PLANT SCIENCE TODAY
Vol 13(2): 1-13
https://doi.org/10.14719/pst.12822

eISSN 2348-1900

RESEARCH ARTICLE

Temporal dynamics of basal soil respiration in agroforestry systems in dry-tropical Central India

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Received: 19 November 2025; Accepted: 13 February 2026; Available online: Version 1.0: 08 April 2026

Cite this article: Sovan D, Badre A, Mushineni A, Sukumar T, Sushil K, Biplab, Manisha K, Akash Y, Rajendra P, Ayyanadar A. Temporal dynamics of basal soil respiration in agroforestry systems in dry-tropical Central India. Plant Science Today. 2026; 13(2): 1-13. https://doi.org/10.14719/pst.12822

Abstract

Agri-silviculture and agri-horticulture systems, which integrate trees and crops on the same land, are important sustainable land-use strategies. However, the dynamics of basal soil respiration (BSR) in such systems are not fully unravelled. This study investigated the effects of agroforestry systems on BSR dynamics [rate (R_{BSR}) and cumulative CO_2 evolution (C_{BSR})] and identified the roles of soil organic carbon (SOC), soil moisture content (SMC) and dehydrogenase (DHA) enzyme activity on BSR. Basal soil respiration was quantified using the alkali trap method over 15 days at 3-day intervals from pre-sowing to crop maturity under 2 agroforestry systems- *Tectona grandis* L.f. (teak; agri-silviculture) and *Phyllanthus emblica* L. (aonla; agri-horticulture) and compared with a sole cropping system without trees. Black gram (*Vigna mungo* (L.) Hepper) and mustard (*Brassica juncea* (L.) Czern.) were cultivated as understory crops. Distinct temporal dynamics in BSR (R_{BSR} and C_{BSR}) were observed. In black gram, C_{BSR} increased from pre-sowing to flowering (by 24.7 % and 32.4 %) and declined toward maturity (by 10.8 % and 15.9 %) at 0–30 and 30–60 cm depths, respectively. The maximum C_{BSR} was observed in the teak-based system at flowering stage of black gram and mustard that ranged from 2.5–13.3 and 1.9–11.2 mg CO_2–C 100 g^{-1} soil at 0–30 and 30–60 cm depths, respectively. Similarly, at flowering stage of the crops, C_{BSR} ranged from 1.2–11.6 and 0.9–9.1 mg CO_2-C 100 g^{-1} soil and 2.3–9.2 and 1.3–6.1 mg CO_2-C 100 g^{-1} soil in aonla-based system and sole cropping at 0–30 and 30–60 cm depths, respectively. DHA activity (67–77 % variance) was the best predictor of C_{BSR} followed by SOC (36–78 % variance) while SMC played a fair predictor (21–25 % variance). The study highlights the potential of agroforestry systems to enhance soil biological activity and managing soil carbon while supporting sustainable crop productivity.

Keywords: agri-horticulture; agri-silviculture; *Phyllanthus emblica*; basal soil respiration; crop phenology; soil organic carbon; *Tectona grandis*

Introduction

Timber and horticulture-based agroforestry systems offer significant potential to mitigate climate change while enhancing food and nutritional security under changing climatic conditions (1). As perennial agroecosystems, agroforestry systems promote soil organic carbon (SOC) accumulation through extensive root networks, continuous litter inputs and sustained ground cover (2). Accordingly, the role of agri-silviculture and agri-horticulture in enhancing environmental sustainability and carbon (C) sequestration is well established (3, 4). Consequently, research on terrestrial soil C dynamics has become central to contemporary studies on C management across diverse land-use systems globally (5).

Soil biological processes play a critical role in regulating the C cycle, particularly through soil respiration, a major pathway of C loss to the atmosphere that exhibits pronounced seasonal variability (6, 7). Basal soil respiration (BSR) represents the steady-state respiratory activity of soil microorganisms and serves as a key indicator of soil biological functioning and health (8, 9). It reflects the inherent capacity of soil microbes to mineralize soil organic matter (SOM) under ambient conditions and is closely linked with SOC content, microbial biomass and nutrient availability (10). Higher BSR generally indicates active microbial metabolism and adequate substrate supply, whereas deviations in BSR relative to microbial biomass may reflect altered microbial efficiency or stress responses within the soil system (11).

In forest ecosystem, the combined effects of soil temperature and moisture substantially influenced BSR (12). Temporal dynamics of BSR is also influenced by crop phenology as reported in rice, maize, soybean (13, 14). However, how the BSR dynamics are modulated in agroforestry systems remains unclear. We hypothesized that agroforestry systems would modulate BSR dynamics by enhancing key soil drivers (SOC, dehydrogenase activity, soil moisture) compared to sole cropping systems. Agroecosystems will impact SOC and other soil biological properties which can elevate BSR relative to monocultures. It was observed that during the growing season, BSR was higher in older alley cropping systems compared to younger ones, pecan orchards and monocultures (15). Short-term alley cropping tends to increase soil respiration, while long-term alley cropping alters soil properties, influencing respiration intensity over time. Meta-analyses showed that agroforestry increases SOC by about 10–20 % globally, especially in arid zones and correspondingly increases soil CO_2 fluxes (16). For example, in Burkina Faso parklands, soil respiration under the canopy of *Parkia biglobosa* was about 1.54 g CO_2 m^{-2} hr^{-1},

markedly higher than in open areas (16). Seasonal changes (dry/wet) in agroecosystems may influence respiration rates as seen in secondary forests which need to be comprehensively assessed (17).

To date, studies examining the influence of agroforestry systems on the dynamics of BSR are limited and none have explicitly evaluated its dynamics across deeper soil profiles (0–30 and 30–60 cm) in the dry tropical region of India, despite the strong practical relevance of agroforestry in these landscapes. Agroforestry systems provide an ideal framework for investigating temporal BSR dynamics across crop growth stages, as tree–crop interactions intensify belowground biological activity and carbon turnover. Trees enhance SOC inputs through litterfall and root exudation, thereby supplying substrates for microbial respiration. Variations in crop phenology, soil biological activity and canopy development further regulate BSR dynamics. Moreover, combined tree and crop canopies buffer soil microclimate and conserve moisture, creating favorable conditions for microbial processes, including basal respiration. Compared with monocropping systems, agroforestry-based tree-crop combinations may sustain more stable BSR rates, thereby enhancing SOM decomposition and nutrient cycling. This study tested the hypothesis that integration of trees and crops within the same land unit significantly modulates BSR dynamics. The specific objectives were to (i) assess the temporal dynamics of BSR under agroforestry systems and (ii) elucidate the influence of tree–crop combinations, crop phenology, soil depth and key soil factors including soil moisture, dehydrogenase activity and SOC on BSR variability.

Materials and Methods

Study location, climate and soil

The experimental site is located at ICAR-Central Agroforestry Research Institute (CAFRI), Jhansi, India (25.5 °N, 78.5 °E, 285 m from mean sea level), which represents dry tropical Bundelkhand region. Climate of the study site is monsoonal dry tropics and is characterized by hot dry summers (April–June) and cold winters (December–January) with mean annual rainfall 908 mm, ~90 % of which is received during July–September. The mean maximum and minimum temperature of the study site is 32.0 °C and 16.9 °C, respectively. Mean soil surface temperature of the study site in kharif (rainy) and rabi (winter) season ranged from 29.9 °C and 19.5 °C, respectively. Soil of the site is black and red intermixed, loam to clay loam in texture with a bulk density 1.31 Mg m^{-3}, slightly alkaline (pH 7.80) in nature without any salinity, with low soil organic C (3.8 g kg^{-1}) and available N (198.1 kg ha^{-1}), medium available P (19.4 kg ha^{-1}) and high available K (410.2 kg ha^{-1}).

