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Spatial and temporal trends of soil nutrient dynamics under different agroforestry systems in Gangatic plain

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Abstract

The most crucial factor in crop production is soil fertility; thus, it directly influences food security. Therefore, to ensure food security, soil fertility level needs improvement. Though, poor cultivation practices led to soil infertility across the Gangatic region, making even more need to identify and implement sustainable farming practices. In this light, this experiment was undertaken to study the dynamics of soil nutrients in different agroforestry systems (AFS) as a sustainable farming practice concerning seasonal and depth-wise variations. The experiment was conducted in the Samastipur district of India, which comes under the Gangatic plain. Three AFS, including Kadamb (*Anthocephalus cadamba* Miq.), Simarauba (*Simarouba glauca* DC), and Litchi (*Litchi chinensis* Sonn.) based AFS along with one fallow land were taken under investigation. Soil samples were collected from three depths (0-15cm, 15-30cm and 30-45cm) during four seasons (Summer, Autuam, Rainy and Winter). Data revealed that agroforestry development had significantly increased soil nutrients (11-19%) in all seasons and depths. The month of June reported higher availability of nutrients over December. Soil depth had significant influence on soil nutrient availability, irrespective of treatments. The variation of available nutrients among the soil layer was more in agroforestry systems over fallow land. This study will help the researchers to understand the influence of seasons and depths on the movements and transformation of soil nutrients.

Introduction

Agroforestry systems (AFS) are acknowledged as sustainable replacements for conventional farming systems, especially in tropics, where the formation of agricultural land has been replacing the existing natural forests at a faster rate. AFS defines growing crops or livestock along with trees (Rosenstock et al. 2019). Plenty of past research has attributed the potentiality of AFS to sustain ecosystem and biodiversity functions without limiting the crop yield (N'Woueni and Gaoue 2022; Santiago-Freijanes et al. 2021; Sagastuy and Krause et al. 2019). Moreover, AFS is closely linked with other vital ecological functions such as nutrient accumulation and recycling (Sileshi et al. 2020), erosion reduction (Fahad et al. 2022), carbon accumulation (Ma et al. 2022), weed control (Staton et al. 2021), pollination (Varah et al. 2020), and (Brown et al. 2018). On the other hand, trees provide farmers with wood, fruits, and other by-products as extra revenue.

The core emphasis of this work was to study the soil nutrient dynamics of Kadamb (*Anthocephalus cadamba* Miq.), Simarauba (*Simarouba glauca* DC), and Litchi (*Litchi chinensis* Sonn.) based AFS. Simaroubha and Kadamba are grown for timber production, while Litchi is widely grown for fruit production in tropical Asia. AFS soil has a profound positive relation with carbon stock, nutrient, and water recycling (Chatterjee et al. 2019). Simaraubha and Kadamb are often described as partially shade tree species for about 10 years, making them ideal for AFS development. In comparison, Litchi trees form more shade over the former two species. Moreover, these AFS enhance overall soil biodiversity (Sarkar et al. 2020). This AFS biodiversity is directly linked with several ecological functions beneficial to society, which makes these AFS an important element of sustainable agriculture in the tropics (Putra et al. 2022). However, soil fertility in Simaraubha and Kadamb based AFS has rarely been studied. Soil fertility is regarded as the soil's capability to develop the environments needed for the optimum growth of the plant (Sileshi et al. 2020). Some researchers particularly studied the effect of different-age Litchi trees on soil fertility in AFS (Naik et al. 2018). The exploration of soil fertility improvement is needed not just based on tree ages but also considering soil depths and seasonal variations to get a clearer view of nutrient dynamics.

The information regarding the effect of these trees on soil nutrient dynamics in India is lacking and has not been studied as per our knowledge. Thus, this investigation is vital, given the ecological importance of these AFS implementations. Land use in agriculture is increasing by transforming forest land, negatively impacting ecological disturbance and climate crisis (Schielein and Börner 2018). In this situation, AFS development can be a win-win solution, as it includes trees. Furthermore, it helps to improve soil fertility that has been degraded by natural causes such as salinity, alkalinity and anthropogenic causes (Fahad et al. 2022). Implementing AFS with locally adaptable tree species is a great way to restore degraded soils and recover soil fertility related to a series of ecological functions.

The current study emphasizes soil nutrient dynamics in three AFS and one fallow land under different soil depths and seasons. We specifically focused on assessing plant-available forms of nutrients. Apart from macronutrients, particular importance had given to micronutrients, as AFS has a greater ability for micronutrient retention. A nutrient-rich soil also helps to predict agricultural production (de Vries et al. 2020). In this perspective, fertile soil improves soil biodiversity as well as other ecological functions. Furthermore, improvement leads enhancement of soil health properties, which reverses soil degradation (Fahad et al. 2022).

The core objective of this investigation was to evaluate the effect of the development of mentioned AFS on soil nutrient dynamics in areas of the middle Gangatic plains. This area's soils have high soil pH due to calcareous soil. We compared soil nutrient dynamics of AFS to that of allowing land to assess seasonal and depth-wise variations. Furthermore, we discuss the potentiality of these AFS to ensure essential soil nutrient availability and the significance of AFS as a strategy to sustain soil fertility in this region. This groundbreaking research is the first of its kind on how the available soil nutrient dynamics are influenced by seasons concerning the changing climate scenarios. Moreover, the variations in different agroforestry systems were also studied. As per our knowledge, this is the first research paper that includes an investigation on all macro and important micronutrient dynamics in seasons and depth perspective with different AFS systems.

Methods

Location and climate

A field experiment was undertaken during 2017-18 and 2018-19 at the Dr. Rajendra Prasad Central Agricultural University is located at 26º 61 N latitude 84º 60 E longitude and 52.08m above sea level of Gangatic plain of Samastipur district of Bihar, India (Fig. 1). The mean annual rainfall of 869 and 1004 mm was recorded during the 1st and 2nd years of the study period. The monthly mean maximum temperature during 2017-18 was 15.3 to 39.7°C and minimum temperature was 7.6 to 27.4°C, which were slightly higher during 2018-19 (maximum temperature 15.7 to 40.1°C and minimum temperature 7.7 to 29.2°C). The highest temperature was recorded during June followed by March, September and December. The mean sunshine hours during the research period varied from 6.49 h (2017-18) to 6.22 h (2018-19). The soil of experimental site was sandy loam, which was highly fertile with good drainage capacity. The soil consists highly $CaCO_3$ (15–40%) and pH is above 8.0.

