



Impact of fruit phenology on water use in Robusta coffee systems in central Uganda

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Abstract Understanding the role played by agroforestry systems in improving water use efficiency (WUE) in coffee is a fundamental issue that could help promote sustainable agriculture. This study determined water use of Robusta coffee at various phenological stages under *Albizia coriaria* shade tree and open sun coffee systems. A randomized complete block design (RCBD) was set up in the two systems; *A. coriaria* coffee system (ACS) and Open sun coffee system (COSS) having three coffee clones. Water use by coffee and shade trees was measured using sap flow meters. In addition, days from inflorescence emergence to ripening and berry size from yellow berries to ripening were also measured. An ANOVA was used to ascertain differences in water use and berry growth duration. The results showed

that Robusta coffee water use per phenological stage was clone and system dependent. COSS significantly ($p < 0.001$) used more water per day (1.43 l/day) compared to coffee under ACS (0.62 l/day), representing a 40% difference in daily water use between the two coffee systems. The fruit phenological stages under ACS required a longer duration (397.78 days) compared to COSS (350.94 days). A significant impact of the coffee system and clone on coffee water use was observed, potentially indicating reduced demand for water under *A. coriaria* compared to open sun coffee.

Keywords *Albizia coriaria* · Coffee berry duration · Coffee berry size · Coffee water use · Sap flow

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Introduction

Coffee is a vital global cash crop, supporting millions of livelihoods and contributing significantly to foreign exchange of many countries (AbacusBio 2023). Over the past decade, Robusta coffee production has grown at 1.8% annually, reflecting its increasing importance in the global coffee market (ICO 2023). However, since the 1990's, production in some regions has declined by 50% due to climate change, rising labor costs, pests, diseases, and competition from other crops (AbacusBio 2023). Robusta's susceptibility to climate variability, especially in low-elevation areas with small intra-seasonal variations, raises concerns about its resilience to future climate

changes, despite predictions that it could be able to offset losses in Arabica coffee production brought on by climate change (Kath et al. 2020). If the environment continues to demonstrate increasing variability in addition to higher heat, the effects of climate change on Robusta production may worsen (Bunn et al. 2015).

Agroforestry is a promising climate adaptation strategy that enhances coffee quality by reducing solar radiation, absorbing rainwater, sequestering carbon, and preventing frost damage (Pinho and Miller 2012). Agroforestry is a land use management technique where trees or shrubs are grown alongside or in the middle of crops or pastureland (Sanchez 1995). It improves water use efficiency by reducing evaporation, increasing water availability in upper soil layers, and creating a favorable microclimate (Padovan et al. 2018). However, shade trees can also reduce water availability for understory crops by increasing transpiration and rainfall interception (Cannavo et al. 2011; Padovan et al. 2015). This competition for water, particularly under extreme conditions, may limit agroforestry's effectiveness as a climate adaptation tool (Abdulai et al. 2018). However, trees such as *Albizia coriaria* are deciduous that reduce water loss during the dry season (Buyinza et al. 2019). *A. coriaria* also exhibits reverse flow thus availing water to coffee plants (Buyinza et al. 2019).

Comprehensive studies exploring the potential for climate resilience in Robusta coffee production, particularly those focusing on growth phases and flowering that are sensitive to climate change, remain limited (Wolkovich et al. 2012; Bilen et al. 2022). Most research studies on water use in coffee agro-systems have centered on Arabica coffee (e.g. Buyinza et al. 2019; Sarmiento-Soler et al. 2019), leaving Robusta coffee comparatively understudied. However, as blends shift toward incorporating more Robusta, there will be a growing need for high-quality Robusta to meet consumer preferences (AbacusBio 2023). In response to emerging environmental challenges affecting household food security, such as land-use changes (Ellison et al. 2017), agricultural land degradation (Muthuri et al. 2005), and climate change (Strobl et al. 2017), research on water use physiology in coffee systems is expanding. We hypothesized that Robusta coffee grown under *A. coriaria* systems uses less water compared to open sun systems due to reduced evapotranspiration, resulting from moderated

microclimatic conditions (Padovan et al. 2018). Previous studies have however shown mixed results. For instance, Sarmiento-Soler et al. (2019) compared water use across Arabica coffee under open sun, coffee-banana systems, and coffee-*Cordia africana* systems, finding no significant differences between treatments. Contrary, Padovan et al. (2018) reported higher water use efficiency in Arabica agroforestry systems compared to open sun. Similarly, Van Kanten and Vaast (2006) observed that while total system water use was greater in shaded systems, coffee transpiration was often higher in open sun systems. Water use in different cropping systems therefore, appears to vary based on the shade tree species and the associated crop (Sarmiento-Soler et al. 2019). Despite these findings, systematic research on how fruit phenological stages affect water use in Robusta coffee remains limited (Kath et al. 2023). Robusta coffee trees have two distinct periods in their phenology: the vegetative phase, which takes place prior to flowering, and the reproductive phase (fruit development) which takes place between flowering and ripening (Kouadio et al. 2021). This study therefore, aimed at determining the impact of fruit phenological stages on water use in Robusta coffee under *A. coriaria* and open sun systems. The specific objectives were to examine the effects of two contrasting coffee systems among selected coffee clones across seasons on: (1) the duration of coffee fruit phenological stages; and (2) coffee water use during different phenological stages. Understanding water use dynamics can provide insights into the water requirements of various farming system components and inform best management practices for farmers facing water stress (Kath et al. 2023).

