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ENVIRONMENTAL PROGRESS & SUSTAINABLE ENERGY

ORIGINAL RESEARCH

Sustainability

Combined effect of land use change, long-term soil management and orchard age on variability of soil quality of fruit orchards under monsoon climate

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Abstract

The combined effect of land use change, long-term soil management, and orchard age (18–40 years) on soil quality of guava (*Psidium guajava* L. cv. Allahabad Safeda) and sapota (*Manilkara achras* Mill. cv. Cricket Ball) orchards was investigated. Besides, the soil quality of the orchards was compared against an adjacent forest soil (AFS, considered a baseline ecosystem). Values of pH, SOC, porosity, PHA, DHA, GSA, ExCa, ExMg, and DTPA-Cu were significantly lower in drip circle soils relative to inter-row space soils. The extent of reduction was prominent in older orchards. There was a significant building up of BD, AvP, AvK, DTPA-Fe, and DTPA-Zn in drip circle soils relative to inter-row space soils. The soil variability between drip circles and inter-row spaces across the soil depths was significant ($p < 0.01$). Principal component analysis (PCA) plots were generated to determine the variability of soil quality among orchards and AFS. Long-term soil management (18–40 years) induced soil spatial variability within the orchards. Analysis of similarity showed a significant difference in variability of soil quality within an orchard, among the orchard types, and between the orchards and the AFS. Except for soil AvK, all soil quality attributes maintained a significant correlation with the PC-axis-1 ($p < 0.05$ and 0.01) that explained maximum variability (40.2%–49.4%). The DHA and SOC contributed the maximum variability ($r = 0.95$ and 0.92, respectively with PC axis-1). In conclusion, the stronger factor of the variability of soil quality was in the order of land use change > soil management > orchard age.

KEYWORDS
Alfisol, guava, sapota, soil enzyme, soil spatial variability, soil sustainability

1 | INTRODUCTION

Soil quality, besides being an ideal indicator of sustainable land management, is increasingly proposed as an integrative indicator of environmental quality, food security, and economic viability.[1] Healthy soil provides a wide range of ecosystem services and intensification of agricultural production has modified the ability of soils to extend its many ecosystem services.[2] Therefore, the intensification of agriculture has raised concerns about the undesirable impacts of farm management on soil health. Soil quality degradation and a considerable decrease in quality and yield have been reported in the long-term monoculture of tea bushes, and have become a matter of great concern in the sustainable development of tea orchards.[3] With growing demand and limited land availability, farmers have been increasingly using fertilizers resulting in unpleasant effects on crop and soil health.[4]

Input intensive agriculture in the monoculture system, commonly observed in fruit orchards, unfavorably affects soil quality.[5] In fruit orchards, fertilizers, manures, irrigation, lime, etc. are applied in the drip circle (irrigation basin, 1.0–1.5 m radius from the tree trunk) and therefore, the soil in the inter-row spaces of trees is less affected. The study revealed significant variability between drip circle and inter-row space soil concerning organic carbon, microbial biomass carbon, soil enzymes activities, hot water extractable carbon, pH, available N, P, K, and S.[6] Therefore, studies on management-induced spatial variability of soil quality are needed for refinement of recommended management practices being adopted for long. Understanding management impacts on spatial variability of soil quality are important to achieve soil improvement, better yields, input optimization, and consequent savings. Most studies on the impacts of land use change, management practices, and orchard age indicated that these factors are the major drivers of spatial variability in soil physico-chemical and biochemical properties, as well as soil biota communities.[7]

The transition from native forest to intensively managed farming often results in significant changes in soil health and is thus likely to modify the processes that affect soil quality.[8] Under tropical monsoon climate, soil quality deterioration may be intense and quick as the ecologically sensitive components are not able to safeguard against the detrimental effects induced by agricultural practices. The changes in soil properties resulting from deforestation and subsequent cultivation of crops in the humid tropics have been reported extensively.[9–12] In India, such studies on soil health focused mainly on seasonal agriculture.[13–15] Specifically, information on the impact of land use change from native forests to fruit orchards and their subsequent long-term management on soil quality is very limited under the monsoon climatic regimes of India.[6,16] Therefore, there is a strong need to assess the land-use-change impact on soil quality in understanding the agro-ecosystem functioning and sustainability of the production systems.[16]

Indian horticulture sector contributes about 33% to the agriculture Gross Value Added (GVA) making a very significant contribution to the Indian economy. Over the last decade, the area under horticulture grew by 2.6% per annum and annual production increased by 4.8%. The area under fruit plantation in 1991–1992 was 2.87 million ha, which increased by more than two-fold (6.51 million ha) in 2017–2018.[17] Many of the fruit plantations were established by clearing native forest land and hence, the land-use-change and associated management practices are expected to have a significant influence on the soil quality and productivity of these orchards.[18] Understanding how soil management, land use change, and orchard age impact soil quality can lead to sustainable management of the orchards. The combined effects of land use change, soil management, and orchard age on soil quality have not yet been studied previously for guava (*Psidium guajava* L.) and sapota (*Manilkara achras* Mill) orchards under tropical monsoon climate. Though, Hazarika and coworkers reported the land use change impact on soil quality under guava and sapota orchards, the data on soil quality attributes across different depths (0–7.5 cm, 7.5–15 cm, and 15–30 cm) and variability between drip circle and inter-row spaces were missing.[19] So, the present study was conducted in the same guava and sapota orchards,[19] to investigate the combined effect of orchard age, type, and long-term soil management on soil quality across soil depths and between drip circles and inter-row spaces. The objectives of the study were (i) to assess how the change in land use from native forest to two different types of fruit orchards with varying ages affects soil quality depth-wise, (ii) to evaluate how the soil quality of the orchards are impacted by long term soil management practices, and (iii) to study how soil management practices affect variability in soil quality spatially within an orchard.

2 | MATERIALS AND METHODS

2.1 | Study area

The study was carried out in the experimental field of Central Horticultural Experiment Station, Kodagu, Karnataka, India (geographic location 12°26′ N, 75°47′ E and 1050 m above mean sea level). The site lies in Western Ghats, India characterized by a tropical monsoon climate with distinct wet and dry seasons. The mean annual rainfall is 1500 mm and the mean annual maximum and minimum temperatures vary from 36°C in May to 8°C in January. Two guava (*P. guajava* L. cv. Allahabad Safeda) orchards of 18 and 24 years (hereafter referred to as GO18Y and GO24Y, respectively) and two sapota (*M. achras* Mill. cv. Cricket Ball) orchards of 22 and 40 years (hereafter referred to as SO22Y and SO40Y, respectively) of age were selected for the study. The orchards were established after clearing secondary forest land (slope within 5%) and there was no record of the initial soil properties of the orchards. Therefore, the adjacent undisturbed forest land was considered as a reference plot for a comparative study of soil quality attributes of the horticultural land use systems. Orchard soils are classified as Alfisols (USDA taxonomy) and these are well-drained, deep, dark-brown, sandy loam to sandy clay loam in texture. The land use classes were distinguished as fruit plantation and forest as baseline ecosystem and the combined effect of land use change, soil management, and orchard age on spatial variability soil quality was evaluated.