Treatments and experimental design

The study plots were designed in a randomized block design (RBD) with five replications. Four treatments include i) Kadamb (*Anthocephalus cadamba* Miq.) based agrisilvicultural system, ii) Simarauba (*Simarouba glauca* DC) based agrisilvicultural system, iii) Litchi (*Litchi chinensis* Sonn.) based agrihorticultural system and iv) fallow land. All agroforestry systems were 13 years old, where turmeric (*Curcuma domestica*, var. Rajendra Sonia) was cultivated during the initial 10 years, which later stopped due to heavy shade on ground surface. The spacing between trees was 7m × 7m, and the total area of land was 0.25 ha for each treatment.

Soil analysis

At each sample point, eight samples were collected under the tree canopy, four from 50 cm away from the tree base and four 2m from tree base in four directions around the tree (Fig. 2). All eight samples were mixed to prepare a composite sample. Soil samples were collected in four seasons Summar (March), Rainy (June), Autuam (September) and Winter (December) from three depths, i.e., 0-15cm, 15-30cm and 30-45cm. The samples were processed and analyzed under standard chemical analyses at laboratory, as shown in Table 1.

Statistical analysis

Statistical techniques were used to evaluate the significance between the seasonal and depth-wise variations of treatments and to develop genuine conclusions (Gomez & Gomez, 1984).

Table 1
Mean initial soil properties

Particulars	2017-18	2018-19	Method followed
	Value		References
Organic matter (%)	0.56	0.59	Walkley and Black, 1935
Soil pH	8.1	8.1	Jackson, 1973
Available N	127–167 kg ha^{-1}	128–170 kg ha^{-1}	Subbiah, 1956
Available P	12–21 kg ha^{-1}	11–22 kg ha^{-1}	Watanabe and Olsen, 1965
Available K	97–135 kg ha^{-1}	99–137 kg ha^{-1}	Jackson, 1973
Available Ca	73–105 mg kg^{-1}	73–106 mg kg^{-1}	Cheng and Bray, 1951
Available Mg	64–90 mg kg^{-1}	63–93 mg kg^{-1}	Cheng and Bray, 1951
Available S	8–12 mg kg^{-1}	9–11 mg kg^{-1}	Chesmin and Yien, 1951
Available Zn	0.49–0.81 mg kg^{-1}	0.51–0.80 mg kg^{-1}	Lindsay and Norvell, 1978
Available Fe	6.05–8.89 mg kg^{-1}	6.18–8.95 mg kg^{-1}	Lindsay and Norvell, 1978
Available Mn	2.21–3.92 mg kg^{-1}	2.27–3.98 mg kg^{-1}	Lindsay and Norvell, 1978
Available Cu	0.60–0.96 mg kg^{-1}	0.63–0.98 mg kg^{-1}	Lindsay and Norvell, 1978

Results

Effect of seasons

The inspection of data (Tables 2, 3, 4, 5, 6 & 7) suggests that June had the highest soil available N (10.39% in Kadamb AFS, 11.64% in Simaraubha AFS, 9.35% in Litchi AFS and 17.90% in Fallow land), available P (36.38% in Kadamb, 45.00% in Simaraubha, 49.4% in Litchi and 44.00% in Fallow land), available K (15.20% in Kadamb, 16.07% in Simaraubha, 12.65% in Litchi and 20.44% in Fallow land), available Ca (5.52% in Kadamb, 6.41% in Simaraubha, 7.70% in Litchi and 11.04% in Fallow land), available Mg (7.88% in Kadamb, 8.19% in Simaraubha, 6.76% in Litchi and 7.68% in Fallow land), and available S (16.32% in Kadamb, 9.22% in Simaraubha, 3.54% in Litchi and 6.12% in Fallow land) on the pooled basis. The lowest available N (146.11 in Kadamb, 151.61 in Simaraubha, 146.1 in Litchi and 127.42 kg ha^{-1} in Fallow land), available P (14.76 in Kadamb, 15.13 in Simaraubha, 13.78 in Litchi and 11.47 kg ha^{-1} in Fallow land), available K (114.92 in Kadamb, 117.74 in Simaraubha, 114.64 in Litchi and 98.16 kg ha^{-1} in Fallow land), available Ca (99.54 in Kadamb, 98.20 in Simaraubha, 94.66 in Litchi and 72.83 mg kg^{-1} in Fallow land), available Mg (85.12 in Kadamb, 82.62 in Simaraubha, 81.45 in Litchi and 63.82 mg kg^{-1} in Fallow land) and available S (9.91 in Kadamb, 10.52 in Simaraubha, 9.88 in Litchi and 8.49 mg kg^{-1} in Fallow land) were reported on December in the pooled analysis. Significantly higher N, P, K, Ca, Mg and S were recorded in Simaraubha (169.25 kg ha^{-1}, 21.94 kg ha^{-1}, 136.76 kg ha^{-1}, 104.50 mg kg^{-1}, 89.39 mg kg^{-1} and 11.49 mg kg^{-1}, respectively) followed by Kadamb (162.06 kg ha^{-1}, 20.13 kg ha^{-1}, 132.39 kg ha^{-1}, 105.67 mg kg^{-1}, 91.83 mg kg^{-1} and 11.67 mg kg^{-1}, respectively), and lowest in Fallow land (150.25 kg ha^{-1}, 16.64 kg ha^{-1}, 118.23 kg ha^{-1}, 82.02 mg kg^{-1}, 68.84 mg kg^{-1} and 9.01 mg kg^{-1}, respectively) on the pooled basis.

