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Effect of Tree Canopy Cover on Soil Moisture Dynamics in Different Agroforestry Systems under Semi-arid Condition

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The experiment was conducted in an Agroforestry plot under the maintenance of AICRP on Agroforestry located in GKVK, Bengaluru, Karnataka, India. This study measures the soil moisture dynamics in different agroforestry systems under semiarid conditions, focusing on the influence of

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tree canopy cover on surface soil moisture. Seven agroforestry systems were analyzed, featuring tree species such as *Tectona grandis*, *Melia dubia*, *Pongamia pinnata*, *Swietenia mahagoni*, *Anacardium occidentale*, *Mangifera indica* and *Syzygium cumini* paired with intercrops. Soil moisture was measured monthly using the gravimetric method, with samples collected inside and outside the tree canopy. The results indicate that soil moisture levels are generally higher inside the canopy due to reduced evaporation, improved microclimate, and enhanced soil structure from leaf litter accumulation. Species with dense canopies, like *S. cumini* and *M. indica*, demonstrated higher soil moisture retention, while deep-rooted species like *S. mahagoni* and *A. occidentale* maintained moisture during dry periods by accessing deeper soil layers. It highlights the significant role of canopy cover in soil moisture conservation within agroforestry systems. It underscores the importance of selecting appropriate tree species and managing canopy density to optimize soil moisture levels, particularly in semiarid regions.

Keywords: Soil moisture; agroforestry systems; tree canopy; season; root system.

1. INTRODUCTION

Agroforestry is a land use system that involves the intentional integration of trees or woody shrubs with agricultural crops and/or livestock within the same farming area, in a spatial arrangement or temporal sequence [1]. It is characterized by the deliberate design and management of interactions between tree and agricultural components to achieve ecological, economic, and social objectives. According to the World Agroforestry Centre (ICRAF), agroforestry is practiced on approximately 1.2 billion hectares worldwide, representing 30% of the global agricultural land [2]. The Food and Agriculture Organization (FAO) estimates that about 40% of global agricultural land is degraded, highlighting the urgent need for sustainable land management practices like agroforestry [3].

Soil moisture is a crucial variable for understanding and predicting various hydrological processes, including flooding, erosion, solute transport, and land-atmosphere interactions. It exhibits significant spatial and temporal variability, with both surface and subsoil moisture profoundly impacting these processes [4]. Soil moisture in agroforestry systems is an important factor that influences the productivity, sustainability, and ecological benefits of these systems. The presence of trees and shrubs can improve soil structure through root activity, which enhances water infiltration and reduces surface runoff. Tree canopy cover can reduce soil temperature and protect the soil surface from direct sunlight, thereby reducing evaporation rates [5]. Litterfall from trees adds organic matter to the soil, improving its moisture retention capacity. Trees act as windbreaks, reducing wind speed and hence the evaporation rate from the soil and crops.

Soil moisture is a critical factor influencing vegetation establishment, yet the patterns of soil moisture in agroforestry systems remain poorly understood. While numerous studies have examined soil moisture distribution across various ecosystems such as forests, grasslands, and croplands [6], and well-defined patterns exist within single ecosystems [7,8], there has been limited research on the soil moisture distribution characteristics in ecotones, the transitional areas between different ecosystems [9]. Research on ecological processes across landscape boundaries is essential for developing effective strategies for restoring and managing agroforestry systems [10]. Understanding soil moisture distribution in agroforestry systems is fundamental for examining the distribution patterns of biodiversity [11] and soil nutrients [12] at forest boundaries. In this study, we examined the soil moisture dynamics of different agroforestry systems under semiarid condition. Tree canopy is considered a major factor influencing the soil moisture dynamics. The objective of the study is to observe the influence of tree canopy cover on surface soil moisture dynamics in different agroforestry systems.

2. MATERIALS AND METHODS

2.1 Study Area

The experiment was conducted in an Agroforestry plot under the maintenance of AICRP (All India Coordinated Research Project) on Agroforestry located in Gandhi Krishi Vignana Kendra (GKVK), the main campus of the University of Agricultural Sciences, Bengaluru, Karnataka, India. Geographically, the site is located at 12° 58’ N latitude, 77°35’ E longitude having an altitude of 930 m above MSL. It is located in the Eastern Dry Zone (Zone-V) of Karnataka, India.