Materials and methods

Study area

The study was carried out at National Coffee Research Institute (NaCORI), Kizuza in Mukono district. The institute is located 35 km east of Kampala, the capital city of Uganda. Mukono is located at about 1200 m above sea level (m.a.s.l) which is a low-to-medium altitude within Lake Victoria Crescent agroecological zone of Uganda (Kobusinge et al. 2023). NaCORI is located at 0° 15' 26.9874"

N and 32° 47' 27.69648" E. The climatic (rainfall and temperature) (Supplementary, Fig. S1), altitude and soil conditions of the study site are described by Kobusinge et al. (2023). The dry season within the study period included June–August 2022, January–February 2023, May 2023–August 2023, December 2023–January 2024 while the wet season included September–December 2022, March–April 2023 and September 2023–November 2023.

Experimental design and treatments

The study was conducted on a coffee plantation which was established in 2009, with the coffee trees last stumped in 2019. The experiment was superimposed on a breeding population segregating for Coffee Wilt Disease (CWD) resistance. A randomized complete block design (RCBD) with four seasonal replications was employed to compare the two coffee systems: open sun coffee system (COSS) and coffee-*Albizia coriaria* system (ACS). Coffee plants were spaced at 3 m × 3 m, while shade trees in the ACS were spaced at 15 m × 15 m.

Three coffee clone (MFCT1, J24/13/20/4, and 203/32/2) surrounding the shade trees were selected for study. All plots received uniform management practices, including; hand-weeding, pruning to control suckers, and NPK 25:5:5 fertilizer application at 250 g per plant during rainy seasons. The plantation was rain-fed with no irrigation being applied during the study period.

Data collection

Water use measurement

Installation and use of sap flow meters Water use in Robusta coffee and *A. coriaria* was assessed using SFM1 Sap Flow Meters (ICT International, Australia) over a period of 20 months (June 2022–January 2024). Sap flow measurement is an indicator of the water use in plants (Burgess et al. 2001). The sap meters, which rely on the heat ratio method to measure sap flow non-destructively, were installed in the direction of sunrise on three coffee clones (MFCT1, J24/13/20/4 and 203/32/2) in each of open sun and *A. coriaria* system including installation on the *A. coriaria* tree, totaling to seven meters. This sap flow meter system set up was replicated in time (4 seasons).

Installation of the sap flow meter was done based on procedures by Buyinza et al. (2019). Each coffee plant served as a replicate, with sap flow monitored at 30 min intervals for 20 months. Destructive sampling was used to measure coffee bark depth and sapwood area. For the shade tree, an increment borer determined sapwood and heartwood thickness, while bark depth was measured using a screwdriver and hammer method. Iodine dye differentiated bark (orange), sapwood (light black), and heartwood (dark black) in samples. Stem part diameters were measured in centimeters (Supplementary, Table 1), aiding the assessment of water use across systems.

Table 1 Coffee leaf area index among coffee varieties and seasons

Variety	LAI (m ² /m ²)			
	Dry season		Wet season	
	ACS	COSS	ACS	COSS
203/32/2	1.75 ± 0.27	1.80 ± 0.30	2.66 ± 0.13a	1.89 ± 0.15
J24/13/20/4	2.08 ± 0.27	2.04 ± 0.30	2.14 ± 0.13b	1.77 ± 0.15
MFCT1	1.68 ± 0.27	1.82 ± 0.30	1.96 ± 0.13b	1.74 ± 0.15
p value: V	0.54963	0.828	0.002757**	0.75438
Cv	39.06	42.16	20.34	28.18
Mean system	1.84 ± 0.17	1.89 ± 0.17	2.25 ± 0.10a	1.80 ± 0.10b
p value: system	0.832		0.002511**	
S	0.2522			
S*system	0.07545			
S*V	0.20743			

Downloading sap flow data Sap flow data were downloaded from the machines using Combined Instrument Software (CIS) then transferred to Sap Flow Tool software. Parameters such as sapwood depth, bark depth and stem diameter were entered into the software that translated sap flow into daily water use. Linear transformation was performed on heat pulse velocity to obtain corrected zero flow baselines for asymmetry of installation (Buyinza et al. 2019, 2023).

Coffee fruit development

Data collection focused on coffee stems connected to sap flow meters. Three stems per treatment were selected, with four primary branches from the upper third of each stem tagged to represent four geographic quadrants (North, West, East and South). Flower buds on the primary branches were tracked up to ripening, with the duration of each phenological stage recorded using the Biologische Bundesantalt Bundessortenamt and Chemische Industries (BBCH) scale (Arcila-Pulgarin et al. 2002) (Supplementary, Table 2). New inflorescences were monitored continuously, with further tagging as coffee flowered continuously. Observations were made daily.

Leaf area index

Leaf Area Index (LAI) was measured biweekly using a Ceptometer LP-80 in the morning. Readings were taken above and below the coffee canopy at four random points (East, West, South, and North) and averaged automatically.

Calculation of potential evapotranspiration

Meteorological data, including wind speed (m s^{-1}), relative humidity (%), maximum and minimum temperatures ($^{\circ}\text{C}$), solar radiation (MJ m^{-2}), and rainfall (mm), were collected daily from a weather station

located approximately 0.5 km from the study site at NaCORI. The Penman–Monteith equation (Allen et al. 1998) was used to calculate potential evapotranspiration (ET_0). As per Fries et al. (2020), a month is classified as dry when ET_0 exceeds precipitation (P) and wet when precipitation (P) surpasses ET_0 .