Among the treatments Simaraubha recorded maximum soil micronutrient presence, irrespective of seasons. Results (Figs. 3, 4, 5 & 6) further revealed that among the seasons, the highest available Zn (0.82 mg kg^{-1}), available Fe (8.92 mg kg^{-1}), available Mn (3.95 mg kg^{-1}) and available Cu (0.97 mg kg^{-1}) were recorded on September which were 0.04, 0.51, 0.15 and 0.04 mg kg^{-1} higher than June and lowest values were recorded (0.72, 8.18, 3.44 and 0.85 mg kg^{-1} respectively) on December in Simaraubha. Similarly, seasonal micronutrient trends were reported in other treatments.

Table 2
Effect of seasons and depths on available nitrogen

Treatments	Kadamb AFS			Simaraubha AFS			Litchi AFS			Fallow land		
	2016-17	2017-18	Pooled	2016-17	2017-18	Pooled	2016-17	2017-18	Pooled	2016-17	2017-18	Pooled
June	160.52	162.06	161.29	167.98	170.55	169.265	158.37	161.17	159.77	148.72	151.77	150.245
September	155.21	159.13	157.17	165.32	166.37	165.845	163.08	163.53	163.305	133.31	137.56	135.435
December	145.48	146.74	146.11	149.52	153.71	151.615	143.95	148.25	146.1	127.23	127.62	127.425
March	151.14	152.08	151.61	165.18	166.43	165.805	155.71	157.32	156.515	122.78	128.53	125.655
Mean	153.09	155.00	154.05	162.00	164.27	163.13	155.28	157.57	156.42	133.01	136.37	134.69
SEm±	1.19	1.21	0.82	1.09	1.16	0.72	1.06	1.11	0.67	0.96	1.02	0.61
CD(p = 0.05)	4.37	4.44	2.93	4.9	5.24	3.08	4.67	4.83	2.98	3.26	3.78	2.48
0–15 cm	181.97	184.47	183.22	186.36	188.15	187.255	172.34	174.97	173.655	156.66	160.86	158.76
15–30 cm	141.09	144.63	142.86	150.14	153.03	151.585	150.72	151.79	151.255	123.64	125.67	124.655
30–45 cm	136.32	136.04	136.18	151.07	151.9	151.485	143.11	146.34	144.725	119.39	121.79	120.59
Mean	153.13	155.05	154.09	162.52	164.36	163.44	155.39	157.70	156.55	133.23	136.11	134.67
SEm±	1.34	1.45	1.02	1.39	1.51	1.45	1.32	1.37	1.09	1.21	1.24	0.71
CD(p = 0.05)	5.32	5.87	3.34	5.92	6.15	3.69	5.76	5.88	3.24	5.26	5.67	2.97

Table 3
Effect of seasons and depths on available phosphorous

Treatments	Kadamb AFS			Simaraubha AFS			Litchi AFS			Fallow land		
	2016-17	2017-18	Pooled	2016-17	2017-18	Pooled	2016-17	2017-18	Pooled	2016-17	2017-18	Pooled
June	19.46	20.81	20.135	21.87	22.02	21.945	21.06	23.05	22.055	16.37	16.91	16.64
September	17.35	17.66	17.505	17.4	18.14	17.77	16.93	17.17	17.05	15.89	16.12	16.005
December	14.76	14.77	14.765	14.97	15.3	15.135	13.54	14.03	13.785	11.93	11.01	11.47
March	16.08	16.83	16.455	15.72	16.82	16.27	15.95	16.98	16.465	13.76	13.96	13.86
Mean	16.91	17.52	17.22	17.49	18.07	17.78	16.87	17.81	17.34	14.49	14.50	14.49
SEm±	0.37	0.41	0.23	0.42	0.47	0.29	0.38	0.42	0.25	0.31	0.35	0.21
CD(p = 0.05)	1.89	1.98	0.77	2.14	2.21	0.91	1.78	1.82	0.74	1.27	1.36	0.56
0–15 cm	26.35	27.32	26.835	28.26	30.66	29.46	26.93	28.62	27.775	24.64	23.71	24.175
15–30 cm	13.43	14.21	13.82	13.93	12.38	13.155	13.7	13.53	13.615	10.46	10.8	10.63
30–45 cm	10.6	10.7	10.65	10.03	11.35	10.69	9.89	10.79	10.34	8.89	8.97	8.93
Mean	16.79	17.41	17.10	17.41	18.13	17.77	16.84	17.65	17.24	14.66	14.49	14.58
SEm±	0.47	0.51	0.25	0.53	0.59	0.29	0.48	0.5	0.28	0.38	0.41	0.19
CD(p = 0.05)	2.07	2.13	1.02	2.19	2.24	1.2	2.08	2.11	1.12	1.57	1.64	1.23

Table 4
Effect of seasons and depths on available potassium

Treatments	Kadamb AFS			Simaraubha AFS			Litchi AFS			Fallow land		
	2016-17	2017-18	Pooled	2016-17	2017-18	Pooled	2016-17	2017-18	Pooled	2016-17	2017-18	Pooled
June	130.07	134.72	132.395	135.41	137.94	136.675	128.79	129.52	129.155	117.03	119.43	118.23
September	126.23	127.91	127.07	129.9	130.05	129.975	124.64	126.98	125.81	109.14	111.32	110.23
December	114.3	115.54	114.92	117.33	118.16	117.745	113.77	115.51	114.64	97.32	99.01	98.165
March	118.11	120.59	119.35	129.31	127.88	128.595	123.68	124.72	124.2	105.56	106.87	106.215
Mean	122.18	124.69	123.43	127.99	128.51	128.25	122.72	124.18	123.45	107.26	109.16	108.21
SEm±	1.11	1.09	0.72	1.21	1.17	0.64	1.13	1.07	0.67	0.92	0.87	0.59
CD(p = 0.05)	3.67	3.78	2.19	3.62	3.51	2.08	3.51	3.42	2.02	2.66	2.97	1.72
0–15 cm	151.55	154.72	153.135	156.01	159.03	157.52	149.23	152.93	151.08	138.58	139.21	138.895
15–30 cm	112.11	114.23	113.17	119.62	116.82	118.22	113.42	113.24	113.33	94.02	96.25	95.135
30–45 cm	102.71	104.69	103.7	107.62	109.64	108.63	105.61	106.23	105.92	88.71	92.08	90.395
Mean	122.12	124.55	123.34	127.75	128.50	128.12	122.75	124.13	123.44	107.10	109.18	108.14
SEm±	1.45	1.38	0.97	1.67	1.54	1.02	1.34	1.29	0.89	1.12	1.17	0.78
CD(p = 0.05)	4.23	4.53	3.01	4.62	4.79	3.16	4.35	4.46	3.11	3.31	3.46	2.87

