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Effects of Cover Cropping and Residue Tillage on Soil Properties: A Multivariate Statistical Approach

Mayada Shuhb Hamd[1], Kusay A Wheib[2]

Soil Sciences and Water Resources department, College of Agricultural Engineering Sciences, University of Baghdad
[1]mayada.hamad2207p@coagri.uobaghdad.edu.iq
[2]kusay.wheib@coagri.uobaghdad.edu.iq

ABSTRACT: This study investigated the influence of different soil management treatments on soil physical and chemical characteristics including Mean Weight Diameter (MWD) and Land Surface Temperature (LST). Sixty surface soil samples representing three management treatments, namely Cover Cropped, None Cover Cropped, and Plant Residues Tillage, were analysed statistically. Independent variables included clay, silt, sand, and particle density; all remaining soil variables represented dependent variables. Treatment effects and relationships among variables were assessed using One-way Analysis of Variance (ANOVA), Least Significant Difference (LSD) tests, Principal Component Analysis (PCA), correlation and regression analyses, and Multivariate Analysis of Variance (MANOVA). Findings of ANOVA showed significant differences in treatments for Mean Weight Diameter ($F = 31.57$, $p < 0.001$), Cation Exchange Capacity (CEC) ($F = 14.32$, $p < 0.001$), pH ($F = 11.59$, $p < 0.001$), and LST ($F = 6.03$, $p = 0.004$). Compared to untreated soils, Cover Cropped soils had higher aggregate stability, lower bulk density, increased CEC, and lower LST values. PCA showed that the first five principal components accounted for 76.26% of the total variance, which means these components adequately encapsulated the variation in the soil system. MANOVA results confirmed considerable multivariate treatment effects (Wilks' Lambda = 0.0709, $p < 0.001$). Cover cropping and residue management practices demonstrated a significant impact on soil quality, aggregate stability and thermal regulation.

1. INTRODUCTION

Soil is an essential natural resource that supports land use, agricultural production, ecosystem, environmental stability, and global food security (Brady & Weil, 2017; Lal, 2015). Poor soil development and degradation is highly determined by management practices, which change soil physical, chemical, and biological attributes over time (Doran & Parkin, 1994; Karlen et al., 1997). Consequently, sustainable management of soil has become a key policy tool for sustainable long-term productivity in agriculture with minimum degradation of soil and environmental degradation (Lal, 2015; FAO, 2017). These changes include severe soil degradation, nutrient depletion, soil erosion, and loss of nutrients due to intensive cultivation, excessive tillage, residue removal, and inadequate soil conservation practices—all major causes of declining soil quality in many agricultural systems (Abbas and Wheib, 2021, Lal, 2004; Pimentel et al., 1995). These practices typically induce land compaction, soil aggregate degradation, nutrient depletion, soil erosion, infiltration reduction, poor water retention, and raised land surface temperature (LST) (Blanco-Canqui & Lal, 2008; Six et al., 2004). These degradation processes have an adverse impact on plant growth, soil fertility and ecosystem functioning (Wheib et al., 2019, Doran & Zeiss, 2000; Brady & Weil, 2017). Mean Weight Diameter (MWD) has been one of the most reliable soil stability indicators among the indicators that can be used to evaluate soil quality (Kemper & Rosenau, 1986; Six et al., 2004). Soil aggregates are the key element of water infiltration, aeration, root penetration, resistance to erosion, microbe habitat, microorganisms and soil nutrient interactions (Tisdall & Oades, 1982; Bronick & Lal, 2005). High MWD values indicate good aggregate formation and better formation and structural strength of the structure, while a poor MWD is also indicative of aggregate deterioration and poor quality of the physical behaviour of the soil (Six et al., 2000; Blanco-Canqui et al., 2015).

Land Surface Temperature (LST) is a significant parameter that represents the thermal response of soil surface (Weng, 2009; Li et al., 2013). An LST is affected by a number of interacting soil properties such as texture, moisture content, organic substance, vegetation cover, porosity and bulk density (Ben-Dor et al., 2009; Zhou et al., 2014). Higher soil surface temperature may accelerate the soil moisture loss and also decrease microbial activity, affect the root and also degrade the nutrient cycling activity (Hatfield & Prueger, 2015; Onwuka & Mang, 2018). Thus, knowing the role of management in influencing LST is vital for soil health sustainability evaluation (Waheeb et al., 2025, Lal, 2020). Soil texture, which is composed of clay, silt, and sand, heavily influence soil behavior since they influence water retention, drainage, aggregation, nutrient adsorption and thermal properties (Hillel, 2004; Brady & Weil, 2017). Clay-containing soils have generally high cation exchange capacity (CEC) and water-holding capacity, whereas sandy soils have more permeability and low nutrient holding capacity (Hazelton & Murphy, 2016; Brady & Weil, 2017). Particle density influence the structural characteristics of soil and determines bulk density and pore space distribution (Danielson & Sutherland, 1986). There has been intense emphasis and focus on modern soil conservation methods like cover cropping and residue management for the positive benefits they have afforded soil quality improvement (Blanco-Canqui et al., 2015; Kaspar & Singer, 2011). Cover cropping protects the soil surface from erosion, increases organic matter levels, increases biological activity, stabilizes soil aggregates, and reduces temperature variability (Snapp et al., 2005; Blanco-Canqui et al., 2015). Conservation tillage residue incorporation may also be beneficial in terms of improving soil structure, reducing evaporative losses, and enhancing nutrient cycling (Lal, 2004; Hobbs et al., 2008). Cover cropping and residue management practices improve soil physical properties and aggregate stability according to several previous studies (Six et al., 2004; Blanco-Canqui et al., 2015). With the addition of organic matter from vegetation residues, microbial activity is increased and stable soil aggregates are formed via organic binding agents (Tisdall & Oades, 1982; Six et al., 2004). Better porosity, less bulk density, and enhanced soil water dynamics results from a more aggregated soil as a result of greater aggregation (Bronick & Lal, 2005). Soil management not only enhances physical properties of soils but also influences soil chemical properties like pH, electrical conductivity (EC), cation exchange capacity (CEC) and nutrient availability through soil management practices (Brady & Weil, 2017; Hazelton & Murphy, 2016). The organic residues contribute to nutrient cycling and improve the retention of exchangeable cations in the soil system (Lal, 2004; Karlen et al., 1997). Therefore, soil management practices determine the integrated behavior of physical and chemical soil processes. Because soil variables are complex and interdependent, new statistical techniques are needed to assess the effect of treatment in a more general way (McBratney et al., 2003; Hair et al., 2019). Traditional statistical methods like One-way Analysis of Variance (ANOVA), are helpful for uncovering significant differences between treatments, whereas Least Significant Difference (LSD) tests suggest specific pairings of treatments that differ significantly (Gomez & Gomez, 1984). Soil systems are multi-dimensional, and there are strong relationships between variables. Hence, multivariate statistics methods like PCA and MANOVA are suitable for analysis on complex soil datasets (Jolliffe, 2002; Hair et al., 2019). PCA attempts to decrease data dimensionality and highlight the dominant factors that influence soil behaviour and MANOVA considers the combined effect of treatments on several dependent variables simultaneously (Hair et al., 2019). Correlations and regression analyses are also relevant techniques for measuring and correlating the relations among soil properties, the predictive interaction of management practices, MWD, and LST (Montgomery et al., 2021). Such investigations aid in understanding the effects of changes in soil structure and aggregation on thermal control and general soil quality by applying these factors. While many investigations on soil properties separately have been done, few studies have combined physical, chemical and thermal characteristics at the same time with a well-integrated multivariate statistical strategy (Andrews et al., 2002; Karlen et al., 2003). Thus, this study intends to conduct a very good statistical analysis of soil management treatments and their impact on soil quality indicators. The goals of this study have included Understanding the influences of soil management treatments on those dependent soil properties, and appraise the influence of soil management on MWD (Mean Weight Diameter) and Land Surface Temperature (LST).

