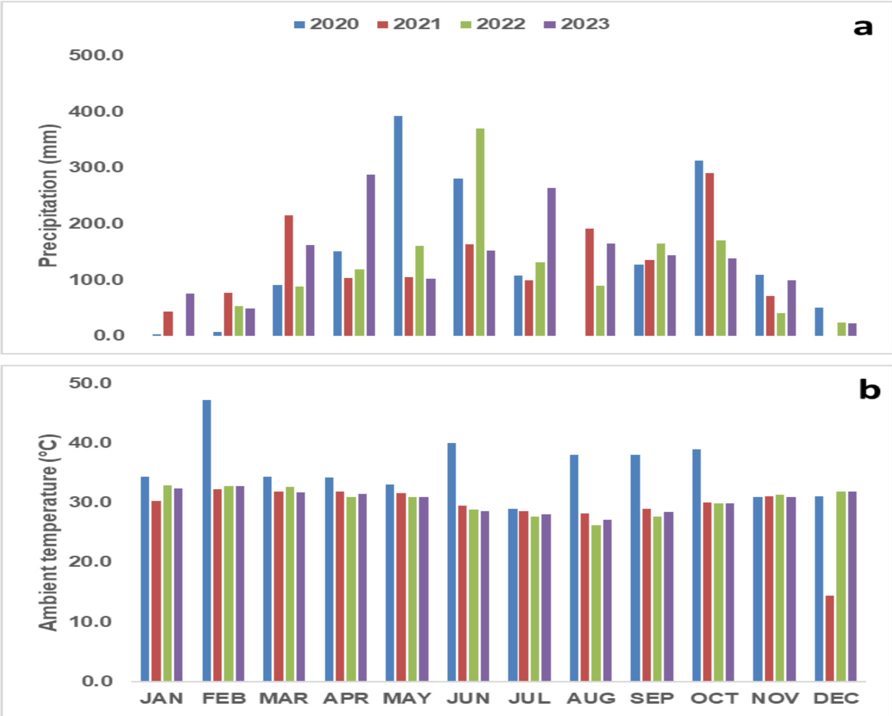

Fig. 1. Total monthly precipitation (a) and average monthly maximum temperatures (b) at the CRIG Bunso substation from January 2020 to December 2023.

In the 2023/2024 season, differences in Fv/Fm among the cropping seasons were not significant ($p > 0.05$). The effect of the citrus trees and sole cropping of coffee led to high Fv/Fm during 2023/2024 season compared to 2022/2023 season (Fig. 2b). Stomatal conductance was highest in the sole coffee system and least in the coffee+avocado system in the 2022/2023 season (Fig.2c). The differences in stomatal conductance between the sole coffee and the other cropping systems were significant ($p > 0.05$). In the 2023/2024 season, stomatal conductance was highest in the coffee+avocado system, and this was significantly different ($p < 0.05$) from that of the remaining cropping systems (Fig. 2c).

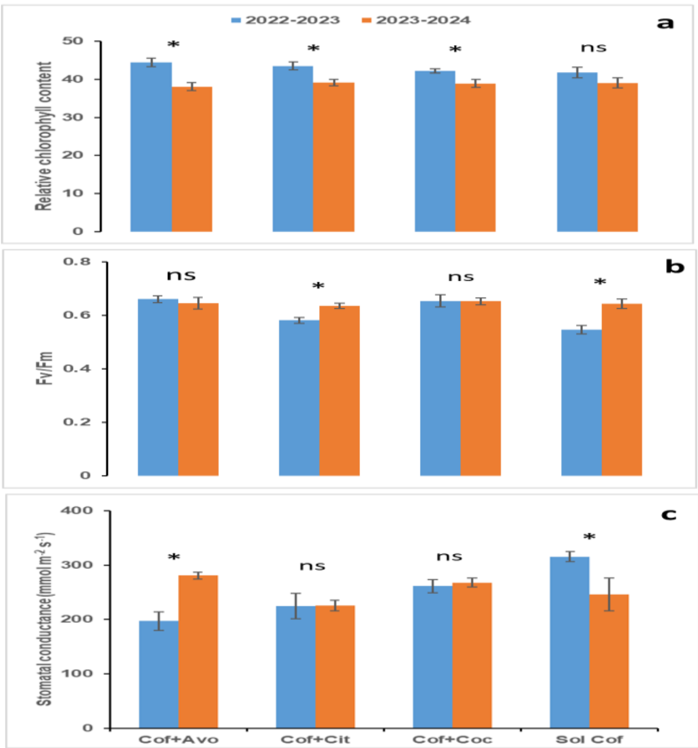

Fig. 2. The relative chlorophyll content (a), Fv/Fm (b) and stomatal conductance (c) of robusta coffee as affected by the cropping systems. Values are means of four replicates with standard error bars. Bars with asterisks indicate significate ($p \leq 0.05$; student t-test) between years. Cof+Avo - Coffee+Avocado, Cof+Cit - Coffee+Citrus, Cof+Coc - Coffee+Coconut, Sol Coff - Sole Coffee.