Table 5
Effect of seasons and depths on available calcium

Treatments	Kadamb AFS			Simaraubha AFS			Litchi AFS			Fallow land		
	2016-17	2017-18	Pooled	2016-17	2017-18	Pooled	2016-17	2017-18	Pooled	2016-17	2017-18	Pooled
June	105.32	106.02	105.67	103.34	105.67	104.505	101.53	102.37	101.95	79.36	84.68	82.02
September	102.47	102.78	102.625	101.15	102.48	101.815	98.41	98.95	98.68	75.81	78.53	77.17
December	99.03	100.05	99.54	97.04	99.37	98.205	94.04	95.28	94.66	72.57	73.09	72.83
March	101.69	101.93	101.81	99.77	100.52	100.145	97.88	99.36	98.62	73.06	73.95	73.505
Mean	102.13	102.70	102.41	100.33	102.01	101.17	97.97	98.99	98.48	75.20	77.56	76.38
SEm±	1.09	1.18	0.7	1.23	1.27	0.85	1.16	1.2	0.94	0.92	0.98	0.54
CD(p = 0.05)	3.24	3.12	2.19	3.45	3.56	2.41	3.33	3.41	2.18	3.06	3.1	1.93
0–15 cm	109.16	110.38	109.77	106.94	108.43	107.685	104.36	105.92	105.14	84.02	85.47	84.745
15–30 cm	101.4	102.66	102.03	98.7	99.31	99.005	96.58	98.46	97.52	76	78.08	77.04
30–45 cm	95.63	97.32	96.475	94.36	96.23	95.295	92.76	93.75	93.255	65.43	66.12	65.775
Mean	102.06	103.45	102.76	100.00	101.32	100.66	97.90	99.38	98.64	75.15	76.56	75.85
SEm±	1.78	1.82	0.94	1.88	1.93	1.04	1.83	1.89	0.99	1.56	1.61	0.67
CD(p = 0.05)	3.77	3.89	2.45	4.09	4.23	2.76	3.79	3.92	2.89	3.26	3.37	2.17

Table 6
Effect of seasons and depths on available Magnesium

Treatments	Kadamb AFS			Simaraubha AFS			Litchi AFS			Fallow land		
	2016-17	2017-18	Pooled	2016-17	2017-18	Pooled	2016-17	2017-18	Pooled	2016-17	2017-18	Pooled
June	90.11	93.56	91.835	87.56	91.23	89.395	86.41	87.51	86.96	68.45	69.23	68.84
September	86.21	87.23	86.72	85.03	86.34	85.685	84.36	84.67	84.515	65.37	66.55	65.96
December	84.94	85.31	85.125	83.24	82.013	82.6265	80.82	82.08	81.45	64.13	63.51	63.82
March	85.83	87.99	86.91	84.39	85.02	84.705	81.95	82.16	82.055	65.19	67.89	66.54
Mean	86.77	88.52	87.65	85.06	86.15	85.60	83.39	84.11	83.75	65.79	66.80	66.29
SEm±	1.18	1.04	0.89	1.18	1.07	0.91	1.06	1.02	0.72	0.83	0.77	0.57
CD(p = 0.05)	3.16	3.14	1.95	3.87	3.76	1.87	3.24	3.19	1.09	2.27	2.19	1.07
0–15 cm	92.8	93.91	93.355	89.6	91.82	90.71	87.54	90.45	88.995	70.18	74.32	72.25
15–30 cm	85.1	85.68	85.39	83.78	85.23	84.505	83.34	86.01	84.675	66.62	67.13	66.875
30–45 cm	82.52	84.02	83.27	80.03	81.49	80.76	79.67	79.94	79.805	60.24	61.52	60.88
Mean	86.81	87.87	87.34	84.47	86.18	85.33	83.52	85.47	84.49	65.68	67.66	66.67
SEm±	1.82	1.89	0.94	1.8	1.86	0.98	1.72	1.63	0.74	1.05	1.03	0.62
CD(p = 0.05)	3.24	3.65	1.46	3.27	3.67	1.23	3.41	3.53	1.29	2.94	3.09	1.09

Table 7
Effect of seasons and depths on available sulphur

Treatments	Kadamb AFS			Simaraubha AFS			Litchi AFS			Fallow land		
	2016-17	2017-18	Pooled	2016-17	2017-18	Pooled	2016-17	2017-18	Pooled	2016-17	2017-18	Pooled
June	10.95	10.87	10.91	11.76	11.23	11.495	10.12	10.34	10.23	8.89	9.14	9.015
September	10.73	10.69	10.71	11.92	11.29	11.605	10.58	10.98	10.78	9.36	9.56	9.46
December	9.88	9.94	9.91	10.11	10.94	10.525	9.84	9.92	9.88	8.05	8.93	8.49
March	10.57	10.32	10.445	11.79	11.61	11.7	10.66	10.5	10.58	9.14	9.1	9.12
Mean	10.53	10.46	10.49	11.40	11.27	11.33	10.30	10.44	10.37	8.86	9.18	9.02
SEm±	0.14	0.17	0.09	0.17	0.18	0.11	0.15	0.12	0.09	0.1	0.11	0.08
CD(p = 0.05)	0.36	0.42	0.27	0.45	0.53	0.32	0.44	0.49	0.3	0.36	0.31	0.27
0–15 cm	9.35	9.68	9.515	10.02	10.67	10.345	9.93	10.08	10.005	7.72	8.04	7.88
15–30 cm	11.98	11.08	11.53	12.69	12.88	12.785	12.38	11.48	11.93	10.92	10.13	10.525
30–45 cm	10.51	10.34	10.425	11.42	11.56	11.49	11.67	11.82	11.745	9.34	9.78	9.56
Mean	10.61	10.37	10.49	11.38	11.70	11.54	11.33	11.13	11.23	9.33	9.32	9.32
SEm±	0.17	0.19	0.11	0.21	0.19	0.12	0.18	0.15	0.11	0.13	0.1	0.09
CD(p = 0.05)	0.37	0.39	0.21	0.33	0.3	0.18	0.24	0.29	0.16	0.19	0.22	0.12

