

Assessment of Soil Physical Quality and Organic Matter Variability Using GIS Techniques in Ghammas District, Iraq

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Abstract

Soil physical quality is an important indicator to provide insights on soil functioning and has implications for agricultural management, especially in semi-arid environments where arable land degradation and low productivity are two major problems. Abstract This study was conducted to assess the variability of selected indicators of soil physical quality and organic matter content under cultivated land and uncultivated land at Ghammas District, Al-Qadisiyah Governorate, Central Iraq using Geographic Information System (GIS) methods. Based on the prominent land-use systems within the study area, soil sampling sites were chosen near 30 cultivated and 10 uncultivated (natural), for a total of 40 analyses. Bulk density, particle density, total porosity, and organic matter analysis were performed in soil samples. The spatial analysis and the thematic maps were performed using ArcGIS Desktop and the Kriging method to analyze the properties investigated. The results showed significant spatial variability in some indicators of soil physical quality throughout the study area. The bulk density varied between 1.22 and 1.59 Mg m⁻³, particle density among 2.61 to 2.69 Mg m⁻³ Total porosity between 40.31% and 54.43% with clear inverse correlation to the bulk density. The content of organic matter was variable and between 0.052% – 1.707%, with an average of the mean value being 0.993%. Compared with several uncultivated sites, characterized by higher bulk density and lower porosity and relatively greater organic matter contents values of soil structural conditions improved by agricultural management (tillage practices) and inputs: crop residues. The combination of laboratory measures and spatial analysis using GIS resulted in a good evaluation of the variability in organic matter and physical quality of soil. This data contributes to find more detailed information for site-specific soil management, land-use, and sustainable agricultural development in semi-arid areas. the study suggests to rely on strategies that increase organic matter inputs by means of residue retention and/or additional organic amendments, as a means to improve soil structure in order to sustain longterm productivity.

Keywords: Soil Physical Quality, Organic Matter, Spatial Variability, Geographic Information System (GIS), Semi-Arid Soils.

Introduction

Soil physic quality is one of the principal driving factors that determine agricultural productivity and environmental sustainability, affecting soil hydration, root penetration, air permeability and nutrient cycling on one hand as well as activity within the soil profile on the other. Evaluating soil physical conditions has generated more interest in semi-arid areas where soil degradation, salinity and water scarcity endanger the sustainability of agriculture systems. Properties like bulk density, particle density, porosity, and soft soil organic matter are widely utilized to assess the condition of soil structure and its potential for the cultivation of crops among various land-use systems [1].

Soil properties in semi-arid agricultural regions of central and southern California are characterized as highly variable in space due to differences in parent materials, topography, patterns of irrigation and cultivation intensity, and processes of sediment deposition. Variation on this scale influences soil hydraulic functions, compactibility aggregation ability and due to this govern soil water holding capacity may restrict plant growth and cause increased susceptibility to environmental stressors [2]. Continuous cropping and land management at high intensity results in altering the soil structure through repeated tillage operations, machinery traffic and depletion of organic residues; by contrast, uncultivated soils were able to maintain natural structural features according to vegetation cover and climate [3].

Bulk density is the most established property for assessing soil compaction and structure, since it reflects the distribution of aggregates and pores in a soil. Higher bulk densities are generally associated with poor aeration, decreased infiltration and root growth, as well as increased

mechanical resistance in soil profile. Conversely, lower bulk density represents better aggregation and better structural stability that is desirable to plant growth [4]. Also, particle density is another important parameter used to predict total porosity as well as mineralogical composition and soil solid-phase characteristics [5].

Soil porosity is a key factor when it comes to the movement of air and water through soil matrix, infiltration, drainage, gas exchange processes volume., structure etc. Most pore continuity in soil gives favourable conditions for root growth and availability of water, while more-or-less compacted soils with reduced porosity usually have poor hydraulic performance [6]. Besides MBC, soil organic matter is a key component determining the physical quality of soils because it helps to stabilize aggregates and enhances water retention capacity as well as structure formation in addition to providing resistance against erosional processes and degradation [7].