Table 1. Details of agroforestry systems tree species and intercrops

Sl. No.	Tree species	Field crop	Year of planting	Age (years)	Height (m)	DBH (cm)	Canopy spread	
							N-S (m)	E-W (m)
1	Teak (*Tectona grandis* L.)	Fodder Sorghum (*Sorghum bicolor*)	2010	14	8.24	51.70	5.70	3.40
2	Melia (*Melia dubia*)	Finger millet (*Eleusine coracana*)	2010	14	12.43	68.49	7.54	7.13
3	Pongamia (*Pongamia pinnata*)	Cowpea (*Vigna unguiculata*)	2017	7	3.47	20.78	3.11	2.84
4	Mahogany (*Swietenia mahagoni*)	Cowpea (*Vigna unguiculata*)	2010	14	12.89	74.38	5.10	4.60
5	Cashew (*Anacardium occidenatle*)	Sunnhemp (*Crotalaria juncea*)	2007	17	6.20	95.80	10.36	9.89
6	Mango (*Mangifera indica*)	Sunnhemp (*Crotalaria juncea*)	2007	17	6.16	77.30	5.90	5.20
7	Jamun (*Syzygium cumini*)	Sunnhemp (*Crotalaria juncea*)	2007	17	7.20	86.36	7.50	7.24

2.2 Climatic Conditions

GKVK has a tropical climate with distinct wet and dry seasons. The average annual rainfall of the station is 920 mm. The major portion of it is received during April to November with two peaks in September (196 mm) and October (164.7 mm). The mean maximum air temperature ranges from 26.3 to 33.8ºC. The mean monthly relative humidity ranges from 76 % in March to 90 % in August. Maximum bright sunshine hours are recorded in February (9.6 hr) and lowest in July (4.4 hr) and the mean wind speed is maximum during June (12.2 km h^{-1}) and the minimum in October (5.4 km h^{-1}). The open pan evaporation is directly related to the maximum and minimum temperature of the month and follows the same trend as that of maximum temperature and is maximum during March (7.5 mm per day) and April month (7.4 mm per day).

2.3 Experiment Details

The experiment was conducted in the Agro-forestry field unit of AICRP on Agroforestry at GKVK, Bangalore, Karnataka, India. Here, seven different agroforestry systems *viz.,* Teak (*Tectona grandis*), *Melia dubia*, *Pongamia pinnata*, Mahogany (*Swietenia mahagoni*), Cashew *(Anacardium occidentale)*, Mango (*Mangifera indica) and* Jamun (*Syzygium cumini)* were studied with different intercrops consisting of either a cereal or a pulse crop (Table 1). The experiment was carried out for one year (June 2022 to May 2023).

2.4 Soil Moisture Content

Soil moisture was estimated at monthly intervals using the gravimetric method [13]. Soil samples were collected in two categories that are inside canopy (area covered by tree canopy) and outside canopy from a depth of 10-20 cm and placed in stainless steel containers. The samples taken outside the tree canopy were collected 1-2 meters away from the tree. 42 soil samples were collected from all the agroforestry systems, with three samples taken from inside the tree canopy and three from outside the tree canopy in each system. These containers were weighed using a digital balance (Acculab and ALC-210) and the initial weight of the container was noted down. The samples were brought to the laboratory and containers were weighed with a soil sample and oven-dried for 24 hours at 105°C. Once the oven drying was complete the samples were weighed. Soil moisture (%) content on a dry weight basis may be calculated using the following formula:

$$\text{Soil Moisture}(\%) = \frac{\text{Weight of wet soil (g)} - \text{Weight of dry soil (g)}}{\text{Weight of dry soil(g)}} \times 100$$

(Black et al., [13].

2.5 Statistical Analysis

The experimental data obtained during the investigation were subjected to statistical analysis by applying the technique of analysis of variance (ANOVA) appropriate to the design to test the significance of the overall differences among treatments. All statistical analyses were carried out by using SPSS 16.0 software.