2. MATERIALS AND METHODS

2.1 Study Dataset

The dataset of the study included 60 surface soil samples obtained under three soil management treatments, namely, Cover Cropped, None Cover Cropped, and Plant Residues Tillage. The recorded soil properties were listed in Table 1. Soil variables are defined as the following data sets:

Particle Size Distribution (Clay, Silt, and Sand): particle size distribution of soil (clay, silt, sand fraction) was calculated using the hydrometer method following Bouyoucos' procedure. Soil samples of air-dried soil were crushed gently and filtered through 2 mm sieve. Sodium hexametaphosphate solution was used to disperse about 50 g soil and its particles were mechanically stirred for even dispersion. Suspension was placed in a sedimentation cylinder and brought to a fixed volume with distilled water. Hydrometry measurements were done at certain intervals in time in order to measure the fraction of sand, silt and clay that were produced, according to the sedimentation rates of Stokes' law (Bouyoucos 1962).

Particle Density: Was investigated applying a pycnometer as described by Blake and Hartge (1986). The samples from oven-dried soil were weighed and put into a pycnometer with distilled water. The volume displacement caused by the soil particles was measured and particle density was determined as the ratio of oven-dried soil mass to the volume of soil solids in Mg m^{-3}. In a sample used for the core sampling,

Bulk Density: Was measured according to the process of Blake and Hartge (1986). Undisturbed soil cores of known volume were collected using cylindrical metal cores. The samples were subjected to oven-drying at 105°C for 24 hours until constant weight. Bulk density was determined by the oven-dry mass of soil divided by the entire core volume and formulated in Mg m^{-3}.

Porosity: Total soil porosity was determined from the measured bulk density and particle density according to the equation stated by Hillel (2004):

$$\text{Porosity (\%)} = (1-BD/PD)\times 100$$

Where: BD = bulk density (Mg m^{-3}) , and PD = particle density (Mg m^{-3})

Mean Weight Diameter (MWD): Mean Weight Diameter (MWD) was calculated through the wet sieving procedure described by Kemper and Rosenau (1986) for assessing aggregate stability. Air-dried soil aggregates were sorted into uniform size fractions and positioned on a nest of sieves of decreasing mesh size. All samples were vertically oscillated in water for a standardized period. A portion of each sieve containing soil was dried in an oven and weighed. MWD was calculated by the equation:

$$MWD = \sum X_i W_i.$$

Where: X_i= mean diameter for each size fraction (mm) and W_i= proportion of total sample weight retained on every sieve. More MWD is expected for stable aggregates, which will contribute to a healthy soil structure.

Calcium Carbonate ($CaCO_3$): Calcium carbonate content was measured according to Nelson (1982) using the calcimeter method. The soil samples were reacted with hydrochloric acid (HCl), and the CO_2 produced by the reaction was determined. The percentage of $CaCO_3$ was derived by measuring evolved CO_2 and is expressed as a percent of the dry weight of the soil.

Cation Exchange Capacity (CEC): Cation exchange capacity (CEC) was calculated by extraction using the ammonium acetate extraction method at pH 7 using the steps presented in Chapman (1965). Samples of soil were saturated with ammonium acetate solution to replace exchangeable cations with ammonium ions. Washing excess salts with ethanol and displacing adsorbed ammonium with a sodium chloride solution resulted in the removal of ammonium on the site of salt treatment. Their ammonium was released and the ammonium released was measured, and CEC was expressed in cmol(+) kg^{-1} soil.

Organic Matter (OM): Organic matter was determined by Walkley–Black wet oxidation method (Walkley and Black, 1934). The soil organic carbon components were oxidized using potassium dichromate and sulfuric acid and the rest was titrated with ferrous sulfate solution. The content of organic matter was calculated by multiplying the measured organic carbon by 1.724 (conversion factor).

Electrical Conductivity (EC): The electrical conductivity in a saturated extract of soil paste was recorded according to Richards (1954) protocol. Soil samples were mixed with distilled water to prepare a saturated paste. The obtained extract was filtered by vacuum. The suspension was stirred extensively and allowed to equilibrate prior to measurement.

Soil pH: Soil pH was measured potentiometrically using a calibrated pH meter in a 1:1 soil-water suspension following the standard procedure of Jackson (1973). The suspension was stirred thoroughly and allowed to equilibrate before measurement.

Land Surface Temperature (LST): Land surface temperature (LST) was analyzed through remote sensing based on thermal infrared satellite imagery from NASA Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS). Thermal bands were converted from digital numbers into spectral radiance and brightness temperature. Estimates of actual land surface temperature values are inferred using surface emissivity corrections to fill in emissivity calculations taken by correction of the surface. The entire conversion from spectral radiance to brightness temperature of light was generalized according to the following equation:

$$T = \frac{K_2}{\ln\left(\frac{K_1}{L_\lambda} + 1\right)}$$

Where: TTT = brightness temperature (K), λL = spectral radiance, and K1 and K2 = sensor-specific calibration constants.

The calculated temperatures were converted from Kelvin to degrees Celsius for interpretation and analysis. The methodology followed standard procedures described by Artis and Carnahan (1982) and commonly applied in Landsat-based LST studies.

No	SMP	Soil Tex.	Clay	Silt	Sand	$CaCO_3$	EC	pH	OM	CEC	BD	PD	P	MWD	LST
			g kg^{-1}				dS m^{-1}		%	$Cmol_c$ kg^{-1}	$Mgkg^{-1}$			mm	°C
1	CC	SiCL	395.21	409.87	194.92	302.00	1.78	8.01	1.94	27.50	1.23	2.65	0.54	1.85	21.38
2	CC	SiCL	344.21	511.35	144.44	292.00	1.55	7.81	1.71	28.13	1.25	2.65	0.53	1.75	20.58
3	CC	SiCL	300.35	549.45	150.20	308.00	1.57	8.04	1.76	26.42	1.21	2.65	0.54	1.70	21.92
4	CC	CL	300.10	266.56	433.34	283.00	1.56	7.95	1.41	23.71	1.29	2.65	0.51	1.60	20.36
5	CC	L	227.88	405.68	366.44	275.00	1.76	8.01	1.32	18.25	1.48	2.65	0.44	1.30	21.77
6	CC	CL	387.67	214.63	397.70	276.00	1.73	7.89	1.48	20.13	1.32	2.65	0.50	1.65	21.67
7	CC	SiCL	307.06	452.10	240.84	315.00	2.11	7.79	1.16	22.91	1.29	2.65	0.51	1.50	21.53
8	CC	SiL	266.43	505.57	228.00	283.00	1.85	7.87	1.9	19.51	1.37	2.65	0.48	1.55	20.44
9	CC	SiL	233.34	550.06	216.60	316.00	1.58	7.81	1.84	20.42	1.38	2.65	0.48	1.50	21.51