Over last few decades, various advancements in the field of Geographic Information Systems (GIS) and geostatistical methods have facilitated enhanced ability to analyse as well as visualize spatial variability of soil parameters over agricultural fields. GIS-based spatial analyses provide regional scaled maps of continuous distributions and potentially support site-specific soil management, precision agriculture (e.g., nutrient availability to plants), sustainable land-use-planning. Kriging has been regarded as a common method to estimate soil characteristics because it also smoothes the data and works directly with spatial estimation uncertainty towards predicting patterns through space [8] for some types of Kriging.

The Ghammas District belongs to the Al-Qadisiyah Governorate located in central

Iraq, which is an important agricultural area producing rice and other field crops under semi-arid climates including wheat; barley. Although the region is very important in terms of agriculture, little information exists about horizontal spatial distribution of soil physical quality indicators and organic matters variability under cultivated lands and forests on uncultivated soils. Therefore, a better understanding of the spatial behavior as

well as regular updates to such properties is necessary for soil management practices and sustainable agriculture.

Thus, this study sought to evaluate the spatial variability of certain soil physical quality indicators (bulk density, particle density and porosity) as well as organic matter content using GIS techniques and interpolation methods in Ghammas District (Iraq), under cultivated vs uncultivated lands.

Material and Methods

Study Area:

This study was performed in Ghammas District, within Al-Qadisiyah Governorate of central Iraq. The study area is located in a semi-arid region subject to high temperature, low annual rainfall and highly cultivated agricultural area. Ghammas District is consisted one of the most important agricultural regions in Al-Qadisiyah Governorate, and it's famous for cultivating rice, wheat barley along with other field as well vegetable crops. The Cultivated lands of the region consist of both cultivated

comprised 10 uncultivated (fallow) sites that had remained without cultivation for at least two consecutive growing seasons prior to soil sampling. This classification enabled a direct comparison of soil physical properties under contrasting land-use conditions while minimizing the influence of climatic and geological variability.

and uncultivated soils, differing in management practices, irrigation systems and vegetation cover.

Soil Sampling Design

Using Geographic Information System (GIS) techniques, a total of 40 soil sampling sites were selected to represent the major land-use systems in the study area. 30 cultivated and 10 uncultivated (fallow) locations in Ghammas District were scattered as sampling sites. The geographical coordinates of all sampling points were taken with GPS devices, and then integrated into GIS environment for further spatial analysis as well as thematic mapping.

The study area was classified into two land-use categories to evaluate the influence of agricultural management on soil physical quality. The first category consisted of cultivated lands, represented by 30 sampling sites under continuous agricultural production, including wheat, barley, rice, forage crops, vegetables, and other seasonal crops. The second category

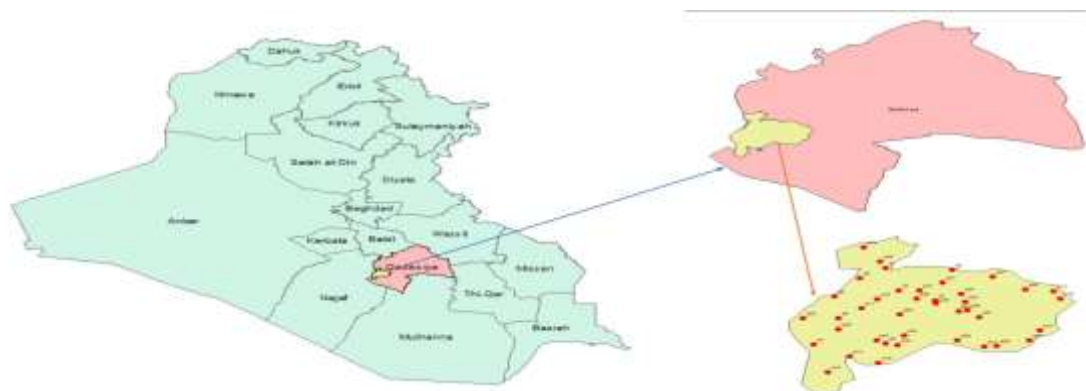


Figure 1. Location of Ghammas District and sampling sites within Al-Qadisiyah Governorate, Iraq.

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Table 1. Geographic coordinates of soil sampling sites in Ghammas District, Al-Qadisiyah Governorate, Iraq.

