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SUBTLE SHIFTS UNDER SLOW-ONSET CLIMATE EVENTS: SOIL HEALTH RESPONSES ACROSS AGROECOLOGICAL AND CONVENTIONAL RICE FARMLANDS IN TROPICAL ASIA

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Abstract: This study assessed soil health of Malaysian rice farms facing prolonged extreme temperatures. 33 soil samples were collected over a period of six months (Phases I, II, and III) from three different types of farming systems: Agroecological, conventional, and mixed (combining agroecological and conventional practices). Samples were analysed for Soil Temperature (ST), Soil Organic Carbon (SOC), Soil Organic Matter (SOM), soil moisture, and pH. The results showed a significant increase in ST (27.33°C–36.00°C) across all farmland types, particularly during Phases I and III. Agroecological farms maintained higher SOM (2.96%–1.05%) and SOC (20.28%–20.54%) as compared to the mixed and conventional systems. Soil moisture decreased progressively while pH remained consistently acidic (5.37–2.42), with conventional farms showing the highest acidity (pH = 2.42). A significant decline in soil moisture coefficients during Phases I and III further indicated climate stress. The findings highlight that rising soil temperature is a major driver of soil health degradation. Conventional and mixed systems face significant adaptation challenges from climate stress and industrial farming practices. Agroecological practices demonstrate better resilience, offering sustainable strategies for preserving soil health under changing climatic conditions.

Keywords: Soil health, conventional agriculture, agroecology agriculture, climate change.

Introduction

Rice is a staple crop in tropical regions such as Thailand, Indonesia, and Malaysia, where its cultivation is facilitated by favourable climate conditions, including abundant sunlight and water availability. In these regions, rice is cultivated two to three times per year under varying farming practices. Agroecological and conventional farming systems dominate rice production, each presenting distinct responses to environmental stressors, particularly under the influence of slow-onset climate events such as rising temperatures (Lin & Fukushima, 2016). Understanding the effects of these gradual climatic shifts on soil health is essential, as soil health plays a pivotal role in maintaining crop productivity, nutrient cycling, and ecosystem sustainability (Elias *et al.*, 2019).

Soil health is a critical determinant of agricultural sustainability, encompassing physical, chemical, and biological properties that regulate nutrient availability, water retention, and microbial activity (Zhao *et al.*, 2018). Agroecological farming emphasises ecological balance through practices such as organic composting, nitrogen-fixing legumes, cover cropping, and crop rotation. These methods promote the accumulation of Soil Organic Matter (SOM), enhance microbial diversity, and improve soil structure, ultimately contributing to better soil health. In contrast, conventional farming systems, characterised by monocropping and the intensive use of synthetic fertilisers and pesticides, often lead to soil degradation. Continuous monocropping depletes soil nutrients, reduces Soil Organic

Carbon (SOC), and disrupts the microbial ecosystem, contributing to erosion and a decline in overall soil quality (Sihi *et al.*, 2017).

In the context of slow-onset climate events, particularly rising ambient temperatures, these divergent farming systems may exhibit distinct soil health responses (Navarro-Pedreño *et al.*, 2021). Temperature increases directly influence Soil Temperature (ST), altering the soil's thermal properties, which in turn affects biological and chemical processes. Soil acts as a heat reservoir and under prolonged temperature exposure, its capacity to store and release heat may disrupt soil–plant interactions, affecting plant growth and soil biological functioning. Elevated ST can delay the decomposition of organic matter and slow nutrient cycling, including the release of essential nutrients like nitrogen, phosphorus, and carbon. Furthermore, soil moisture dynamics are altered by temperature increases, as higher ST accelerates evaporation rates, reducing soil moisture retention (Hoogsteen *et al.*, 2015). The intricate balance between soil moisture and nutrient availability is vital for maintaining plant health, particularly in tropical rice production systems.

Previous research had demonstrated that conventional agricultural practices exacerbates soil degradation by increasing nutrient losses, reducing soil fertility, and decreasing biological activity (Lin & Fukushima, 2016). By contrast, agroecological farming practices have been proposed as a sustainable alternative, capable of mitigating soil degradation through the enhancement of soil organic matter and nutrient cycling. However, the impact of slow-onset climate events on soil health across diverse farming systems remains underexplored. The gradual and persistent changes in temperature regimes may amplify existing disparities between agroecological and conventional farming systems in terms of soil health, particularly in tropical regions.