Agroforestry systems

This study focused on two well–established agroforestry systems comprising 28-year-old teak (*Tectona grandis* L.) and 27-year-old aonla (*Phyllanthus emblica* L.) as tree components spread across 1.0 and 0.5 ha area, respectively. Canopy cover for teak-based and aonla -based agroforestry systems were about 23 % and 25 %, respectively. These tree species are the predominant multipurpose tree species (MPTS) for agroforestry systems in the central India, which involved strategic plantation of tree-rows (teak: 4 × 4 m; aonla: 8 × 8 m spacing), creating alleys for growing crops. Understory crops namely black gram (*Vigna mungo* (L.) Hepper) and mustard (*Brassica juncea* (L.) Czern.) were grown in sequence in the kharif (rainy) and subsequently in rabi (winter) season respectively in the year 2024 where sowing of black gram (cv. Azad-2) was done in the month of July and the matured crop was harvested in the month of November. Subsequently, mustard (cv. Giriraj) was sown in November and harvested in March 2025. Cultivation was done following the recommended agronomic practices for Bundelkhand region where black gram and mustard was cultivated under rainfed and irrigated conditions, respectively. For comparison, there was a sole cropland (without trees which served as control) in an area of 0.5 ha where similar cropping sequence was followed. The crop management practice in the agroforestry systems and in the conventional sole cropland was similar and uniform.

Soil sampling and analyses

Across the studied agroecosystems, soil was sampled at specific intervals that represent key crop phenology stages: pre-sowing (before the seeds sowing stage) (BS-1) of black gram in July 2024; flowering stage (entire crop completely flowered) of black gram (BS-2) in September (2024) and maturity stage (completely matured and crop harvested) of black gram (BS-3) in November (2024). Similar techniques were followed for flowering stage of mustard (MS-1) in February (2025) and maturity stage of mustard (MS-2) in March (2025). For sampling, a conventional zigzag pattern was followed and the soils were collected from two depths (0–30 and 30–60 cm) in quadruplets using a soil auger from the agroforestry systems and sole cropland. This represented 24 soil samples (3 systems × 2 depths × 4 replications) collected in each crop phenology and 120 soil samples collected during the entire study. After removal of plant roots and other visible debris, samples were quickly transported to the laboratory in sterile and clean zippered polyethylene bags and a portion was stored at 4 °C until analysis. Gravimetric soil moisture content (SMC) was promptly measured after drying the samples at 105 °C for 24 hr till a constant weight achieved. Soil moisture content was calculated and expressed in terms of percentage. The other portion of samples were air dried at room temperature, ground and passed through a 2.0 mm sieve and analyzed for SOC by wet-oxidation method (18).

Basal soil respiration

It was quantified as microbial CO_2 evolution method (19). A 100 g field-moist soil sample was placed in an airtight glass bottle (500 mL) for each experimental unit where the soil moisture was adjusted to 60 % of maximum water holding capacity (MWHC) before start of the incubation experiment to maintain microbial activity. The units were pre-incubated for 3 days at 28 °C. Afterwards, the lids of the units were opened and kept at room temperature for 1 hr for natural gas exchange and placed back in the incubator where the units were incubated for 15 days at 28 °C. Following the pre-incubation period, glass vials containing 10 mL of 1 N NaOH to capture CO_2 evolved were placed in the glass bottles. The evolved CO_2 was measured every three days interval by titrating with 1 N HCl in presence of excess 1 M $BaCl_2$. To discern the temporal dynamics of BSR across the crop phenology we have expressed it in two scales: firstly, the basal soil respiration rate (R_{BSR}) throughout a 3-day incubation intervals onward 15 days in mg CO_2-C 100 g^{-1} soil d^{-1} and secondly, cumulative CO_2 evolved over a 15-day period (C_{BSR}) in mg CO_2-C 100 g^{-1} soil.

Dehydrogenase (DHA) enzyme assay

The refrigerated soil samples were thawed at room temperature. One-gram thawed sample (oven-dry basis) was mixed with 0.2 mL of triphenyl tetrazolium chloride (3 % TTC) and 0.5 mL of glucose (1 %) solution in a 15 mL stoppered test tubes and the suspension was shaken vigorously and kept in a heating incubator at 28 °C for 24 hr.

The dehydrogenase enzyme activity was assayed by monitoring the rate of reduction of TTC to pink coloured triphenyl formazon (TPF), which was quantified colorimetrically at 485 nm using a spectrophotometer (AU 2702, Systronics) and was expressed in µg TPF g^{-1} soil 24 hr^{-1} (20).

Statistical analysis

For all analyses, the means and standard errors were calculated based on four replications using MS-Excel software. The data obtained from the experiment were statistically analysed using completely randomized design (CRD). Statistical analysis was conducted using 'OPSTAT', employing a three-way analysis of variance (ANOVA) to assess the statistical significance of the treatments and their interactions. In all cases, post-hoc analysis was performed using Fisher's least significant difference (LSD) test to compare means. Pearson's correlation (r-value) and non-linear regression analysis was done to elucidate the relationship between cumulative basal soil respiration (C_{BSR}) and the measured soil properties using MS-Excel software. Unless otherwise stated, a probability level of 5 % was considered as the threshold for statistical significance.

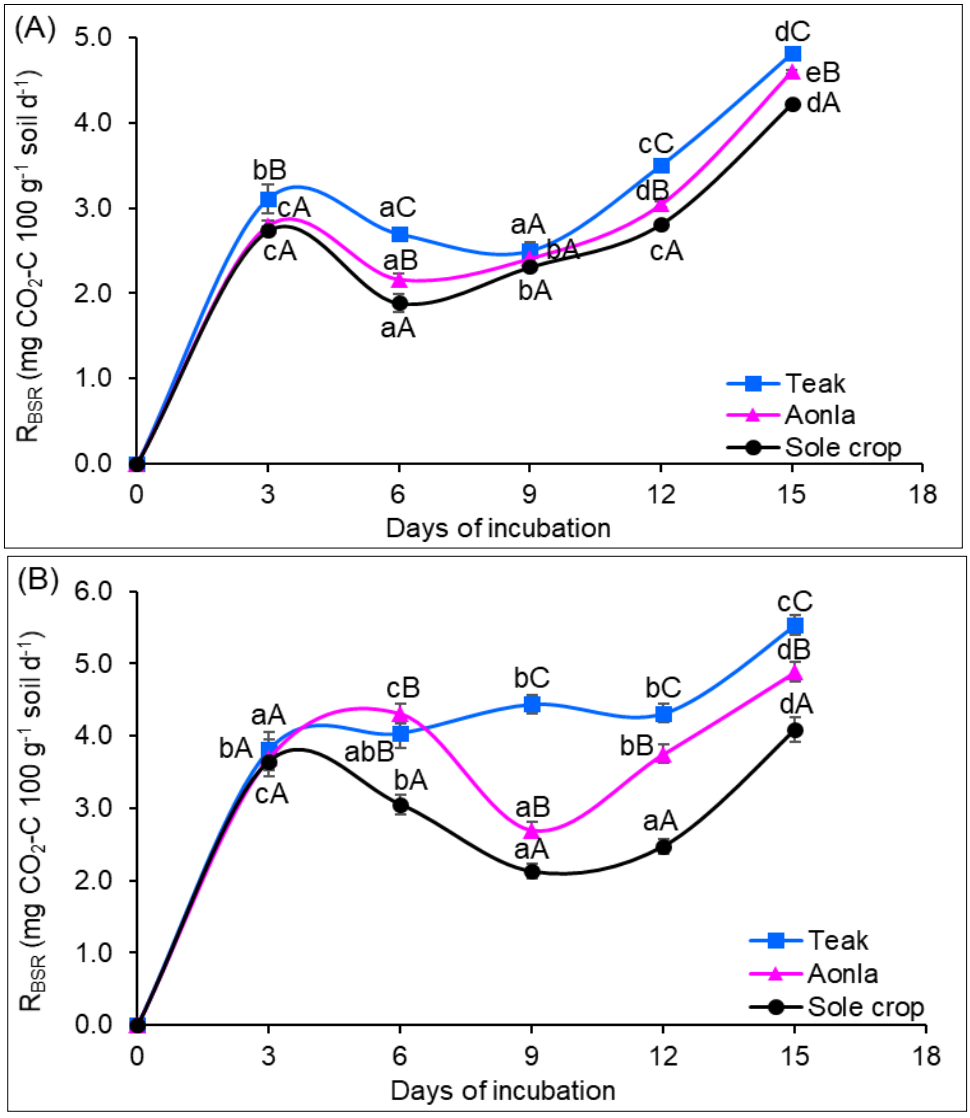
Results

Dynamics of basal soil respiration rate (R_{BSR})

