

Principal component analysis-based soil quality assessment of agronomic management practices in Marawi City, Philippines

ANALIZA C. OUANO, EDGEL O. ESCOMEN*

Department Plant Science, College of Agriculture, Mindanao State University. Marawi City 9700 Lanao del Sur Mindanao, Philippines.

Tel.: +63-9064203396, *email: edgel.escomen@msumain.edu.ph

Manuscript received: 3 March 2026. Revision accepted: 28 March 2026.

Abstract. *Ouano AC, Escomen EO. 2026. Principal component analysis-based soil quality assessment of agronomic management practices in Marawi City, Philippines. Asian J Agric 10 (1): g100141. <https://doi.org/10.13057/asianjagric/g100141>.* Soil Quality (SQ) is essential for agricultural sustainability and food security. This study evaluated 17 agricultural areas at the Mindanao State University Main Campus in Marawi City, Lanao del Sur, Philippines (MSU Main), using a Principal Component Analysis-based Soil Quality Index (PCA-SQI). Composite soil samples (0-20 cm depth) were analyzed for physical, chemical, and biological properties to identify associations with historical management practices. The PCA accounted for 78.00% of the cumulative variance. Ten indicators were retained from 17 measured parameters using PCA-based minimum data set selection criteria (silt, organic matter, pH, porosity, void ratio, volumetric moisture content, total nitrogen, clay, sand, and earthworm density) to formulate the SQI. Fifteen areas exhibited SQI values between 0.50 and 0.80 (medium suitability), while two severely degraded areas had indices of 0.4733 and 0.4932. Descriptive analysis revealed that areas subjected to continuous monocropping, conventional tillage, and exclusive synthetic fertilizer use were associated with lower SQI values, whereas sites employing integrated nutrient management and reduced tillage practices exhibited relatively higher soil functional capacity. Although statistical comparisons showed no significant differences across management categories ($p>0.05$), observable trends suggest that localized agronomic practices are descriptively associated with soil quality dynamics. Overall, the PCA-SQI framework provides a practical, site-specific diagnostic approach to evaluate soil functional status and highlights that integrating organic amendments and reducing tillage are vital for localized rehabilitation, though causal inferences remain limited by the observational study design.

Keywords: Conservation tillage, organic fertilizer, soil degradation, sustainable soil management, upland agriculture

INTRODUCTION

Soil degradation is primarily driven by intensive human activities, climate change, and inappropriate agronomic practices (Mandal et al. 2021). Intensive farming methods, such as continuous monocropping and residue burning, are probable drivers that deplete soil organic matter and compromise aggregate stability (Jiang et al. 2024; Prayogo et al. 2026). Furthermore, the continuous use of synthetic fertilizers without organic amendments has been shown to inhibit biological activity (Chandrakala et al. 2022) and overall soil quality (Fathizad et al. 2020). Implementing scientifically rigorous evaluation frameworks is essential to mitigate this pervasive degradation successfully (Bünemann et al. 2018; Mutiara et al. 2025).

In the Philippines, agricultural ecosystem degradation is closely linked to specific human interventions (Posadas et al. 2022; Ramirez et al. 2022). The Soil Quality Index (SQI) is one of the most commonly used approaches for converting multidimensional, complex soil data into a highly interpretable numeric value (Nikpey et al. 2024). Calculating the SQI comprises three fundamental mathematical steps: selecting a Minimum Data Set (MDS) of soil indicators, transforming the soil indicators using scoring functions, and consolidating the scores into an overall index (Fathizad et al. 2020). Using Principal Component Analysis (PCA) to select the MDS is a widely

adopted approach. The PCA-SQI method minimizes data duplication and bias, ensuring that only the most critical variables driving soil functionality are retained (Nikpey et al. 2024). This multivariate statistical method has been effectively implemented across different agroecosystems to objectively track management-induced changes in soil quality and diagnose the specific biophysical constraints limiting crop yields (Ramirez et al. 2022).

The agricultural areas at Mindanao State University Main Campus in Marawi City, Lanao del Sur, Philippines (MSU Main) present a valuable case study, serving as both students' demonstration farms and productive resources for local farmers. The *Adtuyon clay loam*, the soil series of the area, is characterized by highly weathered soil due to monsoonal precipitation and steep terrain. The institutional setting provides a heterogeneous agricultural mosaic rather than a typical homogenous farmland. Despite years of overlapping academic and commercial use, a comprehensive baseline soil characterization tailored to these specific topographical and climatic pressures has not yet been conducted. Furthermore, local farmers frequently apply synthetic fertilizers without the benefit of soil analysis. While the localized effects are yet to be quantified, existing literature suggests that this management practice can accelerate soil acidification through nitrification and disrupt internal nutrient cycling (Chandrakala et al. 2022). The relationship among different

cultural management practices, such as tillage intensity, crop rotation, and fertilizer regimes, within this specific localized system, remains poorly understood quantitatively.

Implementing a rigorous evaluation framework is particularly critical in this tropical agroecosystem. Recent studies on SQI primarily focus on lowland agroecosystems in Laguna (Ramirez et al. 2022) and specific heavy metal contamination in Davao de Oro (Posadas et al. 2022). Addressing this regional gap, the novelty of this study lies in its focus on upland soil conditions. To address these gaps, this study evaluates whether variations in agronomic management practices are associated with measurable differences in soil functional quality across heterogeneous upland agricultural systems.

Therefore, this study aimed to: (i) establish a contextual baseline by documenting the crops planted, agricultural land use, cropping pattern, land preparation, and fertilizer used in the agricultural areas over the past five years; (ii) develop a Principal Component Analysis-based Soil Quality Index (PCA-SQI) by identifying key indicators from 17 measured soil properties; and (iii) interpret the resulting Soil Quality Index to evaluate how specific farming practices, such as tillage and fertilizer use, are associated with overall soil health and sustainability.

We hypothesize that (i) management regimes characterized by continuous monocropping, intensive tillage, and exclusive synthetic fertilizer use are associated with lower soil quality, whereas (ii) integrated nutrient management and reduced or no-tillage practices are associated with higher soil quality, and (iii) a PCA-based Soil Quality Index (PCA-SQI) can effectively capture these variations by identifying key soil indicators that reflect management-induced changes.

By establishing this unique, PCA-based minimum data set tailored to high-elevation *Typic Kandiuults*, this research provides a crucial empirical baseline designed to

guide targeted, site-specific rehabilitation programs and inform future sustainable agro-environmental policies.

MATERIALS AND METHODS

Locale of the study

This study was conducted at the Mindanao State University Main Campus in Marawi City, Lanao del Sur, Philippines (MSU Main) (08°00' N, 124°18' E) from May to November 2024. Located at an elevation of 700-800 meters above sea level (masl) near Lake Lanao, the area experiences a cool climate classified as Type IV, exhibiting an even distribution of rainfall throughout the year, with an average annual precipitation of 2,791 mm in 2023, which serves as the nearest available complete annual record prior to the study. The Mean Annual Temperature (MAT) ranges from 22.6 °C to 24.0°C.

The soil within MSU is classified as *Adtuyon clay loam*, a subgroup of *Typic Kandiuults*. These soils are characterized by extensive leaching and an accumulation of subsoil clay. The area maintains sufficient moisture throughout the year and has low base saturation, with andesite rock as the parent material (Bureau of Soils and Water Management (BSWM 2010)). Because of this inherent vulnerability to extensive leaching and low base saturation, dynamic indicators sensitive to organic matter depletion, structural compaction, and nutrient retention are particularly critical for diagnosing management-induced shifts in soil functional quality within this specific pedological setting. These agricultural lands support both the Bachelor of Science in Agriculture program and commercial crop production. This unique blend of academic, institutional, and commercial utilization has resulted in a highly heterogeneous landscape of agricultural practices (Figure 1).