Statistical analysis

Number of days taken per coffee fruit phenological stage

Data analysis was carried out using R package version 4.2.3. Two-way ANOVA was conducted to ascertain the significance of difference among clones and between systems for number days taken per phenological stage using the R function aov(). Significance level was set at 5%.

Determination of daily water use, transpiration per ground area, transpiration per unit leaf area and potential evapotranspiration (ET_0) among systems

Three way ANOVA was used in R [aov() function] to examine differences in systems, clones and seasons including interactions for LAI, mean daily water use per ground area and transpiration per unit leaf area. To determine daily water use of coffee trees, the daily water use of one stem was multiplied by number of stems per tree (1 day^{-1}). Transpiration by ground area was determined by multiplying coffee water use (1 day^{-1}) with the number of trees in a hectare and dividing by the area while Transpiration per leaf area was calculated by transpiration per ground area by the leaf area index. A t-test was used to analysis the significant difference between ET_0 among seasons,

Results

Coffee leaf area index per systems and clones

The findings showed that there was no significant ($p \geq 0.05$) interaction between the seasons and either for the system or the varieties. For both ACS and COSS, LAI did not differ significantly ($p \geq 0.05$) amongst varieties during the dry season; however, variety J24/13/20/4 had the highest LAI for both ACS

Table 2 Potential Evapotranspiration among Seasons

Season	Mean $\pm$ SE (mm/day)
Dry	3.77 ± 0.04
Wet	3.54 ± 0.04
p value	$8.67\text{e} - 05^{***}$

(2.08) and COSS (2.04). For ACS, LAI varied substantially ($p=0.002757$) among the varieties during the wet season, with variety 203/32/2 recording the highest LAI (2.66). There was no significant differences ($p \geq 0.05$) in LAI for COSS among the coffee varieties; nevertheless, variety 203/32/2 had the highest LAI (1.89).

Potential evapotranspiration (ET_o) among seasons

The dry season (3.77 mm) significantly ($p < 0.001$) had a high ET_o compared to the wet season (3.54 mm).

Number of days taken per phenological stage per systems

The ACS required significantly more time ($p < 0.001$) for coffee to progress from inflorescence to ripening (397.8 days) compared to the COSS, which took 350.9 days. Though differences were not significant, clones, J24/13/20/4 took the longest time (354.8 days) under COSS, while MFCT1 required the most time (438.8 days) under ACS. For instance, the duration for inflorescence stage of COSS, was significantly longest ($p < 0.001$) for MFCT1 (69 days) and shortest for 203/32/2 (44.6 days). While, under ACS J24/13/20/4 took significantly longest (88.9 days) and least for 203/32/2 (69.9 days). In contrast, the

duration for 10–50 stage of COSS was significantly longest for J24/13/20/4 (106.3 days) and shortest for 203/32/2 (70.8 days). Under ACS, MFCT1 took longest (112 days) while J24/13/20/4 took the shortest (85.8 days). However, the interaction between clones and system irrespective of stage was not significant ($p=0.07225$) (Table 3). Growth patterns showed slower development during the inflorescence stage, followed by rapid flowering. Similarly, growth was slower from yellow berries to 50% size, accelerated from 60 to 90%, and then slowed again from 90% to ripening. ACS significantly ($p < 0.001$) prolonged the inflorescence stage (77.4 days) compared to COSS (58.8 days). From 90% to ripening, ACS also required significantly ($p < 0.001$) more time (141.9 days) than COSS (116.4 days). The interaction between clone and system under 60–90% stage was significant ($p=0.04343$).

Water use per coffee systems

There was a significant season by clone interaction ($p < 0.001$) (Table 4); highest water use was observed for J24/13/20/4 (2.07 l/day) in the dry season compared to 1.18 l/day in the wet season while the lowest water use was for MFCT1 (dry = 0.56 l/day, wet = 0.47 l/day) (Supplementary 3). The interaction between clone and system was significant ($p < 0.001$); highest water use was for J24/13/20/4 (2.19 l/day)

Table 3 Variation in duration (days) of coffee fruit phenological stage among systems and clones