Growth of coffee plants
The stem diameter growth of rejuvenated Robusta coffee plants remained unaffected by the treatments from the 2020/2021 to the 2023/2024 cropping seasons (Table 2). Similarly, plant height measurements did not reveal significant ($p > 0.05$) differences among the treatments in the 2020/2021 and 2021/2022 cropping seasons (Table 2). The number of coffee laterals plant^{-1} differed among the cropping systems and ranged from 27 to 34 (2020/2021), 36 to 43 (2021/2022), and 31 to 48 (2022/2023) (Table 3). In all three cropping seasons, the number of coffee laterals plant^{-1} in the coffee+citrus system was significantly ($p < 0.05$) reduced compared to the sole coffee system (Table 3). In the fourth season (2023/2024), the number of coffee laterals plant^{-1} did not differ significantly ($p > 0.05$) among the cropping systems.

Table 2. Stem diameter and height measurements of rejuvenated robusta coffee plants as affected by cropping systems. Values are means of four replicates with ± standard errors. The means were separated using Fisher LSD method at 0.05 between treatments. Means with different letters are significant.

	Stem diameter (mm)			Height (cm)	
Cropping system	2020/2021	2021/2022	2022/2023	2020/2021	2021/2022
Sole coffee	17.53±0.29a	33.05±1.07a	43.18±0.89a	96.30±5.48ab	161.3±10.35ab
Coffee+papaya*	16.38±0.46a	30.48±2.43a	41.85±1.23a	78.03±4.94b	143.00±10.70b
Coffee+coconut	16.53±0.62a	30.93±0.96a	38.70±1.27ab	100.80±8.23ab	165.80±8.46ab
Coffee+citrus	16.43±1.28a	29.55±2.94a	33.43±2.26b	96.00±13.40ab	161.00±7.42ab
Coffee+avocado	16.60±0.56a	30.73±0.50a	37.93±0.87ab	110.6±11.20a	175.63±5.04a
Coffee+pineapple*	17.98±0.53a	32.25±1.08a	38.30±4.36ab	89.20±11.80ab	154.15±6.26ab
Mean	16.74	31.16	38.90	95.16	160.15

*The coffee+papaya and coffee+pineapple system had no pineapple and papaya plants in the plots as intercropping had stopped due to rapid regrowth and closing of coffee canopies after coppicing. For each year, data on the growth (stem diameter and height) of the coffee plants were collected in March.

Table 3. The number of laterals plant^{-1} of rejuvenated robusta coffee at different stages of growth as affected by cropping systems. Values are means of four replicates with ± standard errors. The means were separated using Fisher LSD method at 0.05 between treatments. Means with different letters are significant.

	Number of laterals per plant			
Cropping system	2020/2021	2021/2022	2022/2023	2023/2024
Sole coffee	34.25±1.65a	43.25±1.70a	48.25±3.35a	26.30±4.14a
Coffee+papaya*	31.50±3.28ab	40.50±2.90ab	42.00±1.73ab	26.88±1.68a
Coffee+coconut	29.75±1.55ab	38.75±1.11ab	36.50±5.61bc	24.00±2.73a
Coffee+citrus	27.25±2.18b	36.25±2.56b	30.50±3.84c	21.55±1.13a
Coffee+avocado	29.00±0.58ab	38.00±0.82ab	33.50±2.10bc	22.65±0.90a
Coffee+pineapple*	34.00±1.78a	43.00±1.78a	47.25±2.56a	26.23±5.94a
Mean	30.96	39.96	39.67	24.60

*The coffee+papaya and coffee+pineapple systems were in the residual phase since the two intercrops were not reintroduced into the coffee plots after coppicing. For each year, the data on the number of laterals plant^{-1} was collected in March.