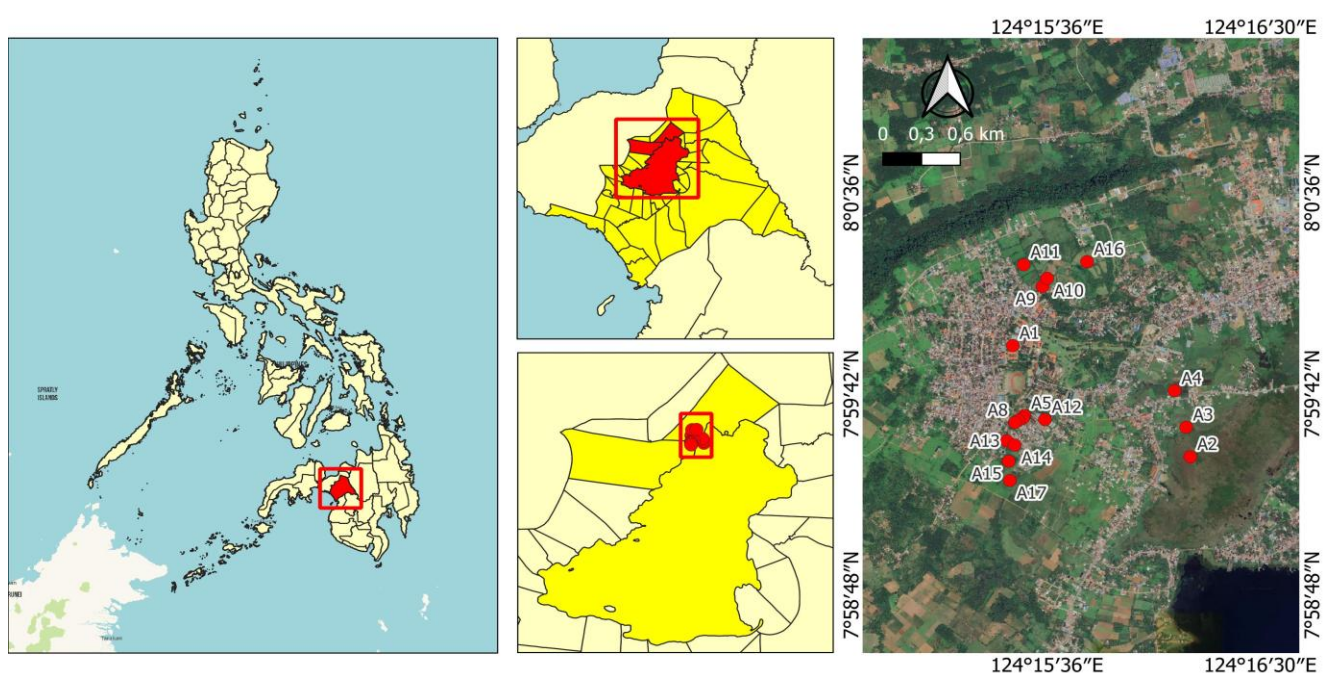


Figure 1. Geographical location of agricultural areas within the MSU Main, Marawi City, Philippines

Area delineation and management regimes

The 17 sampling areas were delineated based on the spatial boundaries of the university cadastral zoning map and classified quantitatively by land-use classes and topographic thresholds (i.e., flat terrain at slopes 0-3% and sloping agricultural land at slopes steeper than 8%). Intermediate slopes (3-8%) were not included because none of the 17 delineated agricultural areas naturally occurred within this topographic class. This stratified selection captured a heterogeneous network of distinct management regimes, enabling the evaluation of long-term agronomic impacts.

To clearly distinguish administrative purpose from field-level practices, the delineated areas were first categorized by their operational land-use function: high-density commercial agricultural activities by local tenant farmers, university revenue-generating projects, instructional and experimental fields, and low-intentional-use zones (used only for aesthetics or pasture). Each area

was then independently classified according to its specific agronomic management regime, providing a comparative evaluation of land preparation, crop rotation, and fertilizer use over the past 5 years, as reflected in Table 1.

To ensure accurate management histories, a triangulation approach was employed during data collection. For institutional and experimental fields, historical management was documented via the university administration's written and laboratory records. For commercial and leased areas with no written logs, histories were reconstructed through structured and recall-based interviews with tenant farmers. On-site visual inspections were used to reduce recall bias, and data were cross-linked with the resident farm managers who oversee the university's agricultural domain. Despite these validation measures, relying on farmer recall over a five-year period inherently introduces some degree of unavoidable uncertainty.

Table 1. Detailed characteristics and historical agronomic management regimes of the 17 evaluated agricultural areas

Area id	Site name	Land area (m ²)	Primary land use	Cropping pattern	Land preparation	Fertilizer used
A1	Botanical Garden	632	Aesthetic landscaping	Permanent perennial	No-till	Unfertilized
A2	Cadayunan-Low	1,256	Commercial (Tenant)	Monocropping	Conventional tillage	Exclusive synthetic fertilizer
A3	Cadayunan-Middle	1,089	Commercial (Tenant)	Monocropping	Conventional tillage	Exclusive synthetic fertilizer
A4	Cadayunan-High	2,987	Commercial (Tenant)	Crop rotation	Conventional tillage	Exclusive synthetic fertilizer
A5	College of Agriculture (COA)-African Daisy	313	Instructional demonstration	Monocropping	Minimum tillage	Unfertilized
A6	COA-Gabi	478	Instructional demonstration	Crop rotation	Conventional tillage	Unfertilized
A7	COA-Agro198	1,503	Experimental/Controlled	Crop rotation	Conventional tillage	Integrated (Inorganic and organic)
A8	COA-Plant Science	754	Experimental/Controlled	Crop rotation	Conventional tillage	Integrated (Inorganic and organic)
A9	Dairy-Experimental	1,496	Experimental/Controlled	Crop rotation	Conventional tillage	Integrated (Inorganic and organic)
A10	Dairy-Gulayan	2,056	Institutional Revenue	Crop rotation	Conventional tillage	Integrated (Inorganic and organic)
A11	Dairy-Napier	3,673	Livestock pasture	Permanent perennial	No-till	Unfertilized
A12	College of Engineering (COE)-Durian	345	Institutional Revenue	Permanent perennial	No-till	Unfertilized
A13	Organic Demo Farm (ODF)-Flat	1,208	Institutional Revenue	Crop rotation	Conventional tillage	Integrated (Inorganic and organic)
A14	ODF-Durian	789	Institutional Revenue	Permanent perennial	No-till	Exclusive organic
A15	ODF-Sloping	477	Institutional Revenue	Crop rotation	Conventional tillage	Integrated (Inorganic and organic)
A16	Carabao Project-Native Pasture	14,673	Livestock pasture	Permanent perennial	No-till	Unfertilized
A17	Rapasun-Corn	3,909	Commercial (Tenant)	Monocropping	Conventional tillage	Exclusive synthetic fertilizer (with residue burning)

Collection and analysis of soil samples

Soil samples were collected using a systematic spatial design. The 17 agricultural areas were divided into three equal blocks. To account for spatial variability, 10 subsamples were collected per block at approximately equal intervals along a zigzag transect. A uniform sample from the 0-20 cm profile was extracted using a soil auger. This depth represents the standard agricultural plow layer, where most crop root's function, nutrient recycling occurs, and management-induced physicochemical changes manifest. The 10 sub-samples from each block were thoroughly mixed, and quartering was repeated until representative composite samples of about half a kilogram were obtained. The three composite samples obtained from the three blocks within each area were analyzed separately solely to account for intra-site spatial variability. To strictly avoid pseudo-replication, the overall area means were used as the single statistical unit (n=17) for the Principal Component Analysis (PCA), one-way Analysis of Variance (ANOVA), and subsequent index scoring and intra-site variance was not used inferentially. Furthermore, because management groups contain highly uneven category sizes, this framework explicitly designates the study as a site-comparative evaluation rather than a management-replicated experimental inference.