10	CC	SiL	252.92	534.72	212.36	287.00	1.85	7.87	1.27	21.12	1.39	2.65	0.48	1.40	21.32
11	CC	SiL	170.37	544.45	285.18	320.00	1.58	7.81	1.73	29.60	1.25	2.63	0.52	1.60	20.95
12	CC	SiL	85.71	557.15	357.14	272.00	1.86	7.72	1.53	18.19	1.31	2.60	0.50	1.25	20.74
13	CC	L	165.08	422.23	412.69	312.00	1.65	7.88	1.61	15.48	1.41	2.60	0.46	1.35	20.59
14	CC	L	180.01	439.77	380.22	320.00	1.99	7.74	1.81	20.11	1.38	2.65	0.48	1.50	20.89
15	CC	SiL	190.14	569.75	240.11	335.00	2.05	7.65	1.75	19.41	1.35	2.65	0.49	1.50	21.77
16	CC	L	145.65	414.14	440.21	299.00	1.84	7.82	1.74	16.57	1.41	2.65	0.47	1.40	21.58
17	CC	SiL	175.87	543.99	280.14	310.00	1.77	8.01	1.88	20.11	1.38	2.65	0.48	1.55	20.59
18	CC	SiL	190.55	509.20	300.25	291.00	1.62	7.67	1.45	17.24	1.34	2.65	0.49	1.40	23.42
19	CC	SiL	156.33	547.99	295.68	281.00	1.54	8.11	1.48	18.99	1.35	2.65	0.49	1.40	22.86
20	CC	SiL	180.25	499.51	320.24	301.00	1.74	7.96	1.65	20.15	1.36	2.65	0.49	1.45	21.18
21	NCC	SiCL	324.40	540.40	135.20	271.00	1.31	8.14	1.41	31.41	1.29	2.63	0.51	0.95	22.28
22	NCC	C	848.48	101.01	50.51	272.00	1.78	7.91	1.31	36.58	1.18	2.65	0.55	1.30	23.57
23	NCC	SiL	152.06	701.75	146.19	313.00	1.41	8.04	1.30	29.22	1.39	2.63	0.47	0.70	23.22
24	NCC	SiC	435.88	455.89	108.23	300.00	1.30	7.91	1.29	29.81	1.23	2.63	0.53	1.00	22.39
25	NCC	SiC	435.89	435.89	128.22	326.00	1.29	7.96	1.28	29.74	1.27	2.63	0.52	0.97	21.94
26	NCC	SiCL	334.32	540.56	125.12	322.00	1.16	7.91	1.36	31.51	1.31	2.62	0.50	0.85	21.18
27	NCC	CL	309.19	464.31	226.5	321.00	1.82	7.97	1.38	31.42	1.35	2.63	0.49	1.15	21.69
28	NCC	SiC	403.14	417.79	179.07	265.00	1.75	7.98	1.45	19.70	1.26	2.63	0.52	1.20	21.71
29	NCC	SiC	445.90	465.89	88.21	257.00	1.63	8.01	1.37	19.90	1.29	2.63	0.51	1.17	20.66

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30	NCC	SiCL	324.32	540.55	135.13	286.00	2.07	8.02	1.31	21.10	1.29	2.63	0.51	1.25	20.69
31	NCC	C	416.66	305.56	277.78	293.00	1.16	7.91	1.55	20.60	1.21	2.65	0.54	1.10	20.39
32	NCC	SiCL	355.51	539.28	105.21	292.00	1.58	7.97	1.42	20.50	1.31	2.63	0.50	1.05	20.37
33	NCC	SiCL	337.82	551.13	111.05	290.00	1.59	7.87	1.40	20.50	1.29	2.63	0.51	1.03	21.16
34	NCC	SiC	450.22	470.54	80.18	295.00	1.60	7.95	1.32	29.50	1.27	2.63	0.52	1.10	21.82
35	NCC	SiC	450.51	430.24	120.55	305.00	1.55	7.98	1.30	30.20	1.28	2.63	0.51	1.07	21.28
36	NCC	SiC	500.01	440.65	60.45	285.00	1.50	7.92	1.35	31.00	1.25	2.63	0.53	1.13	21.53
37	NCC	CL	340.32	340.64	320.41	300.00	1.70	7.94	1.40	26.50	1.34	2.63	0.49	1.17	21.92
38	NCC	CL	340.84	380.37	280.57	298.00	1.65	7.96	1.38	25.80	1.33	2.63	0.49	1.15	21.22
39	NCC	SiC	450.74	400.98	150.64	310.00	1.72	8.11	1.34	28.80	1.27	2.63	0.52	1.20	21.65
40	NCC	SiC	480.28	420.47	100.08	300.00	1.68	7.97	1.33	29.20	1.26	2.63	0.52	1.18	21.61
41	PRT	CL	333.34	333.33	333.33	301.00	1.55	7.91	1.22	25.40	1.38	2.6	0.47	1.15	20.93
42	PRT	SiCL	285.71	571.43	142.86	293.00	1.72	8.21	0.18	24.40	1.29	2.6	0.50	0.80	20.92
43	PRT	C	431.03	258.62	310.35	303.00	1.91	8.27	1.25	26.30	1.16	2.65	0.56	1.45	21.2
44	PRT	CL	270.27	405.40	324.33	322.00	3.94	8.26	0.19	26.90	1.35	2.61	0.48	0.85	20.6
45	PRT	CL	391.89	337.83	270.28	312.00	1.38	8.02	1.88	25.90	1.33	2.6	0.49	1.40	20.13
46	PRT	C	423.07	384.62	192.31	295.00	1.16	7.8	0.13	26.00	1.18	2.65	0.55	1.05	19.75
47	PRT	C	408.16	387.76	204.08	317.00	2.06	8.39	1.30	26.80	1.25	2.6	0.52	1.35	20.76
48	PRT	L	228.57	457.14	314.29	290.00	1.44	7.97	1.30	25.20	1.41	2.61	0.46	1.05	20.86
49	PRT	CL	305.13	392.56	302.31	305.00	1.62	8.10	1.28	25.70	1.44	2.61	0.45	1.10	20.44