Nutrient dynamics influenced by soil depth

The persuasion of data (Tables 2, 3, 4, 5, 6, 7 & Figs. 3, 4, 5, 6) showed that the agroforestry development significantly increased all soil nutrients in soil over fallow land during both years. Among the soil depths, the highest soil available N (183.22 in Kadamb, 187.25 in Simaraubha, 173.55 in Litchi and 158.65 kg ha^{-1} in Fallow land), soil available P (28.83 in Kadamb, 29.46 in Simaraubha, 27.77 in Litchi and 24.17 kg ha^{-1} in Fallow land), soil available K (153.13 in Kadamb, 157.52 in Simaraubha, 151.08 in Litchi and 138.89 kg ha^{-1} in Fallow land), soil available Ca (109.77 in Kadamb, 107.68 in Simaraubha, 105.14 in Litchi and 84.74 kg ha^{-1} in Fallow land), soil available Mg (93.35 in Kadamb, 90.71 in Simaraubha, 88.99 in Litchi and 72.25 kg ha^{-1} in Fallow land) and soil available S (9.51 in Kadamb, 10.34 in Simaraubha, 10.00 in Litchi and 7.88 kg ha^{-1} in Fallow land) were observed in 0-15cm depth than other depths in the pooled analysis, respectively. The increase of available N in 0-15cm depth were 28.87, 29.02, 14.56 and 24.57% over 15-30cm in Kadamb, Simaraubha, Litchi and Fallow land on the polled basis, respectively. Similarly, the decrease of soil available P, K, Ca, Mg and S with depth was reported. The availability of soil N, P, K, Ca, Mg and S further decreases from 15–30 cm to 30–45 cm depth, which varies from 4.32–9.78, 5.8-10.32, 7.54–8.21, 6.93–12.56, 5.71–9.88 and 9.36-14%. No significant change was observed during the two years of study, irrespective of treatments and nutrients.

Surface soil (0–15 cm) had highest available Zn (0.82 in Kadamb, 0.88 in Simaraubha, 0.83 in Litchi and 0.60 mg kg^{-1} in Fallow land), available Fe (8.41 in Kadamb, 8.01 in Simaraubha, 8.47 in Litchi and 6.81 mg kg − 1 in Fallow land), available Mn (3.73 in Kadamb, 4.16 in Simaraubha, 3.69 in Litchi and 2.53 mg kg^{-1} in Fallow land), and available Cu (0.94 in Kadamb 0.98 in Simaraubha, 0.90 in Litchi and 0.73 mg kg^{-1} in Fallow land) presence which were significantly higher over 15–30 cm soil depth. There were significant variations in micronutrient availability with soil depth from treatment to treatment. In general, the depletion of soil micronutrients from 0–15 to 15–30 cm was higher over 15–30 to 30–45 cm.

Discussion

Effect of seasons

Understanding seasonal influence on nutrient dynamics can help to move precise nutrient management (Kumar et al. 2021). The data of soil nutrients (Tables 2, 3, 4, 5, 6 & 7) exposed that seasonal variations significantly influenced nutrient availability in the soil of AFS. Among the seasons, the maximum available N, P, K, Ca, Mg and S were found on June during both years of study, which significantly varied from other seasons. The available N (Table 2) gradually declined from June to September and September to December. While, the available N rapidly increased from December to March and March to June. Experimental findings reveled that the available P, K, Ca, Mg and S followed the same trend with available N. It may be due to the variations in temperature and soil moisture, which influence soil microbes, resulting in differences in nutrient release and availability (Jing et al. 2020). June had the highest reception of rainfall and recorded maximum temperature over the other three selected months. So, more biochemical activities may occur in June, which leads to more availability of these primary and secondary nutrients in soil. On the other hand, December had the lowest rainfall and temperature, causing low biochemical activities and making soil nutrients the least available (Mavi et al. 2018). The favorable weather conditions boost the rate of organic matter decomposition, supplying a better source of consumption for the microbial population, which is related to higher nutrient accessibility (Jing et al. 2020). The available Zn, Fe, Mn and Cu data indicated that different seasons influenced the available micronutrients in polled basis analysis (Figs. 3, 4, 5 & 6**)**. Among the seasons, the higher available micronutrients were recorded on September, followed by June in the pooled analysis. Although, seasonal variations are mostly non-significant among September, June and March. However, it significantly differs between September and December. This may be due to higher decomposition and mineralization of organic matter in September, which improves soil physicochemical characteristics and increases nutrient availability (Kumar et al. 2021). In an earlier agroforestry experiment, Manral et al. (2020) reported more micro-nutrient availability in the post-rainy season.

Effect of soil depths

The data on soil depths (Tables 2, 3, 4, 5, 6 & 7) suggested that significantly higher available nutrients were present in surface soil (0–15 cm) over lower depths in the pooled analysis. Higher soil nutrients in upper soil were probably due to higher presence of organic matter and microbial populations in surface layer over other layers (dos Reis et al. 2020; Jat et al. 2019; Walz et al. 2017). The decrease of nutrients from 0-15cm to 15-30cm was more over 15-30cm to 30-45cm. Agroforestry systems had more availability of soil nutrients over the fallow land, irrespective of soil depths. The increase of soil nutrients from 30-45cm to 15-30cm was relatively low and insignificant in some cases. Nutrient cycles among the vertical soil layers were more active in AFS over fallow land, which may be due to the presence of deep root ways in AFS that helps nutrient movement downwards.