Agroforestry and sole cropping systems significantly ($p < 0.001$) impacted on the temporal dynamics of R_{BSR} across the soil depths throughout the incubation intervals (Fig. 1, 2). At pre-sowing stage (BS-1) with black gram, teak-based system showed higher R_{BSR} with 4.81 and 3.55 mg CO_2-C 100 g^{-1} soil d^{-1} at 0–30 cm and 30–60 cm, respectively and the rate in teak-based system was higher than aonla-based system and sole cropland (Fig. 1, 2). At flowering stage of black gram (BS-2), R_{BSR} increased to 5.53 mg CO_2-C 100 g^{-1} soil d^{-1}, whereas, at maturity (BS-3) it decreased to 2.4 mg CO_2-C 100 g^{-1} soil d^{-1} (Fig. 1, 2). Comparatively higher rate was observed during black gram as understory crop than mustard across all the crop phenological stages and surface soil (0–30 cm) showed relatively higher R_{BSR} than the sub-surface soil (30–60 cm) (Fig. 1, 2). Moreover, relatively much higher R_{BSR} was observed in agroforestry systems than in the sole cropland (Fig. 1, 2).

Dynamics of cumulative basal soil respiration (C_{BSR})

The impact of the tree-crop combinations, crop phenology and the soil-depth as well as their interactions on C_{BSR} over a 15-day incubation period have been comprehensively depicted through ANOVA (Table 1 and Supplementary Table 1–3). Although non-significant, prominent impact of agroforestry and sole cropping systems was observed in C_{BSR} across the soil depths (Fig. 3). Teak-based agroforestry system showed higher C_{BSR} than aonla-based agroforestry system and the sole cropland. With respect to soil depth, the highest C_{BSR} i.e. 66.46 and 55.69 mg CO_2-C 100 g^{-1} soil at 0–30 and 30–60 cm, respectively was observed at BS-2, where black gram was used as understory crop. The C_{BSR} declined from BS-3 stage onwards and significantly reduced during MS-1 and MS-2 where mustard was used as understory crop (Fig. 3). During the flowering stage of black



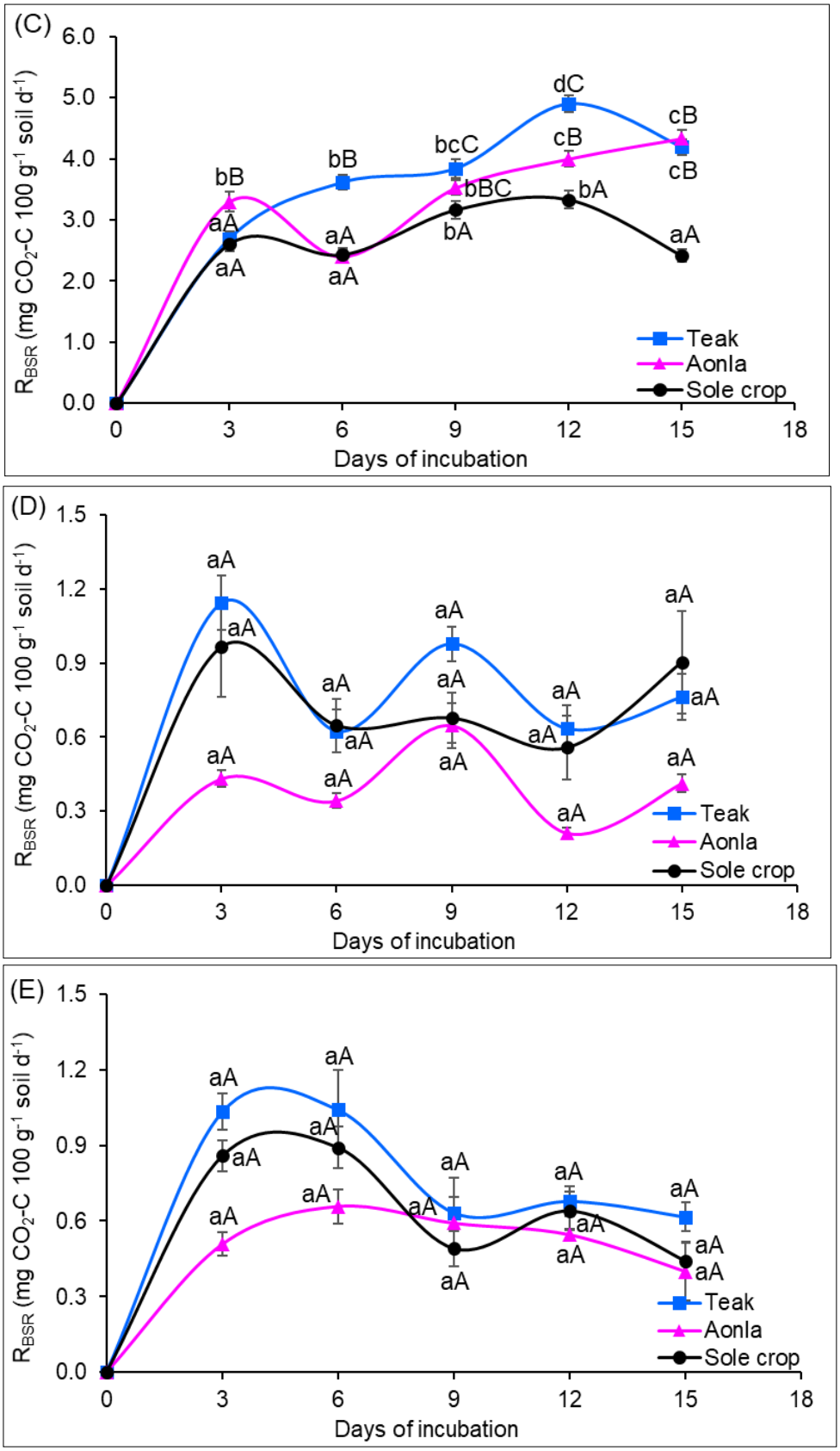
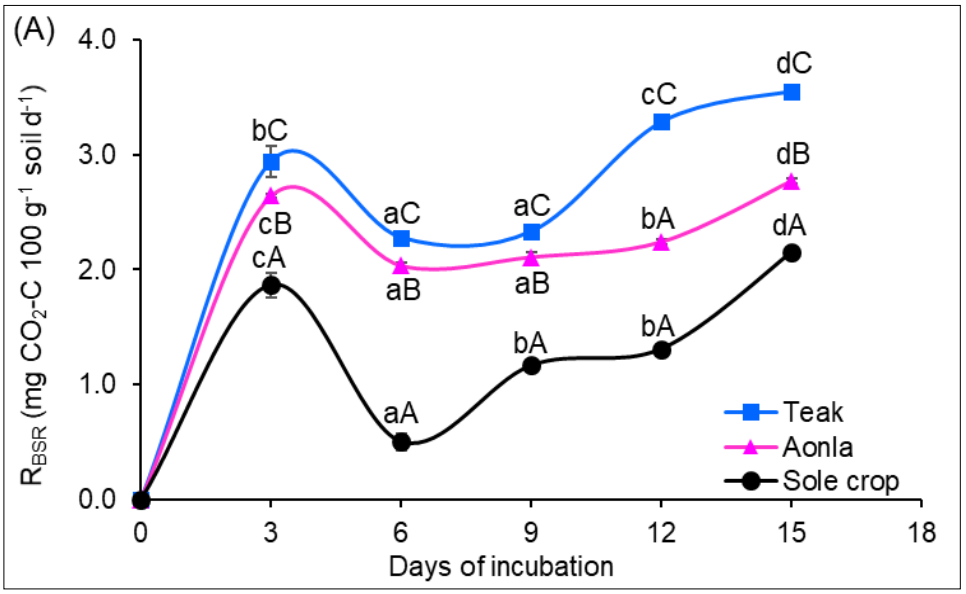
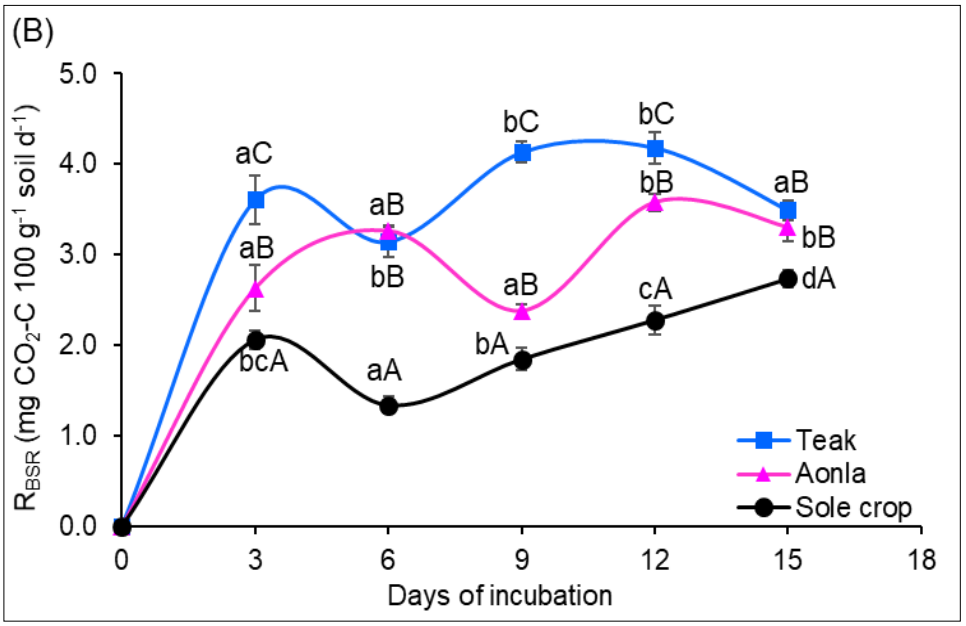
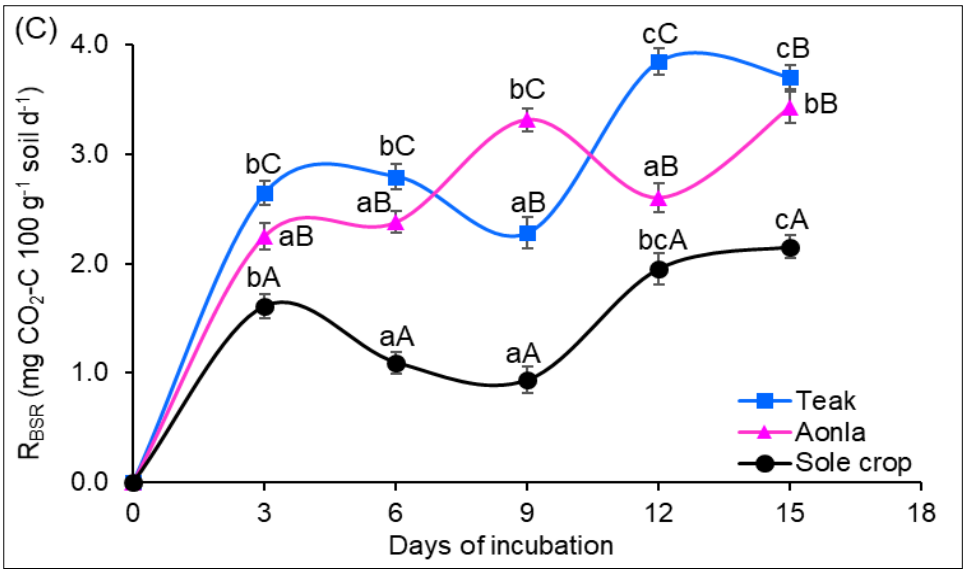