2.2 | Orchard management

The orchard acreage and details of the management practices are presented in Table 1. A bare soil surface was maintained within 1.5 m radius surrounding the tree trunk (hereafter termed as drip circle) to facilitate the application of irrigation and fertilizer/manure. The recommended dose (RD) of nutrients was applied in the drip circle (area with 1.5 m radius from the tree trunk) in two splits i.e. 50% of RD during pre-monsoon (March–April) and the remaining 50% of RD during post-monsoon (September–October).

Well decomposed organic manure was applied to the orchard at 7.0 t ha^{-1} for guava and 3.5 t ha^{-1} for sapota during pre-monsoon (March–April), sporadically. Weeding was done manually and bare soil surface was maintained in the drip circle since the establishment of

TABLE 1 Orchard type, age, acreage and nutrient management in the experimental orchards

Orchard type and age	Orchard area (ha)	RD of N-P_2O_5-K_2O (g plant^{-1} year^{-1})	Spacing between tree	Planting density (No. of trees ha^{-1})	Total quantity of N-P_2O_5-K_2O added (Mg ha^{-1}) since planting
GO18Y	1.4	600-450-600	6 × 6 m	277	2.83-2.12-2.83
GO24Y	3.0	600-450-600	6 × 6 m	277	3.82-2.87-3.82
SO22Y	1.5	400-160-450	7.5 × 7.5 m	148	1.30-0.52-1.47
SO40Y	1.3	400-160-450	7.5 × 7.5 m	148	2.31-0.92-2.60

Abbreviations: GO, guava orchard; N, P_2O_5, and K_2O was applied in the form of urea, single superphosphate, and muriate of potash; RD, Recommended dose of nutrients; SO, sapota orchard, Y, year.

the orchards. In contrast, the surface of the inter-row space soil was not kept bare and the weeds grown in it were slashed followed by incorporation into the soil. Bordeaux paste and solution were applied in orchards as a preventive treatment against fungal diseases. During the post-monsoon season (November–March), irrigation was provided in the drip circle.

2.3 | Soil sampling procedure

Across the slope (1%–5%), each orchard was divided into five replicated blocks to ensure proper randomization of soil sampling and minimization of sampling errors (Figure S1). Soil samples were collected from 3 soil depths (0–7.5, 7.5–15, and 15–30 cm) using a 5 cm diameter core after the withdrawal of the South-West monsoon. Within an orchard block, 40 random soil samples (20 spots each from drip circle and inter-row) were collected from each soil depth and then combined to make one composite soil sample for each depth. Thus, 15 composite soil samples (3 depths × 5 blocks) were obtained from each of the orchards. Similarly, the forest land adjacent to the orchards was divided into five replicated blocks across the slope. From each block, one composite soil sample for each of the three depths consisting of soils from 40 random spots was collected. Altogether, five composite soil samples from each depth were collected from the forest land. Each field moist composite soil sample was divided into two sub-samples. A subsample was air dried under a shade, ground to pass a 2 mm sieve, and stored in a plastic container until analyzed for physical and chemical parameters. A portion of the sieved (2 mm) soil sample was ground to pass through a 0.5 mm sieve for estimation of organic carbon. The remaining field moist composite sub-sample was stored at 4°C for analysis of soil enzymes.

2.4 | Analysis of soil

Bulk density (BD) of soil was determined from intact soil cores of 102 cm^3 volume collected from three depths (0–7.5, 7.5–15, and 15–30 cm) of drip circle and inter-row space. Within a block, 10 core samples (five each from drip circle and inter-row space) from each of the three depths were collected. Fifteen soil cores representing five replicated blocks and three depths were collected from the adjacent forest. Soil porosity was derived using the formula: Porosity $= [1 - (BD/PD) \times 100]$, where PD is the particle density determined using a Keen box.[20] The combined glass electrode was used to measure the soil pH in a 1:2.5 soil: water suspension. Soil organic carbon (SOC) was determined by the wet digestion method.[21] Available fractions of micronutrients viz. Zn, Fe, Cu, and Mn in the soil were determined by the method of Lindsay and Norvell[22] using Atomic Absorption Spectrophotometer (Analyst 200). Available nitrogen (AvN) was determined by the alkaline permanganate oxidation method.[23] Available P (AvP) was extracted using Bray's-I extractant followed by determination of P in the extract with stannous chloride blue color method.[24] Available K (AvK) was extracted using 1 N ammonium acetate (pH 7.0) followed by the determination of K in the extract with a flame photometer. Exchangeable Ca (ExCa) and Mg (ExMg) in soil were determined using AAS after extraction with 1 N ammonium acetate (pH 7.0) solution. The method of Tabatabai[25] was used for the determination of the activity of enzymes viz. dehydrogenase (DHA), acid-phosphomonoesterase activity (PHA), and β-glucosidase (GSA) in soil. Results are expressed based on oven-dry soil.

2.5 | Statistical analysis

All univariate statistical analyses were performed using SPSS version 12.0 (SPSS Inc., Chicago, IL). The dataset of a soil attribute for four orchards and the adjacent forest was checked for normality using the Kolmogorov–Smirnov test. We did the mild transformation of the dataset, that is, square root transformation wherever normality distribution was not followed. Parameter-wise mean difference ($p < 0.05$) between the drip circle and inert row space was analyzed by performing One-way Analysis of Variances incorporating the Levene statistics to test the equality of group variances followed by Tukey's HSD test ($p < 0.05$) for pair-wise comparisons among the means.

To determine the variability among GO18Y, GO22Y, SO22Y, SO40Y, and adjacent forest in terms of the soil attributes, principal component analysis (PCA) was performed on the data matrix where soil attributes were arranged as columns and orchard types and adjacent forest as rows. The multivariate normality distribution was examined by performing a colinearity test and based on this test the dataset was square-root transformed wherever necessary. While performing PCA, the transformed data matrix was normalized to eliminate the effects of different units of soil attributes. The transformed

TABLE 2 Spatial variability (drip circle vs. inter row space) in the soil (0–7.5 cm) quality attributes of fruit orchards as influenced by orchard age and soil management