The data on available micronutrients showed that soil depth significantly influenced micronutrient availability on polled analysis, which is at par with several past studies (Barłóg et al. 2020; Oladele et al. 2019; Yao et al. 2018; Moharana et al. 2017). The availability of Zn, Fe, Mn and Cu were significantly decreased with soil depth (Figs. 3, 4, 5 & 6), which may be because of the higher mineralization rate of total micronutrients in surface soil (Moharana et al. 2017). The higher organic residues (leaf and roots) in surface soil enhanced the soil environment by improving the soil properties (Guo et al. 2020). The accessibility of majority of the micronutrients increases with the increase of soil pH and cation exchange capacity, which are directly influenced by soil organic matter (Domingues et al. 2020). The AFS had deep root development and supplied organic matter through biomass, providing better nutrient regulation throughout the soil layers. A range of organic acids released during the decomposition of organic matter increases the solubilizing rate of insoluble fractions of nutrients. The decrease of organic matter with soil depth also decreases soil microbial biomass, which has a direct relation with soil nutrient release in soil (Jing et al. 2020). The litterfall on the surface soil boosts the organic carbon stimulating microbial activities and their growth, enhancing the mineralization of nutrients in AFS.

Conclusion

Agroforestry development has significantly increased soil macronutrients, irrespective of seasons and soil depths. Among the seasons, June reported higher availability of nutrients, while December recorded the lowest value. While in the case of micronutrients, September had slightly higher nutrient availability than June and both months had significantly higher micronutrient accessibility over December. Soil depth has significantly influenced soil nutrient availability in all treatments. The variations and decreasing rate of available nutrients with soil depth were more in agroforestry systems over fallow land. This experiment will help the research community for better understand the movements and transformation of soil nutrients concerning seasons and depths to restore soil health through agroforestry development.

Declarations

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Author contributions

SS collected and analyzed the data, manuscript prepared; DKD guided the research and reviewed. All authors read and approved the final manuscript.

Data availability

The data will be available on reasonable request.

Conflict of interest: The authors have no relevant financial or non-financial interests to disclose.