Fig. 1. Dynamics of basal soil respiration rate (R_{BSR}) observed during 3-days incubation intervals at surface soil (0-30 cm) as modulated by agroforestry and sole cropping.

A) Pre-sowing stage of black gram (BS-1); B) Flowering stage of black gram (BS-2); C) Maturity stage of black gram (BS-3); D) Flowering stage of mustard (MS-1); E) Maturity stage of mustard (MS-2). Bars on the markers indicate standard error (n = 4). Lines followed by uncommon lowercase letter indicate difference ($p < 0.05$) between incubation intervals within a land use system and by uncommon uppercase letter indicate difference ($p < 0.05$) between land use systems within an incubation interval as per Fisher's LSD.


(A)
4.0
3.0
2.0
1.0
0.0
R_{BSR} (mg CO_2-C 100 g^{-1} soil d^{-1})
bC
cB
cA
aC
aB
aC
aB
cC
bA
aA
bA
bA
dC
dB
dA
Teak
Aonla
Sole crop
0
3
6
9
12
15
18
Days of incubation


(B)
5.0
4.0
3.0
2.0
1.0
0.0
R_{BSR} (mg CO_2-C 100 g^{-1} soil d^{-1})
aC
aB
bcA
aB
bB
aA
bC
aB
bA
bC
bB
cA
aB
bB
dA
Teak
Aonla
Sole crop
0
3
6
9
12
15
18
Days of incubation


(C)
4.0
3.0
2.0
1.0
0.0
R_{BSR} (mg CO_2-C 100 g^{-1} soil d^{-1})
bC
aB
bA
bC
aB
aA
bC
aB
aA
cC
aB
bcA
cB
bB
cA
Teak
Aonla
Sole crop
0
3
6
9
12
15
18
Days of incubation

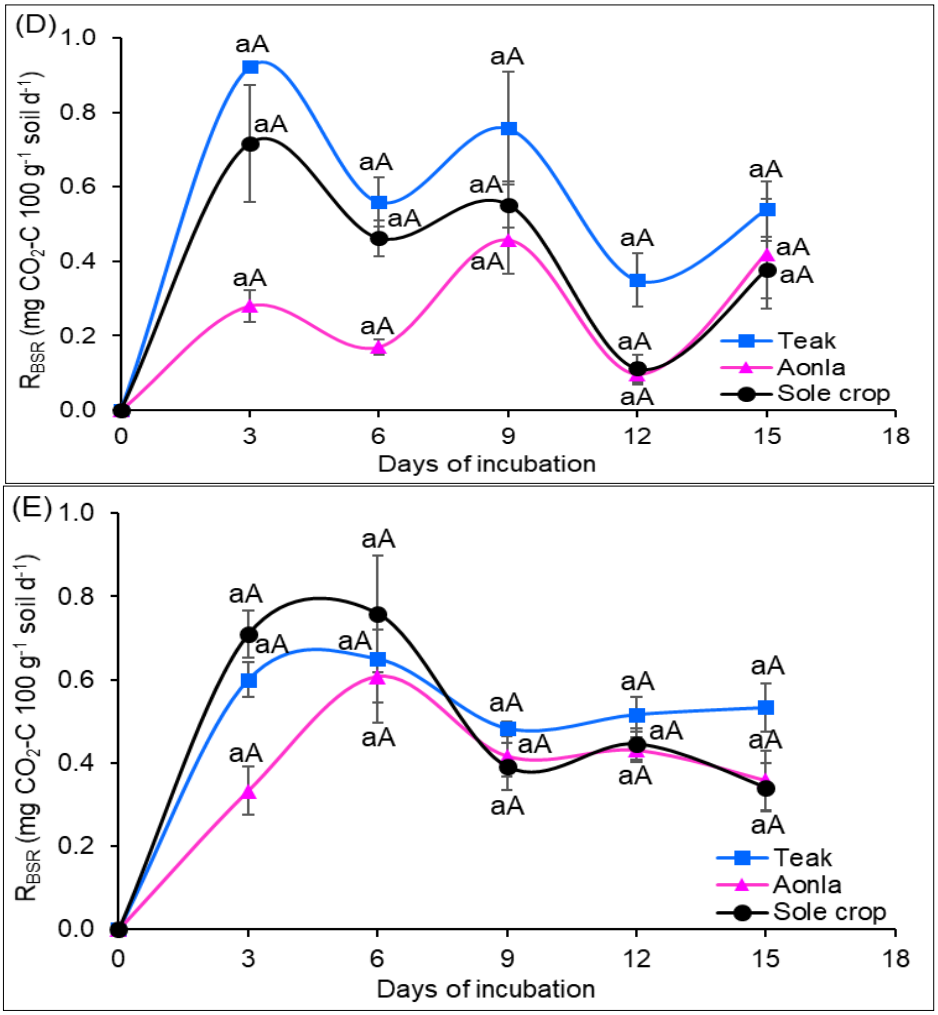


Fig. 2. Dynamics of basal soil respiration rate (R_{BSR}) observed during 3-days incubation intervals at subsurface soil (30-60 cm) as modulated by agroforestry and sole cropping.