Stage	System	Clone(C)			p value: C	c.v. %	mean System	p value: System	p value: C* System
		MFCT1	J24/13/20/4	203/32/2					
Inflorescence	COSS	69.0 ± 3.15 ^a	57.5 ± 3.14 ^b	44.8 ± 3.96 ^c	0.0001417***	23.18	58.9 ± 2.31	6.589e−08***	4.674e−05***
	ACS	72.0 ± 3.20 ^b	88.9 ± 3.05 ^a	69.9 ± 3.22 ^b	0.0001513***	17.96	77.4 ± 2.12		
Flowering	COSS	3.3 ± 0.81	3.3 ± 0.53	4.0 ± 0.61	0.8337	63.84	3.5 ± 0.38	0.3920	0.08161
	ACS	3.7 ± 0.57 ^{ab}	5.4 ± 0.68 ^a	2.6 ± 0.70 ^b	0.04048*	62.82	3.5 ± 0.36		
Yellow berries	COSS	41.6 ± 2.78 ^c	51.1 ± 2.77 ^b	75.0 ± 3.49 ^a	1.68e−08***	22.59	53.2 ± 2.37	0.5900	2.321e−11***
	ACS	68.0 ± 3.23 ^a	44.1 ± 2.76 ^b	51.7 ± 2.83 ^b	2.627e−05***	25.26	54.8 ± 2.18		
10–50%	COSS	81.5 ± 2.80 ^b	106.2 ± 2.79 ^a	70.8 ± 3.52 ^c	8.74e−10***	13.71	88.4 ± 2.68	0.3505	2.321e−11***
	ACS	112.0 ± 6.36 ^a	85.8 ± 3.88 ^b	90.8 ± 4.06 ^b	0.002858**	19.02	92.1 ± 2.74		
60–90%	COSS	28.1 ± 1.64 ^{ab}	30.8 ± 1.63 ^a	23.9 ± 2.06 ^b	0.05287	25.20	28.1 ± 1.28	0.02538*	0.04343*
	ACS	41.9 ± 3.64 ^a	33.1 ± 2.09 ^b	28.3 ± 2.19 ^b	0.006124**	29.05	32.9 ± 1.32		
100-Ripening	COSS	116.8 ± 8.85 ^{ab}	105.8 ± 4.03 ^b	133.1 ± 5.06 ^a	0.0005683***	15.00	116.4 ± 2.71	1.777e−09***	0.0843
	ACS	134.0 ± 3.92 ^b	136.7 ± 1.71 ^b	149.2 ± 1.79 ^a	2.148e−05***	5.46	141.9 ± 2.41		
Total	COSS	348.3 ± 13.08	354.7 ± 6.16	348.3 ± 9.25	0.542	7.45	350.9 ± 5.86	2.966e−06***	0.07225
	ACS	438.8 ± 17.42	390.4 ± 9.66	392.1 ± 10.06	0.056	8.76	397.8 ± 5.96		

ACS: *Albizia coriaria* coffee system; COSS: open sun coffee system

Table 4 Water use per coffee plant, system water use per unit leaf area and system water use per ground area per system and clones

System:	ACS		COSS	
Season:	Dry	Wet	Dry	Wet
<i>Water use per coffee plant (l/day)</i>				
J24/13/20/4	1.25 ± 0.03 ^a	0.37 ± 0.01 ^b	2.57 ± 0.03 ^a	1.88 ± 0.03 ^a
203/32/2	1.11 ± 0.03 ^b	0.77 ± 0.01 ^a	1.39 ± 0.03 ^b	1.10 ± 0.03 ^b
MFCT1	0.37 ± 0.03 ^c	0.27 ± 0.01 ^c	0.74 ± 0.04 ^c	0.67 ± 0.03 ^c
Shade tree	25.59 ± 0.46	18.2 ± 0.64		
<i>p</i> value: C	< 2.2e−16***	< 2.2e−16***	< 2.2e−16***	< 2.2e−16***
<i>cv</i> (%)	29.77	30.95	21.42	29.42
Mean Season	0.91 ± 0.05	0.44 ± 0.04	1.69 ± 0.03	1.24 ± 0.03
Mean system	0.62 ± 0.03		1.43 ± 0.02	
<i>p</i> value: System	< 2.2e−16***			
<i>p</i> value: S	< 2.2e−16***		< 2.2e−16***	
<i>p</i> value: S*C	< 2.2e−16***			
<i>p</i> value System*S	0.7376			
C*System	< 2.2e−16***			
C*S*System	0.02944*			
<i>System Transpiration per unit leaf area (mm/day)</i>				
J24/13/20/4	0.35 ± 0.02 ^a	0.05 ± 0.001 ^a	0.15 ± 0.003 ^a	0.15 ± 0.004 ^a
203/32/2	0.19 ± 0.02 ^b	0.05 ± 0.002 ^a	0.09 ± 0.003 ^b	0.07 ± 0.004 ^b
MFCT1	0.15 ± 0.02 ^b	0.04 ± 0.002 ^b	0.05 ± 0.003 ^c	0.04 ± 0.004 ^c
Shade tree	0.06 ± 0.002	0.04 ± 0.002		
<i>p</i> value: C	2.199e−09***	0.01157*	< 2.2e−16***	< 2.2e−16***
<i>cv</i> (%)	92.72	39.14	30.74	59.96
Mean Season	0.23 ± 0.01 ^a	0.05 ± 0.01 ^b	0.11 ± 0.01	0.09 ± 0.004
Mean system	0.12 ± 0.006		0.10 ± 0.004	
<i>p</i> value: System	5.412e−05***			
<i>p</i> value: S	< 2.2e−16 ***		0.0001634***	
<i>p</i> value: S*C	1.280e−07***			
<i>p</i> value System*S	< 2.2e−16***			
C*System	0.210063			
C*S*System	< 2.2e−16***			
<i>System Transpiration per ground area (mm/day)</i>				
J24/13/20/4	0.25 ± 0.005 ^a	0.15 ± 0.004 ^a	0.29 ± 0.003 ^a	0.21 ± 0.002 ^a
203/32/2	0.23 ± 0.005 ^b	0.12 ± 0.004 ^b	0.15 ± 0.003 ^b	0.12 ± 0.003 ^b
MFCT1	0.15 ± 0.005 ^c	0.10 ± 0.004 ^c	0.08 ± 0.004 ^c	0.07 ± 0.003 ^c
Shade tree	0.11 ± 0.002	0.08 ± 0.003		
<i>p</i> value: C	< 2.2e−16***	< 2.2e−16***	< 2.2e−16***	< 2.2e−16***
<i>cv</i> (%)	20.79	36.61	21.42	29.42
Mean Season	0.21 ± 0.01	0.12 ± 0.004	0.19 ± 0.003	0.14 ± 0.003
Mean system	0.16 ± 0.004		0.16 ± 0.003	
<i>p</i> value: System	0.392			
<i>p</i> value: S	< 2.2e−16***		< 2.2e−16***	
<i>p</i> value: S*C	< 2.2e−16***			
<i>p</i> value System*S	3.045e−08***			
C*System	< 2.2e−16***			
C*S*System	0.1023			