Soil attributes	GO24Y		Significance of paired t test	GO18Y		Significance of paired t test	SO40Y		Significance of paired t test	SO22Y		Significance of paired t test
	Drip circle	Inter-row		Drip circle	Inter-row		Drip circle	Inter-row		Drip circle	Inter-row	
Zn	5.93 ± 0.61	3.94 ± 0.20	**	3.18 ± 0.16	2.48 ± 0.14	**	1.16 ± 0.12	2.06 ± 0.21	**	3.83 ± 0.22	4.14 ± 0.37	0.14
Fe	45.6 ± 2.89	42.4 ± 1.84	0.07	17.7 ± 3.15	16.6 ± 1.70	0.51	43.3 ± 6.76	26.0 ± 12.5	*	35.1 ± 2.70	30.5 ± 4.22	0.07
Cu	3.08 ± 0.10	3.05 ± 0.18	0.75	4.13 ± 0.15	4.25 ± 0.44	0.56	2.88 ± 0.10	3.16 ± 0.05	**	11.2 ± 2.29	12.0 ± 1.29	0.53
Mn	25.2 ± 4.09	12.4 ± 2.42	**	23.0 ± 3.06	23.8 ± 6.40	0.78	13.9 ± 2.64	17.1 ± 1.26	*	17.9 ± 1.90	22.0 ± 3.45	*
AvK	401 ± 20.7	170 ± 39.6	**	461 ± 34.8	278 ± 75.2	**	519 ± 39.2	257 ± 20.1	**	328 ± 15.7	200 ± 25.8	**
ExCa	4.59 ± 0.86	5.11 ± 0.42	0.26	5.13 ± 0.35	5.03 ± 0.38	0.69	2.48 ± 0.59	6.18 ± 1.23	**	5.39 ± 1.07	3.62 ± 0.56	*
ExMg	1.30 ± 0.05	1.79 ± 0.21	**	0.94 ± 0.07	2.08 ± 0.38	**	1.13 ± 0.12	2.27 ± 0.23	**	1.74 ± 0.14	1.02 ± 0.14	**
AvP	117 ± 15.5	57.5 ± 4.49	**	74.8 ± 4.33	74.0 ± 7.45	0.82	265 ± 24.5	5.07 ± 0.42	**	148 ± 14.4	12.4 ± 4.71	**
AvN	170 ± 10.8	165 ± 8.07	0.40	174 ± 14.4	162 ± 7.51	0.14	167 ± 13.7	152 ± 16.1	0.13	158 ± 8.07	166 ± 8.56	0.15
SOC	2.00 ± 0.19	2.06 ± 0.28	0.69	1.73 ± 0.16	1.93 ± 0.18	0.09	1.58 ± 0.19	2.10 ± 0.12	**	1.76 ± 0.10	1.80 ± 0.09	0.58
pH	5.86 ± 0.23	6.32 ± 0.05	**	6.13 ± 0.10	6.43 ± 0.27	*	5.20 ± 0.09	6.41 ± 0.32	**	6.16 ± 0.35	5.94 ± 0.15	0.21
BD	1.49 ± 0.06	1.48 ± 0.08	0.73	1.51 ± 0.04	1.46 ± 0.04	0.11	1.50 ± 0.04	1.39 ± 0.02	**	1.51 ± 0.03	1.50 ± 0.03	0.57
PORO	42.7 ± 2.81	45.2 ± 1.63	0.11	43.9 ± 1.68	45.1 ± 1.34	0.25	43.4 ± 3.00	45.5 ± 0.72	0.16	41.7 ± 1.85	43.7 ± 0.52	*
DHA	1.87 ± 0.22	2.32 ± 0.69	0.20	2.19 ± 0.55	3.63 ± 0.38	**	1.13 ± 0.08	2.84 ± 0.16	**	1.54 ± 0.10	1.17 ± 0.15	**
PHA	311 ± 16.6	402 ± 42.3	**	300 ± 12.9	350 ± 20.0	**	274 ± 16.5	316 ± 14.8	**	228 ± 56.2	353 ± 15.9	**
GSA	165 ± 18.8	163 ± 12.4	0.80	126 ± 15.1	148 ± 19.0	0.07	53.1 ± 10.6	108 ± 15.3	**	93 ± 21.9	108 ± 18.1	0.27

Note: For a soil attribute, the significance (2-tailed) value ≥0.05 indicates no significant difference between drip circle and inter-row spaces; *indicates significance level $\le p_{0.05}$; **indicates significance level $\le p_{0.01}$. Abbreviations: 18Y, 18 years old; 22Y, 22 years old; 24Y, 24 years old; 40Y, 40 years old; AvK, available potassium (kg ha^{-1}); AvN, available nitrogen (kg ha^{-1}); AvP, available phosphorus (kg ha^{-1}); BD, bulk density (Mgm^{-3}); Cu, DTPA extractable Cu (mg kg^{-1}); DHA, dehydrogenase activity (μg TPF g^{-1}(dw) soil h^{-1}); ExCa, exchangeable calcium (meq 100 g^{-1}); ExMg, exchangeable magnesium (meq 100 g^{-1}); Fe, DTPA extractable Fe (mg kg^{-1}); GO, Guava orchard; GSA, β-glucosidase activity (μg PNG g^{-1}(dw) soil h^{-1}); Mn, DTPA extractable Mn (mg kg^{-1}); pH, 1:2.5 soil water suspension; PHA, phosphomonoesterases activity (μg PNP g^{-1}(dw) soil h^{-1}); PORO, porosity (%); SO, Sapota orchard; SOC, soil organic carbon (%); Zn, DTPA extractable Zn (mg kg^{-1}).

and normalized dataset was ordinated based on the scores of the soil attributes in the first two principal components and the Euclidean distance was used as a measure of dissimilarity. To test the significant difference in variability of soil quality within an orchard (drip circle vs. inter-row space), among the orchard types and between the orchards and the adjacent forest, the analysis of similarity (ANOSIM) was carried out using the D1 Euclidean distance matrix (integrating 999 permutations for R statistics) for pair-wise comparisons.[26] The PCA was done using PRIMER-E version 6.1.9 software (Primer-E Ltd., Plymouth, UK).

3 | RESULTS

3.1 | Soil quality indicators as influenced by orchard age and soil management

The study showed that irrespective of the type and age of orchard stands, there was an increasing trend in BD and a decreasing trend in porosity of drip circle soils as compared to the inter row space soils (Table 2). The surface soil (0–7.5 cm) of the drip circle of 40 years old Sapota orchard (SO40Y) had significantly (Table 2, $p < 0.05$) higher BD in comparison with inter row space soil. However, when comparing the BD of drip circle and inter row space soils of other differently aged (18–24 years) orchards, it did not make a significant difference (Table 2). The significant decrease in BD of inter row space soil of SO40Y orchard was not apparent to cause significant increase in porosity of the soil. Barring one exception (SO22Y), there was no significant difference in porosity of soils of drip circle and inter-row space.

The pH of the drip circle soils (0–7.5 cm) of SO40Y, GO24Y, and GO18Y orchard stands decreased significantly as compared to that of inter row space soil. In contrast, the pH of the drip circle soil of SO22Y orchard increased but not significant. The magnitude of drop in pH varied between 0.3 and 1.21 units and the decrease in pH of drip circle soil of the orchards was in the order of GO18Y > GO24Y > SO40Y. The SOC concentration in the drip circle soils of the orchard stands decreased in the order of SO22Y > GO24Y > GO18Y > SO40Y relative to inter row space soil. However, the extent of reduction in SOC (~25%) was significant (Table 2, $p < 0.01$) only in case of SO40Y orchard.

