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Soil Aggregate Stability in Salt-Affected Vineyards: Depth-Wise Variability Analysis

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Abstract: Soil aggregate stability is an ideal integrative soil quality indicator, but little is known about the relevance of such an indicator with soil depth for salt-affected soils. The objective of this study was to determine soil aggregate stability and identify preponderant aggregation factors, both in topsoil and subsoil horizons in salt-affected conditions. We conducted field investigations by describing soil profiles in pedological pits and by collecting soil samples from different field units. Soils were sampled within different soil horizon types, from superficial tilled organo-mineral horizons to mineral horizons. For all soil samples, we determined the mean weight diameter (MWD) as an indicator of soil aggregate stability and also determined associated physical and chemical properties in some samples. The measured MWD value from 0.28 mm to 1.10 mm could be categorised as unstable, with MWD values and variability decreasing drastically from the topsoil to the deepest mineral horizons. Analysis of MWD in relation to physical and chemical properties suggested that the variability in the MWD value of A-horizons was influenced by both clay fraction abundance and soil organic carbon (SOC) content and the nature of the agricultural practices, while at deeper B-horizons, the decrease in SOC content and the variability in other soil properties with soil depth could be used to explain the overall low aggregate stability. In this study, investigations of soil pits coupled with measurements of soil aggregate stability indicated that it could be possible to restore soil structure quality by limiting deep soil profile compaction in order to improve salt leaching and exportation.

Keywords: soil aggregate stability; soil salinity; coastal area; vineyard

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1. Introduction

Soil salinisation is one of the major global soil degradation processes that threatens global agricultural sustainability [1–3]. Salinisation is an increase in the concentration of soil-soluble salts from natural or anthropogenic origins, affecting agricultural yield, environmental quality and human welfare [4,5]. According to the FAO, globally, around 830 million ha of soil, spanning almost all continents, is considered to be salt-affected [6], and nearly 10% of this surface soil is part of agricultural land [7]. In the European Mediterranean, this proportion of affected agricultural land is higher in the coastal areas [2]. In fact, coastal deltas are well adapted territories for agricultural production due to flat topographies and deep soils of alluvial origin, but they are also susceptible to salinisation risks due to seawater intrusions in river beds [8]. Thus, in order to achieve sustainable development goals (United Nation), it is crucial to build a strategy with good practices in order to reduce soil salinity effects, and when needed, to restore soil quality and the soil capacity to function under sustainable land management [9,10].

Soil is a key component for wine production [11,12] and a main component of the terroir concept [13–15]. However, vineyard soils could be severely affected by salinisation processes [8], particularly vineyard soils located in the Mediterranean region and coastal areas [16]. Soil and water salinisation will alter water and nutrient availability for the vine plants [11] and then affect berry yield and wine quality [17–19].

One way to evaluate the overall capacity of soil to function in space and time is to monitor inherent soil properties and effects on human management by using soil quality indicators [20–22]. Of the available indicators, soil aggregate stability is considered an ideal soil quality indicator [21], which depends on several soil properties and environmental biotic factors. Soil aggregate stability is the ability of soil to keep its particles attached under mechanical and physicochemical stresses [23]. Soil aggregates are often categorised based on their size as macro-aggregates (>250 µm) and micro-aggregates (<250 µm) [24,25]. The formation and destruction of soil aggregates involves interrelationships between physical, chemical, and biological soil properties [26]. Overall aggregate stability depends on the agglomeration of mineral particles (silicate and oxides) with organic and inorganic substances that affect aggregate formation and stabilisation, determining soil aggregation potential [27]. One problem, however, is that soil organic carbon (SOC) stocks is low in salt-affected soil conditions [28,29], whereas SOC enhances clays flocculation and favours the formation of bonds with clay particles and polyvalent cations [30–32]. Additionally, the high concentration of sodium in the exchangeable part of soil triggers clay dispersion that destabilises the soil structure [33]. This degradation of soil structure is critical, as soil aggregates regulate the size distribution of soil pores that support soil water infiltration, aeration, the movement of soil organisms, and carbon sequestration. Thus, soil aggregates play an important role in water and nutrient cycling [31].