Therefore, the objective of this study is to evaluate and compare the impacts of slow-onset climate events on soil health, specifically focusing on soil temperature, soil organic carbon, soil organic matter, soil moisture, and pH, across agroecological, conventional, and mixed rice farming systems in tropical Asia. By analysing soil health indicators across different rice farming practices over six months, this study aims to elucidate the subtle shifts in soil properties and its implications on long-term agricultural sustainability under changing climatic conditions.

Materials and Methods

Site Description

The study was conducted in tropical Malaysia, a region situated within the same tropical latitudes across both its peninsular and insular areas, characterised by high temperatures, elevated humidity, and substantial precipitation throughout the year. The region's climate is dominated by two monsoon seasons, creating optimal conditions for rice cultivation, and allowing for two to three harvests annually. This study evaluates the effects of agroecological, conventional, and mixed rice farming systems on soil health under slow-onset climate events, particularly temperature variations, in tropical Malaysia.

The selection of sampling sites was based on their representativeness of diverse rice cultivation systems across Malaysia, which experience varying degrees of climate variability. Climate induced changes such as rising temperatures and altered precipitation patterns can significantly influence soil resources and crop productivity, making these sites ideal for assessing the subtle shifts in soil health under prolonged climatic stress. A total of 33 soil samples were collected from three distinct rice farming systems, each reflecting a different cultivation approach: Agroecological, conventional, and mixed.

These sites allowed for a comparative analysis of soil health responses, particularly in terms of Soil Temperature (ST), Soil Organic Carbon (SOC), Soil Organic Matter (SOM), soil moisture, and pH, across varying farming systems under the influence of slow-onset climate events.

- *Agroecological Farm:* This site, located in the Lintang Valley of Kedah, northern Peninsular Malaysia, at geographical coordinates 047903N, 100.841502E is a remote rural village that practises agroecological rice farming. The farm emphasises sustainable soil management through practices such as crop rotation, the use of compost, and nitrogen-fixing legumes. The region is characterised by its elevated but stable temperatures, which allow for continuous cultivation while maintaining soil health via organic inputs.
- *Conventional farm*: Known as the "rice bowl of Malaysia", this farm is located at Alor Star, Kedah, in the region owned and operated by the Muda Agricultural Development Authority (MADA) at coordinates 6.080505N, 100.372574E. It is responsible for over 50% of the nation's domestic rice production. A flat terrain and vast rice fields typify the geography in this region. Conventional farming practices are dominant here and often involve the intensive use of synthetic fertilisers, pesticides, and mechanised farming techniques. This site is prone to persistent heat waves, which, combined with conventional practices are hypothesised to exacerbate soil degradation and reduce organic matter in the soil over time.
- *Mixed Farm:* The third site is in Sabah, at the foothills of Mt. Kinabalu and Mt. Nungkok, Kampung Tambatuon, Kota Belud with coordinates 6.130648N, 116.444747E. This region's unique farming landscape is the result of a lack of consensus among local farmers regarding sustainable practices. Consequently, both agroecological and conventional farming methods are practised nearby. This mixed approach provides an opportunity to observe soil health disparities within the same environmental setting, influenced by both sustainable and intensive farming practices under the same climatic stressors.

Soil Sampling

Soil sampling was conducted at each farmland site during three distinct phases over six months to capture temporal changes in soil properties in response to varying climatic conditions. The three sampling phases were strategically aligned with key rice growth stages: Phase I (August–September 2019) coincided with the vegetation stage, Phase II (October–November 2019) corresponded to the reproductive stage, and Phase III (December 2019–February 2020) occurred during the harvesting stage. These phases were selected to assess soil health throughout the rice crop's critical growth periods, providing insights into the dynamic interactions between soil health and crop development under slow-onset climate events.

A standardised digital soil analyser (Model: Rapitest) was employed at each sampling point to measure in situ Soil Temperature (ST) and pH. The sampling area for each plot covered a minimum aerial measuring between 2 m² and 4 m², ensuring spatial representativeness of the soil characteristics within the farm plots.