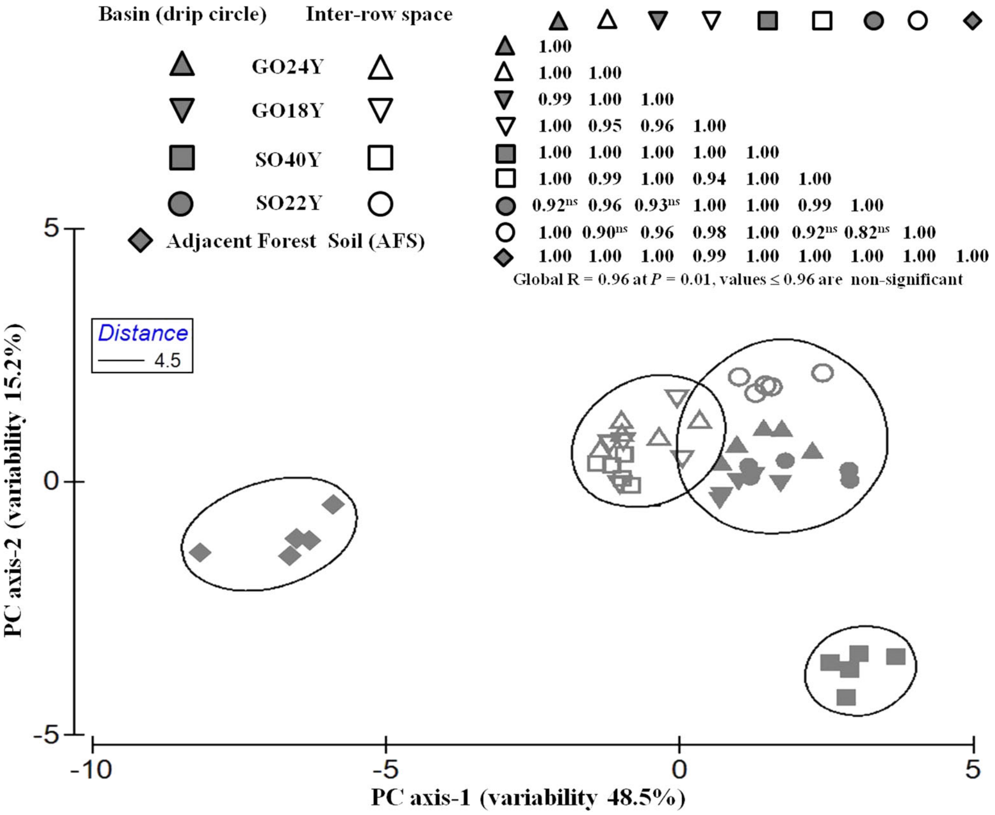
The concentration of AvN, AvP, AvK, ExCa, ExMg, and DTPA extractable Zn, Fe, Cu, and Mn in the drip circle and inter row space soils of the orchards are presented in Table 2. The impact of orchard age and long-term soil management was not apparent to cause detectable changes in AvN of drip circle and inter row space soils. Apart from GO18Y orchard, Av P in drip circle soils of all other orchards increased markedly (Table 2; $p < 0.01$). The oldest orchard (SO40Y) displayed more than 52 times increase in AvP in the drip circle soil. AvK of drip circle soil of all the orchard stands increased significantly (Table 2; $p < 0.01$) and the magnitude of increase varied between 65% and 136%. There is no trend observed with regard to the change in concentration of ExCa in drip circle soil depending on the type (Guava/Sapota) and age of the orchards. However, drop in concentration of ExCa in the drip circle soils of 40 years old sapota orchard was highly significant (Table 2; $p < 0.01$). On the other hand, in majority of the orchard stands (GO18Y, GO24Y, and SO40Y), the concentration of ExMg in drip circle soils dropped to the tune of 27.4%–54.8% which was highly significant relative to the inter row space soils.

DTPA-Zn in the drip circle soil of guava orchard increased significantly (Table 2; $p < 0.01$) whereas it was decreased in sapota orchards with significantly lower value only in case of 40-years old orchard (SO40Y). There was an increasing trend in the concentration of DTPA-Fe of drip circle soils of all the orchard stands. However, the increase was significant (Table 2; $p < 0.01$) only in case of oldest orchards (SO40Y). DTPA-Cu in drip circle soil of the oldest orchard (SO40Y) dropped significantly, whereas in other orchard stands the difference was not apparent. The concentration of DTPA-Mn in drip circle soils of sapota orchards decreased significantly (Table 2; $p < 0.05$) whereas it increased significantly in the 24-years old guava orchard (GO24Y). With very few exceptions, majority of the soil quality attributes of near surface (7.5–15 cm) and sub-surface (15–30 cm) soil layers of drip circle and inter row space exhibited similar trend (Tables S1 and S2) as that of surface soil layer (0–7.5 cm) and therefore, these are not discussed again.

The activity of PHA in the drip circle soils (0–7.5 cm) of all the orchard stands was significantly (Table 2; $p < 0.01$) lower (13.3%–35.4%) as compared to that of inter row space soil. The reduction in the activity of DHA in the drip circle soils of GO18Y and SO44Y orchards was highly significant (Table 2; $p < 0.01$). GSA activity in drip circle soil of 40-year-old sapota orchard (SO44Y) was reduced by more than 50%. However, the change in GSA activity in drip circle soil was not apparent in the other orchards (Table 2).

3.2 | Variability in soil quality between drip circle and inter-row space

The PCA plots with distinct clusters at 95% confidence limit representing different orchard stands and adjacent undisturbed forest site (AFS) based on soil quality attributes (as variables) of surface (0–7.5 cm), near surface (7.5–15 cm) and sub-surface (15–30 cm) soils are presented in Figures 1–3, respectively. The multivariable pair-wise comparison between clusters indicated that the variability in soil attributes between drip circle and inter row space within an orchard was significant (Global $R \geq 0.96$ and ≥ 0.95 at $p < 0.01$; as determined by ANOSIM incorporating 999 permutations for Global R, Figures 1–3) indicating management induced deterioration of soil quality of the drip circle relative to inter row space. The drip circle soil quality of the oldest orchard (SO40Y) was significantly (Figure 1, Global $R \geq 0.96$ $p < 0.01$) different from the inter row space soil of the same orchard (SO40Y) as well as the drip circle and inter row space soils of the other orchard stands (GO18Y, GO24Y, and SO22Y). Because, the cluster representing drip circle soil of 40 years old sapota orchard (SO40Y) formed independently and remained distinctly separated from the same (SO40Y) and other orchard stands (GO18Y, GO24Y,



	▲	△	▼	▽	■	□	●	○	◆
▲	1.00								
△	1.00	1.00							
▼	0.99	1.00	1.00						
▽	1.00	0.95	0.96	1.00					
■	1.00	1.00	1.00	1.00	1.00				
□	1.00	0.99	1.00	0.94	1.00	1.00			
●	0.92^{ns}	0.96	0.93^{ns}	1.00	1.00	0.99	1.00		
○	1.00	0.90^{ns}	0.96	0.98	1.00	0.92^{ns}	0.82^{ns}	1.00	
◆	1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00

Global R = 0.96 at $P = 0.01$, values ≤ 0.96 are non-significant

FIGURE 1 Principal component analysis (PCA) plot depicted spatial variability (drip circle vs. inter-row space) in soil (0–7.5 cm) within an orchard and between soils of adjacent forest (reference site) and differently aged fruit orchards. Soil attributes considered as variables were bulk density, porosity, dehydrogenase activity, β-glucosidase activity, acid-phosphomonoesterase activity, pH, soil organic carbon, soil available nitrogen, soil available phosphorus, soil available potassium, exchangeable calcium, exchangeable magnesium, and DTPA extractable Cu, Zn, Mn, and Fe. PCA was performed on the normalized data-matrix consisted of soil attributes as variables and soil sampling sites as factors. Ellipses represent superimposed hierarchical clusters (Euclidean distance 4.5) deduced using group-average linkage incorporating similarity of profile (SIMPROF) at 95% confidence limit

and SO22Y) with regard to the soils of the inter row space as well as drip circle and inter row space, respectively.