ID	Longitude_X	Latitude_Y	ID	Longitude_X	Latitude_Y
p1	44.586944	31.807500	p21	44.647994	31.781734
p2	44.658574	31.804612	p22	44.602243	31.725984
p3	44.509148	31.673086	p23	44.606667	31.689167
p4	44.600556	31.767778	p24	44.577261	31.680278
p5	44.586745	31.675213	p25	44.497724	31.719348
p6	44.558844	31.789729	p26	44.664154	31.680285
p7	44.640278	31.750000	p27	44.702196	31.792099
p8	44.531310	31.757579	p28	44.665556	31.731667
p9	44.535799	31.719368	p29	44.535576	31.699647
p10	44.577778	31.752778	p30	44.737588	31.769892
p11	44.560833	31.736667	p31	44.687500	31.721389
p12	44.752935	31.698258	p32	44.674722	31.733056
p13	44.767730	31.766832	p33	44.672500	31.747778
p14	44.547911	31.652494	p34	44.668333	31.761944
p15	44.524288	31.624375	p35	44.641111	31.745556
p16	44.774895	31.753216	p36	44.620278	31.753611
p17	44.692946	31.669702	p37	44.623056	31.768056
p18	44.599777	31.671986	p38	44.741746	31.680152
p19	44.578900	31.641105	p39	44.580833	31.818889
p20	44.706397	31.670569	p40	44.563333	31.843889

Soil samples were collected from the surface layer at each sampling site and transported to the laboratory for physical

and chemical analyses. The collected samples were air-dried, gently crushed,

and sieved prior to laboratory measurements.

soil Analyses

Bulk Density (ρ_b):

The core sampling method was employed to measure soil bulk density. Undisturbed soil cores were obtained using 100 to 120 cm long by a cylindrical metal core of known volume. The bulk density was determined according to Black et al. by calculating the ratio between oven-dry soil mass (as previously described) and total core volume as follows: each of the samples were weighed after being dried in an oven at 105 °C until constant weight; in this process, values for both calibrating are recorded separately from one another. [9].

Particle Density (ρ_s)

determined particle density using the pycnometer method. The volume displacement method was employed to calculate particle density of the air-dried soil samples in a pycnometer flask (Black et al., 1965). [9].

Porosity (P)

Soil porosity was mathematically determined from bulk density and particle density using the equation:

$$p = [1 - \frac{\rho_b}{\rho_s}] * 100$$

where:

P = porosity (%)

ρ_b = bulk density (Mg m^{-3})

ρ_s = particle density (Mg m^{-3})

Soil Organic Matter (OM):

Soil organic matter content was determined using the Walkley–Black wet oxidation method based on potassium dichromate oxidation and sulfuric acid digestion according to Nelson and Sommers [10].

GIS Spatial Analysis:

Spatial distribution maps of the investigated soil properties were generated using ArcGIS Desktop (ArcMap, version 10.x) within the Geostatistical Analyst extension. The geographic coordinates of the 40 sampling locations were imported into the GIS environment and linked to the corresponding laboratory data. Spatial interpolation was performed using the Ordinary Kriging method because it provides reliable predictions for spatially continuous soil properties under the assumption of local stationarity. The interpolation model was developed using an experimental semivariogram, and the most appropriate theoretical semivariogram model was selected based on its prediction performance. Semivariogram parameters, including nugget, sill, and range, were estimated automatically within the software. Model performance was evaluated using leave-one-out cross-validation, and prediction accuracy was assessed using Mean Error (ME) and Root Mean Square Error (RMSE). The interpolation model with ME values closest to zero and the lowest RMSE was considered the most appropriate for generating the final spatial distribution maps. The resulting raster layers were subsequently classified and visualized to illustrate the spatial variability of soil physical properties across the study area. [11].

Results and Discussion.

Spatial Variability of Bulk Density, Particle Density, and Total Porosity.