ACS: *Albizia coriaria*
 coffee system; COSS: open
 sun coffee system; C, clone,
 S, season

under COSS compared to 0.70 l/day under ACS while MFCT1 had the lowest water use (ACS=0.31 l/day, COSS=0.69 l/day) (Supplementary 4). However, season by system interaction was not significant ($p=0.7376$).

There was a significance difference ($p<0.001$) in the interaction between clones and season; highest transpiration per unit leaf area was observed for J24/13/20/4 (0.23 mm/day) in dry season compared to 0.10 mm/day in the wet season while lowest transpiration per unit leaf was in MFCT1 (dry=0.10 mm/day, wet=0.04 mm/day) (supplementary 5). The interaction between season and system was significant ($p<0.001$). Transpiration per unit leaf area was higher during the dry season (ACS=0.23 mm/day, COSS=0.11 mm/day) than the wet season (ACS=0.05 mm/day, COSS=0.09 mm/day) (supplementary 6).

There was a significant difference in the interaction between season and clones ($p<0.001$); highest transpiration per ground area was observed under J24/13/20/4 (0.27 mm/day) in dry season compared to 0.17 mm/day in the wet season while the lowest was observed in MFCT1 (dry=0.12 mm/day, wet=0.09 mm/day) (supplementary 7). The interaction between clone and system was also significant ($p<0.001$); transpiration per unit ground area was highest in J24/13/20/4 (0.24 mm/day) in under COSS compared to 0.17 mm/day under ACS while the lowest was observed in MFCT1 (COSS=0.12 mm/day, ACS=0.08 mm/day) (supplementary 8).

Transpiration per unit ground area was significantly ($p<0.001$) higher during the dry season (ACS=0.21 mm/day, COSS=0.19 mm/day) than the wet season (ACS=0.12 mm/day, COSS=0.14 mm/day) (supplementary 9).

Daily water use in both systems fluctuated with rainfall (Fig. 1), with COSS consistently using more water across all study months. *A. coriaria*'s water use declined as the rainy season approached, following a similar pattern in both study years. On the other hand, negative flow began mid-December 2023 through January 2024 when *A. coriaria* lost its leaves (Fig. 2).

Water use per coffee phenological stages

Water use during different phenological stages varied by coffee clone and system, particularly during berry development (Fig. 3). COSS significantly ($p<0.001$) used more water (1.37 l/day) compared to ACS (0.44 l/day) (Table 5). There was significant ($p<0.001$) interaction between system and stage with small differences in water use at flowering (70% more water use for COSS) than the rest of the stages (e.g., 217.2% more water use for COSS at green berry stage).

In the ACS system, significant clone x stage interactions for water use ($p<0.001$) were observed. Clone 203/32/2 consistently used the highest amount of water across all phenological stages. However, from stage 50% up to 100%, the water use of clone J24/13/20/4 increased as that of clone

Fig. 1 Variation in daily mean coffee water use and rainfall in *Albizia coriaria* coffee system (ACS) and open sun coffee system (COSS). Coffee Daily water use presented are means of the three coffee plants per system for 20 months