Yield of coffee and fruit trees
The first yield obtained from the rejuvenated robusta coffee in the second year after coppicing ranged from 60 kg ha^{-1} in coffee+citrus to 172 kg ha^{-1} in sole coffee systems (Table 4). Clean coffee beans produced by the plants in the sole coffee, coffee+papaya, and coffee+pineapple systems were statistically similar. Coffee bean yields from coffee plants in coffee+coconut, coffee+citrus, and coffee+avocado systems were significantly lower ($p < 0.05$) than the harvest from the sole coffee and coffee+pineapple systems. Similar patterns in coffee bean yields were observed in the 2022/2023 and 2023/2024 cropping seasons (Table 5). Cumulatively, coffee bean yield ranged from 1,134 kg ha^{-1} in the coffee+citrus system to 2,210 kg ha^{-1} in the sole coffee system, with significant ($p < 0.05$) differences between the treatments (Table 4). Cumulative coffee bean yield was also significantly ($p < 0.05$) reduced by the coffee+avocado and coffee+coconut systems. Generally, all the treatments reduced the bean yield of rejuvenated robusta coffee in each of the three years, and cumulatively. Even though the intercrops in the residual coffee+papaya and coffee+pineapple systems were not introduced during the rejuvenation phase, bean yield from these systems was lower than that of the sole coffee system, though the reductions were not significant. All the fruit trees produced yields across the four cropping seasons (SD Table 1) proving their potential to stabilise farmer income, especially during rejuvenations periods.

Shelling outturn and seed characteristics
There were no significant ($p < 0.05$) treatment effects on the shelling outturn, mean (100) seed weight (MSW), seed dimensions (diameter length) of coffee bean harvests from rejuvenated Robusta coffee plants monitored over the three cropping seasons (Table 5).

Table 4. Bean yield of rejuvenated robusta coffee under different cropping systems from 2021/2022 to 2023/2024. Values are means of four replicates with ± standard errors. The means were separated using Fisher LSD method at 0.05 between treatments. Means with different letters are significant.

Cropping system	Robusta coffee bean yield (kg ha^{-1})				
	2021/2022	2022/2023	2023/2024	3-year cumulative	Relative yield difference
Sole coffee	172.30±26.60a	1244.00±233.50ab	793.60±95.90a	2210.00±334.00a	-
Coffee+papaya*	147.10±43.10ab	1306±179.00a	746.40±94.45ab	2199.00±179.500a	(11)
Coffee+coconut	78.90±18.20bc	839.00±155.00ab	692.20±92.4ab	1610.00±242.50ab	(600)
Coffee+citrus	60.20±16.15c	556.00±113.00b	518.30±37.40b	1135.00±143.00b	(1,076)
Coffee+avocado	78.10±10.70bc	702.60±66.90ab	564.80±24.10ab	1345.50±55.95ab	(864)
Coffee+pineapple*	160.40±26.70a	990.00±177.50ab	771.00±104.50a	1921.00±263.50ab	(289)
Mean	116.17	939.60	681.05	1736.75	

*The coffee+papaya and coffee+pineapple systems were in the residual phase since the two intercrops were not reintroduced into the coffee plots after coppicing. Harvest of coffee berries started in December and ended in mid-February of the following year. The yield difference describes the difference in yield between each treatment and the sole coffee system.

Table 5. Shelling outturn, mean (100) seed weight (MSW), seed diameter, and seed length of rejuvenated robusta coffee as affected by cropping systems in the 2022/2023 and 2023/2024 seasons. Values are means of four replicates with ± standard errors. The means were separated using Fisher LSD method at 0.05 between treatments. Means with different letters are significant.

Cropping system	Outturn (%)	MSW (g)		Seed diameter (mm)		Seed length (mm)	
	2023/2024	2022/2023	2023/2024	2022/2023	2023/2024	2023/2024	2023/2024
Sole coffee	48.74±2.90a	16.00±0.26a	14.58±0.30a	5.52±0.80a	6.13±0.06a	8.37±0.08a	7.55±0.17ab
Coffee+papaya*	50.60±10.45a	15.60±0.30a	14.98±0.88a	6.38±0.09a	6.33±0.24a	7.94±0.21a	7.57±0.28ab
Coffee+coconut	59.09±5.19a	15.60±0.27a	14.43±0.57a	6.25±0.20a	6.00±0.31a	7.98±0.24a	7.47±0.11b
Coffee+citrus	58.01±2.51a	15.33±0.47a	14.80±0.82a	6.20±0.20a	6.27±0.24a	7.97±0.39a	7.71±0.13ab
Coffee+avocado	54.21±1.79a	15.60±0.39a	15.35±0.99a	6.24±0.09a	6.25±0.13a	8.45±0.06a	7.67±0.24ab
Coffee+pineapple*	47.81±2.22a	15.23±0.43a	15.43±0.33a	6.30±0.16a	6.38±020a	8.29±0.18a	8.06±0.04a
Mean	53.08	15.56	14.93	6.15	6.23	8.17	7.67

*The coffee+papaya and coffee+pineapple systems were in the residual phase since the two intercrops were not reintroduced into the coffee plots after coppicing. The outturn and seed characteristics were obtained from the core plot harvest. MSW_mean seed weight