The soil composite samples were air-dried at ambient room temperature (<35°C). Sample labeling was performed systematically to eliminate contamination and labeling errors. The samples were crushed using a mortar and pestle before being passed through a 2-mm sieve. The resulting fine earth was then prepared for laboratory analysis.

To comprehensively assess soil functional capacity, 17 physical, chemical, and biological parameters were determined using standard analytical methods. Table 2 provides a detailed summary of the specific indicators evaluated, their respective standard units of measurement, the precise analytical approaches utilized, and the corresponding international reference frameworks that guided the laboratory protocols. Earthworm density (EW) was assessed *in situ* by setting up three 1×1 m quadrats at a depth of 20 cm per area and taking population measurements during the wet season, ensuring all surveyed

sites had comparable moisture conditions. Consequently, this specific metric represents the biological condition of the soil only during the wet season.

Soil quality indexing

Standard soil quality indexing generally follows three basic steps: (i) selection of indicators, (ii) indicator transformation, and (iii) soil quality index integration (Andrews et al. 2004; Tesfahunegn 2014; Kahsay et al. 2025; Shokr et al. 2025). From the 17 evaluated SQ indicators, a Minimum Data Set (MDS) was determined using Principal Component Analysis (PCA). This objective approach eliminates the subjective assignment of weights to each indicator (Ghaemi et al. 2014; Rangel-Peraza et al. 2017; Jiang et al. 2020). Principal components (PCs) with eigenvalues >1.0 were retained (Brejda et al. 2000; Singh et al. 2014; Alaboz et al. 2021; Lenka et al. 2022).

To operationalize the selection criteria for the MDS, the highest absolute factor loading within each retained PC was first identified. Any soil indicator within that same PC possessing an absolute factor loading greater than or equal to 96% of this maximum value was retained (Paz-Kagan et al. 2014; Saleh et al. 2021). For each PC, a correlation analysis was performed on the selected indicators to avoid indexing redundant data (Singh et al. 2014; Mandal et al. 2023). Furthermore, as a predefined methodological criterion, indicators meeting statistical retention criteria were evaluated for ecological interpretability and comparative discriminatory value. Specifically, particle density was excluded based on pedological reasoning: it is an intrinsic, stationary mineralogical property of the soil rather than a dynamic indicator sensitive to recent agronomic management. Additionally, extractable Phosphorus (P) was excluded due to field-level analytical incomparability; all P scores derived from the Bray-1 procedure fell uniformly below the lower limit of sustainability across the surveyed landscape (ranging from 1.2 to 2.8 mg/kg). This severely deficient and narrow data spread yielded a variance of only 0.45, generating insufficient comparative discriminatory value across the heterogeneous sites.

Table 2. Analytical methods and units for the 17 assessed soil quality indicators

Indicator	Unit	Analytical method	Reference
Bulk density	g/cm ³	Core/cylinder method	FAO (2023)
Particle density	g/cm ³	Pycnometer method	Estefan et al. (2013)
Porosity	%	Mathematically Calculated	Lal and Shukla (2004)
Gravimetric moisture content	%	Gravimetric oven-drying	Estefan et al. (2013)
Volumetric moisture content	cm ³ /cm ³	Mathematically Calculated	Lal and Shukla (2004)
Water Holding Capacity (WHC)	%	Gravimetric	Estefan et al. (2013)
Void ratio	Unitless	Mathematically Calculated	Lal and Shukla (2004)
Sand, Silt, Clay	%	Hydrometer method	Estefan et al. (2013)
pH	Unitless	Potentiometry (1:2.5 soil-water suspension)	Estefan et al. (2013)
Total Nitrogen (TN)	%	Total Kjeldahl Nitrogen digestion	Estefan et al. (2013)
Extractable Phosphorus (P)	mg/kg	Bray-1 extraction method	Estefan et al. (2013)
Exchangeable Potassium (K)	cmol(+)/kg	Flame emission photometry	Estefan et al. (2013)
Cation Exchange Capacity (CEC)	cmol(+)/kg	Ammonium acetate displacement	Estefan et al. (2013)
Organic Matter (OM)	%	Walkley-Black wet oxidation	Estefan et al. (2013)
Earthworm density (EW)	count/m ²	In-situ 1x1 m excavated field quadrat	Field observation

Homothetic scoring functions

After selecting the MDS, the raw analytical values of each indicator were transformed into a common unitless range from 0.10 to 1.0 using linear homothetic transformation equations (Velasquez et al. 2007; Ozlu et al. 2022). Indicators were ranked according to their biological relation to crop production, e.g., "more is better" for total nitrogen, "less is better" for bulk density, and "optimum" for pH (Tesfahunegn 2014; AbdelRahman et al. 2022).

The "more is better" functional logic was applied to properties where higher absolute values directly correspond to enhanced soil function. For example, higher Organic Matter improves cation exchange capacity and microbial habitat; higher Total Nitrogen directly fuels vegetative growth; higher Silt content improves water retention in these specific porous volcanic soils; and higher Earthworm populations indicate robust biological bioturbation. For these properties, the following equation was applied:

$$Y = 0.1 + \frac{X-b}{a-b} * 0.9$$

The "less is better" logic was explicitly applied to physical properties indicating compaction or structural degradation, most notably Bulk Density. Higher bulk density critically restricts root penetration, limits aerobic gas exchange, and diminishes hydraulic conductivity. For this specific soil property, the inversion equation was utilized:

$$Z = 1 - \frac{X-b}{a-b} * 0.9 \text{ for "less is better" soil property}$$

For "optimum" soil properties, a piecewise function was applied to assign a peak score of 1.0 at the optimal target threshold (O), decreasing linearly toward the defined lower (b) and upper (a) limits:

$$W = 0.1 + \frac{X-b}{O-b} * 0.9 \text{ if } X < O$$

$$W = 0.1 + \frac{X-O}{a-O} * 0.9 \text{ if } X > O$$

Where, Y and Z : Data transformed, X : Data to be transformed, O : Optimal threshold value, a : Upper threshold value, and b : Lower threshold value. Values of a and b are shown in Table 3. While these specific thresholds were adopted from established literature developed in different pedoclimatic contexts, they are used in this study as standardized comparative references to evaluate relative soil functional trajectories, rather than as absolute local optima; applying these uniform boundaries across a shared local baseline ensures that the resulting comparative variance in index scores is driven strictly by differences in field-level agronomic management rather than shifting evaluation criteria.

As each PC explains a portion of the total dataset's variation, this provides a weight for the variables chosen under that PC. The weight of each variable (W_i) was calculated as the ratio of its specific factor variance to the total cumulative variance (Rangel-Peraza et al. 2017).

Finally, the SQI for each agricultural area was computed by summing the products of the indicator weights and their corresponding transformed scores using the following equation:

$$SQI = \sum_{i=1}^n W_i S_i$$

Where, W_i : Weighing factor, S_i : Scored value.

Statistical analysis

Data analysis was performed using the Statistical Tool for Agricultural Research (STAR) software, Version 2.0.1 (International Rice Research Institute (IRRI 2014)). To explore the potential impact of different agricultural practices, a one-way Analysis of Variance (ANOVA) was employed strictly as an exploratory tool. The dependent variable in this model was the Soil Quality Index (SQI). The independent grouping variables were management practices, categorized as agricultural land use, fertilizer management, tillage practices, and cropping pattern.