3. RESULTS AND DISCUSSION

3.1 Soil Moisture Dynamics under Different Agroforestry Systems

Soil moisture dynamics in agroforestry systems are influenced by the interactions between trees, crops, and the environment. Agroforestry systems, which integrate trees with crops or livestock, can have varying effects on soil moisture depending on the specific arrangement and management practices. The soil moisture (%) of different agroforestry systems under both inside and outside canopies over the months is presented in Tables 2 & 3 and Figs. 1 & 2. Inside the canopy, the period of June to August typically corresponds to the monsoon season, leading to higher soil moisture levels. Most tree species show relatively higher soil moisture levels in June and July, with a slight drop in August. *S. cumini* recorded the highest soil moisture content in June (17.04). *A. occidentale* maintains high moisture throughout this period, peaking in June (16.16). October tends to be a month where some species like *S. cumini* (21.33) and *A. occidentale* (20.83) observed peaks, likely due to residual soil moisture from the monsoon. November recorded a marked decrease in soil moisture across most species, indicating the dry post-monsoon period. December to February are typically the driest, with the lowest soil moisture levels recorded. *T. grandis* (6.47 in January) and *P. pinnata* (5.35 in January) recorded low levels. *A. occidentale* maintained slightly higher moisture levels compared to others during this dry period. March to May are the pre-monsoon summer months, where soil moisture increases

Table 2. Monthly Soil moisture (%) content under the tree canopy as influenced by different agroforestry systems

Months	*T. grandis*	*M. dubia*	*P. pinnata*	*S. mahagoni*	*A. occidentale*	*M. indica*	*S. cumini*	Mean
June	13.97	13.24	11.59	15.75	16.16	14.90	17.04	14.66^{b}
July	10.27	9.98	8.08	12.91	13.11	11.01	14.54	11.42^{d}
August	12.35	11.79	8.85	14.85	15.01	13.83	16.10	13.25^{c}
September	10.74	9.11	6.75	12.73	13.55	14.25	14.98	11.73^{d}
October	14.71	15.16	12.98	18.66	20.83	18.71	21.33	17.48^{a}
November	8.18	7.79	7.72	9.37	12.62	9.39	11.62	9.53^{f}
December	9.04	9.28	8.42	11.14	12.12	10.82	11.99	10.40^{e}
January	6.47	5.97	5.35	6.39	7.96	6.98	7.35	6.64^{h}
February	7.07	7.45	6.02	8.77	9.93	8.47	10.32	8.29^{g}
March	7.90	7.03	6.89	8.35	9.95	8.41	10.73	8.47^{g}
April	7.90	7.03	7.89	8.35	9.95	8.41	10.73	8.61^{g}
May	8.63	8.58	8.06	12.87	12.94	10.28	12.05	10.49^{e}
Mean	**9.77^{c}**	**9.37^{c}**	**8.22^{d}**	**11.68^{b}**	**12.84^{a}**	**11.29^{b}**	**13.23^{a}**	
			Months			**Species**		
S.Em±			**0.081**			**0.062**		
CD (P=0.05)			**0.228**			**0.174**		

Note: S.Em – Standard Error of mean
CD- Critical Difference

Table 3. Monthly Soil Moisture (%) content at outside the tree canopy as influenced by different agroforestry systems

Months	*T. grandis*	*M. dubia*	*P. pinnata*	*S. mahagoni*	*A. occidentale*	*M. indica*	*S. cumini*	Mean
June	11.97	11.24	9.59	13.75	14.16	12.90	15.04	12.66^{b}
July	7.77	7.48	5.58	10.41	10.61	8.51	12.04	8.91^{e}
August	10.15	9.59	6.65	12.65	12.81	11.63	13.90	11.05^{c}
September	8.74	7.11	4.75	10.73	11.55	12.25	12.98	9.73^{d}
October	12.21	12.66	10.48	16.16	18.33	16.21	18.83	14.98^{a}
November	5.98	5.59	5.52	7.17	10.42	7.19	9.42	7.33^{g}
December	7.04	7.28	6.42	10.14	11.12	9.82	10.99	8.97^{e}
January	4.466	3.968	3.345	4.388	5.956	4.98	5.347	4.64^{i}
February	5.271	5.652	4.217	6.965	8.134	6.67	8.521	6.49^{h}
March	5.899	5.033	4.894	6.347	7.953	6.414	8.731	6.47^{h}
April	5.799	4.933	5.794	6.247	7.853	6.314	8.631	6.51^{h}
May	6.43	6.38	5.862	10.672	10.735	8.079	9.854	8.29^{f}
Mean	**7.64^{d}**	**7.24^{e}**	**6.09^{f}**	**9.63^{c}**	**10.8^{b}**	**9.25^{c}**	**11.19^{a}**	
			Months		**Species**			
S.Em±			**0.052**		**0.039**			
CD (P=0.05)			**0.144**		**0.110**			

Note: S.Em – Standard Error of mean
CD- Critical Difference

again in preparation for the upcoming monsoon. *S. cumini* observed a notable increase in soil moisture in May (12.05), indicating its ability to retain soil moisture. *S. mahagoni* also shows a significant increase from March (8.35) to May (12.87).