Results showed a high spatial variability for soil bulk density, particle density and total porosity of the cultivated and uncultivated lands of Ghammas District (Table 2). These parameters are considered key indicators of soil physical quality because they have a direct effect on root growth, displacement of air and water in the interior of the environment and functional aspects of the soil. Bulk density results ranged from 1.22 to 1.59 Mg m⁻³. The minimum bulk density was registered at site P3 (1.22 Mg m⁻³), followed by sites P1 and P30 (1.25 Mg m⁻³); the maximum was recorded at site P17 with a value of 1.59 Mg m⁻³. In general, a lower bulk density values indicate a better soil structure with larger pore space which allow for better root penetration and higher value reflect high soil compaction thus reducing pore continuity. The lower bulk density on many of the sites under cultivation may be a result of root action, occasional tillage and the addition of crop residues which help to loosen the soil matrix and improve aggregation. Reynolds et al. also reported similar observations [12] who pinpointed bulk density as one of the most sensitive indicators of soil physical quality and structural condition. Changes in particle density varied very little (2.61 up to 2.69 Mg m⁻³). Site P15 had the greatest particle density (2.69 Mg m⁻³) while the lowest values were at sites P14 and P10 (2.61–2.62 Mg m⁻³). The short range of particle density values indicates that the soils studied are relatively homogeneous in their mineralogical composition, which is reasonable considering that all sites investigated are representative of the same alluvial depositional environment. As

Brady and Weil [13] point out, mineral soils usually have particle density values of up to roughly 2.65 Mg m⁻³ except when differences in composition or organic matter are large.

Total porosity observed between 40.31% and 54.43%. Site P3 recorded the maximum porosity (54.43%) while site P17 exhibited the minimum value of 40.31%. The findings validated the theoretical negative correlation link between bulk density and porosity on all study sites. Sites with a low bulk density usually exhibited higher porosity, and the pore space was diminished in sites with increased bulk density. This relationship defines soil porosity, where the soil arrangement and packing of soil particles in the matrix [14].

Compared to cultivated soil, on the other hand, it was long recognized that physical properties are more favorable in the former, including relatively lower density and higher porosity in many places. You train constantly setting roots, providing biological activity, the you water and stiching residues can all associate with establishing soil pores and therefore a more permanent stucutre. In contrast, some of the settings were shown to have a greater bulk density and lower porosity, likely due to surface sealing and a lack of biological activity along with whatever management had the potential to improve soil structure in uncultivated areas. Keller et al. have also confirmed similar results. Growing Land Use Generally Markopoulos et al. [15] showed that land-use systems have a strong effect on the compaction process and pore network development of soils.

Table 2. Bulk density (ρ_b), particle density (ρ_s), and total porosity (P) of cultivated and uncultivated soils.

Value				Value			
No.p	ρ_b (Mg m ⁻³)	ρ_s (Mg m ⁻³)	P(%)	No.p	ρ_b (Mg m ⁻³)	ρ_s (Mg m ⁻³)	P(%)
p1	1.25	2.68	53.18	p21	1.55	2.64	41.21
p2	1.34	2.66	49.49	p22	1.34	2.64	49.11
p3	1.22	2.67	54.43	p23	1.40	2.63	46.88
p4	1.42	2.68	47.01	p24	1.53	2.67	42.56
p5	1.52	2.65	42.58	p25	1.53	2.62	41.66
p6	1.41	2.67	47.01	p26	1.41	2.63	46.39
p7	1.38	2.65	47.97	p27	1.54	2.64	41.67
p8	1.37	2.67	48.85	p28	1.55	2.68	42.26
p9	1.51	2.66	43.05	p29	1.34	2.63	48.92
p10	1.49	2.62	43.29	p30	1.25	2.62	52.35
p11	1.46	2.63	44.6	p31	1.38	2.64	47.89
p12	1.35	2.64	49.00	p32	1.43	2.63	45.7
p13	1.36	2.62	48.02	p33	1.55	2.62	40.81
p14	1.34	2.61	48.72	p34	1.45	2.68	45.8
p15	1.5	2.69	44.38	p35	1.55	2.66	41.82
p16	1.5	2.63	42.78	p36	1.51	2.63	42.67
p17	1.59	2.66	40.31	p37	1.37	2.67	48.85
p18	1.53	2.62	41.49	p38	1.53	2.64	41.87
p19	1.5	2.63	42.94	p39	1.47	2.66	44.71
p20	1.56	2.64	41.01	P40	1.51	2.65	43.08