Soil samples were collected using a hand shovel, ensuring uniform depth and consistency across all sites. A vertical hole was dug at a depth of between 10 cm and 15 cm, targeting the root zone where critical soil processes influencing plant growth occur. Once collected, the soil samples were carefully placed in polyethylene bags to prevent contamination and preserve their integrity. Immediately after collection, the samples were stored on ice and transported to a cold storage facility maintained at 4°C to prevent any alterations in soil properties due to temperature fluctuations. The samples were subsequently stored at the Environmental Health Laboratory of Universiti Putra Malaysia for further analysis, including the determination of Soil Organic Carbon (SOC), Soil Organic Matter (SOM), and soil moisture content. This systematic soil sampling protocol ensured the reliability and accuracy of the data collected, allowing for a detailed comparison of soil health indicators across different rice farming systems in response to slow-onset climate variations.

Laboratory Analysis

The soil samples were air dried at room temperature to remove moisture and prevent microbial activity that could alter the soil's chemical composition. The air-dried samples were then homogenised using a pestle and mortar to ensure uniformity across the sample. After homogenisation, the soil was passed through a 2-mm mesh sieve to remove coarse materials such as gravel, plant debris, and roots. This process allowed for the isolation of fine soil particles, which are critical for the accurate assessment of key soil health indicators such as Soil Organic Carbon (SOC), Soil Organic Matter (SOM), and other relevant properties.

The sieved soil samples were stored in airtight polyethylene bags to preserve their integrity and prevent contamination or moisture absorption before further analysis. These stored samples were then subjected to subsequent analyses, including determining soil moisture, organic carbon content, and other essential soil properties, in accordance with standardised laboratory procedures. This method ensured that all soil samples were consistently prepared, which reduced variability and enhanced the accuracy of the soil health assessments.

Results

The present study assessed soil quality changes over six months across agroecological, conventional, and mixed rice farmlands, as summarised in Table 1. Significant increases in Soil Temperature (ST) were observed from Phase I to Phase III. Notably, conventional farmland consistently exhibited higher ST compared to agroecological and mixed farms. A statistically significant difference in ST was detected in Phase III across all farming systems ($p < 0.001$).

Soil Organic Matter (SOM) content showed a marked decline across all farmlands over the study period, with agroecological farms maintaining significantly higher SOM levels compared to conventional and mixed farms ($p < 0.001$ in all phases). Similarly, Soil Organic Carbon (SOC) in agroecological farms remained consistently higher than in conventional and mixed farms ($p < 0.001$ in Phases II and III). Soil moisture levels declined over the monitoring phases, indicating prolonged soil surface heating, particularly in agroecological farms ($p < 0.001$ in Phase I). Soil pH values demonstrated increased acidity over time, with conventional farms exhibiting the lowest pH levels across all phases, reaching as low as 4.00 in Phase I.

This study carried out a linear regression analysis to assess the correlation between Soil Temperature (ST) and various soil quality parameters across agroecological, conventional, and mixed rice farmlands, as presented in Tables 2 to 4. Table 2 demonstrates a strong positive correlation between Soil Organic Matter (SOM) and ST across all three phases in the agroecological farm. Additionally, Phase I exhibited a negative correlation between Soil Organic Carbon (SOC) and ST while Phases II and III showed a shift to a positive correlation. Soil Moisture (SM) consistently displayed a negative association with ST across all phases, indicating that as soil temperature increased, soil moisture decreased. The relationship between soil pH and ST was significantly negative in Phase I ($p < 0.001$) but varied in later phases.

Table 3 which focused on the conventional farm, showed a positive correlation between SOM and ST, consistent with the results observed in the agroecological farm. Phases II and III revealed a negative correlation between SOC and ST, indicating that increasing surface temperatures corresponded with declining SOC levels. The correlation between SM and ST remained negative, suggesting that higher temperatures were associated with reduced soil moisture. No significant relationship was found between ST and soil pH across the phases.