3.3 | Variability in soil quality of orchards relative to the reference site

The clusters in the PCA plots (Figures 1 and 2) representing surface (0–7.5 cm) and near-surface (7.5–15 cm) soils of the orchards showed distinct separation between the AFS and the orchards and among the orchards. AFS was significantly different (Global $R \geq 0.96$ and ≥0.95 at $p < 0.01$) from the orchards with varying ages (18–40 years) and management (Table 1). The variability between AFS and group of orchards was the highest along PC1 (explained 48.5% and 49.4% variability) in the PC plots demonstrating the deterioration of quality of orchard soil as compared to AFS. The PCA plots with five distinct clusters at 95% confidence limit representing different orchard stands and AFS based on soil quality variables of 15–30 cm depth are presented in Figure 3. Like surface soil, there is significant variability between AFS and different orchard stands, as the clusters representing AFS and the respective orchard stands are markedly different. It is clear from the PCA plot that the clusters depicting orchards with soil quality indicators (as variables) of the drip circle are conspicuously different from the clusters of the respective orchards representing inter-row space soil. The variability between AFS and group of orchards was the highest along PC1 (explained 40.2% variability) in the PC plots. The spacing between the clusters in the PCA plots (Figures 1–3) also reflected the degree of disturbances, that is, drip circle soils spaced at the maximum distance from AFS relative to inter-row space soil along PC-axis-1. Among the soil attributes, DHA showed the highest loading in PC-axis-1 across the soil depths (0.95, 0.93, and 0.83, Table 3). Apart from DHA, other soil quality attributes viz. SOC, PHA, GSA, pH, BD, PORO, ExCa, ExMg, DTPA-Mn, AvP, and AvN also showed a high degree of correlation with PC1 ($p < 0.01$, Table 3).

4 | DISCUSSION

The impact of land use change and subsequent mono-cropping in different time scales on the variation of soil quality is difficult to interpret based on the variability elucidated by individual soil quality indicators. Soil quality largely depends on the cumulative response of

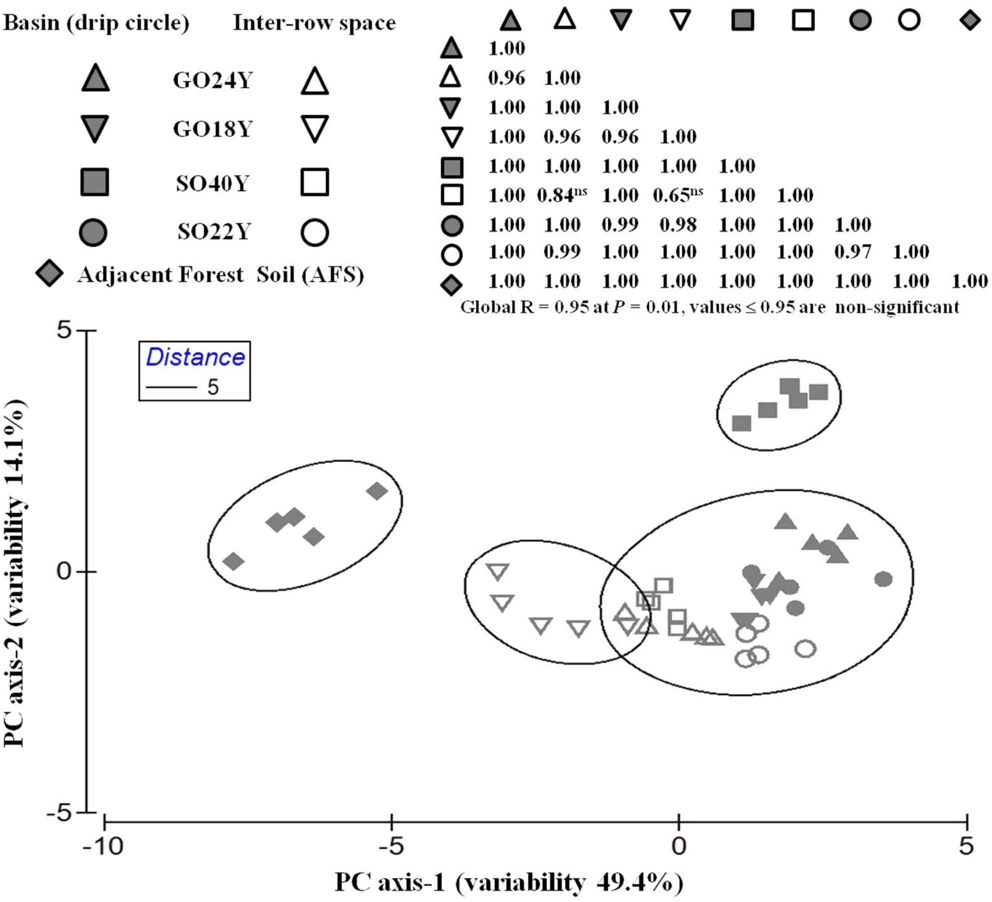


FIGURE 2 Principal component analysis (PCA) plot depicted spatial variability (drip circle vs. inter-row space) in soil (7.5–15 cm) within an orchard and between soils of adjacent forest (reference site) and differently aged fruit orchards. Soil attributes considered as variables were bulk density, porosity, dehydrogenase activity, β-glucosidase activity, acid-phosphomonoesterase activity, pH, soil organic carbon, soil available nitrogen, soil available phosphorus, soil available potassium, exchangeable calcium, exchangeable magnesium, and DTPA extractable Cu, Zn, Mn, and Fe. PCA was performed on the normalized data-matrix consisted of soil attributes as variables and soil sampling sites as factors. Ellipses represent superimposed hierarchical clusters (Euclidean distance 5) deduced using group-average linkage incorporating similarity of profile (SIMPROF) at 95% confidence limit

soil properties to management-induced factors and therefore, soil quality of different land use systems is often compared by employing PCA where changes in soil quality indicator values are considered at a time. Therefore, we examined the variability among different land use systems using PCA taking into consideration all physical, chemical, and biochemical properties examined during the study.