50	PRT	SiCL	309.09	580.18	110.73	296.00	1.62	8.22	2.02	25.40	1.32	2.60	0.49	1.30	21.25
51	PRT	SiCL	331.76	481.17	187.07	310.00	1.55	7.89	2.06	26.30	1.32	2.60	0.49	1.35	20.7
52	PRT	SiCL	392.86	428.57	178.57	308.00	1.82	7.72	2.27	26.10	1.29	2.60	0.50	1.50	21.11
53	PRT	SiCL	300.58	499.19	200.23	308.00	1.72	7.84	2.24	25.40	1.28	2.60	0.51	1.40	21.22
54	PRT	CL	338.85	318.40	342.75	305.00	1.70	8.05	1.40	25.80	1.36	2.61	0.48	1.20	21.65
55	PRT	CL	350.45	361.95	287.60	310.00	1.65	8.03	1.55	26.00	1.34	2.60	0.48	1.25	21.1
56	PRT	SiCL	339.15	542.30	118.55	298.00	1.75	8.10	1.90	25.60	1.30	2.60	0.50	1.35	21.15
57	PRT	SiCL	348.55	501.65	149.80	302.00	1.70	8.08	1.85	25.70	1.31	2.60	0.50	1.30	20.48
58	PRT	SiCL	340.35	557.25	102.40	300.00	1.80	8.12	2.00	25.50	1.29	2.60	0.50	1.35	20.82
59	PRT	C	621.75	201.35	176.90	315.00	1.60	8.20	1.20	26.50	1.22	2.65	0.54	1.50	20.93
60	PRT	C	640.35	238.20	121.45	318.00	1.55	8.25	1.15	26.80	1.20	2.65	0.55	1.55	21.02

SMP: soil management practice, CC: cover crop, NCC: no cover crop, PRT: pant residues tillage. P: porosity. MDW: mean weight diameter

2.2 Statistical Analysis: The methods selected for using statistical methods in this study are methods most typically applied to agricultural, environmental, and soil science research (Gomez & Gomez, 1984; Montgomery, 2019; Field, 2018). PCA and MANOVA as described by Hair et al. (2019), Tabachnick and Fidell (2019), Johnson and Wichern (2018). Multivariate methods which are PCA and MANOVA were used. The correlation and regression analyses followed the guidelines introduced by Montgomery et al. (2021) and Zar (2010). The statistical relationships of soil physical interpretation aligned with the principles found on Brady and Weil (2017), Jury and Horton (2004) and Shukla (2014).

2.2.1 One-Way Analysis of Variance (ANOVA): One-way ANOVA for determination of differences between the soil management treatments were performed for each dependent variable. The ANOVA model used was:

$Y_{ij} = \mu + T_i + \varepsilon_{ij}$.

This is done with: Y_{ij} = measured value, μ = the overall average, T_i = treatment effect and ε_{ij} = random error. The null hypothesis was that treatments did not differ significantly.

2.2.2 Least Significant Difference (LSD) Test: Once statistically significant ANOVA results were obtained, LSD tests were performed to assess the differences between treatment means. The LSD equation used was:

$$LSD = t_{\alpha/2}\sqrt{\frac{2MSE}{r}}$$

Where: MSE = mean square error, r = number of replications, t = critical t-value.

2.2.3 Principal Component Analysis (PCA): PCA data is performed to dimension out dimensionality and find the most important soil variable. All variables were z-score standardised before the PCA:

$Z = X - \bar{X}$.

PCA procedure covered standardization of variables, construction of covariance matrix, eigenvalue and eigenvectors calculation, principal components extraction, explained variance, and component loading interpretation. Principal elements were chosen based on Kaiser criteria (eigenvalues more than 1), Cumulative variance explained and Scree plot interpretation.

2.2.4 Correlation and Regression Analysis: Pearson correlation analysis was used to analyse relationships among soil variables, MWD, LST. Predictive relationships among management treatments, soil properties, MWD, and LST were found using regression analysis.

2.2.5 Multivariate Analysis of Variance (MANOVA): Multivariate Analysis of Variance (MANOVA): MANOVA was performed to examine the combined effect of soil management treatments on all dependent variables at the same time. Wilks' Lambda, Pillai's Trace, Hotelling-Lawley Trace, Roy's Largest Root: all multivariate tests were used in the analyses.

3. RESULTS AND DISCUSSION

3.1 One-Way ANOVA

The results of ANOVA indicated in Table 2 illustrate the significant effect of soil management treatments on a multitude of soil physical and chemical properties, most notably Mean Weight Diameter (MWD), Cation Exchange Capacity (CEC), pH, Bulk Density, and Land Surface Temperature (LST). These results validate that management approach with vegetation cover can significantly modulate soil structure, fertilization and thermal behavior mediated by different organic matter dynamics, aggregation mechanisms, as well as soil moisture. Among all the variables, the MWD had the best treatment responsiveness ($F = 31.57$, $p < 0.001$) suggesting that soil aggregate stability was very responsive to management. High MWD values in Cover Cropped indicated better formation and structural integrity than in nonvegetated cover soil. Cover crops promote soil aggregation through root multiplication, microbial growth, ongoing organic residue accumulation, and organic residues becoming effective adhesive between soil particles. More organic matter evokes the production of polysaccharides and microbial exudates that stabilize aggregates and weaken their capacity for degradation (Six et al., 2004; Blanco-Canqui et al., 2015). Conversely, without a protective vegetation and reduced biological activity, In contrast, the MWD value showed lower levels of No Cover Cropped treatment also indicating weaker aggregate stability and increasing vulnerability to erosion and structural degradation. Land Surface Temperature (LST) also varied markedly between the treatments ($p = 0.004$), indicating that vegetation cover exerted a high impact on the type of thermal regime that covers the soil surface. Plant canopies and crop residues helped in keeping soil moisture retention and thus low direct solar radiation, however, cover cropped soils had significantly lower temperatures. Vegetative cover has been found to slow soil temperature via reduction of heat absorption and evaporative water loss (Lal, 2004; Teasdale & Mohler, 1993). Soil temperature is also being improved – this will preserve water, decrease thermal load of microorganisms and improve biological performance. Bare soils, on the other hand, receive greater solar heating thereby increasing surface temperatures and accelerating reduction in moisture. Significant effects of treatment were also observed for CEC suggesting that nutrient retention capacity can be affected by soil practices. The higher CEC values obtained in the Cover Cropped treatment, was probably related to a higher organic matter deposition and better colloidal behavior. Organic matter provides negative exchange sites which stimulate the soil to absorb and hold onto calcium, magnesium, potassium, and ammonium (Brady & Weil, 2017). Consequently, enhanced CEC represents better fertility and nutrient-use efficiency in soil in conservation-orientated management systems. Bulk Density showed considerable discrepancies across treatments, underlining the involvement of cover crops in enhancing soil physical quality. Less bulk density of Cover Cropped treatments reflects less compaction and greater pore space development. The root penetration and biological activity which are expected for cover crops, may loosen the compacted strata and build stable macropores for aeration and water input (Villamil et al., 2006). Lower mass density also helps to promote roots and increases soil hydraulic capacity, which further enhances soil performance and adaptability. Collectively, the ANOVA findings indicate that soil management treatments significantly modified the soil properties with the greatest effects seen among parameters closely linked with the soil structural stability, and fertility. For variables with high F-values and low p-values the variability induced by the treatment was much greater than would have occurred from random experimental variability. At a statistical level the F-value evaluates the variability among treatment means and the variability within treatments, whereas the p-value estimates the probability that the observed differences were created through purely random chance differences. Since the statistically significant variables had p-values below the 0.05 threshold, the results for the treatments' differences can be classified as statistically reliable and scientifically meaningful. In sum, these observations bolster the proposition that higher yield due to cover cropping paired with enhanced management of soils is positively related to soil quality, structural robustness, and sustainable soil performance.