Exchangeable sodium percentage (ESP), associated with soil aggregate stability, is widely accepted as a relevant indicator for evaluating soil aggregate dispersion. A threshold exceeding 15% [34] would result in soil dispersion with the condition of low soil solution conductivity. However, a different result [35] suggested that there is no threshold value of ESP, as soil aggregate destabilisation could occur at an ESP range of 2 to 5%. Furthermore, aggregate dispersion was not only determined by salinity but also by other factors such as soil pH and clay mineralogy [36]. The interactions between several different factors such as soil properties, environmental conditions, soil management, and plant influence determine the complex dynamics of aggregation [37].

Several studies have investigated the relation between aggregate stability and intrinsic soil properties as aggregation factors [31,38–40], and demonstrated the efficiency of soil aggregate stability as an ideal integrative soil quality indicator [41]. Nevertheless, most of these studies were generally conducted on topsoil horizons (0–15 cm) and not on the entire soil profile scale (from topsoil to subsoil horizons), particularly in salt-affected conditions. Thus, the objective of this study was to investigate the usefulness of soil aggregate stability as an ideal soil quality indicator for salt-affected soil (SAS) conditions at the soil profile scale. To achieve this, we undertook field investigations by describing soil profiles and by collecting soil samples from contrasting agricultural management locations. Subsequently, we used both soil aggregate stability and soil chemical analysis in order to identify preponderant aggregation factors, both in topsoil and subsoil horizons.

2. Materials and Methods

2.1. Study Site and Sampling

Research was conducted in the Sérignan municipality (43°28′ N; 3°31′ E), where the Orb River delta meets the Mediterranean Sea (Figure 1). The study area is bound by the Orb River in the west and the primary economy of the region is through wine production and tourism [8]. Over the last decades, the vineyard production area has faced a reduction in wine yield, attributed to soil salinisation processes by winegrowers. Interviews between the local authority and the local winegrowers' association in the year 2016 suggested that around 43% of Sérignan vineyard land area has been affected by salinisation over the last decades [42].

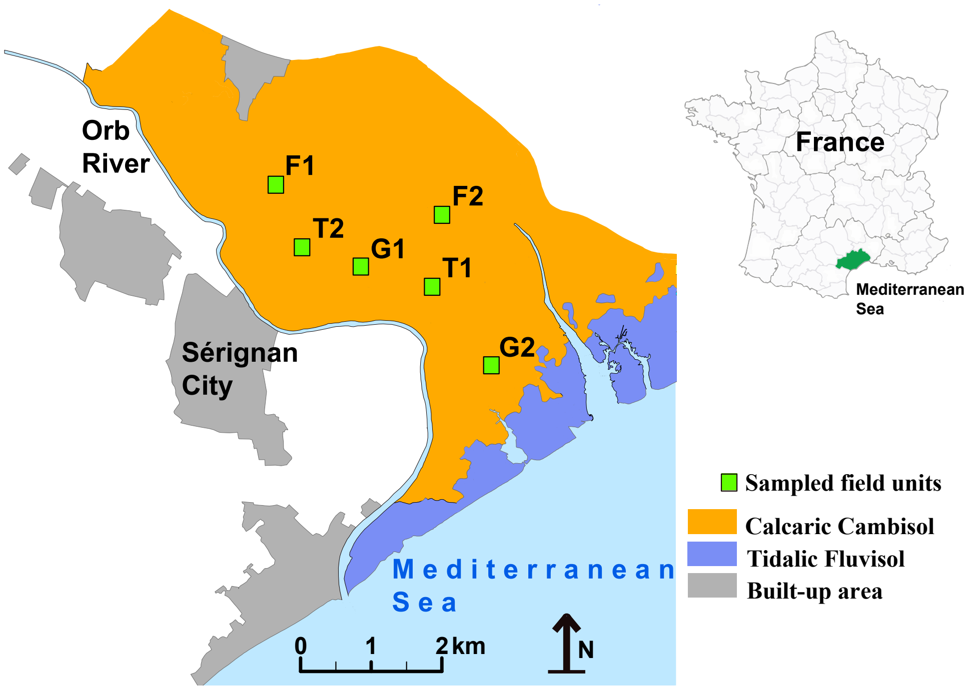

Figure 1. Map of the study area and sampling locations.