Table 4 revealed weaker correlations with regards to the mixed farm compared with the other farming systems. The coefficients for SOM and ST were comparatively lower (ß

Table 1: Comparison of soil health across six-month monitoring at different farmlands

	Type of Farmland	Mean (SD)		
		Phase I	Phase II	Phase III
Soil Temperature (ST)	Agroecological	28.83 (0.74)	30.67 (2.08)	31.33 (0.58)
	Conventional	29.64 (3.99)	33.67 (1.76)	36.00 (1.00)
	Mixed	27.33 (5.78)	30.29 (0.51)	33.88 (1.96)
	p-value[a]	0.195	0.621	< 0.001**
Soil Organic Matter (SOM)	Agroecological	2.96 (1.84)	1.75 (0.09)	1.05 (0.12)
	Conventional	0.68 (0.20)	0.69 (0.24)	0.61 (0.18)
	Mixed	0.96 (0.57)	0.82 (0.29)	0.64 (0.16)
	p-value[a]	0.001*	< 0.001**	0.002*
Soil Organic Carbon (SOC)	Agroecological	20.28 (1.79)	20.41 (0.59)	20.54 (2.25)
	Conventional	15.51 (3.50)	11.96 (0.60)	13.01 (25.07)
	Mixed	15.60 (2.73)	14.74 (1.69)	13.69 (2.63)
	p-value[a]	0.080	< 0.001**	0.001*
Soil Moisture (SM)	Agroecological	5.37 (0.56)	4.76 (0.35)	3.10 (0.87)
	Conventional	2.36 (1.56)	1.96 (0.28)	2.42 (0.25)
	Mixed	3.27 (2.22)	2.62 (1.45)	2.63 (0.86)
	p-value[a]	< 0.001**	0.246	0.570
Soil pH	Agroecological	5.83 (0.29)	5.83 (1.04)	5.67 (0.58)
	Conventional	4.00 (0.50)	4.50 (1.00)	4.33 (0.29)
	Mixed	4.64 (0.76)	4.78 (1.05)	4.94 (0.86)
	p-value[a]	0.012*	0.237	0.147

[a]One-way ANOVA, *p*-value is significant at 0.001 level** and 0.05 level*
Post-hoc test (AF = Agroecological Farm; CF = Conventional Farm; MF = Mixed Farm)
ST (Phase II), CF x MF ($p = 0.024$)*; ST (Phase III), AF x CF ($p<0.001$)**; CF x MF ($p < 0.001$)**
SOM (Phase I), AF x CF ($p = 0.001$)*; AF x MF ($p < 0.001$)**; SOM (Phase II), AF x CF ($p = 0.001$)*;
AF x MF ($p < 0.001$)**; SOM (Phase III), AF x CF ($p = 0.003$)*; AF x MF ($p = 0.001$)**
SOC (Phase I), AF x MF ($p = 0.027$)**; SOC (Phase II), AF x CF ($p < 0.001$)**; AF x MF ($p < 0.001$)**;
CF x MF ($p = 0.009$)*; SOC (Phase III), AF x CF ($p = 0.002$)*; AF x MF (*p* = < 0.001)**
SM (Phase I), AF x CF ($p < 0.001$)**; AF x MF ($p < 0.001$)
Soil pH (Phase I), AF x CF ($p = 0.004$); AF x MF ($p = 0.012$)

range: 0.131–0.400) while SOC had a weak negative correlation with ST (ß range: -0.016 to -0.125) across the phases. Soil moisture showed a decreasing trend in correlation strength from Phase I to Phase III. Unlike the agroecological and conventional farms, soil pH in the mixed farm exhibited no consistent correlation with ST.

Discussion

Soil Health Status among Different Rice Farming Systems

The impact of climate change on soil health presents a significant challenge to food security and agricultural sustainability. Maintaining strong soil health is crucial for building resilient farming systems capable of

Table 2: Linear regression analysis of association between soil temperature and soil quality at agroecological rice farmland

	Phase I[a]			Phase II[b]			Phase III[c]		
	ß	***p*-value**	**R^2**	**ß**	***p*-value**	**R^2**	**ß**	***p*-value**	**R^2**
Soil Organic Matter (SOM)	0.99	0.082	0.983	0.99	0.073	0.987	0.83	0.376	0.690
Soil Organic Carbon (SOC)	-0.95	0.212	0.893	0.99	0.058	0.992	0.95	0.212	0.786
Soil Moisture (SM)	-0.48	0.683	0.229	-0.56	0.619	0.317	-0.38	0.750	0.147
Soil pH	-1.000	< 0.001**	1.000	0.885	0.309	0.783	-0.76	0.454	0.571

[a]Single linear regression, *p*-value is significant at 0.001 level** and 0.05 level*

Table 3: Linear regression analysis of the association between soil temperature and soil quality in conventional rice farmland