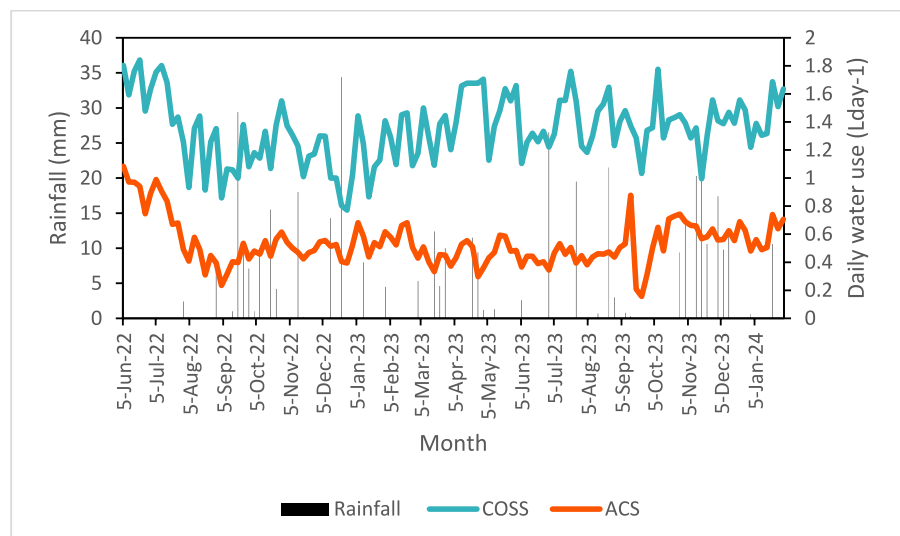


Fig. 2 Variation in daily *Albizia coriaria* shade tree water use and rainfall

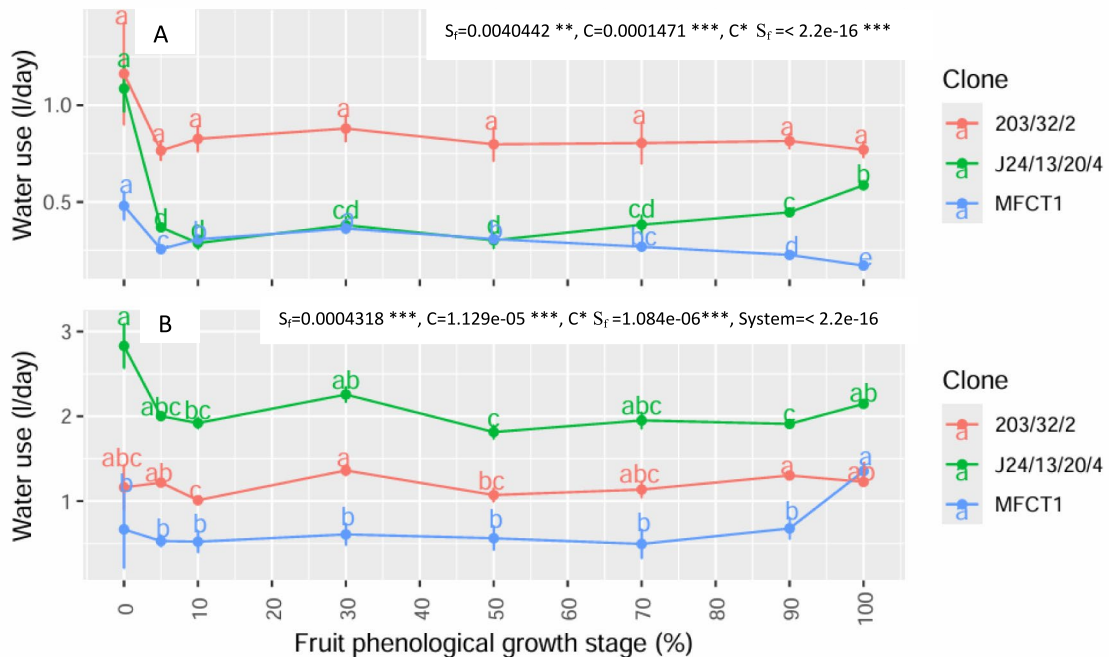
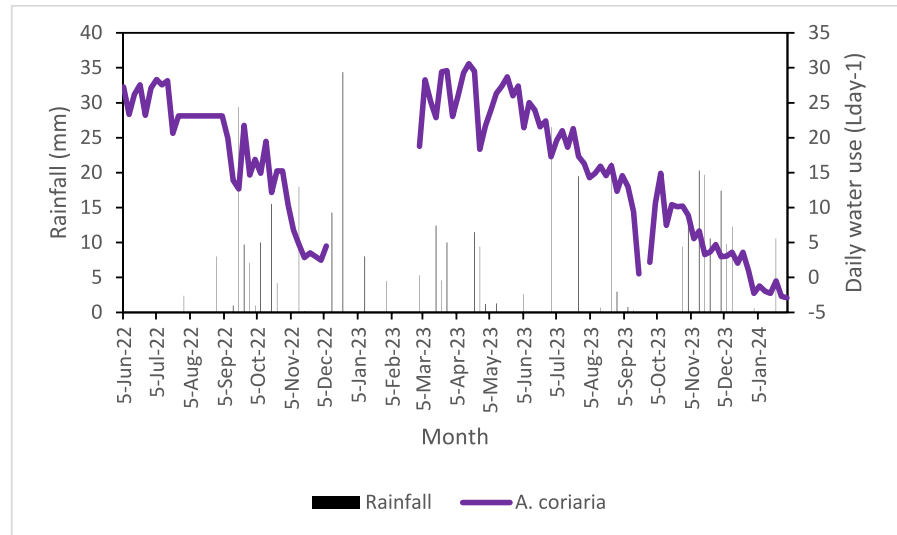


Fig. 3 Water use per phenological stages for three coffee clones and two systems

MFCT1 reduced. Specifically, clones 203/32/2 and MFCT1 used more water during flowering (1.61 l/day, 0.48 l/day respectively) and at 30% berry size (0.88 l/day, 0.36 l/day respectively), with the least water use at the yellow berry (0.77 l/day, 0.26 l/day respectively) and ripening stages (0.77 l/day, 0.17 l/day respectively). In contrast, clone J24/13/20/4

consumed the highest amount of water at flowering (1.09 l/day) and ripening (0.59 l/day), and the least during the yellow berry, 10%, and 50% berry size stages.