The climate is of Csa type (Köppen–Geiger classification). According to data records from local meteorological station (43°19′ N; 3°21′ E), the wet season occurs from September to April with maximum precipitation in November, and the dry season is from May to August. The rainfall interannual mean is of 655 mm over the 1960–2015 period, whereas the mean annual temperature was b16 °C until 2004 and increased to over 18 °C last years. The trend for ET0 showed a regular increase from 750 to 860 mm by 2005.

The field survey was stratified based on the soil map by Bless et al. [8]. This map was used to select six field units of the same soil condition type [43] and selected in order to represent the local diversity of land uses and management. The following six field units were selected: (i) Vineyard units T1 and T2 were trellised vines, which is a modern system with vines tied up to metal wires to maintain rows. The age of these vineyards is less than 30 years. (ii) Vineyard units G1 and G2 were gobelet-trained vines, which is an old traditional system without metal wires. The age of these vineyards is at least 50 years. (iii) Fallow units F1 and F2 are fallow fields, where vines were grubbing-up 3 and 10 years ago, respectively (see Supplementary Materials for photography).

For each field unit, we conducted a field investigation based on both pedological trench description and sampling. For pedological trenches, soil descriptions and classification were conducted following the guidelines for soil description by the FAO [44]. Soil samples were collected in each pedological trench, for soil depths ranging from 0.0–1.5 m, within each soil horizon type, from superficial tilled organo-mineral horizon (Ap-horizon) to organo-mineral horizon (A-horizon) and mineral horizon (B-horizon). The soil bulk density, estimated according to the soil core method (95 cm^3), was determined by sampling three undisturbed soil cores in each soil horizon.

2.2. Soil Analysis

A total of 79 soil samples were collected from soil trenches for aggregate stability measurements. Of these, 25 soil samples were sub-sampled to allow for both aggregate stability measurements and classical soil test determinations. For soil aggregate stability measurements, sub-samples were air dried (40 °C) for 5 days and sieved in order to select the 3–5 mm size fractions. The fast-wetting method [45], certified ISO 10930:2012 in 2012 (ICS: 13.080.05), was used to calculate mean weight diameter value (MWD). This simple method was adopted for checking the stability of soil, which can be tested on all soils including salt-affected soil. About 5 g of each soil sample was soaked in deionised water for 10 min and wet sieved (50 µm mesh) with ethanol and dried at 40 °C for 24 h in an oven. The samples were then dry-sieved using different diameters of soil sieves: <2.00 mm, 1.00–2.00 mm, 0.50–1.00 mm, 0.25–0.50 mm, 0.10–0.25 mm, 0.05–0.10 mm, and <0.05 mm. All soil samples were replicated thrice. We collected and weighed the mass of each size fraction. The aggregate stability for each breakdown mechanism was expressed by the MWD value, as in (1) [46]:

$$\mathrm{MWD} = \sum_{i=1}^{n} Xi.Wi \quad (1)$$

where Xi is the mean diameter of the size fraction i that corresponds to the mean aperture of the adjacent sieves, and Wi is the proportion of the total sample weight remaining on each sieve after sieving. In our case, MWD values were calculated for 6 apertures ranging from 25 µm to 3.5 mm.

For classical soil-test determinations, we followed the method by Pansu et al. [47]. The relevant parameters measured were soil texture (pipet method), pH-H_2O, soil organic matter (SOM) (dry combustion of organic C), soil electrical conductivity of saturated paste extraction (ECsp), cation exchange capacity (CEC), Fe/Al Oxide and carbonate content, and soil gravimetric water (GW). Soil determinations were performed in a certified lab (CIRAD soil lab, Montpellier, France). In addition, ESP values were calculated following the equation by Richard [48]. The ESP values were obtained using the ratio between Na^+ in the saturation extraction ($\mathrm{cmol}_{(+)}\ \mathrm{kg}^{-1}$) and CEC from the soil analysis. Due to technical issues, soil properties for the F2 field unit could not be measured.