Gross income from coffee beans and intercrops

The sole coffee systems did not generate any income one year after coppicing. Seasonal gross income from the sale of coffee beans two years after coppicing onwards was highest in the sole coffee and least in the coffee+citrus systems (SD Table 2). Contrary to the sole coffee systems, cropping systems with fruit tree intercrops generated income in the 2020/2021 cropping season when the rejuvenated coffee plants were too young to produce berries. Seasonal gross income from the sale of avocado fruits was consistently highest, followed by the sale of citrus and coconut fruits throughout the four years (SD Table 2). Gross income from treatments in the 2020/2021 cropping season was low because only the sales of intercrop produce contributed to it, with the highest gross income obtained from the sale of avocado fruits (SD Table 3). From the 2021/2022 season onwards, coffee bean sales contributed to the total gross income of all treatments. However, gross income from the coffee+avocado system remained highest throughout, except in the 2022/2023 season when the coffee+citrus system returned the highest gross income. The total variable cost of production was generally highest in the coffee+citrus system due to the labour cost required for the maintenance of citrus trees (SD Table 3). The variable cost associated with the maintenance of the coffee+avocado system was the highest in the 2023/2024 cropping season.

Net income from treatments

In the first season (2020/2021), after copying the robusta coffee plants, positive net income was generated only from the coffee+avocado and coffee+citrus systems (SD Table 4). Although the coffee+coconut systems generated income, this was less than the seasonal variable cost associated with the maintenance of the system. In the second season (2021/2022), only the coffee+avocado system generated positive net income. This system was consistent throughout the following seasons. In the third season (2022/2023), only the coffee+citrus system failed to generate a net positive income. However, in the fourth season (2023/2024), all the systems generated positive net incomes. Cumulative net income from the coffee+avocado (US$8,432.07) and coffee+citrus (US$5,667.71) systems was higher than that of the sole coffee system (US$5,426.28), while net income from the rest of the systems was lower. Relative to the sole coffee system, therefore, the coffee+avocado and coffee+citrus systems increased cumulative net income by US$3,005.79 and US$241.43, respectively, over the control. The remaining systems had a relatively reduced cumulative net income between US$58.20 in the coffee+coconut and US$168.76 in the coffee+pineapple systems (SD Table 4).

Discussion

Implications of the baseline soil characteristics

Good soil chemical properties are very important to the growth and yield of robusta coffee as they significantly influence cation balance, nutrient availability, root development, nutrient uptake and the overall plant health, which directly affect productivity (DaMatta et al., 2007; Van Asten et al., 2011; Wairigi et al., 2010). The pH levels in the lower and upper soil depths in this study were considered to be an indication of strong and moderate. acidity, respectively. While the upper soil layer showed acidity levels similar to the minimum acceptable for coffee production, the lower layer was below this threshold, indicating acidity levels that may be detrimental to coffee plants. Several studies indicate that pH below 5.0 promotes solubility of manganese (Mn) and Aluminium (Al), to toxic levels which may then inhibit root development, water and nutrient uptake and eventually lead to stunting (Jemo et al., 2014; van der Vossen et al., 2015). At the same time, Essential nutrients such as phosphorus (P), calcium (Ca), and magnesium (Mg) may become less available under low pH conditions, leading to deficiencies that directly reduce plant vigor and bean development (Wintgens, 2009; van der Vossen, 2005). Low soil pH is also reported to suppress beneficial microbial populations responsible for organic matter decomposition and nutrient cycling, indirectly affecting coffee nutrition and soil fertility (Avelino et al., 2015). In this study, the upper layer, which is the predominant rooting zone of coffee plants, had a pH comparable to the critical minimum, indicating that such adverse effects associated with low soil pH were not experienced.

The lower level of SOC within the surface layer indicated a high activity by soil fauna in the surface layer, which resulted in high SOC incorporation compared to the subsurface depth. This incorporation has been shown to release nutrients, improve cation exchange capacity, reduce Al toxicity and stimulate the activity of soil microorganisms (Wintgens, 2009; Lal, 2005; Brady and Weil, 2016). The surface depth had SOC above the critical minimum, which is reportedly adequate for coffee production (Winston et al., 2005). Similarly, the total soil nitrogen (TN) content for the surface depth was higher than that of the subsurface depth and above the critical minimum (Winston et al., 2005), indicating that the soil had adequate inherent N to support the growth and development of the coffee plants. The high N content in the surface depth was due to the mineralization of surface litter or organic matter, which was high in the surface depth, as shown by the high SOC compared to the subsurface depth. Soil available phosphorus (AP) contents for the surface and subsurface depths were below the essential minimum of 60 mg kg^{-1} (Winston et al., 2005). The low soil exchangeable cations are due to the highly mobile nature of these cations that are usually leached beyond the active root zone of 30 cm in the study area, which has high annual rainfall.