	Phase I[a]			Phase II[b]			Phase III[c]		
	ß	***p*-value**	**R^2**	**ß**	***p*-value**	**R^2**	**ß**	***p*-value**	**R^2**
Soil Organic Matter (SOM)	0.89	0.302	0.791	0.87	0.328	0.757	0.62	0.573	0.387
Soil Organic Carbon (SOC)	0.93	0.242	0.862	-0.79	0.425	0.617	-0.78	0.433	0.605
Soil Moisture (SM)	-0.76	0.453	0.574	-0.83	0.375	0.691	-0.66	0.541	0.436
Soil pH	0.50	0.667	0.250	-0.33	0.788	0.107	-0.87	0.333	0.750

[a]Single linear regression, *p*-value is significant at 0.001 level** and 0.05 level*

Table 4: Linear regression analysis of association between soil temperature and soil quality at mixed rice farmlands

	Phase I[a]			Phase II[b]			Phase III[c]		
	ß	***p*-value**	**R^2**	**ß**	***p*-value**	**R^2**	**ß**	***p*-value**	**R^2**
Soil Organic Matter (SOM)	0.13	0.560	0.02	0.28	0.299	0.077	0.40	0.111	0.160
Soil Organic Carbon (SOC)	-0.02	0.944	0.01	0.28	0.300	0.077	-0.13	0.634	0.016
Soil Moisture (SM)	-0.30	0.169	0.09	-0.04	0.881	0.002	-0.14	0.616	0.018
Soil pH	0.13	0.554	0.02	-0.10	0.712	0.009	0.20	0.437	0.041

[a]Single linear regression, *p*-value is significant at 0.001 level** and 0.05 level*

withstanding extreme weather conditions. This study investigates the climate resilience of various rice farming systems in tropical Asia, focusing on their ability to preserve soil health with regards to slow-onset climate events. Conventional farming is very often reliant on synthetic chemicals, which significantly alters soil composition and adversely affects soil biodiversity (Davis *et al.*, 2018), whereas agroecological practices, which rely on minimal external inputs, promotes sustainable agricultural methods that are particularly suited for smallholder farmers (Lin *et al.*, 2019; Siebrecht, 2020).

Soil Temperature (ST) is a reliable indicator of climate change, as it rapidly responds to thermal shifts (Fang *et al*., 2019; Bradford *et al.*, 2019). In tropical regions like Malaysia, soil temperature fluctuates seasonally, influencing its chemical and physical properties. During the six-month monitoring period, this study observed a consistent increase in ST from Phase I to Phase III, a geographically consistent finding. These rising temperatures reflect slow-onset climate changes, with similar trends reported in previous studies (Kopittke *et al.*, 2019; Bradford *et al.*, 2019), suggesting that increasing ST alters the thermal regime of tropical soils, which could have profound effect on soil health and crop productivity.

Soil Organic Matter (SOM) is critical for assessing agricultural productivity and overall soil health (Morrow *et al.*, 2017). Agroecological farmlands demonstrated higher SOM levels compared to mixed and conventional systems, though SOM gradually declined over the six months. Agroecological systems, which integrate practices such as composting and cover cropping, exhibited improved soil drainage, water retention, and reduced runoffs. These practices help sustain SOM, contributing to soil stability and resilience in the face of climate change. By contrast, conventional farming practices accelerated SOM depletion, leading to increased soil degradation (Kunlanit *et al.*, 2020). The disparity in SOM content across different farming systems emphasises the role of sustainable farming in maintaining soil fertility, nutrient retention, and soil structure.

Soil Organic Carbon (SOC), a key component of SOM plays an essential role in carbon storage and ecosystem services that support plant nutrition. Over the six-month course of this study, agroecological systems consistently showed higher SOC levels when compared with conventional systems, reflecting their superior capacity for carbon sequestration. The loss of SOC in conventional farms highlights the detrimental effects of synthetic inputs and intensive land use, which reduces the soil's ability to store carbon and maintain long-term productivity (Kobierski *et al.*, 2020). Agroecological practices, which prioritise organic inputs, contribute to more stable SOC levels, supporting the resilience of farming systems to gradual climate changes.