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Figures

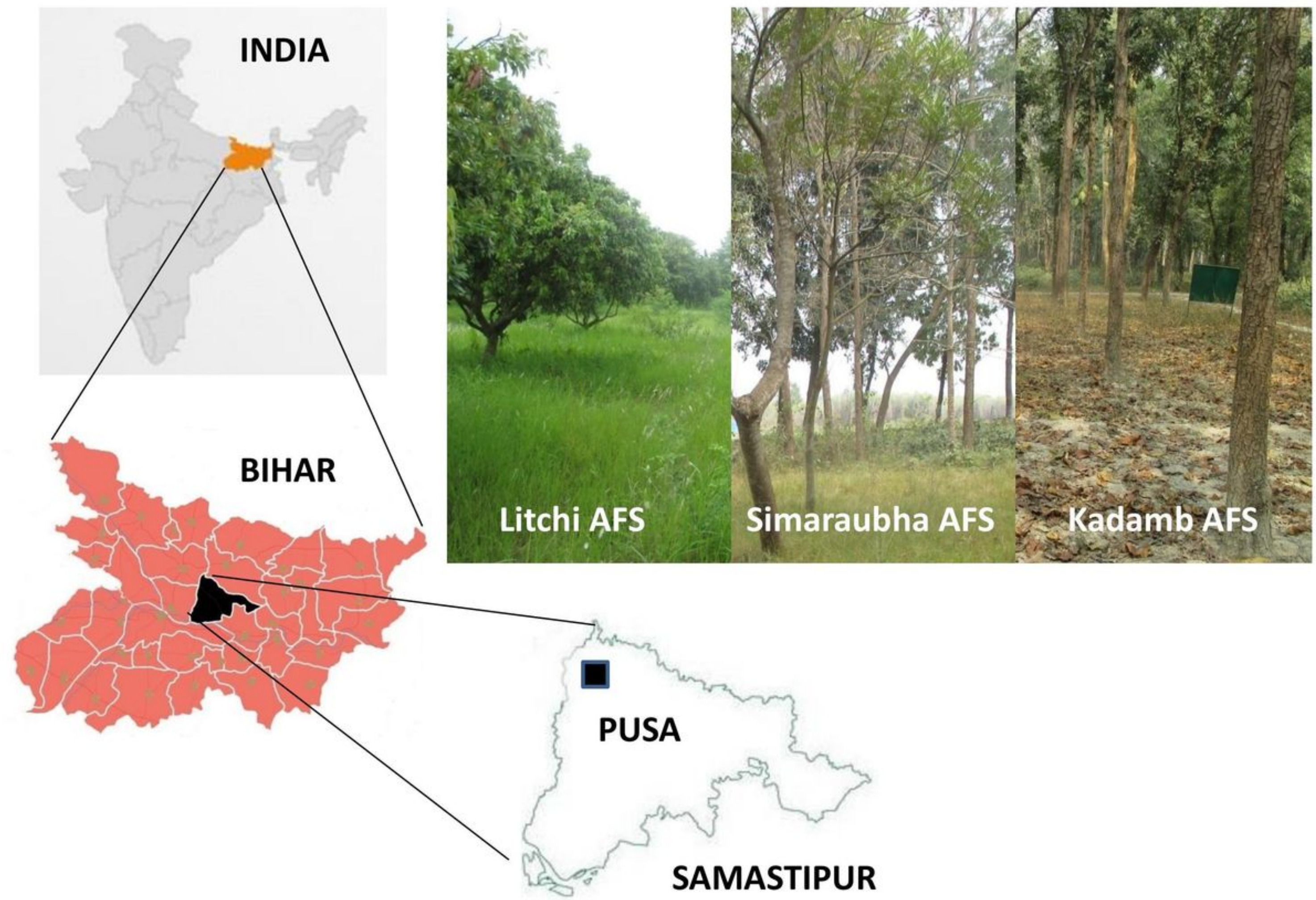

Figure 1

Location of experiment site

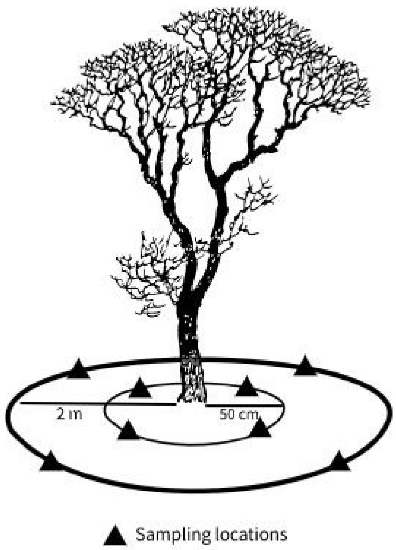

Figure 2

Locations of soil sampling around tree

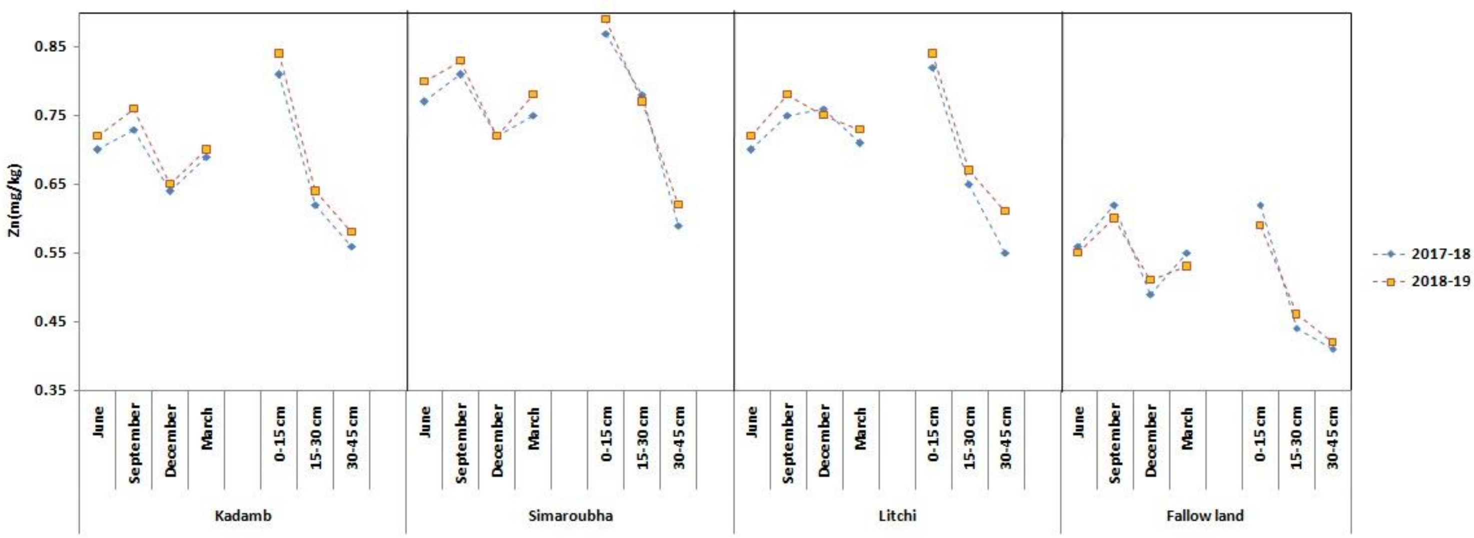

Figure 3

Effect of seasons and depths on available zinc