Implications of rainfall and temperature

Adequate rainfall is crucial for the growth and yield of Robusta coffee due to its direct influence on various physiological processes and developmental stages of the plant. It is widely reported that sufficient rainfall amounts are required for nutrient uptake, continuous vegetative growth, flower initiation and fruit set, reduction in flower and fruit abortion and good berry development and bean size (DaMatta et al., 2007; Wintgens, 2009; Davis et al., 2012; Kath et al., 2020a). The annual rainfall values for all the seasons under this study were within the 1,200 to 1,800 mm range considered suitable for producing Robusta coffee (Tadesse and Tadesse, 2021). Therefore, rainfall was not a limiting factor to the growth and productivity of the robusta coffee plants. Monthly rainfall, however, exhibited wide fluctuations. Despite these wide fluctuations in rainfall across the months and years, the average maximum temperatures were stable, except in some of the months of 2020, when average maximum temperatures exceeded 35 °C (Fig. 1b).

Like rainfall, minimum and maximum atmospheric temperatures can have significant effects on the productivity of coffee plants. High temperatures above 30-33°C have been shown to cause heat stress and reduce photosynthesis, which increases vulnerability to pests and diseases, while temperatures below 15°C tend to limit metabolic functions. On the other hand, a suitable temperature range supports good vegetative growth, flower set, fruit development and bean quality (DaMatta et al., 2007; Bunn et al., 2015; Kath et al., 2020b). The extremely high average maximum temperature recorded in February 2022 probably resulted from low precipitation in the preceding two months. This average monthly maximum temperature was mostly above the upper limit of 24.1 °C (Kath et al., 2020b) or even 30 °C (Patil et al., 2022), considered suitable for coffee production elsewhere.

Effect of the cropping systems on physiological attributes of coffee plants

Chlorophyll content is crucial for the growth and yield of Robusta coffee because it directly influences photosynthetic capacity, biomass accumulation, and ultimately bean yield. Higher chlorophyll levels typically indicate better plant health and nutrient status, especially nitrogen, and lead to more efficient light energy conversion and resilience to abiotic stresses (DaMatta et al., 2007; Martins et al., 2014). There have been reports of strong positive correlations between SPAD readings and bean yield (Jemal and Amare, 2022), showing its importance as a reliable proxy indicator of coffee yield. The increase in leaf relative chlorophyll content in the 2022/2023 cropping season was likely due to overhead shade, which mitigated the adverse effects of unfavourable weather conditions. A similar result was reported by Aidoo et al. (2024) in the leaves of shaded cocoa plants that were exposed to natural drought conditions in the field. This behaviour was attributed to a mechanism for coping with stress. When plants are exposed to environmental stress conditions, the degradation of leaf chlorophyll accounts for the slow growth of sole or non-shaded coffee plants in this study. Reduced leaf chlorophyll content in coffee leaves negatively affected photosynthesis and hence the buildup and allocation of biomass, similar to the findings of Hailemichael et al. (2016).

Stomatal conductance is critical in coffee production because of its regulatory effects on gas exchange, particularly CO_2 uptake for photosynthesis and water vapour loss through transpiration (Martins et al., 2014). The balance of these processes directly affects the plant's growth, productivity, and response to environmental stress, especially under tropical conditions (DaMatta et al., 2007; Romalho et al., 2018). The differences in the stomatal conductance and Fv/Fm among treatments and across seasons might be because of the alteration of environmental conditions, to which the plants were exposed in the field. These conditions may have been influenced by the shade trees, as observed in the coffee plants under avocado trees, indicating that the regulation of cellular moisture losses, particularly during the 2022/2023 season, when weather conditions were unfavourable (Martins et al., 2014). Exposure of coffee plants to direct sunlight has been reported to decrease stomatal conductance due to an increase in air temperature, which limits the rate of CO_2 exchange (Ayalew, 2018).

Chlorophyll fluorescence provides insight into how effectively a plant is converting light energy into chemical energy, and it is especially useful for detecting early signs of stress (e.g., drought, heat, nutrient deficiency) before visible symptoms appear. If properly estimated, chlorophyll fluorescence can be used as an indicator of photosystem II efficiency (Martins et al., 2014), early detection of environmental stress (Romalho et al., 2018) and monitoring recovery after stress (Netto et al., 2005). In plant breeding studies, chlorophyll fluorescence is very often utilised to identify stress-tolerant genotypes (Rodrigues et al., 2016).