3. Results

3.1. Soil Morphology

The soil horizon geometry of all pedological trenches is provided in Table 1. The first general geometrical characteristic was the overall thickness of soils over 1.0 m depth, with no underlying regolith or rock layer observed within a depth of 1.5 m. The second main geometrical characteristic was the preponderant effect of soil tillage on soil horizon distribution with soil depth. Except for the T1 unit, irrespective of the soil profile, we observed (i) a first Ap-horizon with a thickness that varied from 0.15 to 0.22 m, most likely in relation to superficial and frequent soil tillage operations, and (ii) an underlying organo-mineral (A-horizon) that had a deep underlying boundary between a depth of 0.4 and 0.6 m, most likely in relation to deep tillage. Below this organo-mineral boundary, all soil horizons were of Bk type, followed by mineral horizons with significant carbonate contents. For the G1, G2, and F2 units, these Bk-horizons evolved into Bwk-horizons for deeper and waterlogged (w) mineral horizons. During the soil morphological description, we observed and characterised a generalised compacted layer, at a depth of 0.4 m to 0.6 m.

The main soil texture class in almost all soil horizons was silt loam, with an overall decrease in clay fraction with soil depth (Table 1). The silt texture fraction was over 50% for all soil depths, except for the G2 unit, that had a layer of sandy texture at a depth over 0.7 m. The soil colour was primarily 7.5 YR4/2 with chroma ranging from 4/2 to 4/3 for brown colour. The shape of the soil structure was sub-angular blocky, except for unit F1, which had a platy shape at a depth greater than 0.9 m. During field description, we observed that soils had a high carbonate content as it sparkled on reaction with hydrochloric acid solution. This field observation was corroborated by laboratory analysis and the measured total carbonate content (Table 1). Soils of the study site were low in stoniness (<2%). When proceeding with MWD calculation, this coarse fraction was weighed to correct the MWD values.

Table 1. Soil profile horizonation and associated physical and chemical properties. (A—horizon with accumulation of humified organic matter (humic horizon); B—subsurface horizons of illuvial concentration of different soil components; p—signs of ploughing or other human disturbance; k—accumulation of pedogenetic carbonates; w—development of colour or structure; GW—gravimetric water).

			EC_{sp} dS m^{-1}	ESP (%)	GW (%)	BD (g cm^{-3})	SOC (%)	Saturated Paste Extracted (cmol$_{(+)}$ kg^{-1})			CEC	Total Carbonate (%)	pH H_2O	Soil Texture (%)		
Field	**Horizon**	**Depth (m)**						**Ca**	**Na**	**Cl**				**Clay**	**Silt**	**Sand**
Trellised																
T1	Apk	0.00–0.40	7.02	9.17	17.38	1.49	2.25	1.75	1.18	2.18	12.85	5.70	8.04	21.3	59.4	19.3
T1	Bk1	0.40–0.60	7.38	11.77	19.71	1.48	1.77	1.13	1.45	1.97	12.35	6.50	8.19	18.3	60.5	21.2
T1	Bk2	0.60–0.90	8.01	12.82	23.75	1.51	1.81	0.97	1.44	2.37	11.25	5.90	8.26	17.8	69.5	12.7
T1	Bk3	0.90–1.00	9.11	19.40	26.27	1.40	1.71	0.76	2.39	2.86	12.35	5.70	8.45	16.2	70.9	12.9
T1	Bk4	1.00–1.40	8.92	35.48	25.70	1.46	1.67	0.67	3.14	3.10	8.85	6.10	8.58	12.7	64.3	23.0
T1	Bk5	>1.40														
T2	Apk	0.00–0.20	0.85	0.53	14.61	1.64	2.32	0.22	0.06	0.07	11.50	5.70	8.41	19.5	53.4	27.1
T2	Ak	0.20–0.40	2.34	3.16	14.12	1.57	2.29	0.59	0.39	0.37	12.25	6.50	8.26	17.4	53.2	29.4
T2	Bk1	0.40–0.60	1.64	3.92	13.32	1.57	1.78	0.51	0.45	0.38	11.55	6.10	8.34	14.6	52.7	32.7
T2	Bk2	0.60–1.20	2.66	6.08	17.04	1.50	1.71	0.31	0.69	0.35	11.35	6.70	8.51	14.7	61.5	23.8
T2	Bk3	>1.20	2.34	7.22	21.06	1.52	1.44	0.11	0.79	0.29	11.05	7.00	8.87	16.6	63.3	20.1
Goblet																
G1	Apk	0.00–0.15	2.50	0.27	32.90	1.28	2.31	0.88	0.03	0.01	12.60	6.22	7.96	17.9	57.3	24.8
G1	Ak	0.15–0.40	0.69	0.30	24.21	1.57	1.65	0.25	0.03	0.02	9.70	7.19	8.32	17.4	55.6	27.0
G1	Bk1	0.40–0.80	0.89	0.48	31.77	1.41	1.45	0.31	0.05	0.07	10.60	6.51	8.30	12.2	54.8	33.0
G1	Bk2	0.80–1.00	1.92	2.21			1.24	0.62	0.24	0.42	10.70	8.03	8.38	12.1	69.9	18.0
G1	Bwk	>1.00														
G2	Apk	0.00–0.23	2.13	1.48	26.08	1.41	2.02	0.75	0.16	0.07	10.80	8.04	8.16	18.0	52.8	29.2
G2	Ak	0.23–0.52	0.79	1.06	25.18	1.53	1.20	0.23	0.12	0.10	11.30	7.79	8.43	14.6	70.7	14.7
G2	Bk1	0.52–0.71	1.22	2.74	19.78	1.67	0.58	0.31	0.21	0.25	7.60	9.51	8.48	13.6	43.6	42.8
G2	Bk2	0.71–1.00	0.95	5.45	47.52	1.60	0.23	0.20	0.13	0.15	2.41	13.94	8.76	5.6	6.8	87.6
G2	Bwk	>1.00														
Fallow																
F1	Apk	0.00–0.20	2.38	0.38	23.63	1.31	2.08	0.86	0.04	0.03	11.30	5.79	8.04	18.5	53.9	27.6
F1	Ak	0.20–0.60	0.80	0.57	17.56	1.64	1.53	0.26	0.06	0.08	10.50	5.66	8.30	18.6	56.2	25.2
F1	Bk1	0.60–0.91	0.49	0.52	19.46	1.62	0.97	0.18	0.05	0.04	10.50	6.59	8.39	14.0	51.3	34.7
F1	Bk2	>0.91	0.53	0.84	17.48	1.76	1.03	0.1	0.08	0.02	9.80	6.10	8.44	14.2	55.7	30.1
F2	ApK	0.00–0.25														
F2	Ak	0.25–0.60														
F2	Bwk	0.60–1.40														