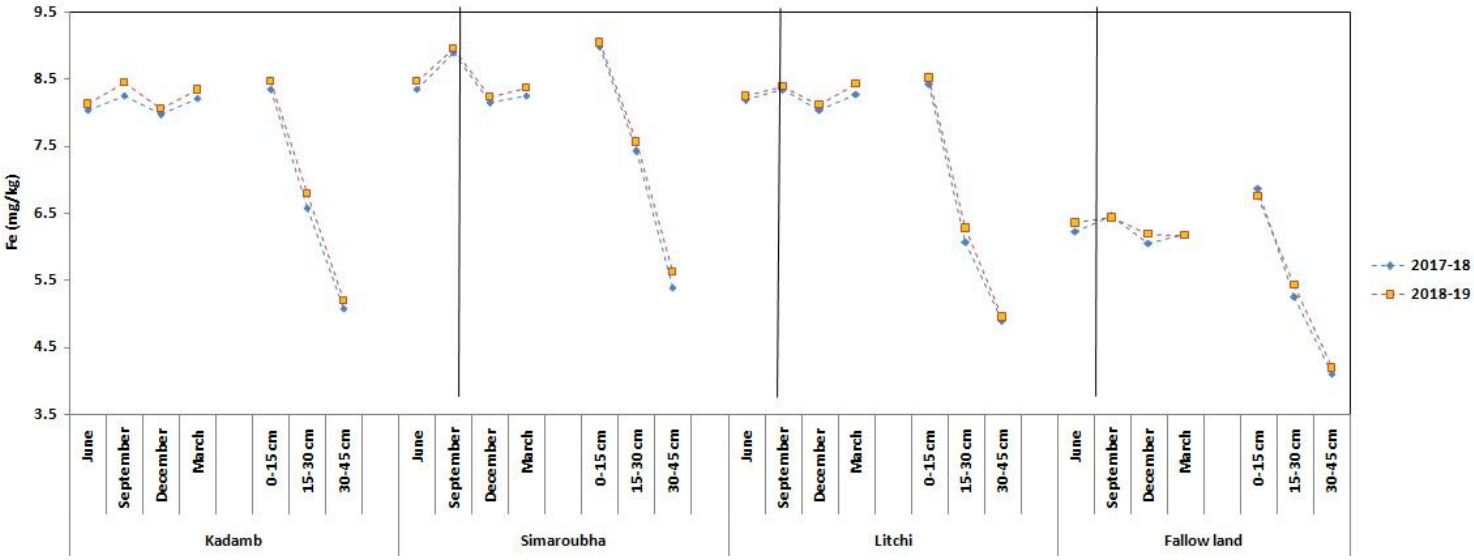

Figure 4

Effect of seasons and depths on available Iron

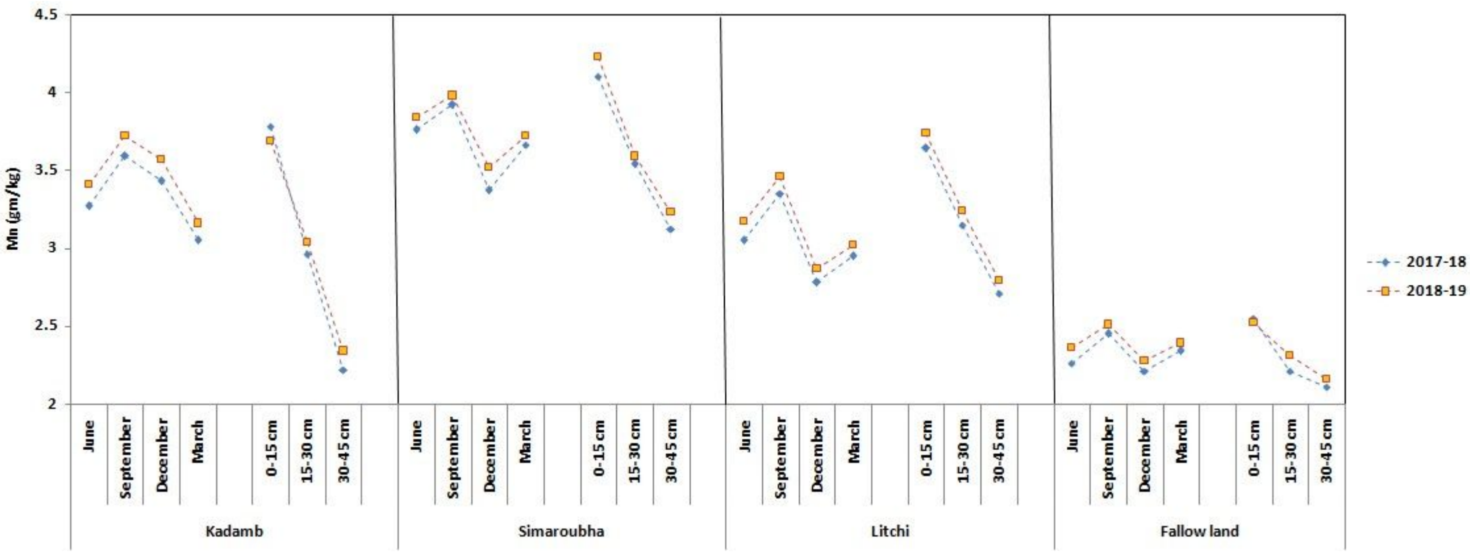

Figure 5

Effect of seasons and depths on available manganese

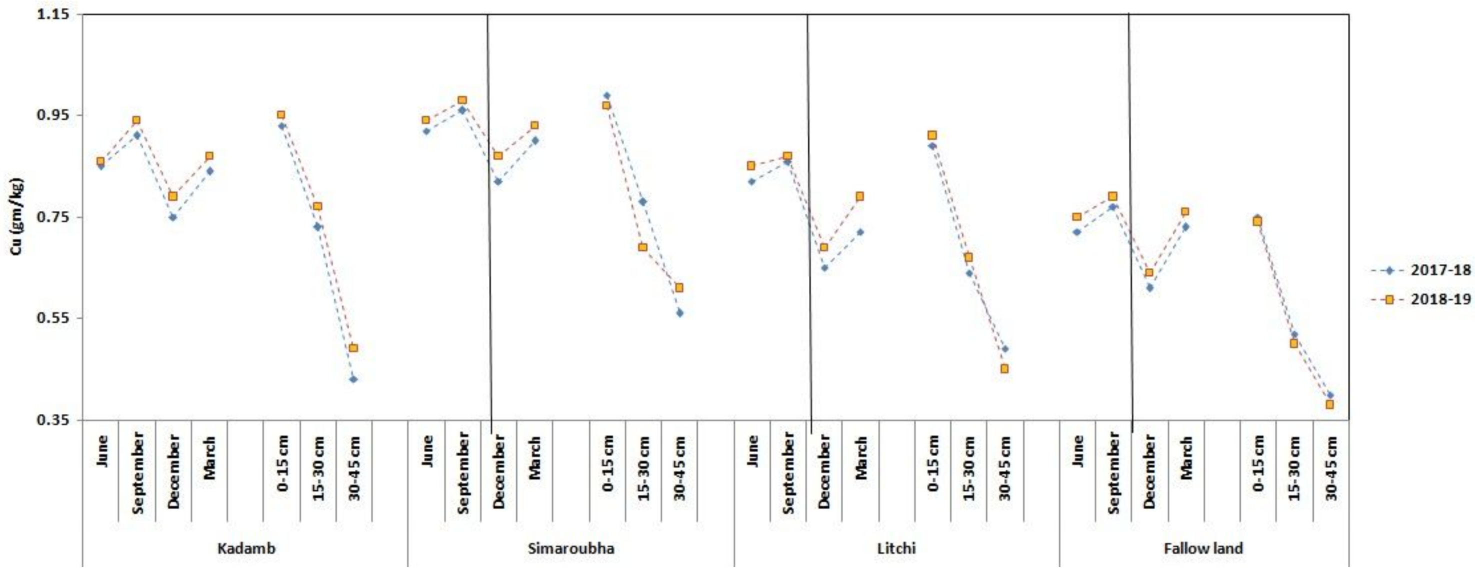

Figure 6

Effect of seasons and depths on available copper