Prior to analysis, the fundamental statistical assumptions were confirmed: the Shapiro-Wilk test verified normality, and Levene's test confirmed equal variances across management groups, though it is acknowledged that these statistical assumptions remain fragile under such extreme category imbalance. Significance was evaluated at $p = 0.05$. However, because the dataset contains extreme sample size discrepancies—specifically management categories with only a single observational site ($n=1$)—the application of Tukey's Honestly Significant Difference (HSD) post hoc test lacks statistical power. Consequently, the ANOVA results and subsequent pairwise comparisons are evaluated cautiously as descriptive comparative trends rather than definitive inferential relationships. Lastly, the resultant SQI values were coded into high, medium, and low suitability levels according to the established framework by Spandana et al. (2013) and Kahsay et al. (2025), as shown in Table 4.

Table 3. Defined upper, lower, and optimum threshold values utilized for the homothetic transformation of different soil properties

Soil property	Scoring value	LTL ¹	UTL ²
Silt ^a	More is better	0	38
OM ^a	More is better	1.72	11.18
pH ^a	Optimum	4.5	6.5
Porosity (E) ^b	More is better	30	70
Void ratio (e) ^b	More is better	0.4	2.2
Volumetric moisture content (Θ _v) ^b	More is better	0	70
Total Nitrogen ^a	More is better	0.05	0.54
Clay ^a	More is better	0	31
Sand ^a	Optimum	0	60
Earthworm (EW) ^a	More is better	0	11

Note: ^aTesfahunegn (2014) and AbdelRahman et al. (2022), ^bLal and Shukla (2004) and Hadija et al. (2023), ¹LTL: Lower Threshold Limit, ²UTL: Upper Threshold Limit

Table 4. Interpretative framework for the continuous soil quality index values

SQI	Suitability of soil for crops	Interpretation
>0.80	High	System exhibits minimal functional limitations; requires only baseline maintenance for optimal crop production.
0.50-0.80	Medium	System exhibits moderate biophysical limitations; requires immediate targeted interventions (e.g., intensive organic matter application, agricultural liming).
<0.50	Low	System exhibits severe biological and structural limitations; requires extensive, long-term agronomic rehabilitation protocols.

RESULTS AND DISCUSSION

Overview of agronomic management practices

As shown in Figure 2 and Table 5, the agricultural areas on MSU-Main Campus varied across the landscape by utilization and were planted with various crops. Documenting this spatial crop diversity is critical, as varying root architectures, continuous canopy covers, and vegetative residue inputs directly drive localized differences in soil organic matter accumulation, nutrient cycling, and physical aggregate stability.

However, while broad administrative designations describe the operational purpose of each site (Figure 2.B), it is the underlying localized agronomic management practices, rather than the administrative categories themselves, that directly drive the subsequent soil quality interpretation.

Regarding these localized practices (Figures 2.C-E), continuous monocropping characterized several commercial and instructional sites; conversely, crop rotation was actively employed across other fields, while permanent perennial plants ensured continuous soil cover in pasture and agroforestry areas. Conventional tillage was the primary method of land preparation, utilized in 65% of the areas, with the remainder maintained under no-till or minimum tillage regimens.

Farmers operating in the commercial areas used pure, unbuffered synthetic chemical fertilizer, whereas a more holistic combination of inorganic and organic fertilizers was applied in other managed fields. It was also documented that fundamental soil-restorative practices, such as fallowing and agricultural liming, were not practiced in any of the 17 areas, and farmers in the Rapasan area practiced the highly detrimental practice of burning crop residues, which rapidly volatilizes essential surface carbon.

Principal component analysis

To objectively reduce the dimensionality of the raw data and select the Minimum Data Set (MDS), strict statistical criteria were applied as shown in Table 6. First, only Principal Components (PCs) with eigenvalues >1.0

were retained for analysis. Second, within each retained PC, indicators were included in the MDS only if their absolute factor loading was within 96% of the highest loading for that component. Finally, a correlation analysis was utilized to eliminate redundant variables within the same PC. Furthermore, ecological interpretability was applied after this statistical screening to ensure the retained indicators were dynamically responsive to agronomic interventions.

Using these objective criteria, the majority of the variance was accounted for by PC1 (30.92%), and the absolute factor loadings for Organic Matter (OM), silt, and gravimetric moisture content met the initial mathematical threshold. Statistically, gravimetric moisture content qualified for inclusion; however, it was subsequently excluded, leaving only OM and silt in the final MDS for PC1, both of which are critical drivers of structural stability and nutrient retention in highly weathered soils.

In PC2 (14.73% variance), factor loadings were highest for particle density and pH. Consequently, pH was the sole indicator retained, reflecting its direct control over nutrient availability. For PC3 (13.22% variance), porosity (E), void ratio (e), and volumetric moisture content exhibited the highest loadings. All three interacting physical properties were retained because they capture functionally distinct ecological dynamics: porosity defines the total potential pore volume, void ratio evaluates the structural packing from mechanical tillage, and volumetric moisture reflects the actual field-level water retention capacity.

In PC4 (9.75% variance), Total Nitrogen (TN) and extractable Phosphorus (P) showed high loadings. Thus, only TN was retained, serving as a primary indicator of fertility and organic cycling. Finally, earthworms (EW), clay, and sand had the largest loadings on PC5 (9.37% variance) and were included in the composite index to capture biological bioturbation and inherent textural constraints.

The final equation was:

$$\text{PCA-SQI} = 0.2007_{\text{silt}} + 0.2007_{\text{OM}} + 0.0956_{\text{pH}} + 0.0858_{\text{E}} + 0.0858_{\text{e}} + 0.0858_{\text{Ov}} + 0.0638_{\text{TN}} + 0.0608_{\text{clay}} + 0.0608_{\text{sand}} + 0.0608_{\text{EW}}$$

These weights were calculated directly from the PCA results by dividing the proportion of variance of a given principal component by the total cumulative variance, explicitly assigning higher proportional weights to indicators from principal components that capture a larger share of the dataset's variability.

Integrated soil quality index interpretations

Table 7 presents the calculated SQI values for the 17 agricultural areas in MSU Main. The index is a useful diagnostic indicator of the historical manifestation of land management and environmental pressures on current soil functionality. The SQI across 15 areas falls within the moderate range (0.50-0.80). This classification indicates significant but manageable functional limitations. These require targeted soil management to prevent further decline. This type of medium-level stabilization is

commonly found on institutional lands, where baseline nutrient depletion is often offset by experimental or heterogeneous crop rotation, aligning with similar Philippine agroecosystems evaluated by Ramirez et al. (2022).

However, it must be noted that the broad breadth of this medium classification (0.50-0.80) presents a practical limitation in discriminatory power. Because 15 of the 17 sites fall within this single broad tier, the standard categorical framework may be too wide to accurately

differentiate subtle but important variations in field management outcomes. For instance, an area with an SQI of 0.51 (near severe degradation) functionally requires more urgent and intensive restorative interventions than one at 0.79 (near optimal capacity), yet both are grouped under the same prescriptive umbrella. This suggests that while the standard interpretative framework is useful for baseline assessment, future studies may need to subdivide the medium class to better inform precise, localized agronomic decisions.