The chlorophyll fluorescence (Fv/Fm) under all treatments was high, particularly in coffee plants grown under the avocado and citrus trees. This indicates that under full sunlight, robusta coffee plants are photo-inhibited, which can reduce the efficiency of photosystem II (Scotti-Campos et al., 2019). This might also have contributed to the slow growth of the coffee plants under full sunlight in this study.

Effect of the cropping systems on the growth of coffee plants

Regardless of the environment, healthy growth of coffee plants is essential for achieving optimal yields, sustaining bean quality, and ensuring long-term farm productivity (Gichuru et al., 2023; Muschler, 2024). The increase in stem diameter and height of robusta coffee plants was similar, irrespective of the species of fruit tree or their presence. This indicates that the shade cast by the fruit trees over the coffee plants does not have a significant adverse effect on their growth during rejuvenation. Overhead shade in other studies was reported to improve robusta coffee growth, although this effect depended on the age of the coffee plants, with effects on younger trees insignificant (Piato et al., 2020; Ehrenbergerová et al., 2021). The lack of difference among the treatments for the growth of robusta coffee in this study can, therefore, be attributed to the relatively young rejuvenants, less dense shade or both. Unlike stem diameter and height increase, lateral development was adversely affected by fruit trees during the first three years of rejuvenation. Early growth in coffee is characterised by rapid increases in vegetative parts. This often requires higher rates of photosynthesis, which is fueled by higher interception of photosynthetically active radiation. The lower lateral production in coffee plants in the coffee+citrus system was probably due to insufficient light penetration through the dense citrus canopy, which affected the overall dry matter production by the coffee plants and their assimilation for lateral development. The general decrease in lateral numbers in the fourth year after coppicing of the coffee plants was probably due to nutrient deficiency (Evizal and Prasmatiwi, 2022), senescence, previous heavy fruiting (DaMatta et al., 2007), or management practices, since treatment effects were not observed. This behaviour of lateral shedding as it advances in age is widely reported in coffee plants (DaMatta et al., 2007).

Effect of the cropping systems on the yield of coffee plants

The most economic product from a coffee farm is the clean beans. High bean yield allows for the maximisation of farm profitability, ensuring supply chain sustainability, and meeting global market demand in the face of climate and economic challenges (do Rosario et al., 2023). Generally, the presence of fruit trees in the rejuvenated robusta coffee plots had real effects on berry yield. This was probably due to competition for light since the taller trees likely intercepted most of the incident radiation. Findings from earlier studies involving different tree species in robusta coffee plantations support this observation (Charbonnier et al., 2013). The yield differences observed persisted over 3 years, affecting the long-term productivity of the robusta coffee plants. Though this finding contradicted the report by Piato et al. (2020) when they assessed how shade levels improved young robusta coffee growth and productivity, it affirms the report by Khusnul et al. (2021), indicating that coffee farming systems that introduced shade trees caused a decline in coffee productivity. This contradiction and corroboration of our findings with some earlier studies suggests that the type of fruit tree and its orientation in the intercropping system play a significant role in their overall effect on coffee production.

Although the presence of the fruit trees affected overall berry production, coffee bean characteristics such as shelling outturn, mean 100-seed weight and seed dimensions were largely unaffected. Reports by Bote and Struik (2011) that intercropping robusta coffee with fruit trees resulted in larger and heavier fruits compared to sole coffee could not be supported by this study, which reported similar bean size and weight over three cropping seasons. This may be due to a strong genetic control of coffee bean characteristics with minimal environmental influence (Leroy et al., 2006) since the coffee plants in the study were clones from the same genetic background. The relative reductions in bean yield in the coffee+pineapple and coffee+pawpaw systems, which were now sole coffee plants, indicate possible residual adverse effects of these intercrops on the long-term productivity of robusta coffee. These adverse residual effects were probably due to high nutrient uptake by the pawpaw and pineapple plants when they were grown as intercrops in the coffee plots.