T. grandis has a relatively open canopy which allows some sunlight to penetrate, leading to moderate evaporation rates. It has deep roots, which can access deeper soil moisture but also create competition for surface moisture. *M. dubia* is a fast-growing tree with a moderate canopy density and a relatively shallow root system which mainly accesses surface moisture. Lower soil moisture compared to other species due to higher transpiration rates and less efficient water retention. Peaks in October post-monsoon and decreases significantly in winter and summer due to lack of rain and higher evaporation.

P. pinnata has medium canopy density with nitrogen-fixing abilities, enhancing soil structure. It has a Deep-rooted system capable of accessing lower soil layers. It showed Moderate soil moisture, with a sharp decline during the dry season due to competition for water between the tree and understory crops. *S. mahagoni* has a dense canopy providing significant shade, reducing evaporation. and deep roots that can draw water from deeper soil layers. High soil moisture levels during monsoon and post-monsoon due to efficient water retention by the dense canopy and deep roots accessing subsurface moisture.

A. occidentale showed Consistently high moisture levels, peaking in October. The tree's ability to reduce surface evaporation and draw moisture from deeper layers helps maintain higher soil moisture throughout the year. It has a Moderate to dense canopy providing good ground cover and moisture retention. A deep-rooted system capable of accessing deeper soil moisture.

M. indica has a dense canopy providing significant shade, reducing evaporation Deep root system accessing lower soil moisture. High soil moisture levels during monsoon, with significant moisture retention post-monsoon due to canopy shading. Lower levels in winter and pre-monsoon are due to lower precipitation and higher evaporation rates.

S. cumini has a dense canopy with high shade provision, reducing surface evaporation and deep root system effectively accessing deeper soil moisture. Highest soil moisture levels among the species studied, peaking in October. The tree's dense canopy and deep roots help maintain high moisture levels even during dry periods.

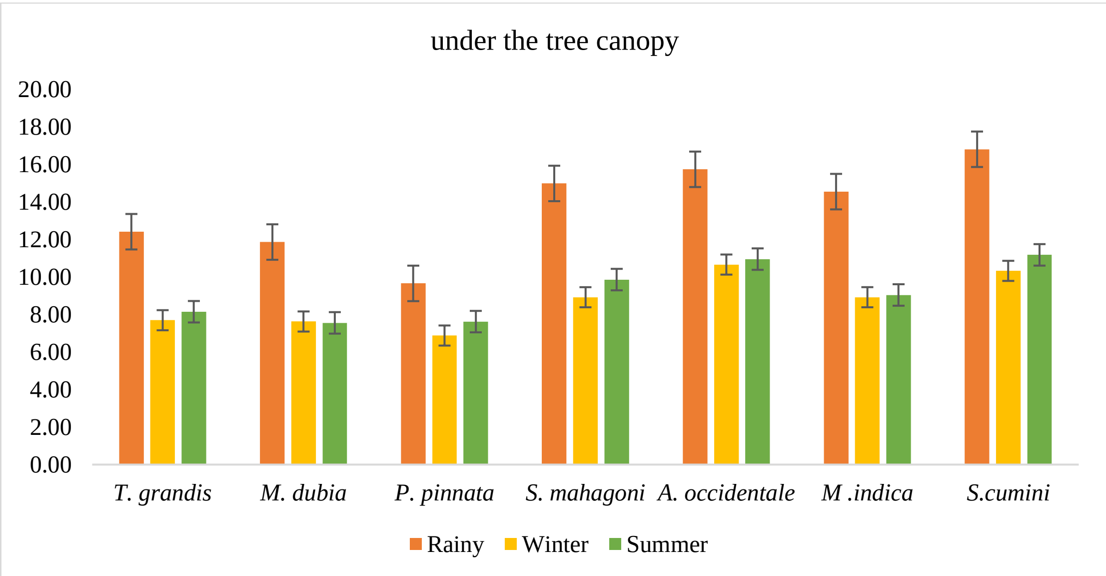

Fig. 1. Seasonal variation of Soil Moisture content (%) under the tree canopy as influenced by different agroforestry systems