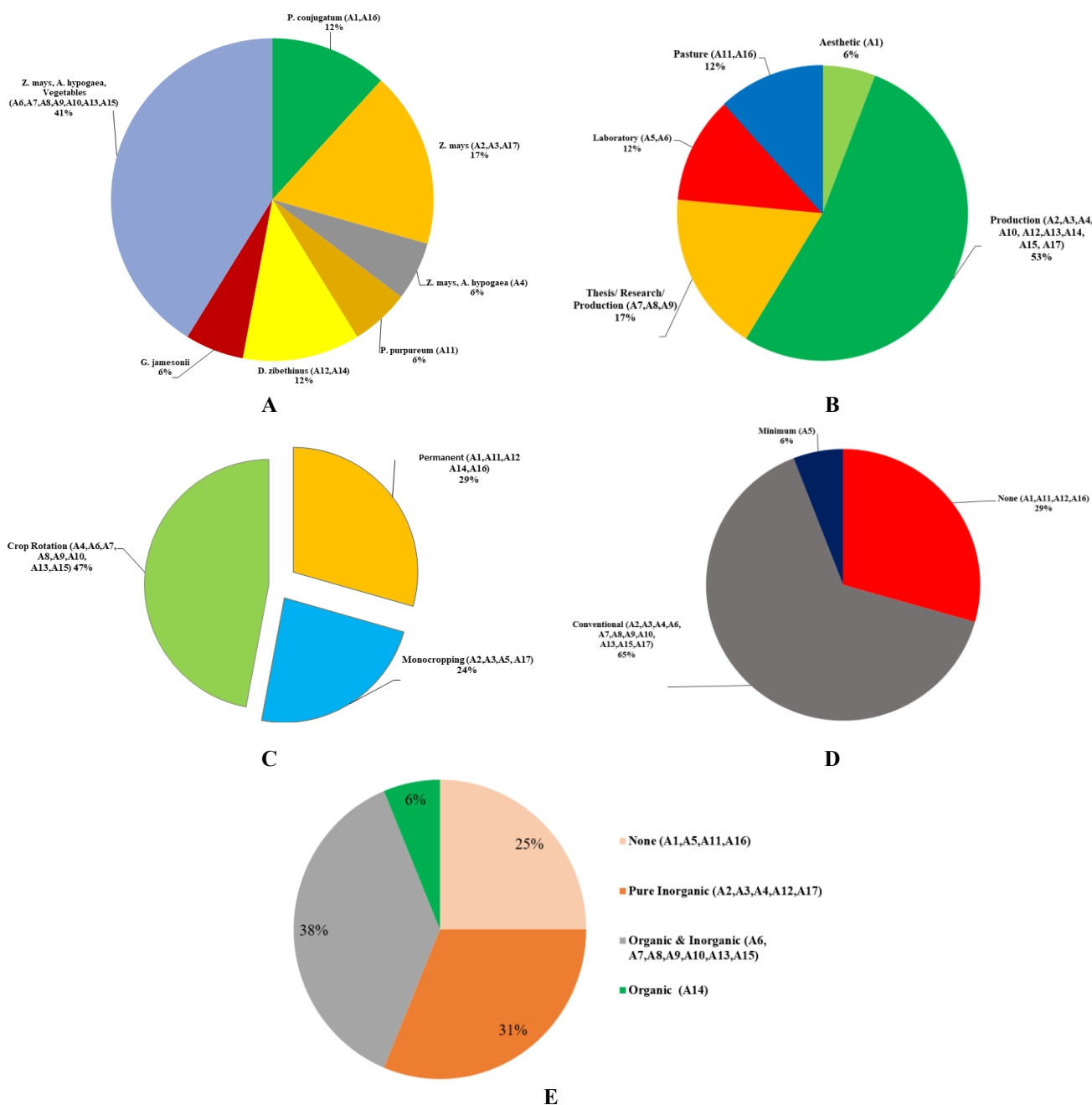


Figure 2. Overview of the agricultural profiles and management regimes. A. Encompassing crops planted, B. Agricultural land use, C. Cropping patterns, D. Land preparation, and E. Fertilizer used -implemented across the 17 surveyed agricultural areas at Mindanao State University Main Campus in Marawi City, Lanao del Sur, Philippines (MSU Main). These distributions map the spatial heterogeneity of field-level interventions, establishing the specific descriptive agronomic context for the subsequent soil quality evaluation

Table 5. Distribution of crops planted across the 17 agricultural areas

Crop category	Specific crops	Number of areas	Percentage	Specific sites (Area IDs)
Intensive Cash Crops	<i>Zea mays</i> , <i>Arachis hypogaea</i> , and vegetables	7	41.20%	A6, A7, A8, A9, A10, A13, A15
Permanent Perennial Plants	<i>Paspalum conjugatum</i> , <i>Pennisetum purpureum</i> , <i>Gerbera jamesonii</i>	4	23.50%	A1, A5, A11, A16
Agroforestry	<i>Durio zibethinus</i> (Durian)	2	11.80%	A12, A14
Commercial Grain	<i>Z. mays</i> (Corn) / Crop Rotation	4	23.50%	A2, A3, A4, A17
Total		17	100%	

Table 6. Principal component analysis results and factor loadings for the evaluated soil quality indicators across the 17 agricultural areas

Statistics	PC1	PC2	PC3	PC4	PC5	MDS Status
Standard Deviation	2.2928	1.5825	1.4991	1.2875	1.2622	-
Proportion of Variance	0.3092	0.1473	0.1322	0.0975	0.0937	-
Cumulative Proportion	0.3092	0.4565	0.5887	0.6863	0.78	-
Eigen Values	5.257	2.5042	2.2473	1.6578	1.5932	-
Variables						
Organic Matter (OM)	0.3932	0.0659	0.183	-0.0245	-0.0711	Retained
Silt	-0.3182	-0.0434	-0.0548	-0.2348	-0.1884	Retained
Gravimetric Moisture (Θ_m)	0.3398	0.148	0.1621	0.1587	-0.1084	Excluded
pH	0.0123	0.4978	0.0267	-0.0115	0.0518	Retained
Particle Density (ρ_s)	0.1629	0.3379	-0.1959	0.0762	-0.3637	Excluded
Porosity (E)	0.3289	-0.0361	-0.3692	-0.0696	-0.2316	Retained
Void ratio (e)	0.3421	-0.0599	-0.0351	-0.0676	-0.2047	Retained
Volumetric Moisture (Θ_v)	0.1964	0.3191	0.3196	0.2447	-0.1301	Retained
Total Nitrogen (TN)	0.1605	0.089	0.027	-0.6093	0.0584	Retained
Extractable Phosphorus (P)	-0.1981	0.2855	-0.0105	-0.3439	-0.14	Excluded
Sand	0.118	0.2447	-0.3026	0.2793	0.4857	Retained
Clay	0.1934	-0.2397	0.3503	-0.0425	-0.3648	Retained
Earthworm density (EW)	0.1455	0.211	0.1189	0.1895	0.3422	Retained
Bulk Density (ρ_b)	-0.271	0.3089	0.273	0.1479	-0.0123	Excluded
Exchangeable Potassium (K)	-0.1416	0.3575	-0.2401	-0.2836	-0.1019	Excluded
Cation Exchange Capacity	0.2107	0.2311	0.2764	-0.2357	0.255	Excluded

Table 7. Final computed Soil Quality Index (SQI) values and corresponding qualitative functional interpretations for the 17 evaluated agricultural areas

Area	SQI	Interpretation
A1 Botanical Garden	0.6002	Medium
A2 Cadayunan-Low	0.4733	Low
A3 Cadayunan-Middle	0.4932	Low
A4 Cadayunan-High	0.5427	Medium
A5 College of Agriculture-African Daisy	0.5149	Medium
A6 College of Agriculture-Gabi	0.5603	Medium
A7 College of Agriculture-Agro 198	0.5722	Medium
A8 College of Agriculture-Near Plant Science	0.5485	Medium
A9 Dairy-Experimental	0.6051	Medium
A10 Dairy-Gulayan	0.5804	Medium
A11 Dairy-Napier	0.5486	Medium
A12 College of Engineering-Durian	0.6430	Medium
A13 Organic DemoFarm-Flat	0.6152	Medium
A14 Organic DemoFarm-Durian	0.6123	Medium
A15 Organic DemoFarm-Sloping	0.5690	Medium
A16 Carabao Project-Native Pasture	0.5700	Medium
A17 Rapasun-Corn	0.6176	Medium

More importantly, two agricultural areas, Cadayunan-Low (A2) and Cadayunan-Middle (A3), had SQI values below the critical threshold of 0.50 (0.4733 and 0.4932, respectively). Because both values fall within the same qualitative classification tier for severe degradation, this minor numerical difference is not practically meaningful, indicating instead that both sites suffer from identical fundamental biophysical constraints. Low SQI in these areas was linked to continuous *Z. mays* monocropping. Unbalanced synthetic fertilizers and conventional tillage also contributed to this degradation. Observational data indicate that physical disturbance from deep plowing aligns with a disrupted soil matrix and poorer pore-space architecture. Furthermore, the absence of organic amendments corresponds with a depleted soil microbiome and lower earthworm populations. These factors combine to accelerate the oxidation of the organic carbon store.