A) Pre-sowing stage of black gram (BS-1); B) Flowering stage of black gram (BS-2); C) Maturity stage of black gram (BS-3); D) Flowering stage of mustard (MS-1); E) Maturity stage of mustard (MS-2).

Bars on the markers indicate standard error (n= 4). Lines followed by uncommon lowercase letter indicate difference ($p < 0.05$) between incubation intervals within a land use system and by uncommon uppercase letter indicate difference ($p < 0.05$) between land use systems within an incubation interval as per Fisher's LSD.

Table 1. The results of analysis of variance (ANOVA) showing means and statistical significance of three main effects [crop phenology (C), land use system (L) and soil depth (D)] and their interactions on measured soil properties.

Within each soil property and fixed effect, means followed by uncommon letter are significantly different as per Fisher's LSD.

Main effect	Measured soil properties			
	Cumulative BSR	Dehydrogenase	Soil moisture	Soil organic C
	mg CO_2-C 100 g^{-1} soil	µg TPF g^{-1} soil 24 hr^{-1}	(%)	(%)
Crop phenology (C)				
BS–1	7.88c	3.61d	14.38b	0.43a
BS–2	10.10a	5.11c	23.75a	0.44a
BS–3	8.77b	4.16d	13.42bc	0.4a
MS–1	1.67d	7.16a	13.00c	0.47a
MS–2	1.76d	5.87b	7.17d	0.48a
Land use system (L)				
Teak–agroforestry	7.22a	5.90a	16.40a	0.56a
Aonla–agroforestry	6.07b	5.32b	15.34b	0.47b
Sole cropping	4.81c	4.33c	11.30c	0.34c
Soil depth (D)				
0–30 cm	6.93a	6.15a	14.93a	0.57a
30–60 cm	5.14b	4.22b	13.76b	0.34b
P-values				
C	<0.0001	<0.0001	<0.0001	0.2171
L	<0.0001	<0.0001	<0.0001	<0.0001
D	<0.0001	<0.0001	0.0053	<0.0001
C × L	<0.0001	0.5292	0.0032	0.9999
C × D	0.0074	0.0030	0.0014	0.9998
L × D	0.1992	0.1953	0.4981	0.0010
C × L × D	0.9242	0.9198	0.8045	0.9560

BS-1: Pre-sowing stage of black gram, BS-2: Flowering stage of black gram, BS-3: Maturity stage of black gram, MS-1: Flowering stage of mustard, MS-2: Maturity stage of mustard

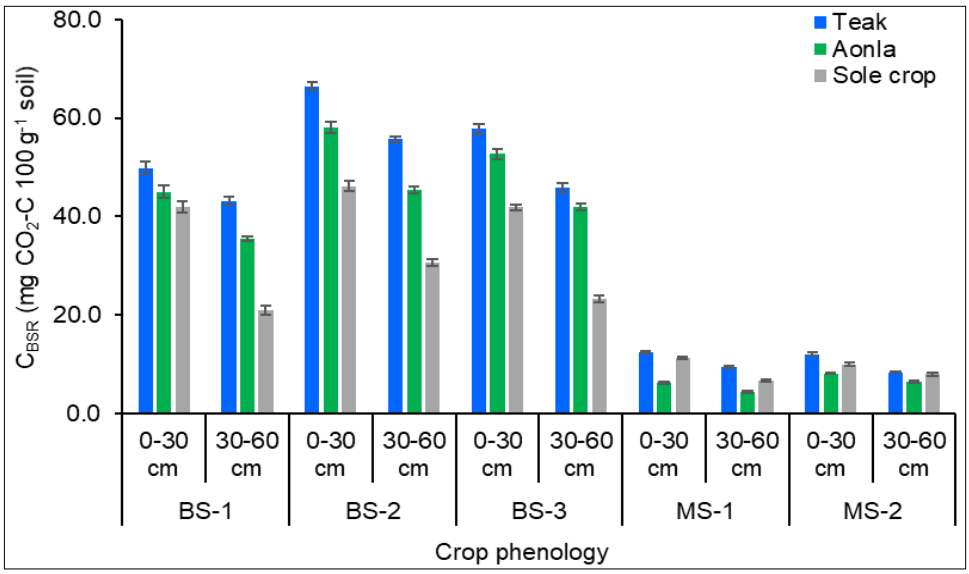


Fig. 3. Dynamics of cumulative basal soil respiration (C_{BSR}) over a 15-day incubation period as modulated by agroforestry and sole cropping.

BS-1: Pre-sowing stage of black gram, BS-2: Flowering stage of black gram, BS-3: Maturity stage of black gram, MS-1: Flowering stage of mustard, MS-2: Maturity stage of mustard. Columns followed by bars indicate standard error (n= 4). For clarity, analysis of variance (ANOVA) results showing the interactive effects (crop phenology, land use system and soil depth) on C_{BSR} have been given in Table 1 that showed a non-significant three-factor interaction.

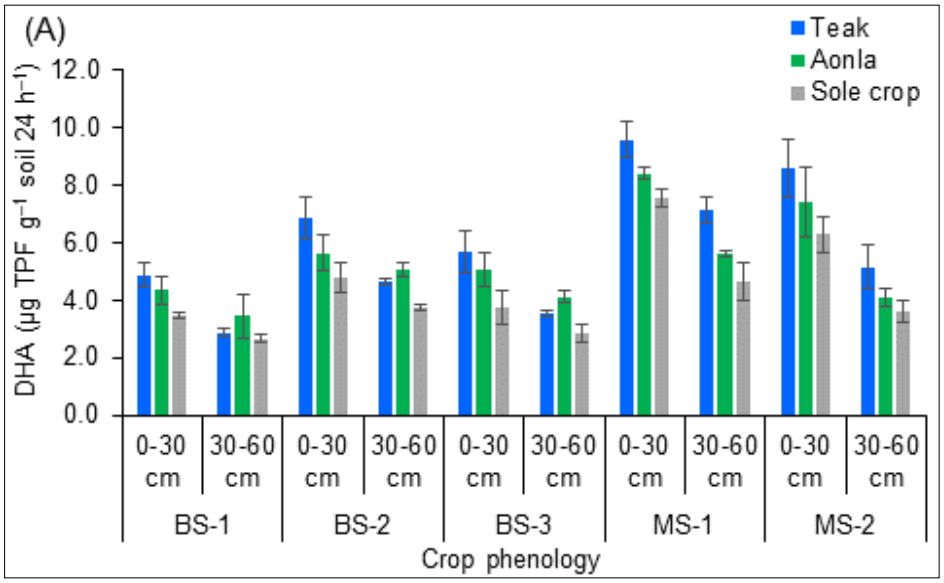
gram (BS-2) relatively higher C_{BSR} was observed across the land use systems and the soil depths. Across agroforestry and crop phenology, surface (0–30 cm) soil showed relatively higher C_{BSR} over a 15-day incubation period that ranged from 6.14 to 66.46 mg CO_2-C 100 g^{-1} soil over the subsurface (30–60 cm) soil where it ranged from 4.27 to 55.69 mg CO_2-C 100 g^{-1} soil (Fig. 3).