4.1 | Soil physico-chemical quality indicators

The marked increase in BD value (~8.0%) of drip circle soil of 40-year-old orchard relative to inter-row space soil is the result of long-term (40 years) disturbance due to intercultural operations like weeding, fertilizer application, irrigation, etc. Moreover, a significant reduction in SOC of drip circle soils (paired t test, $p < 0.01$; Table 2) caused detectable changes in BD of the drip circle soil. Because of the stronger influence of organic matter (OM) on soil physical conditions, one may expect noticeable changes in soil physical properties with differences in OM content.[6,27] Though, there is an increasing trend in BD values of drip circle soils of other orchards relative to inter-row space soil, the difference was not apparent. Soil disturbances for 18–24 years could not bring about a significant reduction in SOC to cause marked change in BD of drip circle soils.

One of the major causes of soil acidity is the nitrification process.[28] Inputs of N fertilizer result in increased acidification and lowers the soil pH.2,[29–31] Depending on the age of the orchards (18–40 years), a substantial amount of N fertilizer (2.9–8.4 Mg ha^{-1} urea) were applied in the orchard drip circle and it has caused a significant reduction in pH of soils as compared to that of inter-row space. The relative difference in pH of the orchard (drip circle and inter-row) and AFS, as well as drip circle and inter-row space soils, are presumably due to the differences in the period of cultivation, level of fertilization, and quality and quantity of plant litter produced in orchards. Usually, several years of different land use are required to detect significant changes in the total soil organic C pool.[32] The 25% reduction of SOC in drip circle soil compared to inter-row space soils of 40 years old sapota orchard indicates that the carbon cycle in the drip circle soils is deeply altered.[33] The weeding and other intercultural operations are routinely done in the drip circle to facilitate irrigation and fertilizer/manure application. Therefore, the amount of organic input returned to the soil is much lesser than that of inter-row space soil, where an input of leaves, twigs, and roots of orchard trees, as well as cutting of inter-row grassland, occurs. Though there is a scope for incorporating fallen leaves into the drip circle soil for building up SOC, the guava and sapota fallen leaves are expected to have detrimental effects on earthworm density and biomass in soil. The authors previously explained the vermicidal activities of guava and sapota leaves due to the presence of higher concentrations of tannin and saponin. Therefore, the fallen liters of guava and sapota need bioconversion to compost before its application as a soil amendment to support better soil health. In fact, the C deficit in drip

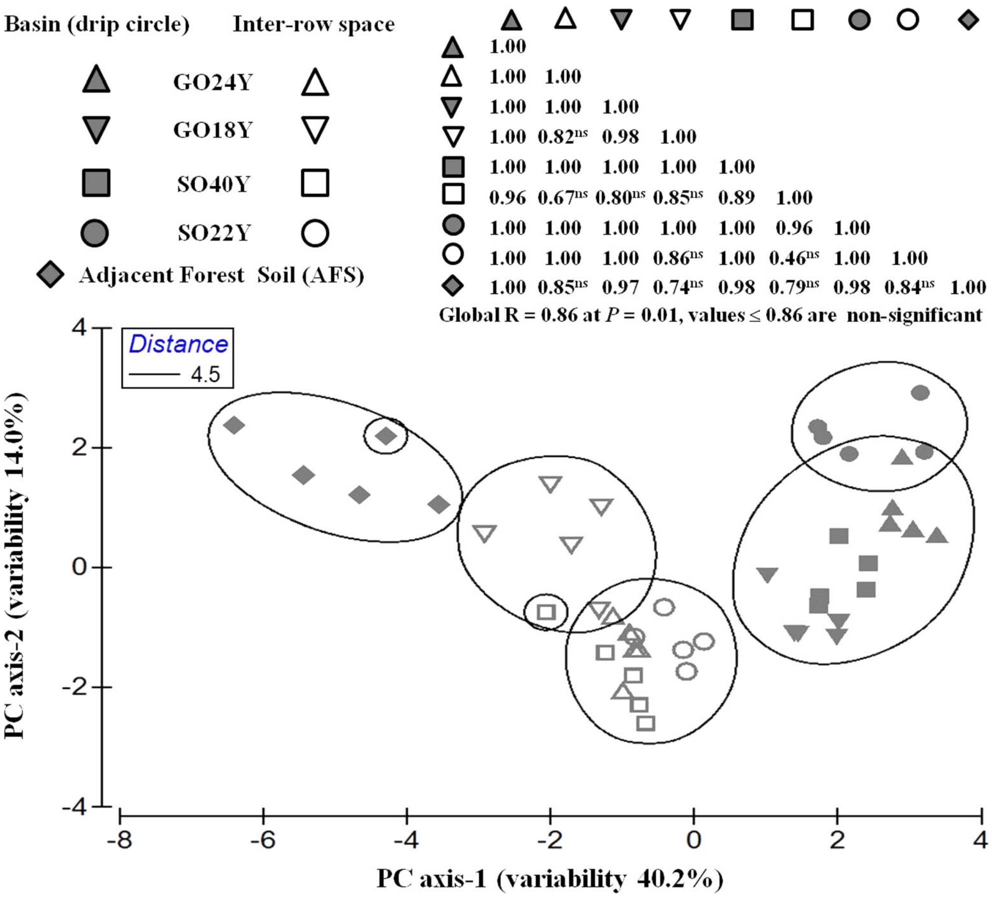


FIGURE 3 Principal component analysis (PCA) plot depicted spatial variability (drip circle vs. inter-row space) in soil (15–30 cm) within an orchard and between soils of adjacent forest (reference site) and differently aged fruit orchards. Soil attributes considered as variables were bulk density, porosity, dehydrogenase activity, β-glucosidase activity, acid-phosphomonoesterase activity, pH, soil organic carbon, soil available nitrogen, soil available phosphorus, soil available potassium, exchangeable calcium, exchangeable magnesium, and DTPA extractable Cu, Zn, Mn, and Fe. PCA was performed on the normalized data-matrix consisted of soil attributes as variables and soil sampling sites as factors. Ellipses represent superimposed hierarchical clusters (Euclidean distance 4.5) deduced using group-average linkage incorporating similarity of profile (SIMPROF) at 95% confidence limit

TABLE 3 Pearson correlation coefficient (*r*) between principal component axis and soil quality attributes of three depths used as variables to discriminate drip circle and inter-row space soil within an orchard and between native forest (reference site) and fruit orchards established by clearing native forest

	0–7.5 cm depth		7.5–15 cm depth		15–30 cm depth	
Parameters	PC1	PC2	PC1	PC2	PC1	PC2
Zn	0.32*	0.66**	0.48**	−0.45**	0.44**	0.08
Fe	0.33*	−0.22	0.39**	0.38**	0.41**	0.07
Cu	0.37*	0.42**	0.37*	−0.37*	0.23	0.13
Mn	0.50**	0.47**	0.47**	−0.29*	0.46**	−0.06
AvK	0.21	−0.75**	0.14	0.75**	0.42**	0.31*
Ca	−0.84**	−0.01	−0.77**	−0.11	−0.68**	0.37*
Mg	−0.78**	−0.03	−0.76**	−0.07	−0.70**	0.26
AvP	0.57**	−0.70**	0.45**	0.77**	0.61**	0.31*
AvN	−0.71**	−0.29*	−0.69**	0.25	−0.54**	0.38**
SOC	−0.92**	−0.01	−0.80**	0.01	−0.71**	0.26
pH	−0.86**	0.30*	−0.79**	−0.38**	−0.76**	0.22
BD	0.85**	0.15	0.77**	−0.07	0.72**	−0.14
PORO	−0.86**	−0.17	−0.83**	0.10	−0.78**	0.14
DHA	−0.95**	−0.12	−0.93**	0.02	−0.83**	0.32*
PHA	−0.83**	0.08	−0.79**	−0.10	−0.80**	0.01
GSA	−0.56**	0.50**	−0.45**	−0.43**	−0.42**	0.09

Note: Values are ($r \geq 0.29$* at $p \leq 0.05$ and 0.38** at $p \leq 0.01$, $n = 45$) significant.