3.2. Soil Physio-Chemical Properties

The measured pH values within the first 0.20 m ranged from 7.96 to 8.87 and reached a maximum value at deep B-horizon. The total carbonate content followed the same general trend with soil depth (Table 1). When compared to the regional scale mean topsoil organic carbon of the vineyard (1.32%), the SOC content was higher in the entire soil profile [39]. Moreover, calculated SOC stocks were locally important within one metre depth (around 30 kgC m^{-2}) when integrating (i) the SOC content, mainly those over the value of 1% even for B-horizons, and (ii) the values for soil bulk density, mainly those over the value of 1.4 g cm^{-3}. The CEC values presented a low variability with a mean value of 11.81 cmol$_{(+)}$ kg^{-1} for tilled organo-mineral horizons (Ap-horizons), which is considered as a local mean value for topsoil horizons [49]. The CEC values decreased with soil depth in association with decreases in both SOC and clay fraction. When considering the saturation of the CEC, measurements showed that both Ca^{2+} and Na^{+} were preponderant, and calcium had the maximum value (10.96 cmol$_{(+)}$ kg^{-1}), which was higher than sodium (maximum value of 0.51 cmol$_{(+)}$ kg^{-1}). Sodium saturation, as represented by ESP values, showed a wide range of values, the highest value was measured at a greater depth of unit T1. This T1 unit can be considered as sodic soil, particularly at B-horizon, as the ESP value was over 15%.