Under COSS, the clone $\times$ stage interaction for water use was also significant ($p < 0.001$). Clone J24/13/20/4 consistently used the most water

Table 5 Water use of coffee under *Albizia coriaria* and open sun systems across fruit phenological stages

System	Fruit phenological stage								
	0	5	10	30	50	70	90	100	Mean $\pm$ SE
ACS	0.91 $\pm$ 0.27	0.39 $\pm$ 0.04	0.39 $\pm$ 0.05	0.57 $\pm$ 0.08	0.41 $\pm$ 0.07	0.38 $\pm$ 0.08	0.48 $\pm$ 0.04	0.48 $\pm$ 0.03	0.44 $\pm$ 0.02
COSS	1.55 $\pm$ 0.27	1.25 $\pm$ 0.03	1.17 $\pm$ 0.06	1.37 $\pm$ 0.08	1.10 $\pm$ 0.08	1.13 $\pm$ 0.10	1.54 $\pm$ 0.04	1.57 $\pm$ 0.05	1.37 $\pm$ 0.02
Mean	1.21 $\pm$ 0.19	0.79 $\pm$ 0.03	0.75 $\pm$ 0.04	0.95 $\pm$ 0.06	0.73 $\pm$ 0.05	0.73 $\pm$ 0.06	0.97 $\pm$ 0.03	0.99 $\pm$ 0.03	0.91 $\pm$ 0.02
D	0.6435	0.8577	0.773	0.7997	0.6813	0.7499	1.0622	1.0857	0.93
%D	70.76872	217.1942	197.1939	139.515	164.4064	195.6942	223.6211	224.6896	211.3636
S.E.D	0.6887	0.06121	0.06028	0.1167	0.09715	0.1206	0.04648	0.05226	0.04648
L.S.D (=5%)	1.912	0.1204	0.1191	0.2329	0.1937	0.2417	0.0915	0.1029	0.0915
p value	0.403	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
p value S _F *System	<0.001								

D, Differences between mean of COSS and ACS; %D, percentage differences

(1.81–2.83 l/day), with MFCT1 using the least (0.50–1.35 l/day) across all stages. At ripening stage (100% berry size), the water use for clone MFCT1 (1.35 l/day) slightly surpassed that of 203/32/2 (1.23 l/day).

A, ACS; B, COSS; 0, flowering; 5, yellow berries; 100, Ripening; S_F, Fruit phenological growth stage; C, clone; ACS, *Albizia coriaria* coffee system; COSS, coffee open sun system. Same letters within the same clone and treatment indicate non-significant differences.

Discussion

Influence of system on duration of coffee fruits phenology

A deeper understanding of coffee fruit phenology is essential for effective harvest planning (Salazar et al. 2019), as the duration of each phenological stage varies between systems and among clones. For instance, the inflorescence stage took longer under ACS (77.4 days) compared to COSS (58.8 days), as also reported by Kimenia and Njoroge (1988) and Campanha et al. (2005). This could be influenced by lower soil moisture in ACS, which affects floral bud breaking (DaMatta et al. 2007). The interaction between clone and system for duration of yellow berry stage was significant. Under COSS, clone 203/32/2 took the longest (75 days), while MFCT1 took the shortest (41.6 days). Under ACS, clone 203/32/2 also

took longer (51.7 days), while J24/13/20/4 took the least (44.1 days). This stage typically lasts between 42 and 70 days, but climate can impact its duration (Sureshkumar et al. 2013). Results also showed that there was no significant difference in days required to move from 10 to 50% among systems but there were significant differences between varieties of a system. Variety J24/13/20/4 significantly ($p > 0.001$) took longer time to move from 10% berry size to 50% under COSS (106.3 days) while variety 203/32/2 took (90.8 days) under ACS. Sureshkumar et al. (2013) reported that the second stage of berry development took 70–117 days in Kenya and is characterized with increase in size due to rapid cell expansion. There was also a significant difference in number of days taken for the berries to move from 60 to 90% between systems (ACS = 32.9 days, COSS = 28.1 days). The duration among varieties was only significant under ACS. MFCT1 (41.9 days) significantly took longer days compared to 203/32/2 (28.3 days). The fast growth at 60% to 90% is characterized by accumulation of organic compounds (De Castro and Marzaccini 2006; Salazar et al. 2019). From 90% berry size to ripening, ACS took significantly longer (141.9 days) compared to COSS (116.4 days). The extended ripening time in shaded systems has been attributed to lower daily temperatures (Damatta et al. 2007). Ripening in Robusta typically takes 57 days, while in Arabica it takes 88 days, with Robusta's full cycle from inflorescence to ripening lasting 416 days (Salazar et al. 2019). This study included the period from 90% berry size to ripening, which accounts

for the longer duration observed. Additionally, coffee fruit ripening is influenced more by endogenous signals than by environmental factors (Gaspari-Pezopane et al. 2012). The study found that ACS took 390.4–438.8 days from inflorescence to ripening, while COSS took 348.3–354.7 days, consistent with findings by Ricci et al. (2006), who reported slower maturation in coffee grown in agroforestry systems. This contrasts with da Silva Neto et al. (2018), who found faster maturation in coffee cherries closer to shade trees. Overall, the time needed for fruit to ripen is influenced by clone, climate, and management practices (Dinh et al. 2022). Shade lowers temperature and this slows down maturation which is beneficial for better cup quality, resulting in higher market value compared to coffee grown in full sun (Lopez et al. 2021; da Silva Neto et al. 2018).