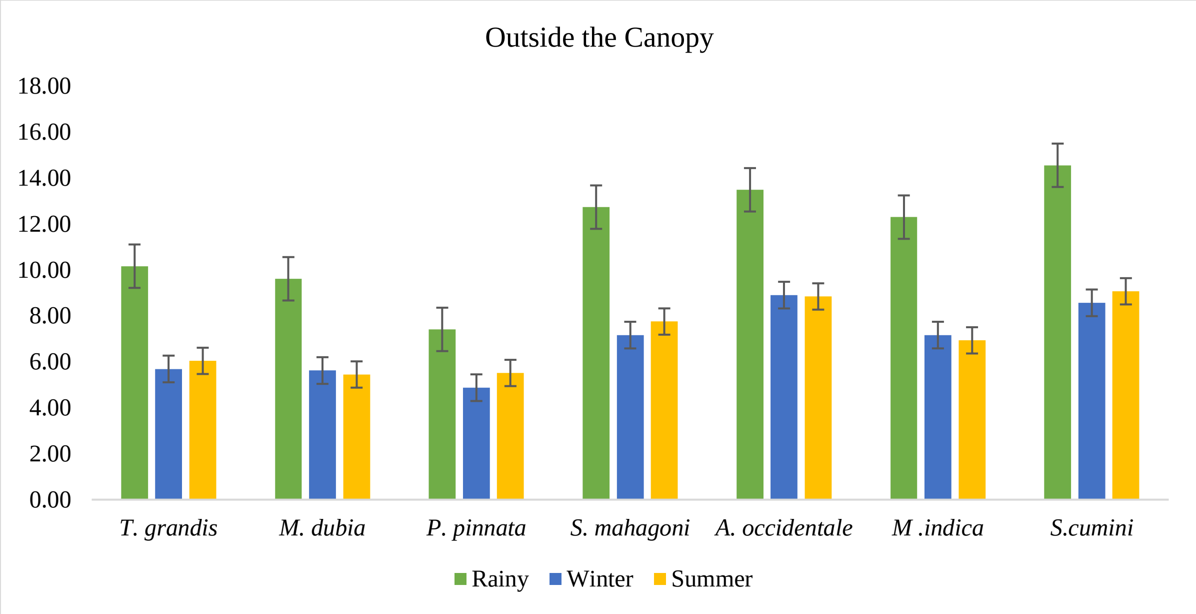

Fig. 2. Seasonal variation of soil moisture (%) content outside the tree canopy as influenced by different agroforestry systems

Trees with denser canopies (*S. cumini* and *M. indica*) tend to have higher soil moisture levels due to reduced evaporation and better microclimate conditions under the canopy. Deep-rooted species (*S. mahagoni* and *A. occidentale*) can access water from deeper soil layers, helping to maintain soil moisture during dry periods. Soil moisture is generally higher during the monsoon and post-monsoon periods due to increased rainfall and lower during the winter and pre-monsoon periods due to reduced precipitation and increased evaporation. Species that improve soil structure through leaf litter and organic matter (*T. grandis* and *P. pinnata*) can enhance soil moisture retention, although competition for water can affect overall moisture levels.

Outside the canopy, *T. grandis* exhibited the highest Soil Moisture in October (12.21) and the Lowest in January (4.47). Soil moisture decreases significantly from June to September. Peaks in October are likely due to high rainfall compared to other months and decrease again towards January. Moderate increases in the pre-monsoon months. *M. dubia* shows a similar pattern to *T. grandis* with a peak in October (12.66) and a significant drop in January. Soil moisture levels are generally lower than *T. grandis* due to the tree's faster growth and higher water uptake. *P. pinnata* exhibited Lower overall soil moisture levels outside the canopy compared to other species. Peaks in October (10.48), likely benefiting from post-monsoon rains. Sharp decrease (3.35) during the dry season due to less canopy cover and higher evapotranspiration rates.