Dehydrogenase, soil moisture and soil organic C

Agroforestry and sole cropping systems significantly ($p < 0.05$) influenced DHA, SMC and SOC across the soil depths (Fig. 4, Table 1). Teak-based agroforestry showed higher DHA (9.59 µg TPF g^{-1} soil 24 hr^{-1}), soil moisture (27.60 %) and SOC (0.73 %) at 0–30 cm respectively than the other two systems (aonla and sole crop). Similarly, teak-based agroforestry exhibited higher DHA (7.16 µg TPF g^{-1} soil 24 hr^{-1}), soil moisture (24.18 %) and SOC (0.42 %) at 30–60 cm respectively than the other two systems (aonla and sole crop). These parameters (DHA, SMC and SOC) were found higher at the flowering stage of the understory crops than other phenological stages (Fig. 4, Table 1, Supplementary Table 1). For instance, the highest value of DHA (9.59 µg TPF g^{-1} soil 24 hr^{-1}), soil moisture (27.6 %) and SOC (0.72 %) were observed at MS-1, BS-2 and MS-1 i.e. at respective flowering stages of the understory crops at 0–30 cm of teak-based agroforestry. However, these values were noted higher in surface soil (0–30 cm) than the sub-surface soil (30–60 cm) across in all the systems (Supplementary Table 3). For example, DHA, soil moisture and SOC of surface soil ranged from 3.47 to 9.59 µg TPF g^{-1} soil 24 hr^{-1}, 5.92 to 27.60 % and 0.40 to 0.73 % while in subsurface soil it ranged from 2.66 to 7.16 µg TPF g^{-1} soil 24 h, 5.29 to 24.18 %, 0.24 to 0.42 % across the 3 agroecosystems (Fig. 4).

Interrelationships between C_{BSR} and other measured soil parameters

Our results showed significant correlations between C_{BSR} and DHA ($r = 0.87$, $p < 0.01$ in black gram; $r = 0.78$, $p < 0.01$ in mustard) and between C_{BSR} and SOC ($r = 0.84$, $p < 0.01$ in black gram; $r = 0.57$ in mustard) (Table 2). Although there was moderate correlation ($r = 0.46$ in black gram; $r = 0.33$ in mustard) between C_{BSR} and SMC (Table 2), a non-linear regression fitting showed that 21 to 25 % of variation in C_{BSR} could be predicted by SMC across the cropping systems (Fig. 5). However, about 67 to 77 % and 36 to 78 % of variation in C_{BSR} was regulated by DHA and SOC across the cropping systems as indicated from the non-linear regression analysis,



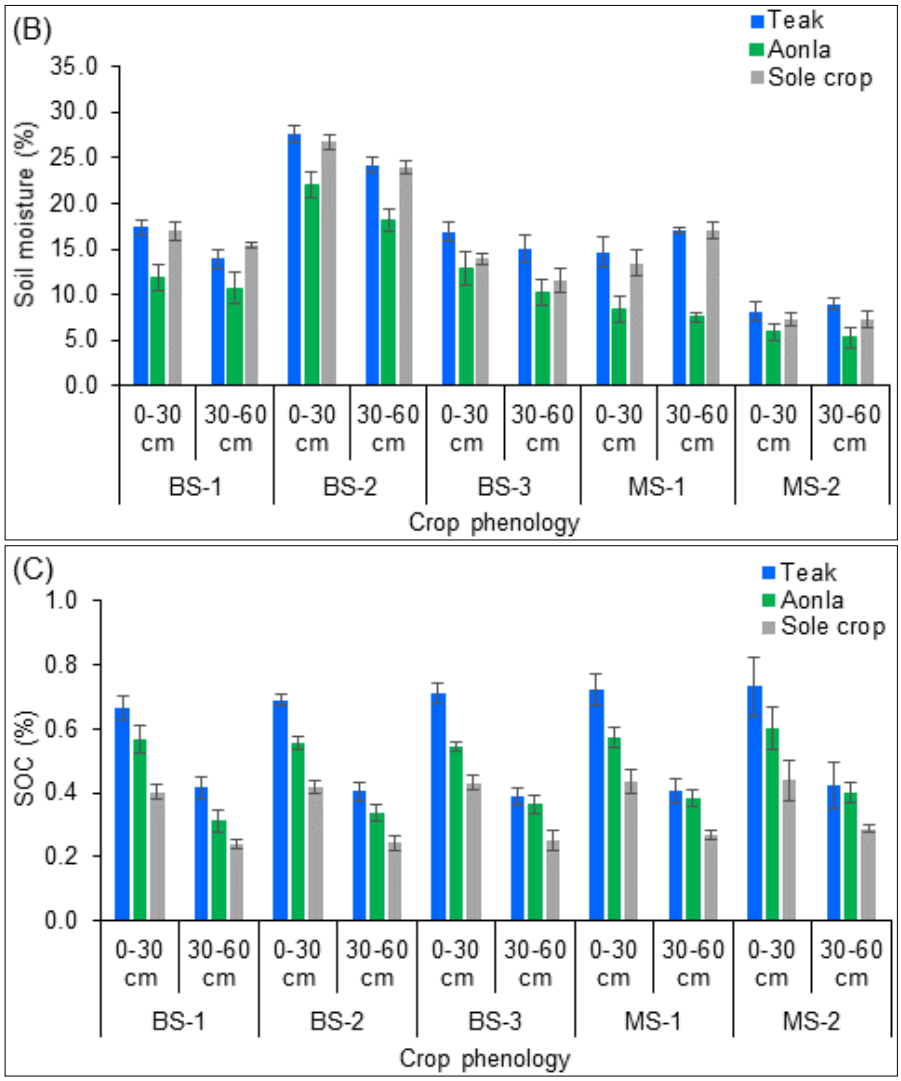


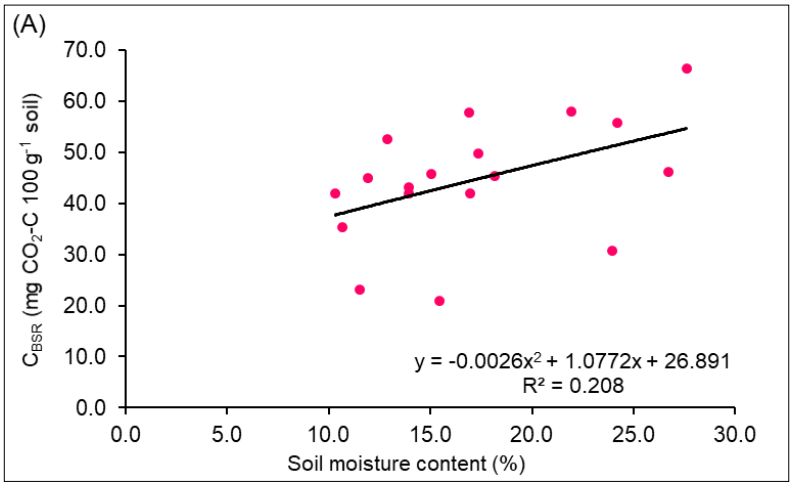
Fig. 4. Dynamics of (A) dehydrogenase activity (DHA), (B) soil moisture content (SMC), and (C) soil organic carbon (SOC) as influenced by agroforestry and sole cropping. BS-1: Pre-sowing stage of black gram, BS-2: Flowering stage of black gram, BS-3: Maturity stage of black gram, MS-1: Flowering stage of mustard and MS-2: Maturity stage of mustard. For clarity, analysis of variance (ANOVA) results including the interactive effects (crop phenology, land use system and soil depth) on DHA, SMC and SOC have been given in Table 1 that showed non-significant three-factor interaction.