Soil moisture is another crucial factor in maintaining soil health and promoting biomass activity. Agroecological systems, which use organic compost to enhance water retention, maintained higher soil moisture levels compared to mixed and conventional systems. In conventional farming, reduced soil moisture is exacerbated by soil degradation and erosion, making these systems more vulnerable to climate fluctuations. Previous studies have shown that higher soil moisture enhances pesticide degradation (Yang *et al.*, 2018), but conventional farms struggle to retain adequate moisture levels, further diminishing soil fertility and resilience to extreme weather conditions.

Soil pH is another key indicator of soil health, with optimal levels ranging between 6 and 7.5 for plant growth (Pawar, 2015). Our findings indicate that agroecological and mixed farms maintained more favourable pH conditions for crop growth while conventional systems exhibited more acidic soil. The use of nitrogen-based fertilisers in conventional systems most likely contributed to the observed decline in soil pH, as synthetic chemicals often lead to nutrient leaching and soil acidification. The ability of SOM to regulate pH and retain essential nutrients highlights the importance of maintaining high organic matter levels to sustain soil health and crop productivity in the face of slow-onset climate changes.

Influence of Soil Temperatures (ST) on Soil Health

Rising soil temperatures due to climate change have adversely impacted the agricultural sector, particularly affecting soil health and crop productivity. Soil Temperature (ST) plays a crucial role in regulating various physicochemical and biological processes essential for crop development. These processes include seed germination, seedling emergence, root growth, and nutrient availability (Ahmad Sabri *et al*., 2017; Onwuka & Mang, 2018). Higher soil temperatures can accelerate these processes, but they also pose risks to soil fertility and structure in the long term.

Agroecological farming has demonstrated effective strategies to address the impact of rising temperatures. For instance, the use of shade trees is a well-established method to buffer crops such as coffee, wheat, and rice from excessive heat. Additionally, agroecological practices emphasise landscape-scale interventions such as maintaining optimal tree cover and promoting groundwater recharge to enhance resilience against temperature fluctuations (Carpio *et al*., 2021). In the current study, a positive correlation was observed between Soil Organic Matter (SOM), Soil Organic Carbon (SOC), and mean ST in agroecological systems over the six-month monitoring period. These findings suggests that higher soil temperatures lead to faster decomposition of organic matter, a process consistent with previous research (Almendro-Candel & Zorpas, 2021). Although this accelerated decomposition supports short term nutrient cycling, it may also result in the long-term depletion of SOM if organic inputs are not replenished regularly.

During Phase I, Soil Organic Carbon levels (SOC) had a negative correlation with average Soil Temperature (ST). This could be attributed to higher temperatures increasing microbial activity, which in turn raises carbon dioxide production in the soil (Sinclair *et al.*, 2019). Notably, agroecological farms consistently showed higher SOC levels, which contributed to improved soil structure stability (tilth). Higher SOC levels enhance soil aeration, water drainage, and retention while reducing the risks of erosion and nutrient leaching. In agroecological systems, this increase in SOC leads to more stable carbon cycles and overall improvements in agricultural productivity.

Previous studies by Sihi *et al.* (2016) also suggest that rising ST decreases soil moisture, which can be explained by the reduced viscosity of water, allowing faster percolation through the soil. However, agroecological farming practices, which focus on building soil rich in organic matter and employing water conservation techniques helps counteract these moisture losses. By promoting diversified agricultural systems, agroecological practices bolster the resilience of farmlands against slow-onset climate changes such as gradual temperature increases. These approaches not only enhance the farm's ability to withstand and recover from climate induced stress but also provide critical ecosystem services, including improved water retention, biodiversity, and nutrient cycling (Broadbent, 2015).

Meanwhile, the measurement of soil pH is critical owing to its role in regulating interactions between plants, soil, and water, which directly influence microbial behaviour, the solubility and ionisation of soil components, and soil enzyme activity (Altieri *et al.*, 2015). In the agroecological farm examined in this study, located in a rural farming village, the landscape requires traversal through wooded areas, cultivated lands, cliffs, bodies of water, and cascades. It is hypothesised that variability in the correlation between soil pH and Soil Temperature (ST) in these agroecological soils may be attributed to excessive leaching of soluble salts, intensified by nearby recreational activities. This leaching, combined with the humid tropical climate, leads to increased acidity in the upper soil layers. However, a previous study (Karcauskiene *et al*., 2018) showed that soil pH in these regions remains relatively stable between 5.8 and 5.67, just below the critical threshold of 5.5. This suggests that the accumulation of organic matter on the soil surface, derived from both agricultural and non-agricultural sources, contributes to maintaining the soils moderate acidity.