S. mahagoni showed a significant peak in October (16.16) indicating high water retention post-monsoon. The dense canopy likely helps in reducing evaporation, but soil moisture drops significantly in the dry season (4.39) due to water uptake by the deep roots. *A. occidentale* exhibited consistently high soil moisture levels with a peak in October (18.33). The tree's characteristics help to retain moisture, but there is a noticeable drop in the dry season. High levels throughout indicate good water retention capabilities. *M. indica* showed peaks in October (16.21), similar to other species. Significant drop in the dry season, but higher moisture retention compared to some other species due to the tree's extensive root system and dense canopy [14]. *S. cumini* shows the highest overall soil moisture levels among the species, especially in October (18.83). The dense canopy and deep roots help maintain high soil moisture even outside the canopy. Significant decrease in the dry season but retains more moisture than other species.

Soil moisture levels are consistently higher inside the canopy for all tree species. This is due to reduced evaporation, better shade, and microclimatic conditions created by the canopy.

S. cumini and *A. occidentale* show the highest soil moisture retention both inside and outside the canopy, indicating their effective moisture retention capabilities. *P. pinnata* and *M. dubia* show the lowest soil moisture levels, reflecting higher water uptake and less efficient moisture retention.

The tree canopy provides shade, reducing the amount of direct sunlight reaching the soil. This lowers the soil temperature and consequently reduces the rate of evaporation. It also creates a cooler and more humid microclimate under the tree, which helps in retaining soil moisture [15]. Tree canopies intercept rainfall, reducing the direct impact of raindrops on the soil, which minimizes soil erosion and helps in better infiltration [16]. Some of the intercepted water runs down the trunk (stemflow) or drips off the leaves (dripline), which can enhance soil moisture around the base of the tree and the area just inside the canopy [17].

The accumulation of leaf litter and organic matter under the canopy improves soil structure, enhances water infiltration, and increases the soil's water-holding capacity. The litter layer acts as a mulch, reducing evaporation by covering the soil surface and conserving moisture [18]. Trees like *A. occidentale* and *M. indica* often have a substantial litter layer under their canopy, which acts as a mulch, conserving soil moisture.

Tree roots are often more extensive and deeper than those of understory vegetation, allowing trees to access water from deeper soil layers [19]. This can leave more surface moisture available. Some tree species can perform hydraulic lift, where deep roots pull up water from lower soil layers and release it into upper layers, increasing soil moisture under the canopy [20].

Soils outside the canopy receive more direct sunlight, which increases soil temperature and evaporation rates. Without the protective canopy, wind speeds are higher, leading to increased evaporation and soil drying [21]. There is typically less organic matter and leaf litter accumulation outside the canopy, leading to poor soil structure and lower water retention capacity. Areas outside the canopy may be more prone to compaction due to less root penetration and lower organic matter, reducing water infiltration [22].

All tree species showed a clear pattern of higher soil moisture during the monsoon season (June to August) and lower during the dry season (December to February). Typically observed in October, reflecting the accumulation of monsoon rains. Generally, occurs in January, likely due to reduced rainfall and lower evapotranspiration rates. For all tree species and in all seasons, soil moisture levels are higher inside the canopy compared to outside. This indicates that the canopy cover plays a crucial role in retaining soil moisture [17]. Soil moisture levels are highest during the rainy season, followed by winter, and lowest in summer both inside and outside the canopy [23]. This reflects the natural seasonal rainfall patterns and the associated soil moisture retention.

4. CONCLUSION

Soil moisture dynamics in agroforestry systems are significantly influenced by the interaction between tree species, their canopy characteristics, and environmental factors. Canopy cover plays a crucial role in retaining soil moisture, with species like *S. cumini* and *A. occidentale* exhibiting the highest moisture retention inside and outside the canopy. Deep-rooted species like *S. mahagoni* and *A. occidentale* can access water from deeper soil layers, helping to maintain moisture during dry periods. Conversely, species with less efficient moisture retention, such as *P. pinnata* and *M. dubia*, exhibit lower soil moisture levels due to higher water uptake and less canopy coverage. The agroforestry systems demonstrate that trees with denser canopies and deep root systems are more effective at retaining soil moisture, which is vital for sustaining crop productivity, especially during dry seasons. It underscores the importance of selecting appropriate tree species and managing canopy cover in agroforestry practices to optimize soil moisture levels throughout the year.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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