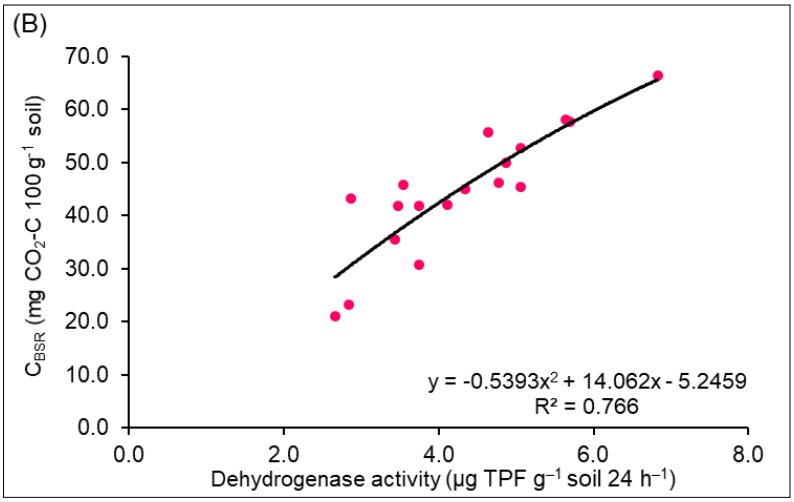
Table 2. Pearson's correlation matrix (r-value) between cumulative basal soil respiration (C_{BSR}) and soil properties

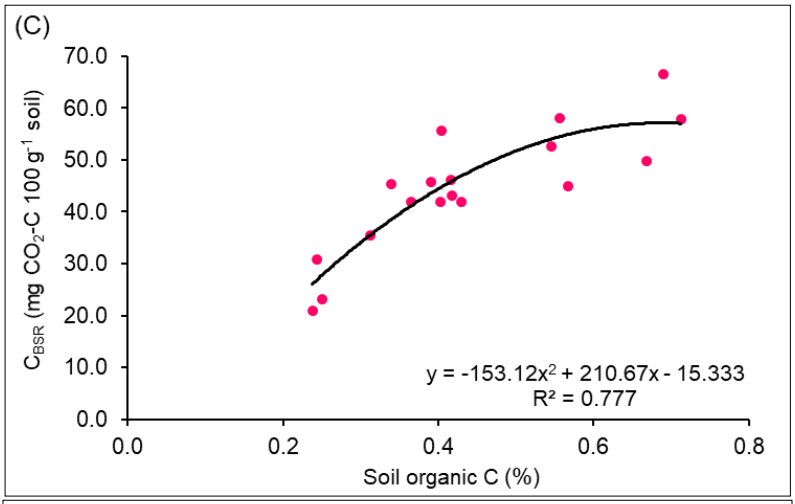
Soil property	Cumulative basal soil respiration (C_{BSR})	
	Black gram	Mustard
Soil moisture (SMC)	0.46	0.33
Dehydrogenase (DHA)	0.87**	0.78**
Soil organic C (SOC)	0.84**	0.57

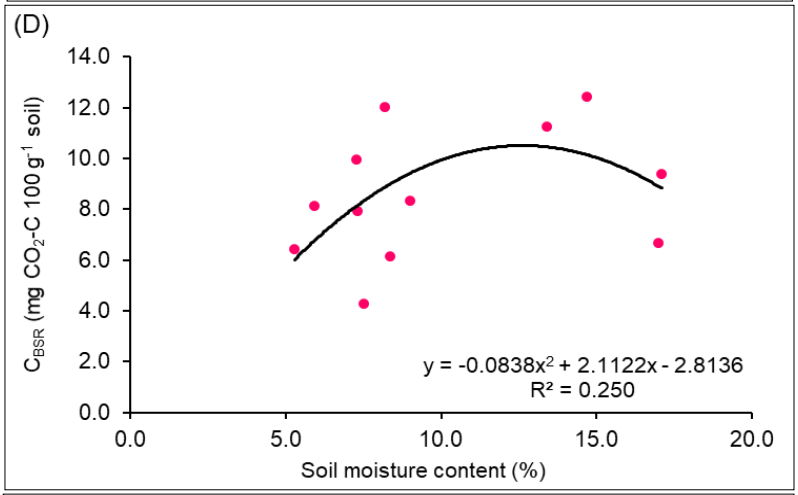
**Correlation is significant at $p = 0.01$ level (two tailed)

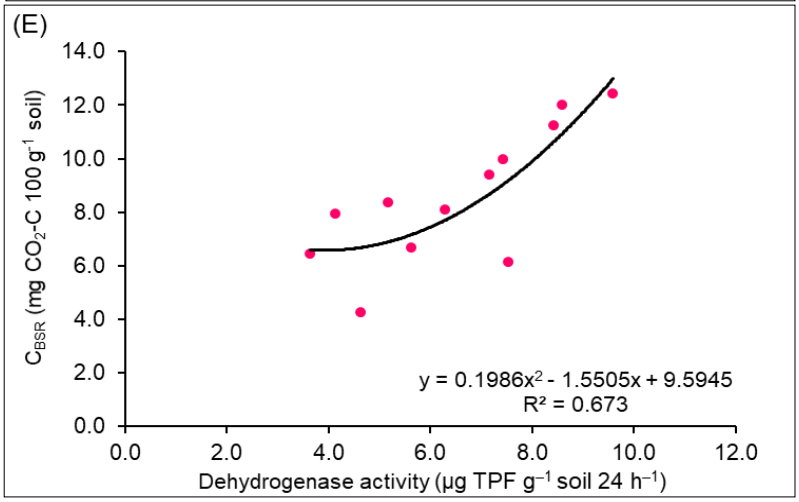
*Correlation is significant at $p = 0.05$ level (two tailed)




(B)
C_{BSR} (mg CO_2-C 100 g^{-1} soil)
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.0
2.0
4.0
6.0
8.0
y = -0.5393x² + 14.062x - 5.2459
R² = 0.766
Dehydrogenase activity (µg TPF g^{-1} soil 24 h^{-1})


(C)
C_{BSR} (mg CO_2-C 100 g^{-1} soil)
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.0
0.2
0.4
0.6
0.8
y = -153.12x² + 210.67x - 15.333
R² = 0.777
Soil organic C (%)


(D)
C_{BSR} (mg CO_2-C 100 g^{-1} soil)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0.0
5.0
10.0
15.0
20.0
y = -0.0838x² + 2.1122x - 2.8136
R² = 0.250
Soil moisture content (%)


(E)
C_{BSR} (mg CO_2-C 100 g^{-1} soil)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
y = 0.1986x² - 1.5505x + 9.5945
R² = 0.673
Dehydrogenase activity (µg TPF g^{-1} soil 24 h^{-1})

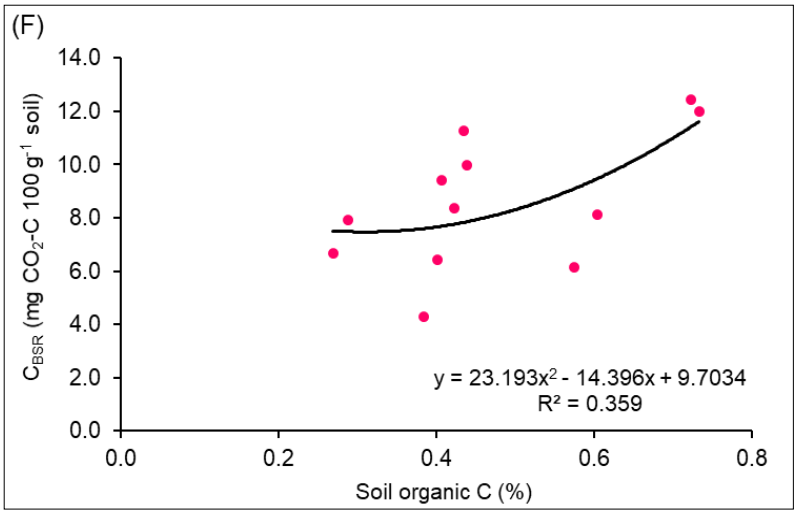


Fig. 5. Non-linear regression between cumulative basal soil respiration (C_{BSR}) over a 15-day incubation period and other measured soil properties. (A–C): Black gram; (D–F): Mustard *$p < 0.05$; **$p < 0.01$

respectively.

Discussion

Strong temporal dynamics of BSR (C_{BSR} and R_{BSR}) was observed in the studied agroecosystems. Microbial respiration and plant growth in temporal scale was previously reported for soils in temperate climate (21). We observed a greater BSR at flowering than at crop maturity. Similar trend as peak soil respiration during anthesis followed by a decline at maturity was reported in field crops previously (13, 22, 23). These results were attributed of higher root volumes and greater deposition of root exudates during anthesis that attract microorganisms by providing food and energy (23). This, in turn, flourishes the rhizosphere microbial populations that can eventually produce higher CO_2, through microbial respiration and corroborates with our observation (13). The positive influence and higher microbial activity indices under agroforestry (36 % higher enzymatic activity, 65 % higher soil respiration) compared to conventional farming system has been suggested earlier (24).