The local environmental context likely exacerbates these limitations. The highly weathered *Aduyon clay loam* is situated on high-elevation terrain. This area is subject to heavy monsoonal rainfall averaging 2,791 mm annually. The topographical location of these specific degraded commercial areas can accelerate soil erosion during rainfall events, further stripping away topsoil and essential nutrients.

The Rapasun-Corn area (A17) also practiced intensive monocropping, conventional tillage, and pure inorganic fertilizer application, yet maintained a medium SQI of 0.6176. While not a definitive explanatory conclusion, we propose a field observation hypothesis regarding biological buffering. It was visually noted that diverse subsistence vegetables (mostly legumes) were planted nearby for family consumption, which may have acted as an ecological buffer, an intercropping effect supported by recent findings by Bünemann et al. (2018). However, because this peripheral vegetation was not quantitatively measured, this potential functional buffering remains strictly an observational hypothesis and lacks definitive empirical evidence within this study.

To mitigate further decline across the campus, it is strongly advised to correct acidity in low-pH regions through liming. Because Organic Matter (OM) plays a key biological role in aggregate stability, farmers must abandon continuous cultivation and destructive residue burning. Adopting crop rotation with nitrogen-fixing legumes, alongside the systematic composting of agricultural residues, is required to rebuild the carbon pool and ensure long-term sustainability.

Land use categorization and descriptive SQI trends

When evaluating the data, the SQI values for diverse agricultural purposes did not differ significantly ($p>0.05$) (Figure 3.A), reflecting the high variance and unequal sample sizes across the functional categories. This finding is in direct agreement with the longitudinal results presented by Mulumba (2004) and the more recent spatial results by Fathizad et al. (2020), which clearly demonstrate that broad administrative management of land use categorization has no direct mechanistic implications for SQI values. Rather, it is the specific, localized agronomic interventions applied within those designated zones that are associated with variations in soil properties. For example, intensively managed commercial production areas exhibited the lowest functional capacity, with specific site SQI values situated below the critical threshold of 0.50 (0.4733 and 0.4932). The high-intensity, commercial perspective of these specific sites promotes a cycle of traditional tillage and the application of synthetic chemical fertilizers only. In tropical agroecosystems, this combination is associated with lower vital levels of Principal Component markers that drive SQI values, including Organic Matter (OM) and Earthworm (EW) populations, while mechanical soil inversion corresponds with degraded critical pore-space architecture (Jiang et al. 2024). On the contrary, specific areas managed for natural land uses inherently support maintaining permanent perennial cover and no-tilling, sustaining higher comparative indices (ranging from 0.5486 to 0.6002). Although these differences were not statistically significant at the category level, such management practices are associated with the preservation of soil structural integrity and reduced rapid oxidation of organic carbon, thereby

supporting moisture retention and maintaining optimal bulk density in highly weathered tropical soils (Ramirez et al. 2022).

Cropping pattern diversity and SQI associations

Statistical analysis indicated that the cropping pattern had no significant main effect on the functional soil quality of the evaluated areas ($p>0.05$). Whether a plot utilized diverse crop rotation, maintained permanent perennial vegetation, or underwent continuous monocropping, no statistically significant effect on the composite SQI was detected (Figure 3.B). While lacking statistical significance, a quantitative comparison of mean SQI values (Figure 3.B) highlights an observable trend across the various cropping patterns. Continuous monocropping yielded the lowest average SQI (mean \approx 0.52), with certain specific sites dropping below the 0.50 threshold (Table 7). Conversely, areas maintaining permanent perennial cover recorded the highest mean SQI (\approx 0.59), followed by crop rotation systems (\approx 0.57). While these mean differences lack inferential significance to confirm a causal relationship within this specific dataset, the observational trend aligns with broader empirical findings wherein continuous monocropping is frequently associated with steeper structural degradation compared to permanent cover or strategic crop rotation. The need to adopt management practices that integrate plant biodiversity is highly favorable for maintaining soil functional capacity, particularly within highly weathered tropical environments where complex crop diversity and agroforestry systems have been shown to buffer against rapid organic carbon depletion (Muchane et al. 2020; Zsögön et al. 2022).

Mechanical tillage intensity and physical matrix integrity

Regarding mechanical intervention, quantitative comparisons (Figure 3.C) descriptively indicate that no-till areas exhibited observationally higher mean SQI values (\approx 0.59) than conventionally tilled areas (\approx 0.56), though these categorical differences were not statistically significant. The single minimum-tillage site recorded an SQI of approximately 0.51 (Table 7). However, because this category includes only one observation, it was excluded from broader comparative interpretation and remains statistically non-comparable. The physical disintegration of the soil matrix under conventional plowing is observationally linked to compromised aggregate stability, accelerated oxidation of the organic carbon pool, and diminished existing macrofauna populations. This descriptive trend is fully consistent with evaluations of tropical soils by Rangel-Peraza et al. (2017), Mandal et al. (2021) and Damiba et al. (2024), which established that less destructive tilling systems facilitate the recovery of important soil physical properties and biological activities critical for mitigating land degradation in humid tropical environments.