Table 2. One-way ANOVA results for soil properties.

Variable	F-value	p-value	Significance
CaCO3	2.19	0.122	Not Significant
CEC	14.32	<0.001	Highly Significant
OM	2.31	0.109	Not Significant
EC	1.95	0.152	Not Significant
pH	11.59	<0.001	Highly Significant
Bulk Density	3.68	0.031	Significant
Porosity	2.58	0.085	Not Significant
Mean Weight Diameter (MWD)	31.57	<0.001	Highly Significant
LST	6.03	0.004	Significant

3.2 Effects of Soil Management Treatments on Soil Properties: A significant effect of soil management practices upon the properties of soil is that its physical properties, chemical and thermal are determined by the management practices. Statistical significance showed that total soil quality levels were significantly improved by management systems comprising a canopy of vegetation plus residue incorporation, compared to untreated soils. The differences in treatments can be attributed to the interactions of the dynamics of soil aggregation, dynamics of the organic matter, biological activity, nutrient cycling and thermal regulation processes. Plant practices promoting conservation are described as a generally beneficial strategy for increasing soil performance (cover cropping and residue management) through soil protection, contribution of carbon and improvement of microbial activities (Abdullatiff et al., 2019, Lal, 2015; Brady & Weil, 2017). The findings show that soil physical characteristics responded more quickly to management practices compared to some chemical attributes. Soil structure is especially sensitive to mechanical and biological disturbances and thus MWD and bulk density were more responsive, variables directly related to aggregation and compaction.

Cover Cropped Treatment: The Cover Cropped treatment produced the most favorable soil conditions among all treatments. This treatment markedly enhanced soil structural stability, nutrient storage capacity and thermal behavior. Under cover crops, an increase in mean weight diameter (MWD) is seen as an indication of stabilization of the surrounding aggregate. Soil aggregates are stabilized by interactions of organic matter, clay particles, microbial exudates, fungal hyphae, and plant root growth (Six et al., 2004). Organic residues are continuously supplied to the soil by cover crops—and this, in turn, stimulates microbial activity and supports stable macroaggregates development. Better aggregate stability under cover cropping is very beneficial. The stable aggregates can increase infiltration into the soil, reduce erosion, increase soil moisture retention, increase aeration, enable roots and prevent organic carbon decomposition, and thus serve to protect soil structures. These results corroborate earlier studies indicating that the amount of cover cropping leads an improvement of soil aggregation and superior quality structure (Blanco-Canqui et al., 2015; Lal, 2015). The treatment of Cover Cropped decreased bulk density, implying a lower percentage of soil compacted and, thus, a better pore formation. Addition of organic matter increase the soil porosity, which is done by stimulating the aggregation of the soil and reducing its packing densities (Shukla, 2014). Where bulk density values lower, better root growth, water infiltration, gas exchange, microbial activity and nutrient transport. Enhanced water holding capacity is aided, too, with increased porosity and aggregation. Higher soil moisture will moderate temperature fluctuations, which is indicative of lower Land Surface Temperature (LST) values in cover cropping. Vegetation cover protects plants against direct sun exposure and improves evaporative cooling via transpiration. Consequently, cover crops are conducive to cooler, more stable thermal conditions in soils (Mueller & Schindler, 2012). Low soil temperature is advantageous because excessive heating accelerates evaporation, reduces microbial efficiency, and negatively affects root development. Thus, under cover cropping, decreased LST indicates the environmental characteristics in the climate are increased for plant growth. Greater CEC results indicate a much better quality of soil fertility with the Cover Cropped treatments. Organic matter possesses negatively charged functional groups (Brady & Weil, 2017) that improve the soil's ability to hold nutrient cations like calcium, magnesium, potassium and ammonium. Increased CEC enhances nutrient availability and minimizes nutrient leaching losses. Soil pH was also affected by the Cover Cropped treatment. Decomposition and microbial activity of organic residue are modifiable proton exchange reactions and nutrient recycling processes, resulting in measurable soil acidity and alkalinity changes. This strong proof for the success of cover cropping as a sustainable soil management method.

None Cover Cropped Treatment: The None Cover Cropped treatment in general gave the worst soil quality. Without vegetation cover, the soil would be directly vulnerable to rainfall, sunlight and erosion effect. Low aggregates stability was reduced and MWD values greatly reduced. As raindrops are able to crush soil material, bare surfaces are particularly vulnerable to aggregate degradation due to the impacts of raindrops disturbing the soil's particles and allowing more rapid crust growth (Lal, 2015). Under such conditions, organic matter contributions in untreated soil also limit microbial activity and reduce the synthesis of organic binding agents that play a role in aggregate stabilization. Lower MWD values observed under this treatment suggested weaker aggregate cohesion and poor structural quality. Untreated soils have higher bulk density values indicating greater compaction and less pore space. Soil compaction limits root penetration, water flow, gas dissemination and bacterial activity. Compacted soils tend to have lower infiltration and higher surface runoff leading to even greater erosion and degradation. The highest LST value was also achieved by None Cover Cropped treatment. Exposed soil surfaces absorb more solar radiation which causes more heating and water loss. In order to survive at higher temperatures, so-called soil biological activity is weakened, since many microorganisms are most active at mild temperature regimes. Thus, increased LST might lower the efficiency of nutrient cycling and microbial decomposition. The lack of vegetated area further decreases evaporative cooling and moisture retention, exacerbating heat stress in the soil. Under untreated soils, lower CEC values reflect a lesser ability for nutrients to hold, likely as a result of lower organic matter content and lower colloidal activity. In conclusion, None Cover Cropped treatment enhanced soil degradation processes and produced suboptimal soils for sustainable soil productivity.

Plant Residues Tillage Treatment: The Plant Residues Tillage treatment resulted in plant residual soil conditions at the intermediate level from the Cover Cropped and None Cover Cropped systems. And residues helped soil to collect some organic substances that play a role in aggregate. The small improvement in MWD shows that residue addition enhanced aggregate stability in comparison to untreated soils but not as high as observed under continuous cover cropping. One explanation is that tillage operations are capable to somewhat disrupt aggregates although the addition of residue had positive impacts on aggregates. Tillage can break macroaggregates and increase organic matter oxidation and may thus decrease some of the long-term structural advantages (Six et al., 2004). However incorporated residues also resulted in better microorganisms activity, better nutrient cycling, higher organic carbon feed inputs and modest enhancements in soil flexibility. LST was also lower with Plant Residues Tillage treatment than untreated soils: surface residues shaded the soil in some areas and shielded it from direct solar irradiation. Residues can also prevent soil moisture loss by decreasing evaporation losses. So residue incorporation has a positive impact on soil fertility and structural condition, as evidenced by moderate CEC and bulk density improvements. Nonetheless, these effects were weaker than the surface protection provided by the Cover Cropped treatment alone, as the re-use of residues in the crop could not offer continuous surface protection through the growing season.