The measured values of soil salinity, based on the electrical conductivity of a saturated paste extraction of soil (ECsp), ranged from 0.49 to 9.11 dS m^{-1}. The mean value for both ECsp and ESP were 2.98 dS m^{-1} and 5.72%, respectively. Thus, in general, this soil was categorised as saline soil, following the categorisation by [48]. The trellised vine (T1 and T2) had a similar trend of soil salinity that increased with soil depth. The Ap-horizon was less saline compared to the B horizon. However, the field T1 located about 500 m from the Orb River bank had the highest mean ECsp value (7.02 dS m^{-1} < ECsp < 9.11 dS m^{-1}) (Table 1) and was categorised as very saline soil. Gobelet vine (G1 and G2) and fallow (F1) presented a similar trend that showed a lower saline value with an average of 1.27 dS m^{-1}. Thus, in general, (i) irrespective of the horizon type, the highest values of salt concentration were observed at T1; (ii) the lowest value of salinity for Ap-horizon (0.85 dS m^{-1}) was recorded in T2; and (iii) similar results were observed for G1, F2, and F1 for Ap-horizon (mean absolute value of 2.34 dS m^{-1}) and lower values for underlying soil horizons (0.49 dS m^{-1} < ECsp < 1.92 dS m^{-1}). Most previous studies have reported a clear relation between soil salinity as characterised by ECsp and ESP. However, the results from our dataset did not show such significant relationships. The only relevant observation was found in samples from T1, where the mean ESP value was over 15% and the mean ECsp value was over 8.00 dS m^{-1}. Two exceptions for high ECsp values associated with a very high ESP value (35.48%) were also observed for T1, particularly in the deep B-horizons affected by waterlogging (Bwk). For the other soil samples, ESP values were always below the threshold value of 15%, as proposed by [50], and not correlated with corresponding ECsp values.

3.3. Soil Aggregate Stability

MWD values (N = 237) measured from all soil samples (N = 79) (Figure 2) ranged from 0.19 to 1.68 mm, whereas the external reference value of MWD obtained from a topsoil horizon from a local natural area (within a kilometre) was over 3 mm. Based on the classification of MWD values by Le Bissonnais and Arrouays [51], we concluded that a predominant part of samples would be considered very unstable or unstable, and more stable MWD values were noticed in topsoil horizons.

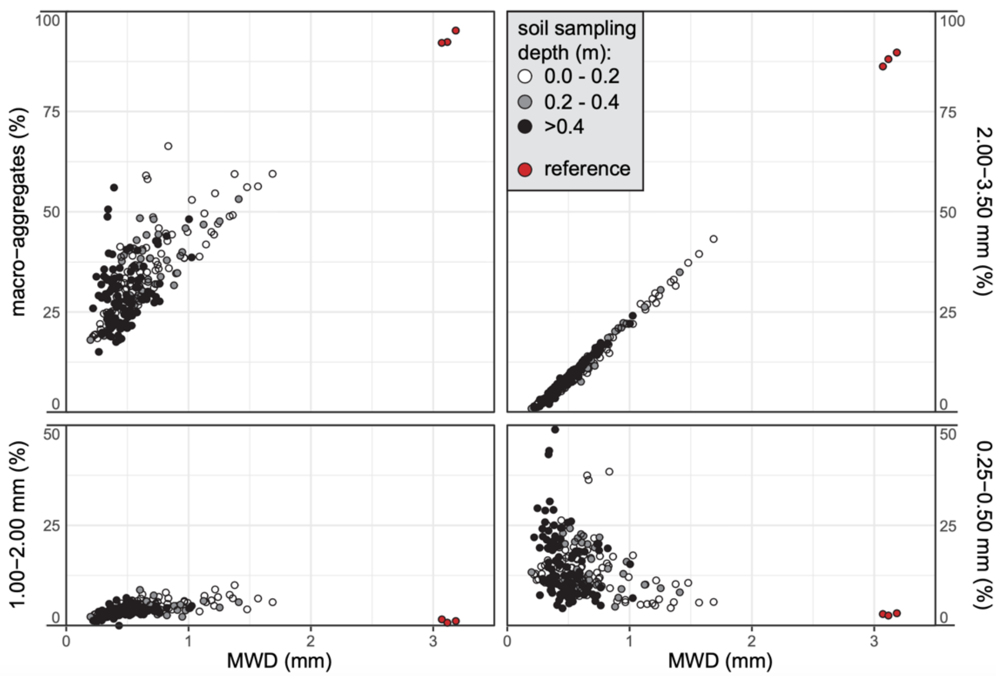

Figure 2. Contribution of the macro-aggregate fraction and associated sub-fractions to the mean weight diameter (MWD) value (% proportion of each sub-fraction to the soil sample dried mass).