Effects of the cropping systems on farm income

Intercropping in coffee farms enhances income stability and overall profitability by diversifying production, improving efficiency of resource use, and reducing economic risks (Worku et al., 2023; Rahn et al., 2024). Returns on treatments from the sale of coffee beans were improved by the sole and residual coffee systems due to their higher berry yield. However, during the first year after coppicing of the coffee plants, berry harvests were not obtained from the sole coffee system. Sales from the fruit tree harvests in the intercropped systems provided income, indicating that these systems were more suitable for small to medium-scale coffee farmers, as they ensured increased income as well as income stability during periods when coffee is coppiced for rejuvenation. The returns from the sale of produce from the fruit trees and coffee beans led to intercropped systems generating higher gross incomes with a corresponding increase in the cost of farm maintenance. Despite the increases in farm maintenance costs associated with the intercropped systems, gross returns more than compensated for the expenditure, leading to higher net incomes compared to the sole coffee system. These net incomes were positive in the coffee-fruit tree systems, although it was cumulatively lower in the coffee-coconut systems than in the sole coffee system. The higher revenue from the coffee-fruit tree systems relative to the sole coffee system in this study corroborates findings in a coffee-banana system (van Asten et al., 2011) and coffee-food crops systems (Opoku-Ameyaw et al., 2003). Net income from the coffee+papaya and coffee+pineapple systems, which were in a residual phase, was also relatively lower than the sole coffee system, showing that these intercrops have residual adverse effects on the long-term income of the coffee farmer. The integration of tree crops such as avocado, citrus and coconut, with long life cycles, into coffee farming systems is more profitable and sustainable with time compared to short-cycle fruit crops like papaya and pineapple. Similar observations were made by Moreira et al. (2024). The coffee+avocado and coffee+citrus systems improved the productivity of the farms compared to the sole coffee system, in addition to serving as the only source of income for the farmer during the robusta coffee rejuvenation phase.

Materials and methods

Experimental site

The experiment was conducted at the Bunso Sub-station (Latitude 6° 17' 30" N; Longitude -0° 28' 05" W; at 211.2 m ASL) of the Cocoa Research Institute of Ghana (CRIG). Bunso is located within the warm, humid tropics with temperatures ranging between 23.3 to 33.4 °C. The site experiences bimodal rainfall with total annual precipitation of 1500 - 2000 mm, with the major peak rainfall in May-June and the minor peak in September-October. Precipitation occurs over 85-130 days, with June, July and September being the wettest months, while December and January are the driest. Humidity ranges from 63% in January to 95% in September, with consistently elevated values of 76 - 87% most of the year. Daylight hours are longest in April (12 hours, 16 minutes) with 10.7 hours of sunshine day^{-1}. Data on rainfall and temperature for the site were obtained from the meteorological station of the Bunso CRIG substation.

Experimental design and treatments

The experiment was carried out on an existing mix-clone coffee farm that was initially intercropped fruit tree varieties, including avocado (Ryan), citrus (Citrus sinensis), coconut (West African Tall palm), pawpaw (Solo dwarf) and pineapple (smooth cayenne) (Konlan et al., 2019). Following the completion of the initial phase, the coffee trees were coppiced in April 2020 after harvest, for rejuvenation under the existing fruit trees, so that the effects of their shade on the regrowth and yield of the coffee plants could be studied. Two stems were maintained per plant following coppicing. The experiment was laid out in a randomised complete block design with six treatments and four replications. Aside from the three fruit tree treatments (avocado, citrus and coconut), the residual effect of prior intercropping of robusta coffee with pineapple and pawpaw was also evaluated. All coffee plants were planted at 3 m^2 while the fruit trees were planted at 12 m x 12 m (avocado), 10 m x 10 m (citrus) and 10 m triangular (coconut). The sixth treatment was a sole coffee plot that served as the control (Table 1).

Table 1. Cropping systems evaluated from 2020 to 2024 during the rejuvenation of Robusta coffee plants

Treatment	Description
1	Sole coffee
2	Coffee+papaya (no papaya intercrop during this phase)
3	Coffee+coconut
4	Coffee+citrus
5	Coffee+avocado
6	Coffee+pineapple (no pineapple intercrop during this phase)

Baseline soil characteristics

From the experimental site, composite soil samples were obtained from nine (9) spots sampled for each of the surface depth (0-15 cm) and subsurface depth (15-30 cm) as baseline samples to characterize the soil for its chemical properties, before the commencement of fertilizer application and data collection. The soil samples were air-dried and crushed to pass through a 2 mm mesh after all visible stones and plant debris had been removed. Total nitrogen was determined by the modified Kjeldahl method (Bremmer, 1965). Available phosphorus and organic carbon were determined by the methods of Truog

(1930) and Tinsley (1950), respectively. The calcium, magnesium and potassium contents of the soil were determined by atomic absorption spectrometry using ammonium acetate extraction (Page et al., 1982). Data on precipitation, relative humidity and temperature of the study site were obtained from the on-station weather station of the Cocoa Research Institute of Ghana.