In contrast, conventional farming practices, which involve the extensive use of synthetic chemicals and mechanisation can negatively impact non target organisms and disrupt essential soil metabolic processes necessary for maintaining soil fertility and facilitating pesticide degradation (Mandal *et al*., 2019). Over the six-month monitoring period, a clear depletion of Soil Organic Matter (SOM) was observed in conventional farming systems, along with a weakening association between SOM and Soil Texture (ST). The conversion of natural ecosystems into industrial farmlands has further exacerbated the depletion of Soil Organic Carbon (SOC) stocks, creating a carbon deficit within the soil. This depletion is driven by the reduction in root biomass, lower plant residue being returned to the soil, and increased rates of soil decomposition and erosion (Joko *et al.*, 2017; Kobierski *et al*., 2020). As a result, more carbon is being released into the atmosphere, intensifying the environmental impact of conventional agricultural practices.

The release of carbon dioxide (CO_2) from the soil has significant implications on the continued rise in atmospheric CO_2 levels and global temperatures. Elevated soil temperatures can disrupt the carbon balance by reducing water availability and photosynthesis rates. This study reveals similar trends, with a substantial decrease in soil moisture levels in conventional farmlands over the six-month monitoring period. Soil moisture at conventional farms was consistently lower when compared to agroecological and mixed farming systems. This may be attributed to the open, shadeless conditions typical of conventional farms, which adhere to industrial farming principles. Increased Surface Temperature (ST) accelerates evaporation, hindering water infiltration into the soil (Hatfield & Dold, 2019).

Furthermore, the application of synthetic fertilisers and pesticides significantly impacts soil pH. Soil samples from conventional farms with a pH below 5.5 showed marked deficiencies in phosphorus (P), calcium (Ca), magnesium (Mg), and molybdenum (Mo) while also exhibiting heightened susceptibility to aluminium (Al) and iron (Fe) toxicity (Altieri *et al*., 2015). The observed soil acidity is likely a result of mineral leaching and weathering in humid tropical regions, where low soil moisture and high ST characteristic of slow-onset climate changes trap these minerals within the soil interlayers.

Conventional agriculture is linked to numerous environmental challenges, including greenhouse gas emissions, biodiversity loss, contamination from synthetic inputs, soil degradation, and potential health risks. In contrast, agroecological farming, characterised by biologically diverse systems provides a more sustainable solution to meeting global food demand (Elias *et al*., 2019). Some farming systems such as the mixed farming system examined in this study, attempt to combine elements of both industrial and agroecological approaches. However, our findings suggest that this hybrid approach has not been effective in maintaining soil health, particularly under gradual climate stress.

Agroecological practices, though more labour intensive are essential for long term soil restoration and sustainability. In contrast, conventional farming contributes to the deterioration of soil quality. This study recommends prioritising continuous soil restoration through practices such as maintaining soil cover, increasing microbial populations, promoting biodiversity, and avoiding synthetic chemicals. Given the significant environmental and public health impact of current agricultural systems, a shift towards a more sustainable agrifood system is critical, and resources should be allocated to support this transition.

Conclusions

This study highlights that soil health is significantly influenced by both land-use practices and the gradual onset of climate events. Specifically, agroecological farms exhibited better soil health indicators higher Soil Organic Matter (SOM), Soil Organic Carbon (SOC), Soil Moisture (SM), and pH compared to mixed and conventional farms over a six-month monitoring period. Despite these variations, all farming systems showed a general decline in SOM, SOC, SM, and pH, together with an increase in Soil Temperature (ST).

The results revealed a positive correlation between ST and SOM and a negative correlation between ST and both SOC and SM. These findings align with the study's objective to assess the impact of different farming systems on soil health under slow-onset climate conditions. The results indicate that agroecological farming practices effectively mitigate the adverse effects of rising soil temperatures compared to conventional or mixed systems, underscoring their role in preserving soil health under slow-onset climate change conditions.

In conclusion, a shift towards more sustainable agricultural practices, particularly agroecology is essential for preserving soil health and addressing the challenges posed by climate change.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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