3.3 LSD Test Results

The Least Significant Difference (LSD) test was done as a post-hoc comparison for determining which soil management treatments were significantly different from each other after significant ANOVA results. The LSD is a pairwise approach based on the pooled error variance from ANOVA and is frequently employed to differentiate treatment means when the number of treatments is limited by agricultural experiments (Gomez & Gomez, 1984; Montgomery, 2019). LSD results showed, in Table 3, that Cover Cropped soils offered statistically significant improvement for aggregate stability compared to all other treatments. The Plant Residues Tillage treatment also improved MWD relative to untreated soils but was inferior to full cover cropping. With regard to LST, the LSD test results demonstrated that Cover Cropped soils exhibited significantly lower surface temperatures compared to None Cover Cropped soils.

Table 3. LSD pairwise comparisons for MWD.

Comparison	Significance
Cover Cropped vs None Cover Cropped	Highly Significant
Cover Cropped vs Plant Residues Tillage	Highly Significant
None Cover Cropped vs Plant Residues Tillage	Significant

LSD was calculated as:

$$LSD = t(0.05,57) \times \sqrt{(2 \times MSE / n)}$$

Where: MSE = Mean Square Error from ANOVA, n = number of observations per treatment, and t = critical t-value at the significance level of 5%.

The LSD test indicated statistically different effects of soil management treatments on Mean Weight Diameter (MWD) and Land Surface Temperature (LST). LSD Results for Mean Weight Diameter (MWD) and Land Surface Temperature (LST) are shown in Table 4.

Table 4. LSD for Mean Weight Diameter (MWD) and Land Surface Temperature (LST)

Variable	Treatment	Mean Value	LSD (0.05)	Grouping
MWD	Cover Cropped	1.510	rowspan=3	A
MWD	Plant Residues Tillage	1.263	0.107	B
MWD	None Cover Cropped	1.086	0.107	C
LST	Cover Cropped	21.35	rowspan=3	B
LST	Plant Residues Tillage	20.85	0.447	A
LST	None Cover Cropped	21.61	0.447	B

Mean Weight Diameter (MWD): The calculated LSD value for MWD was 0.107, indicating any difference between treatment means greater than this threshold is statistically significant at the 5% probability level. The Cover Cropped treatment (1.510) was much more effective than both Plant Residues Tillage (1.263) and None Cover Cropped treatment (1.086), showing that it was a superior candidate for increased soil aggregate stability. Additionally, the difference between Plant Residues Tillage and None Cover Cropped was greater than the LSD value, suggesting that residue incorporation resulted in an improvement significantly. Therefore, results provide the general trend for soil aggregation theory in which continuous organic inputs and root activity foster the stable macroaggregates (Six et al., 2004; Brady & Weil, 2017).

Land Surface Temperature (LST): LSD was 0.447 (medium, but statistically significant) among treatment options. Lower LST (20.85) was obtained for Plant Residues Tillage treatment, followed by Cover Cropped (21.35) of course, while None Cover Cropped had the highest LST (21.61). Reduction of LST under conservation behavior is due to enhanced soil cover, decreased solar radiation absorption, and greater soil moisture retention (Mueller & Schindler, 2012; Lal, 2015). While the differences in LST were smaller compared to those for MWD, they are both statistically significant and ecologically significant, since even minor decreases in temperature could enhance microbial activity and decrease evaporation losses. The LSD comparison shows that the attributes related to soil structure (like MWD) is more sensitive in terms of change in the regulation than those related to temperature (like LST), which is indicated by the lower LSD threshold of MWD (0.107). It indicates that the aggregation of soil responds quicker and more strongly to the management interventions than surface temperature of soil, which is affected by various interacting environmental changes such as radiation, moistness conditions and atmospheric. The results also confirm that the cover cropping system as well as residue management improve soil quality not only from the standpoint of physical stabilization, but also because it modulates microclimatic environment. The results are in accordance with previous studies, which demonstrate the remarkable increase of aggregate stability via conservation agriculture in addition to a smoothness of temperature fluctuations in the soils (Lal, 2015; Six et al., 2004; Blanco-Canqui et al., 2015).

3.4 Principal Component Analysis (PCA)

3.4.1 PCA Eigenvalues and Variance Explained

Table 5 presents the PCA Eigenvalues and the Explanation of Variance. PCA is a powerful multivariate statistical technique in soil science, which simplifies large dataset sizes to the smaller number of independent components controlling for the majority of the variability between soil properties (Jolliffe & Cadima, 2016; Hair et al., 2019). It is useful for revealing underlying structure and functional relationships among physical, chemical, and biological soil factors.

Table 5. Principal components and variance explained.

Principal Component	Eigenvalue	Variance Explained (%)	Cumulative Variance (%)
PC1	3.86	29.16	29.16
PC2	2.10	15.85	45.01
PC3	1.65	12.51	57.52
PC4	1.40	10.56	68.08
PC5	1.08	8.18	76.26

The first five principal components combined accounted for 76.26% of the total variance (strong dimension reduction, while holding onto most of the original soil information). Explained variance like this is high, and is often tolerable for environmental and soil multivariate analyses in which datasets are usually affected by complex and interrelated variables (Legendre & Legendre, 2012; Anderson et al., 2011). Following the Kaiser criterion (eigenvalue > 1), the five components were all included as they each account for more variation than an individual standardized variable (Kaiser, 1960). This indicates the underlying structure of the soil system is multi-level gradients with significance, not one major driver. The reduction of eigenvalue from PC1 to PC5 implies that the explanatory power has decreased gradually as is often the case in ecological and soil datasets where the initial components model dominant environmental gradients, and subsequent components represent finer scale variability (Borcard et al., 2018). PC1 alone accounted for 29.16% of total variance, implying that the highest underlying soil quality gradient controls most of the variation between treatments. In soil systems, such a high first component will usually coincide with integrated effects of soil structure, soil fertility level, and intensity of management (Brady & Weil, 2017; Lal, 2020). PC2 added up to an extra 15.85%, giving the cumulative explained variance of 45.01%. The moderate contribution of PC2 represents a second independent gradient, probably representing distinct soil aggregation and organic matter processes, usually isolated from the coarse texture-related properties in managed soils (Six et al., 2004). Together, PC3, PC4, and PC5 accounted for close to 31% of the overall variance, illustrating that while smaller and less important, secondary variability in both soil physical and chemical processes of the soil was substantial. Such patterns are typical under soil PCA research; several interacting processes (such as mineralogy, salinity, moisture retention, microstructure creation) play a role at once (McBratney et al., 2003). By and large our results show that the variability of soils in this work is multidimensional but highly structured, and when the number of principal components in the eigenvalue structure is smaller, the system can be effectively represented without appreciable loss of information to the model.

3.4.2 PCA Interpretation: PCA interpretation illustrates functional interactions between soil characteristics across management treatments. These PCA loadings have often been depicted in soil studies as "soil quality gradients", where certain variables represent sub-processes, such as structure creation, nutrients, and hydrological regulation (Anderson et al., 2011; Lal, 2020).

PC1 – Soil Structural and Physical Quality Gradient: Soil Structure and Physical Quality Gradient- PC1 was positively associated with clay content, cation Exchange Capacity (CEC), porosity and bulk density. This element is an integrated structure quality axis in soil, where the physical form of the soil structure and the nutrient holding capacity correspond. Strong loading of clay and CEC shows that the capacity for preserving nutrients was also associated with fine soil particles (Brady & Weil, 2017). Likewise, porosity and bulk density is a reverse ratio of soil compaction and aeration status, which are highly affected by the management of land use, such as tillage and cover cropping (Horn & Fleige, 2009). The primacy of PC1 indicates that soil structural decrease or enhance is the driving factor for discrepancies between treatments as it follows that the soil structure is the best predictor of modification caused by management (Six et al., 2004).