The spatial distribution map of bulk density results obtained by Kriging interpolation (Fig. 2) showed a heterogeneous pattern in the Ghammas District. Low bulk density values of (1.20–1.25 Mg m⁻³) were mostly restricted to the southwest, northwest and northeast corners of the study area. Locations like these often demonstrate greater soil structure, more pore space and less compaction. While bulk density values measured at various places in Chile between 1.35–1.45 Mg m⁻³ throughout the mid and southeast are slightly high in order for soil to appear densely packed since it increases normal cutting of pores, compared against smaller. The spatial variation is hypothesized to be driven in part by soil texture, organic matter, a

history of cultivation and land management. Higher biological activity, root penetration and residue accumulation resulted in soil aggregation that may reduce compaction were also likely to be the cause of lower bulk density. Alternatively, locations with a higher bulk density might tend to be these that have been compacted by the targeted traffic of machines, lower natural influence or heavier loading of finer particles exactly where texture normally is coarse and affects packing density [16]. Figure 2 shows the spatial distribution Soil Physical Quality is not uniform in space along the area studied. Sampling locations on cultivated lands showed pronounced differences, even for the same land use, indicating that management differences

only partly account for spatial variability in soil properties. Anticipating higher or lower iron levels in soil samples from specific localities is difficult, and the widespread patterns of bulk density at the landscape scale are determined by soil-forming factors interacted on a range with land use and local conditions. Cambardella et al. Some studies have also shown similar spatial heterogeneity of bulk density both in agriculture soils. High-resolution clip and area based geostatistical and GIS methods to delineate management zones to support precision soil management were emphasized [17]. The widespread occurrence of low/moderate whole soil bulk density values over the majority of the study area suggests that physical conditions for crop production are, in general terms, agronomically favourable. Although relatively high bulk density values are established in some sites, for such areas soil improvements (increasing attributes with organic amendments or residues and lower traffic intensities) may be necessary before their long-time conditioning and productivity in ongoing degradation conditions as semi-arid ones. These spatiotemporal differences across scales have important implications for agriculture productivity and water management. Soils that are not compacted, with higher porosity create an environment conducive for root development,

infiltration processes helping to store water, high field power [3], and gas exchange leading to more robust crops. In contrast, soils with a high bulk density can restrict root growth, decrease infiltration and water availability. Therefore, controlling the soil structure is crucial in order to maintain soil productivity in semi-arid environments [18]. They exhibited high spatial variability across the study area and might provide welfare indicators of physical quality with respect to pb, Ps and P at the regional scale. Combining laboratory quantitative measurements and a GIS-based spatial analysis, we delineated subregimes of differential structural states likely beneficial for sustainable soil management practices within agricultural soils. planning across central Iraq.

The spatial distribution pattern generated through Ordinary Kriging clearly demonstrates that bulk density is not uniformly distributed throughout the study area. The observed spatial heterogeneity reflects the combined influence of soil texture, cultivation history, machinery traffic, organic matter content, and irrigation management. Such spatial information is particularly valuable for identifying areas susceptible to soil compaction and for supporting precision agriculture practices through site-specific soil management.

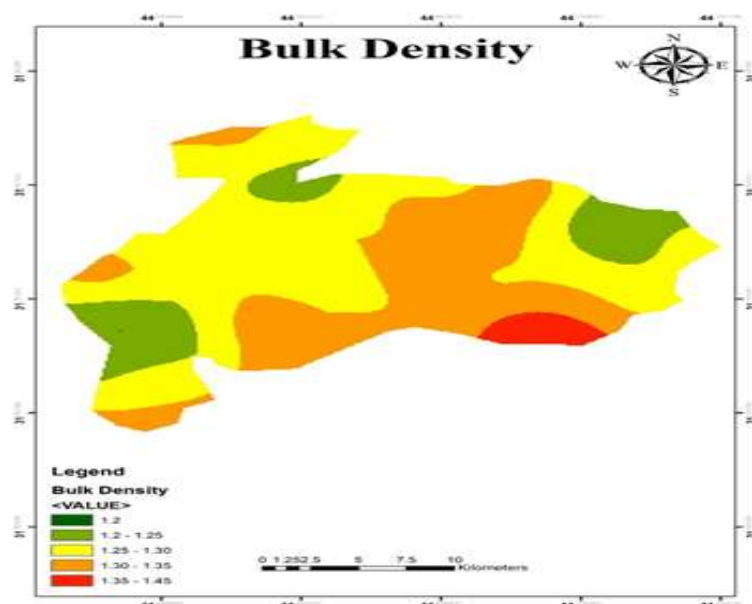


Figure 2. Spatial distribution of soil bulk density (Mg m^{-3}) in cultivated and uncultivated lands.