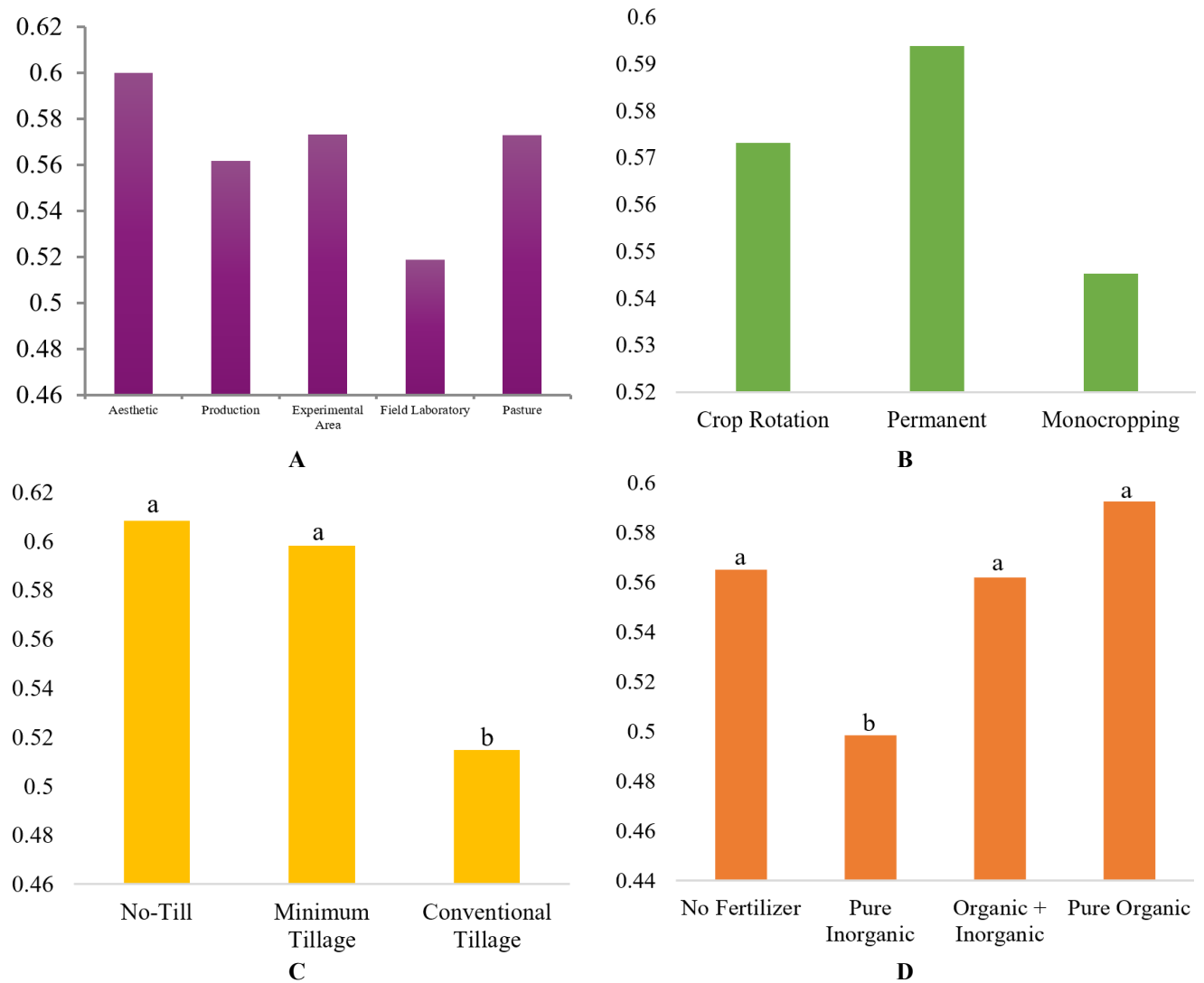


Figure 3. The effects of various agricultural management practices on the resulting Soil Quality Index (SQI) scores, specifically illustrating the impacts of A. Land use categories, B. Cropping patterns, C. Mechanical tillage intensity, and D. Fertilizer management regimes. These descriptive distributions directly guide visual interpretation by illustrating that conservation practices, such as no-till and integrated fertilizer use, correspond with higher median soil functional capacities despite the absence of categorical statistical significance

Fertilizer regimes and internal nutrient cycling dynamics

Regarding fertilizer management (Figure 3.D), quantitative assessments reveal a non-significant descriptive trend where areas relying exclusively on synthetic chemical fertilizers observationally display lower overall SQI values. Conversely, fields receiving integrated (inorganic and organic) or purely organic amendments descriptively exhibit higher average SQI scores. The continuous application of unbuffered synthetic fertilizers aligns observationally with disrupted internal nutrient cycling and depleted organic carbon pools over time (Chandrakala et al. 2022), a vulnerability particularly pronounced in highly weathered tropical agroecosystems.

While these findings highlight a meaningful field-associated pattern wherein organic inputs correspond with enhanced soil functional capacity, they do not constitute

definitive proof of fertilizer superiority under non-experimental field conditions. Because these observations are drawn from a heterogeneous landscape with multiple overlapping agronomic variables, specifically the strong confounding overlap between fertilizer regimes, tillage intensity, and cropping patterns, between fertilizer regimes, tillage intensity, and cropping patterns future controlled validation is required to establish explicit causal mechanisms.

In conclusion, this study developed a Principal Component Analysis-based Soil Quality Index (PCA-SQI) to evaluate soil functional status across 17 agricultural areas at MSU Main. The PCA explained 78.00% of the total variance, reducing 17 measured parameters to a minimum data set of 10 key indicators. The resulting SQI values ranged from 0.4733 to 0.6430, with 15 areas classified as having moderate soil quality (0.50-0.80) and

two areas identified as degraded (<0.50). Lower SQI values were associated with continuous monocropping, conventional tillage, and exclusive synthetic fertilizer use, whereas higher values were observed in areas practicing integrated nutrient management and reduced tillage. These findings indicate that management intensity is closely associated with soil functional condition; however, due to the observational study design and unequal sample sizes across management categories, these relationships should be interpreted as descriptive and associative rather than causal. Additional limitations include spatial heterogeneity across sites, potential variability in reconstructed management histories, and the absence of controlled experimental validation. Future research should incorporate controlled field experiments, longitudinal monitoring, and multi-location validation to strengthen causal inference. On a broader agronomic scale, these findings reinforce the generalization that integrating organic amendments and reducing tillage intensity are vital strategies for promoting long-term ecological productivity in similar highly weathered tropical agroecosystems.

ACKNOWLEDGEMENTS

The authors are thankful to MSU Main, Philippines, for the use of the Soils and Plant Tissue Laboratory, College of Agriculture, where the analyses were conducted. Moreover, gratitude is due to the local farmers and the person in charge of the areas who willingly gave their time for the interview conducted.