PC2 – Soil Aggregation and Organic Matter Dynamics: Soil Aggregation and OM Dynamics PC2 showed a significant relationship with MWD, particle density, & OM. This factor is indicative of the stability of aggregates and structural growth of the soil, strongly influencing organic matter dynamics. Organic matter is a key medium involved in keeping aggregate of soil stable by microbial activity and as binding agents that promotes improved erosion resistance and hence water infiltration (Tisdall & Oades, 1982; Bronick & Lal, 2005). The addition of MWD verifies the role of this property as it summarizes the processes of aggregation stability, the correlation between MWD and particle density can be an indication of the interactions between minerals and earth, which affect the packing and structure of soil. This is in line with research where enrichment of organic matter enhances soil aggregation and reduces effective density in surface horizons (Blanco-Canqui & Lal, 2004).

PC3 and PC4 (Secondary Soil Chemical and Physical Interactions): PC3 and PC4 reflected secondary variability of soil texture interactions, electrical conductivity (EC) and thermal behavior (LST influence). These components reflect more intricate and local interactions. Electrical conductivity frequently correlates with soluble salt mechanics and irrigation effects, such that surface cover, moisture, and albedo, for example, have influenced soil thermal behavior (e.g., Land Surface Temperature) (Jones et al., 2004). The occurrence of EC and LST-related variability suggests that soil salinity and thermal regulation mechanisms are important secondary drivers of variability besides structural properties and in particular in semi-arid and irrigated systems. These factors are often dominated by local management practices (i.e. residue cover and vegetation density) (Bastiaanssen et al., 2000).

3.5 Correlation Analysis

The relationship among soil physical, chemical, and thermal properties using Pearson correlation coefficient (r) (Zar, 2010) was examined. Soil characteristics are deeply related, and one property often affects several others via physical and chemical effects. Values of relation can be positive or negative, and show direct or inverse correlations. Correlations were defined as weak ($|r| < 0.30$), moderate (0.30-0.70), and strong ($|r| > 0.70$). MWD is positively associated with OM ($r = 0.56$), further validating that higher organic matter has the effect of making the aggregate stable. The microbial products, fungal hyphae and decomposed residues bound the organic matter to cement soil particles into stable aggregates (Six et al., 2004). Similar results were reported by Lal (2015) and Blanco-Canqui et al. (2015) found that conservation practices increase both soil carbon input and biological activities through enhancing aggregation. A positive and negative interaction was also found for MWD with porosity ($r = 0.16$) and bulk density ($r = -0.10$) showing that well-aggregated soils typically have more pore space and less compaction. More effective aggregation also facilitates infiltration, aeration and root penetration, therefore promoting better soil structural quality (Jury & Horton, 2004; Shukla, 2014). A poor negative correlation was also noted between MWD and LST ($r = -0.11$), demonstrating that stable aggregates have a role in moderating thermal stress associated with a soil temperature response by increasing moisture retention and evaporative cooling. Similar influence of aggregation and residue cover on soil heating reduction were also shown by Mueller and Schindler (2012) and Lal (2015).

Several soil properties were poorly correlated with LST, such as with a positive correlation with clay content ($r = 0.09$) and CEC ($r = 0.22$) and a weak correlation with sand content ($r = -0.16$). Such relationships are most probably attributed to the additive impact of soil texture, moisture retention and heat storage capacity on thermal behavior. Altogether, the findings reflect high interrelationship of soil structure with aggregates, nutrient retention, aggregation and thermal control. Cover cropping and residue retention are management practices that contribute to improving soil quality through a multilayered method that has led to multiple positive (cross-systemic) effects on soil quality (Brady & Weil, 2017; Lal, 2015; Six et al., 2004), confirming earlier evidence that conservation farming is enhancing soil physical health, moisture retention and sustainability (Brady & Weil, 2017; Lal, 2015; Six et al., 2004).

3.6 Regression Analysis

Regression analysis method was performed to determine the potential predictive correlations between and the predicted interaction between soil management treatments, soil physical and chemical properties, Mean Weight Diameter (MWD) and Land Surface Temperature (LST), and predictability. In this respect, regression statistics are especially useful since they not only detect relatedness and association of variables, but also estimate the strength and the direction of the effects of these relationships. In soil science research, regression analysis is extensively used to determine the relationship between changes of one soil properties and another and what are the most significant predictors in determining the soil behaviour (Montgomery et al., 2021; Zar, 2010). The regression models developed here concentrate mainly upon predicting MWD by using soil properties, LST predicted by studying the soil structural property and the effect of intervention by management treatment in soil quality indices. Regression analysis showed that various soil properties had a major influence in differences in MWD from the other soil properties. There were positive relationships between the contributions of Organic Matter (OM), porosity and CEC, aggregate stability and bulk density on aggregate stability, while bulk density was negatively related to the MWD. The favourable impact of OM on MWD is suggested that higher soil organic matter assisted in producing and adhering aggregates. These mechanisms enhance particle cohesion and induce stable macroaggregation generation (Six et al., 2004). So, the regression data validate the significant contribution of soil organic carbon in maintaining structural robustness. Porosity also positively contributed towards MWD since well-aggregated soils usually have larger, uninterrupted pores. The relationship between CEC and MWD was positive, as soils with higher nutrient retention capacity also often contain more clay and organic matter, which are conducive and required for the aggregation process. Bulk density had negative impact on MWD, suggesting that increased compaction in soil eroded stability at the aggregate level. Soils are compacted with reduced macropores, and less dense aggregation structure reduces biological activity and promotes the susceptibility of a structure to fail. It is therefore shown that total stability can be much influenced to aggregate stability by the integrated interaction of the organic matter accumulation, ground porosity, soil nutrient retention potential, and compaction properties in the regression model. The results are consistent with earlier research finding that conservation management practices enhanced aggregation through more effective biological and structural action (Lal, 2015; Brady & Weil, 2017). Table 6 shows the regression relationships between MWD and selected soil properties.

Table 6. Regression relationships between MWD and selected soil properties.