Spatial Variability of Soil Organic Matter Content.

As can be seen in Table 3, results showed considerable variation and differences between soil organic matter (OM) content at the various cultivated and uncultivated sites of Ghammas District. The organic matter values varied from 0.052% to 1.707%, demonstrating considerable dissimilarity in accumulation of organic residue, biological activity, vegetation cover and land management practices across the study area. Site P8 (1.707%); site P24: (1.655), site P34 and site P1 were the highest values of organic matter content, followed by sites P39 (0.052%), p40(0.207)and p38(0.155%) respectively). In general, the concentration of organic carbon in soils was less than 1.5%, characteristic for soils from arid and semi-arid regions with low reserves of organic carbon. Organic matter accumulation in these environments is usually constrained by conditions of high temperature (a short

growing season) and relatively low biomass production, rapid decomposition of plant residues, and reduced contribution from allochthonous inputs. Furthermore, comparable tendencies were identified for agricultural soils over dry land ecosystems also characteristically climatic limited to longer-lasting organic carbon sequestration [19].

Results showed significant contrasts also between cultivated and uncultivated lands. That could be mainly attributed to constant input of crop residues, root biomass, irrigation with water-nonrestricted soils and environmental management practices associated with agricultural systems increased some organic parameters in cultivated spots, that normally have larger natural matter contents than several uncultivated sites. Root biomass represents an important source of belowground carbon inputs and supports microbial

activity in the soil as well by inclusion with feeding sources, which influence organic matter accumulation and passive stabilization within the through a balance between product formation and turnover rates. On the contrary, some of the on-

farmed sites exhibited very low organic matter contents probably due to reduced cover with vegetation and biomass return into soil systems, high exposure to erosive processes and depletion of organic matter [20].

Table 3. Organic matter content (%) of cultivated and uncultivated soils.

No.p	Value	No.p	Value
p1	1.603	p21	1.034
p2	1.345	p22	0.517
p3	1.552	p23	1.138
p4	1.293	p24	1.655
p5	0.310	p25	0.259
p6	1.396	p26	1.034
p7	1.293	p27	0.983
p8	1.707	p28	1.345
p9	0.310	p29	1.241
p10	0.983	p30	1.190
p11	1.034	p31	1.552
p12	1.241	p32	0.931
p13	1.138	p33	1.138
p14	0.724	p34	1.603
p15	0.517	p35	1.241
p16	0.362	p36	1.293
p17	0.465	p37	1.500
p18	0.362	p38	0.155
p19	1.086	p39	0.052
p20	0.931	P40	0.207

From frequency distribution and kernel density estimation, Figure 3 provides an alternative perspective of the spatially heterogeneous accumulation of organic matter in our study area. Most observations are between around 0.9% –1.4%, but there are less sites (only two here) that result in low organic matter content, as shown in the histogram. Distribution pattern is moderate: indicated that some local regions of better soils organic characteristics relative to landscape. As expressed in statistical parameters, the mean OM value was 0.993% and medium OM value was 1.112% (for all datasets), listed in Figure3 Mean is lower than median, indicating slight negative skewing, given that several sites have very little

organic matter and some of the hills have been mined. The mean would reflect lower value observations which depress the overall mean, and casts shadows of significant suboptimal organic matter for others. The very variability of this process is a well-known challenge in Cultivated lands capes that experience spatial heterogeneity in cropping systems, residue management, irrigation and soil texture [21].