When deciphering all sub-fraction contributions to the MWD values, we observed that the macro-aggregate fraction (>250 μm) was critical for aggregate stability. Within this macro-aggregate fraction, the 2.00–3.50 mm fraction had a linear relation with MWD values, indicating that soil aggregate stability is mainly linked to this fraction. Contributions of the 1.00–2.00 mm and 0.50–1.00 mm fractions (0.50–1.00 mm are not represented in Figure 2) presented similar trends and proportions, and seemed to have second order contributions to the macro-aggregate fraction. The most important observation for the 0.25–0.50 mm fraction was that its relation to the MWD value was not of a linear type, and its variability was higher than the 1.00–2.00 mm or 0.50–1.00 mm fractions. When focusing on the reference sample, it seemed that stable aggregates were those dominated by the macro-aggregate fraction, which is mainly composed of the 2.00–3.50 mm fraction, with a non-significant contribution of the 0.25–0.50 mm fraction.

The determined value of MWD and soil properties of the soil horizon for 25 samples are represented in Figure 3. When considering all soil units together, the overall trend was that MWD value decreased with increasing soil depth. The highest variability was observed for topsoil A-horizons, and the variability decreased for B-horizons, where the deepest MWD values converged to a very unstable aggregate stability class at 1 m depth. An interesting element was the well-stratified ranking of MWD profiles according to soil use type, from gobelet-trained vines (G1 and G2) to trellised vines (T1 and T2) and fallow (F1), from unstable to more stable MWD profiles. We noticed that the F1 profile was characterised by a gradual decrease in MWD values, from topsoil (MWD = 1.1 mm) to subsoil horizons (MWD = 0.4 mm).

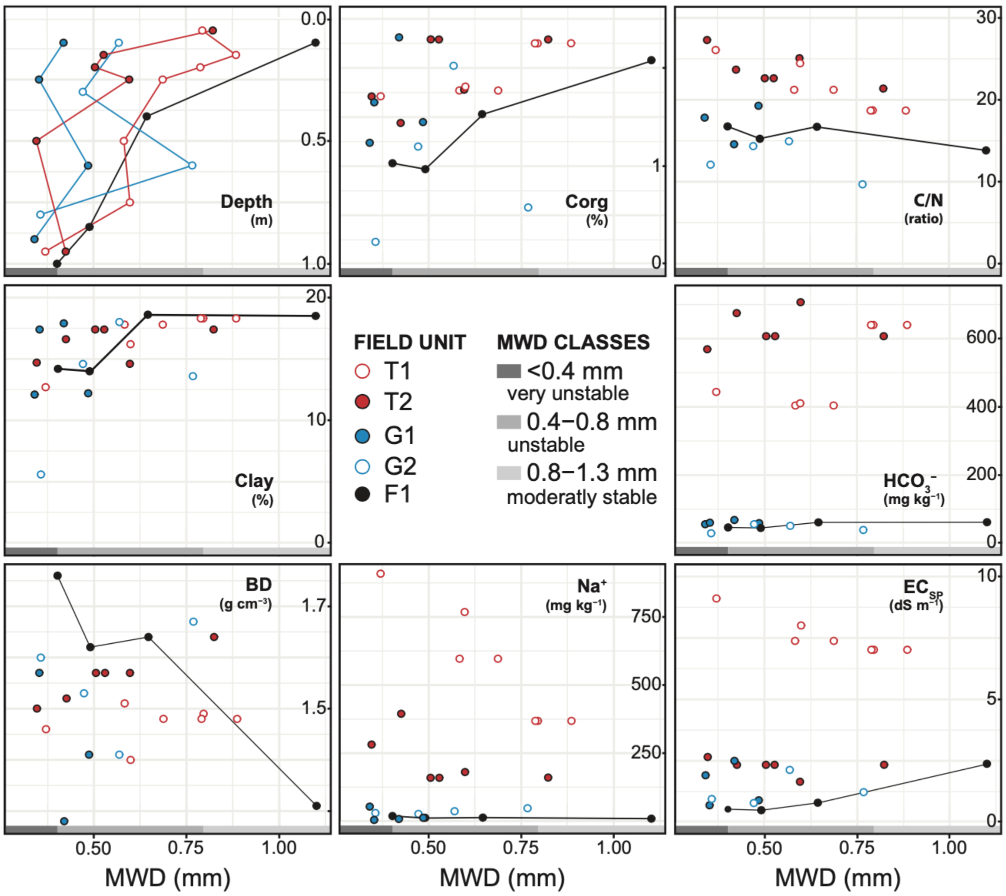

Figure 3. Mean weight diameter (MWD) values in relation to soil sampling depth (m) and preponderant soil properties of the sampled soil horizon.