Abbreviations: AvK, available potassium; AvN, available nitrogen; AvP, available phosphorus; BD, bulk density; Ca, exchangeable calcium; Cu, DTPA extractable Cu; DHA, dehydrogenase activity; Fe, DTPA extractable Fe; GSA, β-glucosidase activity; Mg, exchangeable magnesium; Mn, DTPA extractable Mn; PC, Principal component axis; pH, 1:2.5 soil water suspension; PHA, phosphomonoesterases activity; PORO, porosity; SOC, soil organic carbon; Zn, DTPA extractable Zn.

circle soil is only partially counterbalanced by the application of very few exogenous organic amendments. Further, SOC loss from drip circle soil due to water erosion cannot be ignored (mean annual rainfall of 1500 mm). The organic carbon pool is concentrated in the vicinity of the soil surface and is lighter than mineral particles (density of organic carbon is 1.2–1.5 Mg m^{-3} compared with 2.5–2.7 Mg m^{-3} for mineral particles). Therefore, it is preferentially removed by runoff water[34,35] and resulted in a significant reduction of SOC in drip circle soil as compared to that of inter-row space soil.

The improvement of the level of P and K in the drip circle soils of the orchard stands could be attributed to the addition of these nutrients through inorganic fertilizers for a substantially long period (18–40 years) of application. The quantification of changes in major and trace elements in soils has been attempted in several long-term fertilizer experiments.[36] Phosphorus (P) deficiency is a universal crop production constraint and constitutes the second most important soil fertility problem throughout the world.[37] The results from a study on the effects of 42-year long-term fertilizer management on soil phosphorus availability indicated that the continuous addition of higher P doses decreased resistance to P release and thus increased the P supply in the soil.[38] The decreasing trend of ExCa and ExMg in the drip circle soils of the majority of the orchards could be the result of leaching due to the combined effect of enhanced acidity (0.3–1.21 units drop in pH) and occurrence of high rainfall (>1500 mm $annum^{-1}$) in the region. Several studies showed that phosphorus fertilization limits Zn availability for plants[39,40] There is a general agreement regarding an antagonistic relationship between Zn and P in soil and its contribution to the P-induced Zn deficiency.[41,42] The marked decline in the concentration of DTPA-Zn in the drip circle soil of 40 year old orchard was the result of its precipitation as $ZnPO_4$ complex as the plant available fraction of P in the drip circle soil increased by 52 times as compared to the inter-row space soil. The magnitude of increase in available P in the drip circle soils of guava orchards is relatively less (1–2 times only against 52 times in SO40Y) and the antagonistic effect might have been suppressed due to increased solubility of Zn as a result of a drop in pH of drip circle soils (0–3–0.46 unit). Like DTPA-Zn, a significant reduction in DTPA-Cu and DTPA-Mn in the drip circle soil of 40 years old orchard (SO40Y) resulted from increased availability of P. Plant available Cu and Mn in soil have been limited by an elevated level of P concentration in soil.[43,44] Increase in concentration of DTPA-Fe in drip circle soils resulted from a decrease in soil pH and prolonged application of inorganic fertilizers. Commercial fertilizers, particularly phosphatic ones, contain trace elements as contaminants.[45] All P fertilizers had a high Fe content, an element that is found in greater amounts concerning other heavy metals and trace elements in phosphate rock used as raw material for P fertilizer production. Iron concentration ranges were 0.51%–0.68% in TSP, 0.71%–0.92% in MAP, and 0.71%–1.1% in DAP.[46]

4.2 | Soil enzymes as quality indicators

The marked reduction in the activity of PHA in drip circle soils of all the orchard stands resulted from the application of a substantial amount of inorganic P continuously over a long period. Depending on the orchards' age (18–40 years), 3.25–17.9 Mg ha^{-1} of SSP was applied in the drip circle soils. Application of inorganic P can repress the synthesis of phosphomonoesterases in soil because it inhibits the expression of PHO genes[47] and, indeed, phosphate inhibits the phosphatase activities of soil.[48,49] The activity of phosphatase is inversely proportional to the concentration of available P in soil.[50] It confirms the argument that the production and activity of acid phosphatases are connected with the demand of microorganisms and plants for P. Phosphatases being typical adaptive enzymes, their activity increases when the concentration of plant available P decreases. Kinetics studies indicate that orthophosphate ions are competitive inhibitors of their activity in soil.[51] The significant reduction in the activity of DHA in drip circle soil of GO18Y and SO40Y orchards stands can be attributed to the substantial reduction (10.4% and 24.8%, respectively) in SOC. Soil enzymatic activity is strongly connected with soil OM content. The higher OM level can provide enough substrate to support higher microbial biomass, hence higher enzyme production.[52] Many authors reported a positive correlation between DHA and SOC concentration in soil[52–54] The role of soil pH in the reduction of DHA activities in drip circle soil cannot be ruled out. There was a significant fall in the pH of the drip circle soils and generally, enzyme activities tend to increase with soil pH.[52,55] Our findings corroborated with the results of many workers.[56,57] According to Frankenberger and Johanson,[58] the weakening of enzymatic activity in soil with the increase of soil acidity is the effect of destroying ion and hydrogen bonds in the enzyme active centre. It is often assumed that pH may affect soil enzymes by changing in the ionic form of the active sites, by altering the three-dimensional shape of enzyme, and affecting the affinity of the substrate to the enzyme.[59] Thus, the pH factor is considered to be the best predictor of DHA in the soil environment.[53,60] Substantial reduction (>50%) in the GSA activity in the drip circle soil of 40 years old sapota orchard can be attributed to the significant reduction in SOC. Many previous studies have described significant positive correlations between β-glucosidase with organic C.[61,62] The significant positive correlation indicates the important role of OM in maintaining enzyme activity. Furthermore, OM can play an important role in the immobilization of soil extracellular enzymes in the three-dimensional network of clay-humus complexes[63] The increased level of enzyme activity in the organic-amended soil may reflect a greater number of protective sites within the soil as a result of enhanced humus content. Generally, β-glucosidase activities can provide advanced evidence of changes in organic carbon long before it can be accurately measured by other routine methods.[64]