Effect of coffee system on water use

Water use during coffee fruit phenology varied by clone and system, as also observed by Carr (2001). Water use was higher in the dry season under COSS followed by dry season under ACS for clone J24/13/20/4. Similar trends were observed for clones 203/32/3 and MFCT1. Earlier, Sarzynski et al. (2021) found differences in water use across *Coffea arabica* hybrids in agroforestry systems. Righi et al. (2008) also noted that shaded coffee plants had lower water use efficiency (WUE-Kg/mm) compared to monocropped plants. In the same vein, Dang et al. (2017) found that coffee uses more water during flowering than at any other stage. This could be due to the need for water to break the bud dormancy (Carr 2001). Stages yellow berries (5%), 10%, 50% and 70% used the relatively least amount of water partly due to dormancy thus requiring less water (Dinh et al. 2022). However, variety 203/32/2 utilized the least amount of water at 10% berry size, MFCT1 at 70% berry size, and J24/13/20/4 at 50%. As the berries expand, water use increases due to higher water demands which arises with increased need for assimilates (Dinh et al. 2022), making it crucial for this stage to align with the wet season (DaMatta et al. 2007). However, Petek et al. (2009) noted a strong correlation between water availability and fruit ripening, suggesting that reduced water availability could speed up the ripening process.

Studies on agroforestry water use are essential for understanding interactions between shade trees and understory crops (Ong et al. 2007; Sarmiento-Soler et al. 2019). Daily water use per coffee tree was higher under COSS compared to ACS across seasons and clones as also reported by Righi et al. (2008). This difference may be attributed to increased radiation reaching unshaded coffee plants and reduced competition for soil water. This could also be attributed to the higher stomata sensitivity of the coffee plants under more illuminated conditions, in the open sun system (Righi et al. 2008). Conversely, the lower water use under ACS could be linked to the cooler microclimate created by shade trees (Carvalho et al. 2017; Sarmiento-Soler et al. 2019). Daily water use ranged from 0.37 l/day to 2.57 l/day, quite consistent with findings by Buyinza et al. (2023) (0.7–2.2 l/day) and Sarmiento-Soler et al. (2019) (0.9–1.6 l/day) for Arabica coffee, with variations likely due to differences in coffee clones. Transpiration per leaf area and ground area was significantly higher under ACS compared to COSS, except during the wet season for clone J24/13/20/4. Clone J24/13/20/4 consumed significantly more water across systems and seasons, likely due to its larger diameter at breast height (DBH)—3.6 cm under COSS and 3.8 cm under ACS; compared to MFCT1, which had 3.2 cm under COSS and 2.1 cm under ACS. Tree water use is proportional to tree size (Phillips et al. 2003). Higher transpiration per leaf area under ACS could also be attributed to shade trees contributing to system transpiration. However, Siles (2007) reported higher transpiration per leaf area under COSS, which was attributed to a higher leaf area index (LAI) under COSS compared to ACS. In this study, LAI was higher under ACS, which may explain the differences. Variation in transpiration per leaf area also correlates with LAI, as reported by Sarmiento-Soler et al. (2019). While transpiration rates per leaf area were low compared to studies by Padovan et al. (2018) and Sarmiento-Soler et al. (2019), transpiration per ground area was higher under ACS, consistent with findings by Sarmiento-Soler et al. (2019), Partelli et al. (2014), and Van Kanten and Vaast (2006). However, the rates were lower than previously reported, possibly due to the lower coffee densities (1111 trees/ha) in this study compared to 1,875–1,950 trees/ha in Sarmiento-Soler et al. (2019) and 4,000 trees/ha in Padovan et al. (2018). In ACS, most transpiration was due to coffee

plants rather than shade trees, owing to the higher coffee density. Coffee plants accounted for 53.1% of water transpired per ground area in the dry season and 55.6% in the wet season, similar to findings by Padovan et al. (2018). On the other hand, the lower water use of MFCT1 suggests it is a water-conserving clone and could be well-suited for drought-prone regions (DaMatta 2004).

During the study period, coffee water use increased during the dry months and decreased with rainfall, consistent with findings by Sarmiento-Soler et al. (2019). This pattern is primarily due to the coffee trees' higher evaporative demand (as observed from this study) and reliance on groundwater resources during the dry season compared to the wet season (O'Grady et al. 1999). *A. coriaria* exhibited negative water flow during the dry season of mid-December 2023 to January 2024, coinciding with its leaf-shedding period. Similar observations were reported by Buyinza et al. (2023), who noted reverse water flow in *A. coriaria* when the tree shed leaves or underwent pruning. Research suggests that reduced soil water potential can trigger reverse flows in trees (Smith et al. 1999). When the atmosphere is wetter than the soil, water moves from the tree to the soil because the soil has a lower water potential than the atmosphere. Within the tree, water flows toward areas with the lowest water potential, a process known as hydraulic redistribution, which can occur through or across the stem (Hafner et al. 2017). Buyinza et al. (2023) also documented reverse flow in *Cordia africana* during the rainy season. There is need to investigate the potential impact of shade tree leaf phenology on coffee water use as neither this study nor for Buyinza et al. (2023) delved into this aspect.

Conclusion

Coffee water use differed between systems with coffee in open sun demanding more water at 1.43 l/day than coffee under *A. coriaria* system at 0.62 l/day. The fruit phenological stages under ACS required a longer duration (397.78 days) compared to COSS (350.94 days). A significant impact of the coffee system and clone on coffee water use was observed, potentially indicating reduced demand for water under *A. coriaria* compared to open sun coffee.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no conflict of interests.

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