REFERENCES

- AbdelRahman MAE, Engel B, Eid MSM, Aboelsoud HM. 2022. A new index to assess soil sustainability based on temporal changes of soil measurements using geomatics - An example from El-Sharkia, Egypt. *Earth Obs* 2: 147-166. <https://doi.org/10.1080/27669645.2022.2103953>.
- Alaboz P, Dengiz O, Demir S. 2021. Barley yield estimation performed by ANN integrated with the soil quality index modified by biogas waste application. *Zemdirbyste-Agric* 108: 217-226. <https://doi.org/10.13080/z-a.2021.108.028>.
- Andrews SS, Karlen DL, Cambardella CA. 2004. The soil management assessment framework: A quantitative soil quality evaluation method. *Soil Sci Soc Am J* 68: 1945-1962. <https://doi.org/10.2136/sssaj2004.1945>.
- Brejda JJ, Moorman TB, Karlen DL, Dao TH. 2000. Identification of regional soil quality factors and indicators: I. Central and Southern High Plains. *Soil Sci Soc Am J* 64: 2115-2124. <https://doi.org/10.2136/sssaj2000.6462115x>.
- Bünemann EK, Bongiorno G, Bai Z, Creamer RE, De Deyn G, de Goede R, Fleskens L, Geissen V, Kuyper TW, Mäder P, Pulleman CE, Sukkel W, van Groenigen JW, Brussaard L. 2018. Soil quality-A critical review. *Soil Biol Biochem* 120: 105-125. <https://doi.org/10.1016/j.soilbio.2018.01.030>.
- Bureau of Soils and Water Management (BSWM). 2010. *Soil Surveys and Classification*. Department of Agriculture, Quezon City.
- Chandrakala M, Prasad B, Niranjana KV, Srinivasan R, Sujatha K, Basavaraj B, Maske SP, Hegde R, Dwivedi BS. 2022. Paddy lands of the South Telangana plateau (Rayalseema), Andhra Pradesh, India: A detailed suitability assessment. *Indian J Soil Conserv* 50 (1): 57-65.
- Damiba WAF, Gathenya JM, Raude JM, Home PG. 2024. Soil Quality Index (SQI) for evaluating the sustainability status of Kakia-Esambumbur catchment under three different land use types in Narok County, Kenya. *Heliyon* 10: e25611. <https://doi.org/10.1016/j.heliyon.2024.e25611>.
- Estefan G, Sommer R, Ryan J. 2013. *Methods of Soil, Plant, and Water Analysis: A Manual for the West Asia and North Africa region*. 3rd ed. International Center for Agricultural Research in the Dry Areas, Beirut.
- Fathizad H, Ardakani MAH, Heung B, Sodaiezadeh H, Rahmani A, Fathabadi A, Scholten T, Taghizadeh-Mehrjardi R. 2020. Spatio-temporal dynamic of soil quality in the central Iranian desert modeled with machine learning and digital soil assessment techniques. *Ecol Indic* 118: 106736. <https://doi.org/10.1016/j.ecolind.2020.106736>.
- Food and Agriculture Organization of the United Nations (FAO). 2023. *Standard Operating Procedure for Soil Bulk Density, Cylinder Method*. FAO, Rome. <https://doi.org/10.4060/cc7568en>.
- Ghaemi M, Astarai AR, Emami H, Nassiri Mahalati M, Sanaeinejad SH. 2014. Determining soil indicators for soil sustainability assessment using principal component analysis of Astan Quds, east of Mashhad, Iran. *J Soil Sci Plant Nutr* 14: 1005-1020. <https://doi.org/10.4067/S0718-95162014005000077>.
- Hadija, Kuswinanti T, Jayadi M, Larekeng ST. 2023. Soil function analysis in determining the soil quality index of paddy fields in Salassae Village, Bulukumba Regency, South Sulawesi Province, Indonesia. *Agric Sci Dig* 43: 40-45. <https://doi.org/10.18805/ag.DF-476>.
- International Rice Research Institute (IRRI). 2014. *Statistical Tool for Agricultural Research (STAR) version 2.0.1: Biometrics and Breeding Information*. PBGB Division, Los Baños, Laguna.
- Jiang K, Teuling AJ, Chen X, Huang N, Wang J, Zhang Z, Gao R, Men J, Zhang Z, Wu Y, Cai L, Huang Z, Ma Z, Pan Z. 2024. Global land degradation hotspots based on multiple methods and indicators. *Ecol Indic* 158: 111462. <https://doi.org/10.1016/j.ecolind.2023.111462>.
- Jiang M, Xu L, Chen X, Zhu H, Fan H. 2020. Soil quality assessment based on a minimum data set: A case study of a county in the typical river delta wetlands. *Sustainability* 12: 9033. <https://doi.org/10.3390/su12219033>.
- Kahsay A, Haile M, Gebresamuel G, Mohammed M. 2025. Developing soil quality indices to investigate degradation impacts of different land use types in Northern Ethiopia. *Heliyon* 11 (1): e41185. <https://doi.org/10.1016/j.heliyon.2024.e41185>.
- Lal R, Shukla MK. 2004. *Principles of Soil Physics*. CRC Press, Boca Raton. <https://doi.org/10.4324/9780203021231>.
- Lenka NK, Meena BP, Lal R, Khandagle A, Lenka S, Shirale AO. 2022. Comparing four indexing approaches to define soil quality in an intensively cropped region of Northern India. *Front Environ Sci* 10: 865473. <https://doi.org/10.3389/fenvs.2022.865473>.
- Mandal D, Chandrakala M, Alam NM, Roy T, Mandal U. 2021. Assessment of soil quality and productivity in different phases of soil erosion with the focus on land degradation neutrality in the tropical humid region of India. *Catena* 204: 105440. <https://doi.org/10.1016/j.catena.2021.105440>.
- Mandal D, Patra S, Sharma NK, Alam NM, Jana C, Lal R. 2023. Impacts of soil erosion on soil quality and agricultural sustainability in the North-Western Himalayan region of India. *Sustainability* 15: 5430. <https://doi.org/10.3390/su15065430>.
- Muchane MN, Sileshi GW, Gripenberg S, Jonsson M, Pumariño L, Barrios E. 2020. Agroforestry boosts soil health in the humid and sub-humid tropics: A meta-analysis. *Agric Ecosyst Environ* 295: 106899. <https://doi.org/10.1016/j.agee.2020.106899>.
- Mulumba LN. 2004. *Land Use Effects on Soil Quality and Productivity in the Lake Victoria Basin of Uganda*. [Dissertation]. The Ohio State University, Columbus.
- Mutiara C, Bolly YY, Hutubessy JIB, Aggrey H, Dahiba S, Palelet EY, Romadhon MR, Irmawati V, Hasanah K. 2025. Rice field soil quality assessment through various environmental diversity sources in Ende District, East Nusa Tenggara, Indonesia. *Asian J Agric* 9 (1): 264-275. <https://doi.org/10.13057/asianjagric/g090128>.
- Nikpey M, Robotajazi J, Garmehei S, Lasar HGW, Nghia NK, Agyei BK. 2024. Assessment of agricultural soil quality indices using mechanistic models. *Open J Soil Sci* 14 (6): 333-352. <https://doi.org/10.4236/ojss.2024.146019>.
- Ozlu E, Gozukara G, Acar M, Bilen S, Babur E. 2022. Field-scale evaluation of the soil quality index as influenced by dairy manure and inorganic fertilizers. *Sustainability* 14: 7593. <https://doi.org/10.3390/su14137593>.
- Paz-Kagan T, Shachak M, Zaady E, Karnieli A. 2014. A spectral Soil Quality Index (SSQI) for characterizing soil function in areas of

- changed land use. *Geoderma* 230-231: 171-184. <https://doi.org/10.1016/j.geoderma.2014.04.003>.
- Posadas RC, Salting AAA, Evangelista RDA, Real RM Jr, Casidsid LA, Sagarino EO. 2022. Soil quality index for the two agricultural areas along the Naboc River in Davao de Oro, Philippines, contaminated with mercury. *Philipp J Sci* 151 (5): 2031-2046. <https://doi.org/10.56899/151.05.39>.
- Prayogo C, Arfarita N, Luthfiningsih F, Fajrina N, Sholih NA. 2026. Soil respiration and microbial communities across different farming management of shaded coffee and pines on agroforestry system. *Biodiversitas* 27 (2): d270205. <https://doi.org/10.13057/biodiv/d270205>.
- Ramirez MAJP, Visco RG, Predo CD, Galang MA. 2022. Assessment of soil condition using the soil quality index of different land use types in Liliw, Laguna, Philippines. *Philipp J Sci* 151 (3): 1157-1169. <https://doi.org/10.56899/151.03.29>.
- Rangel-Peraza JG, Padilla-Gasca E, López-Corrales R, Medina JR, Bustos-Terrones Y, Amabilis-Sosa LE, Rodríguez-Mata AE, Osuna-Enciso T. 2017. Robust soil quality index for tropical soils influenced by agricultural activities. *J Agric Chem Environ* 6 (4): 199-221. <https://doi.org/10.4236/jacen.2017.64014>.
- Saleh AM, Elsharkawy MM, AbdelRahman MAE, Arafat SM. 2021. Evaluation of soil quality in arid western fringes of the Nile delta for sustainable agriculture. *Appl Environ Soil Sci* 2021: 1434692. <https://doi.org/10.1155/2021/1434692>.
- Shokr MS, Jalhoum MEM, Sayed ASA, Saeed M, Rebouh NY, Mohamed ES, Yousif IAH, Abdelhameed HH. 2025. Assessment of soil quality in arid zones using principal component analysis and GIS-based modeling. *PLoS ONE* 20: e0337063. <https://doi.org/10.1371/journal.pone.0337063>.
- Singh AK, Bordoloi LJ, Kumar M, Hazarika S, Parmar B. 2014. Land use impact on soil quality in the eastern Himalayan region of India. *Environ Monit Assess* 186: 2013-2024. <https://doi.org/10.1007/s10661-013-3514-7>.
- Spandana MP, Suresh KR, Prathima B. 2013. Developing a soil quality index for the Vrishabavathi command area. *Intl J Eng Res Technol* 2: 1114-1121.
- Tesfahunegn GB. 2014. Soil quality assessment strategies for evaluating soil degradation in Ethiopia. *Appl Environ Soil Sci* 2014: 646502. <https://doi.org/10.1155/2014/646502>.
- Velasquez E, Lavelle P, Andrade M. 2007. GISQ, a multifunctional indicator of soil quality. *Soil Biol Biochem* 39: 3066-3080. <https://doi.org/10.1016/j.soilbio.2007.06.013>.
- Zsögön A, Peres LEP, Xiao Y, Yan J, Fernie AR. 2022. Enhancing crop diversity for food security in the face of climate uncertainty. *Plant J* 109 (2): 402-414. <https://doi.org/10.1111/tpj.15626>.