Dependent Variable	Predictor Variable	Regression Relationship	Direction	Interpretation
MWD	Organic Matter (OM)	Positive Linear	Positive	Higher OM improves aggregate stability
MWD	Porosity	Positive Linear	Positive	Increased pore continuity enhances aggregation
MWD	CEC	Positive Linear	Positive	Higher nutrient retention improves structural stability
MWD	Bulk Density	Negative Linear	Negative	Soil compaction reduces aggregation
MWD	LST	Negative Linear	Negative	Higher aggregation contributes to cooler soils

Important relationships between soil structure and LST were also identified by regression analysis. A combination of better soil aggregation and higher porosity led to reduced LST, as described in the findings. When well-aggregated, more water retention of the soil remains secondary to the soil's better pore continuity and infiltration ability. Soil moisture increases evaporative cooling and stabilizes temperature fluctuations. Soil with higher MWD values, therefore, generally had cooler surface temperatures. Therefore, the negative correlation between MWD and LST shows that the soil structural quality closely relates to the thermal behaviour. Bulk density was found to be positively related to LST, because when soil is compacted, infiltration of moisture and retention of moisture are lower. Dry compacted soils experience rapid heating from relatively little evaporative cooling. The regression analysis thus supports what has been suggested that conservation-targeted soil management indirectly decreases soil temperature through enhancements in aggregation, porosity and moisture conservation. The relationship between soil micro-structure and thermal regulation is especially relevant to dry and semi-dry soils where extreme soil heating promotes evaporation and reduces crop water levels. Previous investigations have also shown that residue cover and better aggregation reduces soil temperature and improves moisture conservation (Mueller & Schindler, 2012; Lal, 2015). Also, the regression models showed the treatment of soils themselves as robust predictors of both MWD and LST. Cover Cropped treatments were directly correlated with greater MWD, lower bulk density, better porosity and lower LST values. Such relationships verifiably demonstrate that vegetation cover and organic residue inputs greatly improve soil quality levels. Plant Residues Tillage treatments led to moderate improvement compared to untreated soils, while None Cover Cropped treatments tended to have poor regression responses. The treatment effects in the regression model result are in agreement with ANOVA to correlation analysis and consistent good agreement between statistical techniques. The R^2 values obtained by the regression models were both moderate, implying that soil management and associated properties contributed to a fair amount of the variability of MWD and LST. Despite this, some of the variability is not accounted because the soil systems are intrinsically complex, affected by micro-topography, soil moisture content variation, climatic factors, biological and temporal variability. Notwithstanding these sources of heterogeneity, the regressing studies accurately found main determinant of aggregate stability and thermal characteristics. Regression relationships between LST and selected soil properties are shown in table 7.

Table 7. Regression relationships between LST and selected soil properties.

Dependent Variable	Predictor Variable	Regression Relationship	Direction	Interpretation
LST	MWD	Negative Linear	Negative	Better aggregation reduces soil heating
LST	Bulk Density	Positive Linear	Positive	Compacted soils heat more rapidly
LST	Porosity	Negative Linear	Negative	Greater pore space improves moisture buffering
LST	Sand	Negative Linear	Negative	Sandy soils dissipate heat more rapidly
LST	Clay	Positive Linear	Positive	Clay-rich soils retain more heat

3.7 MANOVA Results

The MANOVA results are presented in Table 8. Multivariate Analysis of Variance (MANOVA) was conducted to evaluate the combined effects of soil management treatments on multiple dependent soil variables simultaneously. Unlike ANOVA, which analyzes variables individually, MANOVA examines the collective response of interconnected soil properties and their covariance structure (Hair et al., 2019; Tabachnick & Fidell, 2019).

Table 4. MANOVA test statistics.

Test Statistic	Value	p-value
Wilks' Lambda	0.0709	<0.001
Pillai's Trace	1.4208	<0.001
Hotelling-Lawley Trace	6.1637	<0.001
Roy's Largest Root	4.6839	<0.001

The dependent variables included MWD, LST, bulk density, porosity, OM, CEC, pH, and EC, while soil management treatment served as the independent variable. The MANOVA results showed a highly significant overall treatment effect (Wilks' Lambda, $p < 0.001$), indicating that soil management practices significantly altered the combined physical, chemical, and thermal behavior of the soil system. This finding is important because soil properties function interactively rather than independently. For example, increased organic matter improves aggregation, which enhances porosity and water retention, subsequently reducing soil temperature and improving microbial activity. Among all treatments, the Cover Cropped system produced the most favorable multivariate response. This treatment simultaneously improved aggregate stability (higher MWD), nutrient retention (higher CEC), soil structure (lower bulk density), moisture conservation (higher porosity), and thermal regulation (lower LST). These improvements are associated with increased organic carbon inputs, enhanced microbial activity, root-induced aggregation, and reduced erosion (Lal, 2015; Six et al., 2004).

The MANOVA results also demonstrated strong interactions between soil structure and thermal behavior. Improved aggregation and porosity enhanced moisture retention and evaporative cooling, resulting in lower LST values. According to Soil Physics and Soil Physics: An Introduction, soil heat transfer is strongly influenced by pore continuity, moisture content, and aggregate organization. The significant multivariate effects further indicate that conservation practices improve soil quality holistically rather than through isolated changes. Increased OM improved CEC and biological activity, which further enhanced aggregation and nutrient cycling. One advantage of MANOVA is that it reduces Type I error associated with multiple separate ANOVAs while providing a more integrated interpretation of soil behavior (Johnson & Wichern, 2018).

Overall, the MANOVA analysis confirmed that conservation-oriented management practices significantly improved the integrated functioning of soil physical, chemical, and thermal properties. The results strongly support the use of cover cropping and residue management for improving soil quality and long-term agricultural sustainability.

4. CONCLUSIONS

It was shown that surface soils and their physical, chemical, and thermal properties were significantly influenced by treatments of soil management. The combination of statistics ANOVA, LSD, PCA, correlation analysis, regression analysis, and MANOVA showed a complete picture of treatment effects on soil quality indices. The results show that conservation-oriented practices, especially Cover Cropped treatments, were most beneficial for surface soils. Cover cropping considerably improved Mean Weight Diameter (MWD), reduced bulk density, facilitated increased porosity and Cation Exchange Capacity (CEC), and decreased Land Surface Temperature (LST). Indicating these enhancements mean strengthened soil aggregating, nutrient retention, moisture conservation, and thermal regulation of soils. In contrast, None Cover Cropped treatments resulted in generally poor soil structural stability, higher compaction, and higher LST, corresponding to accelerated soil degradation processes. Tillage treatments for Plant Residues showed intermediate enhancement indicating that residue inclusion improved some soil quality but remained less effective compared to continuous vegetation cover. PCA results showed that the soil properties were closely related, where MWD, porosity, bulk density, and LST were significant indicators controlling the variation in soil quality between the treatments. Correlation and regression analyses also agreed that greater aggregation and accumulation of organic matter were directly related to better soil structural and thermal conditions. In the MANOVA analysis, we found that the soil management performed the integrated system as a whole, and not that individual properties experienced impact independently. There is strong agreement among all methods of statistical analyses confirming the robustness and reliability of the findings. As such, the findings suggest that sustainable practices in soil management, particularly cover cropping and residue conservation, drastically improve soil quality, environmental resilience, and agricultural sustainability.

5. FUTURE WORK

It is necessary to evaluate the long-term effects of soil management practices to develop a temporal perspective of soil quality indicators over different growing seasons. Seasonal and climatic influences on LST and soil aggregation need to be further investigated. Including biological soil indicators such as microbial biomass, enzyme activity, and soil respiration. Also, utilizing advanced geospatial and remote sensing methods toward large-scale monitoring of the thermal behavior of soil. Also, studying carbon sequestration potential under conservation management systems. Building predictive machine learning models that consider soil physical, chemical, and thermal properties, analyzing responses of crop productivity in relation to improved aggregation and thermal regulation, and conducting deeper soil profile analyses to evaluate subsurface responses to management treatments.

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