Because of the role it plays in aggregation, porosity, water retention and nutrient availability as well as biological activity organic matter is often regarded as one of the best indicators of soil quality. The relatively higher organic matter contents

measured for various cultivated sites may therefore contribute in part to the apparent advantages regarding soil structural properties that were revealed by the bulk density and porosity analyses. Organic compounds play the role of bonding and agglomeration, increasing resistance to structural degradation through polymerization. As a result, soils of higher organic matter contents more often than not have lower bulk density and increased connection between pores when compared with organic carbon-depleted soils [22]. An agricultural perspective implies low organic matter level present over the entire study area indicates that management practices directed towards increasing soil carbon stock is necessary for improving sustainability of soil quality. Implementation of practices, including residue retention, cover cropping, organic amendments and reduced soil disturbance is likely to enhance the accumulation of organic matter and improve physical conditions if semi-arid soils. These results highlight the importance of enhancing soil

organic matter as a key factor underpinning sustainability in agricultural land management for Ghammas District. In general, these results show that soil organic matter at both levels has wide variability between cultivated and uncultivated lands that result from the effect of land use, vegetation cover, residues inputs and environmental conditions acting together. This variability underlines the need for including assessments of organic matter in soil quality assessment programs and in sustainable land management systems.

The integration of laboratory measurements with GIS-based spatial interpolation substantially improved the interpretation of soil variability by revealing spatial patterns that cannot be recognized through conventional tabulated data alone. The generated maps provide a practical decision-support tool for identifying management zones, optimizing agricultural inputs, and improving sustainable land-use planning in semi-arid environments.

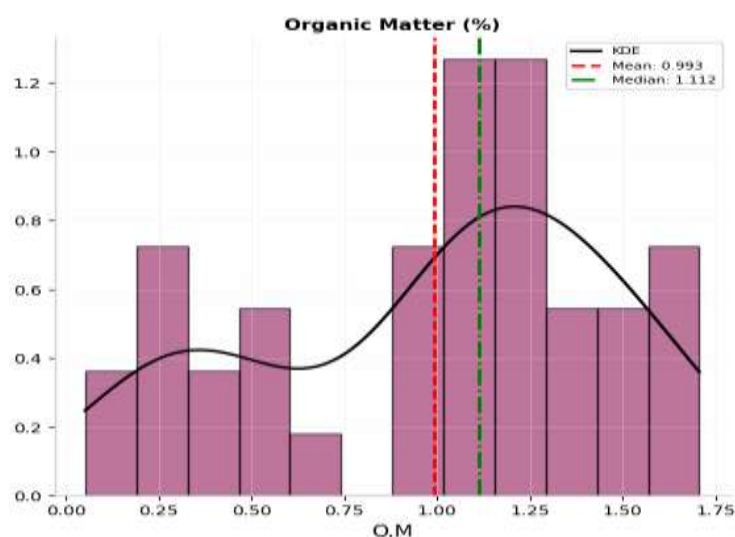


Figure 3. Distribution pattern of soil organic matter content (%) in cultivated and uncultivated soils.

Conclusions and Recommendations

Results revealed high variability in soil physical quality indicators and organic matter

content between cultivated lands against uncultivated areas in opposite locations of

Ghammas District. Bulk density values ranged between 1.22 and 1.59 Mg m⁻³, whereas total porosity varied from 40.31% to 54.43%, which is directly related to soil structure and compaction degree characterizing the studied area as well. Organic carbon varied across the range of 0.052% – 1.707%, reflecting the overall influence of both land use and management on soil condition and health or quality. Compared to soils at neighbouring uncultivated sites, soils in cultivation had lower bulk density and greater porosity (averaged across four previously uncultivated sites), slightly higher porosity (averaged across two makeshift lands and higher organic matter (averaged from one uncultivated site). The GIS-based spatial analysis permitted the demarcation of differing soil conditions, which may serve as an indicator for soil quality. The spatial variability identified in this study demonstrates that uniform soil

management practices are unlikely to achieve optimum agricultural performance across the entire district. Instead, management decisions should consider local variations in soil physical properties to improve water-use efficiency, maintain soil structure, and enhance long-term productivity. It is suggested that management practices such as retention of crop residues or returning plant biomass to the soil (through amendments) and site-specific management of soils along with monitoring using GIS-based technologies yield higher sustainable land-use planning in relation to the existing state. This practice improves soil structure and as a result enhances soils contributing toward the long-term sustainable management of agricultural production in semi-arid dryland regions.