4.3 | Variability in soil quality of the orchards relative to reference site

The adopted orchard management practices for a prolonged duration of time (18–40 years) impacted the soil quality attributes of the orchards relative to AFS besides causing spatial variability within the

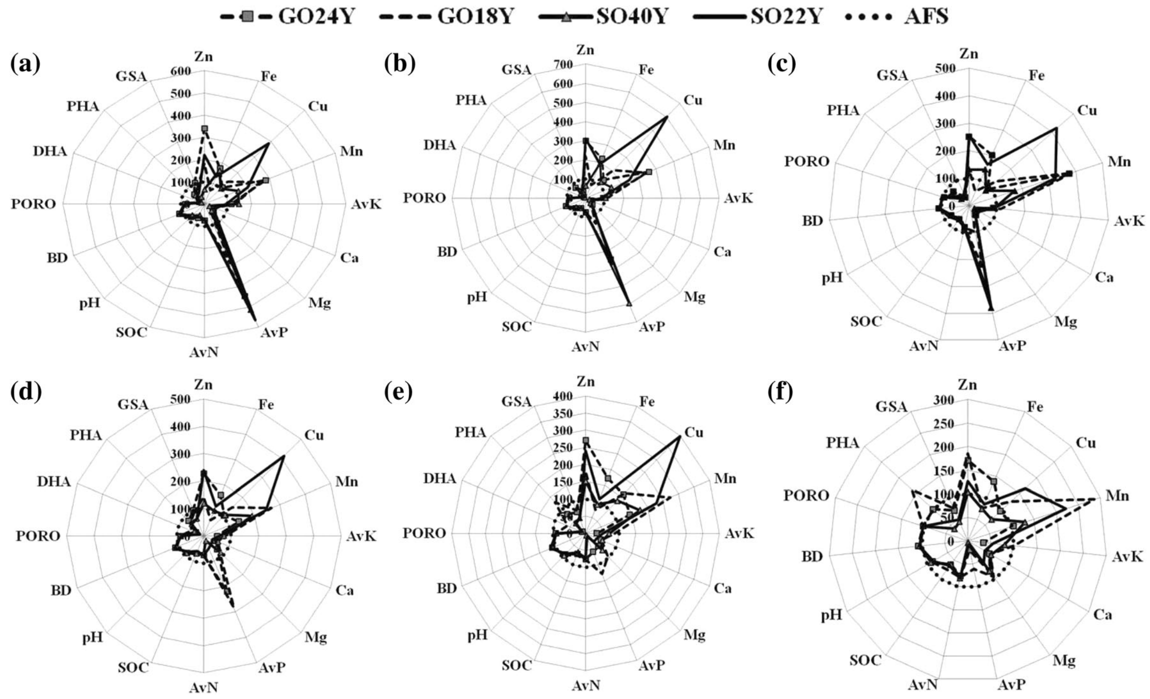


FIGURE 4 Graphical representation of soil properties of different sampling sites (Drip circle, (a) 0–7.5, (b): 7.5–15, and (c) 15–30 cm and Inter-row space, (d) 0–7.5 cm, (e) 7.5–15 cm, and (f) 15–30 cm soil depth) as influenced by orchard age, type, and long-term soil management. The star diagram indicated the percentage variation in soil properties at sampling sites scaled to 100% of the values of the adjacent forest soil (reference site)

orchards. PCA further revealed that the influencing factors of the variability of soil attributes were in the order of land use change > soil management > orchard age. Because, the clusters in the PCA plots (Figures 1–3) representing the orchards remained distantly apart from the cluster representing AFS along the PC-axis-1 exhibiting maximum variability of soil attributes. Following deforestation, intensive agricultural practices deteriorate soil quality due to the declined biomass inputs and increased degradation after land use change. Soil degradation results from the decline in physical, chemical, and biological parameters, depending not only on soil, topography, and climate but also on land use, anthropogenic activities, and agricultural management.[65,66] The spatial (drip circle and inter-row) variability in soil attributes was also apparent because the clusters depicting the drip circle soil quality attributes as variables was conspicuously different from that representing the inter-row space soil. The magnitude of deterioration of the drip circle soil quality of the oldest orchard (SO40Y) was apparent from the PCA plots (Figures 1–3) where the clusters representing the SO40Y orchard remained independently as well as distantly apart from the other orchard clusters. A higher degree of soil disturbance in the drip circles relative to AFS and inter-row space resulted from prolonged (18–40 years) exposure of soils to management practices (viz. forking, weeding, drip irrigation, fertilizer application, etc.) and soil erosion (rainfall >1500 mm annum^{-1}). Because of the greater length of disturbance time (40 years), the effect was more pronounced in the SO40Y orchard. Our results demonstrated that the influence of soil disturbance due to management practices has caused spatial variability within the orchard. Among the soil attributes, the major influencing factors of soil variability (across the soil depths) between the orchards and the AFS and within an orchard (drip circle vs. inter-row) is the DHA because, it showed the highest degree of correlation with PC- axis-1 (0.95, 0.93, and 0.83; Table 3). Apart from DHA, other soil quality attributes viz. SOC, PHA, GSA, pH, BD, PORO, ExCA, ExMg, DTPA-Mn, AvP, and AvN also contributed to creating the variability since these influencing factors also showed a high degree of correlation with PC-axis-1 of the PCA plots. Thus, it appears that these soil quality attributes were the main controlling factors and have a high degree of influence on all other soil quality attributes of the orchards for creating variability. It was also evidenced by the high degree of percentage change in the values of these soil quality attributes depicted by the radar plots (Figure 4a–f).

5 | CONCLUSION

The land use change from native forest to horticultural orchards, the subsequent orchard soil management practices and, the age of the orchard exerted a noticeable negative impact on the soil quality attributes under tropical monsoon climate. Our study demonstrated the excessive build-up of soil P and K fertility within the drip circle upon continuous long-term application of inorganic P and K fertilizers. Among soil enzymes studied, DHA maintained the strongest positive correlation with soil OM and pH. The retention of weed biomass and external application of organic manures in the inter-row spaces resulted in better soil fertility compared to drip circle soil. However, it is not advisable to incorporate leaf litters of guava and sapota in soil due to its vermicidal activity. So, the bio-conversion of leaf litter of Guava and Sapota to organic manure is proposed to be a pre-requisite for soil incorporation. In addition to routine application of organic manure, application of lime in the drip circle should be made to manage pH, Ca, and Mg in the soil. Taking into consideration of the present findings, the existing orchard soil management practices may be modified/ improved to prevent or delay the deterioration of soil quality for achieving the long-term sustainability of the production system.

AUTHOR CONTRIBUTIONS

Samarendra Hazarika: Conceptualization (lead); funding acquisition (lead); investigation (lead); methodology (lead); project administration (lead); resources (lead); supervision (lead); validation (lead); visualization (lead); writing – original draft (lead). **Dwipendra Thakuria:** Data curation (lead); formal analysis (lead); software (lead); writing – original draft (equal); writing – review and editing (equal). **Thandavarayan Sakthivel:** Conceptualization (supporting); data curation (supporting); investigation (supporting); supervision (supporting); visualization (supporting).

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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