Maintenance of experimental plots
Based on the nutrient levels observed, the treatment plots were supplied 300 kg N, 100 kg P_2O_5 and 300 kg K_2O, equivalent to 856.5 g sulphate of ammonia, 130 g triple superphosphate and 300 g muriate of potash per plant, during the major rainy season (July 2020). The coffee plants were topped and maintained at 1.5 m height throughout the trial. Weed control in treatment plots was done manually. Six weed control operations were carried out during each cropping season. Pruning, which was mainly in the form of de-suckering and removal of side shoots, was carried out quarterly, while the height restriction was carried out at the end of the harvest season. Before harvesting, a single application of Lambda cyhalothrin EC 5% (25 mL in 11 L of water) was carried out to reduce the ant population to facilitate easy handpicking of ripe berries.

Data collection

Physiology and growth of rejuvenated coffee plants
Relative chlorophyll content, chlorophyll fluorescence (Fv/Fm) and stomatal conductance were measured to understand the physiology of rejuvenated robusta coffee plants intercropped with fruit trees. Chlorophyll content, Fv/Fm and stomatal conductance were assessed in the 2022/2023 to 2023/2024 seasons. Two fully expanded leaves per plant from the third lateral from the apex of each plant were selected from three coffee plants in each treatment plot for the measurement of these parameters. The soil and plant analysis development (SPAD 502 plus) leaf chlorophyll meter (Spectrum Technologies, 3600 Thayer Ct, IL, USA) was used to measure relative chlorophyll content. A leaf fluorescence meter (Fluorpen FP 110, Drásov, Czech Republic) was used to measure Fv/Fm, while a leaf porometer (Decagon Devices, Inc., 2365 NE Hopkins Court, Pullman, WA 99163) was used to estimate stomatal conductance.
The growth data collected on the rejuvenated coffee plants included stem diameter, height and number of branches or primary laterals per plant. The diameter of each of the two stems maintained per plant was measured 15 cm from the point of development from the mother plant with digital calipers. The multi-stem measurement method by Semere et al. (2022) was followed to determine the coffee stem combined diameter since the coffee trees had two stems per tree. The height of the two stems per plant was also measured from the point of its attachment to the coppiced stump to the tip with a meter rule. The procedure used to determine the representative stem diameter for each treatment was also used to determine the representative height for all the treatments. The number of laterals for the 48 core plants was counted, summed up and divided by the number of plants to obtain a representative number of laterals per plant for each treatment.

Yield of coffee and intercrops
At maturity, ripe berries from the core plants were carefully handpicked and weighed immediately on each treatment plot. The fresh berry weight was multiplied by a factor of 0.22 (FAO, 1995) to obtain the corresponding clean coffee weight for each core experimental plot. This was extrapolated to yield on a per-hectare basis. The ripe berries were then placed in clearly marked special trays for drying. The dried berries were weighed in their hulls before dehulling using a commercial hulling machine installed at the Bunso. After dehulling, the clean coffee beans were weighed to aid in the determination of shelling outturn (%), which was estimated as the ratio of clean coffee beans to the unhulled coffee, multiplied by 100. Five groups of 100 seeds were randomly sampled from each treatment and weighed. The average of the five groups was determined as the representative weight of 100 seeds of the respective treatments. Further, five seeds per treatment were randomly picked and their diameter and length were measured with digital calipers. The average of the five seeds for each parameter was then determined as the representative diameter and length for the respective treatments.

Estimation of net income
The amount of labour required to carry out all the farm management activities was recorded and converted into man-days. The expected income from the clean coffee beans was determined using the average of local (Kumasi and Accra) prices per kilogram in each cropping season. Throughout the season, harvests from the intercrops were recorded. At each harvest, the local market prices of the produce were used to determine the income from that harvest. At the end of the season, the various harvest records were summed up to obtain the total annual harvest and income.

Data analysis
Data on coffee growth, physiology, yield and yield components were subjected to analysis of variance using GenStat statistical software version 12.1. Differences between means were established using the least significant difference at a 5% probability level. Data on the cost of treatments and income obtained from the sale of harvests were subjected to partial farm budgeting to determine the profitability of treatments.

Conclusion

Although the presence of the matured avocado, citrus, and coconut trees during the rejuvenation of robusta coffee plants resulted in adverse effects on coffee leaf chlorophyll, Fv/Fm, and stomatal conductance, these did not translate into direct effects on the growth (stem diameter, height, and lateral development) of the coffee plants. Clean coffee yield was, however, adversely affected by the fruit trees, leading to reduced income from coffee bean sales per unit land area in the intercropped plots. These reductions were, however, more than compensated for by the income generated from sales of avocado and citrus fruits, making the coffee+avocado and coffee+citrus systems more beneficial than the sole coffee system. The coffee+avocado and coffee+citrus systems are therefore recommended, the choice of which should be informed by the farmer's location and demand for produce from each fruit tree.

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Conflict of Interest Statement
We declare that there is no conflict of interest.

Data Availability Statement
Data on this study is available upon reasonable request

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