We observed that BSR was higher under black gram as understory crop than mustard. This is because soil surface was extensively covered by the crop and the soil moisture was abundant as black gram is considered as an effective cover crop (25). This vegetative cover alters the microclimate by reducing direct solar radiation and minimizing surface evaporation, thereby retaining more soil moisture. This could be the reason for higher soil moisture in black gram growing season. Additionally, monsoonal precipitation during black gram growing season saturated the soil, filling its pores and enhancing soil moisture through increased micropore water storage. Conversely, during the mustard growing season (winter or rabi), less tree canopy coverage, due to the deciduousness of the trees, resulted in reduced soil cover causing evaporation losses of soil moisture. Moreover, scanty precipitation during this period contributed to decreased soil moisture availability, which could be another factor responsible for it (17). Thus, phenology-driven canopy cover change and seasonal attributes (precipitation) significantly influenced BSR and soil moisture dynamics, with higher magnitude during the flowering stage of black gram compared to mustard. Decrease of soil moisture and DHA from flowering to maturity stage are again attributed to the lowered soil rhizo-microbial activity (13). On the other hand, temporal variation in SOC was subtle, reflecting its recalcitrant nature as a fraction of SOM that undergoes little change over short timeframes (26).

The magnitude of observed BSR was much intensified in the agroforestry systems over the sole cropland. Higher magnitude of BSR indicates a more active soil microbial community, leading to better SOM mineralization and permanence, nutrient availability and overall soil health (11). The findings align with recent studies highlighting that teak-based agroforestry significantly improves soil C dynamics and microbial functioning, ultimately enhancing soil respiration and fertility (27). This enhancement was primarily attributed to relatively higher soil moisture and SOC, which collectively stimulated microbial processes such as SOM decomposition, mineralization and respiration throughout the crop phenology. Similarly, a previous study reported that soil respiration significantly depends on available soil nutrients, SMC and SOC (9). Total soil microorganism count is often determined by SOC (28), which serves as energy source and harbours greater number of soil microorganisms (11). A high number of soil microorganisms makes respiration high because it produces higher quantities of CO_2. Similarly, another study observed significantly higher microbial respiration, growth and biomass at the forest site, which contained 4.3 % SOC compared to the agricultural site with 0.9 % SOC, which supports our results (21).

Surface soil consistently recorded higher BSR, DHA, SMC and SOC than sub-surface soil, irrespective of agroforestry and crop phenology. Higher BSR could be due to adequate soil moisture, higher SOC levels, better nutrient content and improved aeration in the topsoil and all of which favoured microbial proliferation and respiration (29, 30). It also could be due to continuous accumulation of organic carbon near the soil surface (29). Microorganisms that decompose organic matter are most active in surface layers, enhancing C-cycling and SOM stabilization. These findings underscore the strong interaction between cropping systems, crop phenology and soil depth in regulating soil respiration (16, 22).

Higher SOC under teak-based agroforestry may be due to a greater biomass addition to the soil, through litters, twigs and dead/decaying roots, in comparison to aonla-based agroforestry. A previous study observed that litter biomass enhanced SOC under the vegetation and crop canopy cover (31). Previous studies showed

that annual litter biomass under teak and aonla-based agroforestry ranged from 6.0 to 7.65 t ha^{-1} and 1.15 to 1.61 t ha^{-1} respectively, that aligns with our findings (32–34). This helps in higher SOM accretion on soil surface that leads to the better aggregation, porosity, as well as reduction in soil compactness, causing higher soil moisture retention under teak-based agroforestry system (29). As DHA is a respiratory enzyme, its higher activity corresponding to the higher microbial respiration across the agroforestry and crop phenology is justified (35).

Soil respiration often exhibits an excellent relationship with SMC, increasing from low moisture levels, reaching an optimum and then decreasing at high moisture levels due to reduced oxygen diffusion (35, 36). Similarly, our study explicitly showed that temporal trend of C_{BSR} is in similar line with the SMC. To unearth the effect of temporal changes of SMC on C_{BSR}, if there be any, we examined the dependency of the later the former through a non-linear regression model fitting. SMC predicted C_{BSR} and aligns with the previous studies (37, 38). In other words, temporal dynamics of SMC moderately affected microbial respiration. This indicates a complex web of interaction between soil hydrological and biological properties under the studied agroecosystems. The possible reasons for this observation could be different SMC between the soil at two different soil depths and variations in substrate availability as SOC was less in sub-surface soil which is responsible for respiration (38, 39). Dehydrogenase activity is a measure of microbial oxidative activity that indicates an active and metabolically capable microbial community, which in turn, leads to soil respiration and so it can be directly related (34, 40, 41). Strong, significant and positive correlation between C_{BSR} and SOC was noteworthy and similar linkage was reported in land-use changes in an earlier study (42). Thus, the impact of agroforestry systems on the dynamics of BSR through the presence of understory crops, crop phenology and their interactions with different major drivers of BSR has been clearly depicted. The findings established the significance of the tree-crop combinations in agroforestry systems for modulating the BSR dynamics, which holds promise towards augmenting the utility of land use for soil carbon management under changing climate perspective.

In essence, the results suggest that judicious tree–crop selection substantially enhances soil biological health and carbon turnover. Integration of a leguminous intercrop (e.g., black gram) within teak-based agroforestry systems significantly improves SOC accumulation and microbial activity, highlighting its potential to restore soil fertility and sustain productivity in degraded landscapes of central India.

Conclusion

The results clearly suggest that the temporal dynamics of BSR was strongly modulated by tree–crop combinations, crop phenologies and SOC content in the studied agroforestry systems. The study also provides valuable finding that teak-based agroforestry can considerably enhance soil biological activity in dry-tropical central India. Temporal trends observed for SMC, dehydrogenase activity (DHA) and SOC emphasized the strong linkage between the tree components, understory crops and soil biological activity. These findings highlight the importance of agroforestry tree species, tree-crop combinations and crop phenologies in modulating belowground processes and maintaining soil health in agroforestry ecosystems. These findings revealed that selecting appropriate tree-crop combinations can enhance soil biological health and carbon turnover. Integrating leguminous crops (e.g., black gram) with suitable tree species can improve SOC status and microbial functioning, thereby supporting sustainable productivity and long-term soil fertility in the degraded central Indian lands. Nevertheless, evaluating system performance across diverse climate and soil conditions will aid in refining land-use planning strategies that integrate agriculture with timber and horticultural components for enhancing soil health through climate-smart agroecosystems. The findings of this study provide valuable insights for assessing and understanding the efficiency of agroecosystems, particularly in the context of SOC management.

Acknowledgements

This research was funded by the ICAR-National Agricultural Science Fund (NASF), New Delhi, under the project entitled 'Comparative study on carbon dynamics and functional rhizosphere microbial biomass of agroforestry systems in dry- and wet-tropical climatic situations' (Grant number: NASF/PA-10023/2023-24). The authors gratefully acknowledge the Indian Council of Agricultural Research (ICAR), Department of Agricultural Research and Education, Government of India and ICAR-NASF for financial support and ICAR-Central Agroforestry Research Institute, Jhansi, for providing the necessary research facilities.

Authors' contributions

SD was responsible for the experimental setup, planning, methodology, conducting experiments, and writing the original manuscript draft. BA contributed to conceptualization, coordination of the research project grant, conducting field experiments, manuscript writing and data interpretation. MA was involved in writing and editing the original draft manuscript. ST performed the formal statistical analysis and contributed to data interpretation. SK participated in monitoring field experiments, formal analysis and manuscript writing. B conducted experiments and carried out data collection and processing. MK and AY were involved in field experiments and data collection. RP contributed to data interpretation and the writing and editing of the final manuscript. AA provided critical interpretation of data and results and contributed to editing the final manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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