References

- [1] **Reynolds, W.D., C.F. Drury, C.S. Tan, C.A. Fox and X.M. Yang. 2009.** Use of indicators and pore volume-function characteristics to quantify soil physical quality. *Geoderma*, 152(3–4): 252–263.
- [2] **Mueller, L., U. Schindler, W. Mirschel, T.G. Shepherd, B.C. Ball, K. Helming, J. Rogasik, F. Eulenstein and H. Wiggering. 2010.** Assessing the productivity function of soils: A review. *Agron. Sustain. Dev.*, 30(3): 601–614.
- [3] **Keller, T., M. Sandin, T. Colombi, R. Horn, D. Or and M. Lamandé. 2019.** Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning. *Soil Tillage Res.*, 194: 104293.
- [4] **Hamza, M.A. and W.K. Anderson. 2005.** Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil Tillage Res.*, 82(2): 121–145.
- [5] **Flint, A.L. and L.E. Flint. 2002.** Particle density. In: Dane, J.H. and G.C. Topp (eds.). *Methods of Soil Analysis: Part 4. Physical Methods*. Soil Sci. Soc. Am., Madison, WI, pp. 229–240.
- [6] **Horn, R. and A. Smucker. 2005.** Structure formation and its consequences for gas and water transport in unsaturated arable and forest soils. *Soil Tillage Res.*, 82(1): 5–14.
- [7] **Minasny, B. and A.B. McBratney. 2018.** Limited effect of organic matter on soil available water capacity. *Eur. J. Soil Sci.*, 69(1): 39–47.
- [8] **Li, J. and A.D. Heap. 2014.** Spatial interpolation methods applied in the environmental sciences: A review. *Environ. Model. Softw.*, 53: 173–189.

- [9] **Black, C.A. (Ed.), 1965.** Methods of Soil Analysis. Part I. Physical and Mineralogical Properties. Madison, Wisconsin: American Society of Agronomy.
- [10] **Nelson, D.W. and L.E. Sommers. 1996.** Total carbon, organic carbon, and organic matter. In: Sparks, D.L. (ed.). Methods of Soil Analysis: Part 3. Chemical Methods. Soil Sci. Soc. Am., Madison, WI, pp. 961–1010.
- [11] **Webster, R. and Oliver, M.A., 2007.** *Geostatistics for Environmental Scientists*. 2nd ed. Chichester: John Wiley & Sons.
- [12] **Reynolds, W.D., C.F. Drury, C.S. Tan, C.A. Fox and X.M. Yang. 2009.** Use of indicators and pore volume-function characteristics to quantify soil physical quality. *Geoderma*, 152(3–4): 252–263.
- [13] **Brady, N.C. and R.R. Weil. 2017.** The Nature and Properties of Soils. 15th ed. Pearson Education, Harlow.
- [14] **Hillel, D. 2004.** Introduction to Environmental Soil Physics. Elsevier Academic Press, Amsterdam.
- [15] **Keller, T., M. Sandin, T. Colombi, R. Horn, D. Or and M. Lamandé. 2019.** Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning. *Soil Tillage Res.*, 194: 104293.
- [16] **Lipiec, J., R. Horn, J. Pietrusiewicz and A. Siczek. 2012.** Effects of soil compaction on root elongation and anatomy of different cereal plant species. *Soil Tillage Res.*, 121: 74–81.
- [17] **Cambardella, C.A., T.B. Moorman, J.M. Novak, T.B. Parkin, D.L. Karlen, R.F. Turco and A.E. Konopka. 1994.** Field-scale variability of soil properties in central Iowa soils. *Soil Sci. Soc. Am. J.*, 58(5): 1501–1511.
- [18] **Horn, R. and A.J.M. Smucker. 2005.** Structure formation and its consequences for gas and water transport in unsaturated arable and forest soils. *Soil Tillage Res.*, 82(1): 5–14.
- [19] **Lal, R. 2020.** Soil organic matter and water retention. *Agron. J.*, 112(5): 3265–3277.
- [20] **Six, J., R.T. Conant, E.A. Paul and K. Paustian. 2002.** Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant Soil*, 241(2): 155–176.
- [21] **Minasny, B., B.P. Malone, A.B. McBratney, D.A. Angers, D. Arrouays, A. Chambers, V. Chaplot, Z.S. Chen, K. Cheng and B.S. Das. 2017.** Soil carbon 4 per mille. *Geoderma*, 292: 59–86.
- [22] **Lehmann, J. and M. Kleber. 2015.** The contentious nature of soil organic matter. *Nature*, 528: 60–68.