Our findings suggested that the highest content of SOC was not correspondingly equal to high MWD values; more stable aggregates had high SOC but the inverse was not true. A more robust relation for organic matter could be found with C/N ratios. When categorised according to the field unit type, we observed that an increase in MWD value was linked to a slight decrease in C/N ratio value, at each profile scale.

Clay fraction is another commonly used explanatory factor for MWD values. In our study, textural evolution at the soil profile scale was substantial but textural contrast between soil profiles was limited. Therefore, no additional information could emerge from the representation, except an overall decrease in clay fraction with increasing soil depth, which was similar to the decrease in mean MWD value with increasing soil depth. A structured gradient did not emerge for bulk density, for which the only pattern was in the overall compaction, with half of the measured bulk density values ranging between 1.5 and 1.76 g cm^{-3}. Relations between MWD and Na^+, HCO_3^-, and ECsp allowed us to discriminate trellised vines (T1 and T2) from gobelet vines (G1 and G2), where T1 and T2 presented significantly higher HCO_3^- and Na^+ content when compared to other profiles, and T1 was also associated with the highest ECsp conductivity. Despite these characteristics, T-type soil profiles had more stable aggregates than G-type ones.

4. Discussion

4.1. Factors Explaining Soil Aggregate Stability

The aim of this study was to explore the usefulness of soil aggregate stability as an ideal soil profile structure quality indicator, with a focus on salt-affected soils. To achieve this, we selected and described soil morphological traits for six different field units (Table 1), based on a previous study by [8]. In the first order, the saline and compacted soils in the study area showed low to very low structural stability values. The main findings of this classical pedological investigation demonstrated that the overall soil profile morphology and geometry was well controlled by soil tillage practices operating at different soil depths, and responsible for the A- and B-horizon boundary between 0.4 and 0.6 m depth. This field observation was corroborated by a significant content of SOC (Table 1) in the A-horizons, in comparison with the regional scale mean topsoil organic carbon (1.32%) of the vineyard [39]. Additionally, SOC content in the B-horizons was substantial (>1%), even for the deep horizons. This SOC abundance with depth is certainly related to vine root architecture and the associated biomass and exudates [52].

For the six field units, global characterisation of the aggregate stability (Figure 2) confirmed the preponderant effect of the macro-aggregate fraction for stable aggregate formation. An analysis of all macro-aggregate sub-fractions indicated that the main contribution was from the 2.00–3.50 mm sub-fraction and that the 0.25–0.50 mm sub-fraction certainly played a major role in aggregate stabilisation. A possible assumption could be that the overall aggregation potential depends on the 0.25–0.50 mm sub-fraction to merge with other sub-fractions to create higher-level aggregates. The stability of aggregates seemed to be linked to soil depth and therefore to SOC, clay fraction, and other chemical gradients at the profile scale.

A comparison of MWD values to hypothetical aggregation factors, as measured on pedological trenches, confirmed the complex interactions responsible for soil aggregation; none of the paired relations in Figure 3 could clearly explain the MWD value distributions. Soil depth and agricultural practices were asserted to be the first-order parameters that affected SOC distribution at the soil profile scale. This is the most plausible explanation for the variability in MWD values in A-horizons and the associated decrease of MWD values and variability with soil depth (Figure 3). It is widely known that SOM and clay content play important roles as agents of soil aggregation on the soil surface [37,38,53], as both these properties create an organo-mineral association [54–56] or a mineral-organic association [57], which are considered as building blocks for micro-aggregate formation [40]. The question we aimed to answer was related to the low stability class that we determined for topsoil aggregates, while, in our conditions, the SOM content and clay fraction were locally considered as satisfactory, when compared to those of regional reference values [49]. Certainly, the answer lies in the nature of the considered organic matter, as it can be partially revealed by the C/N ratio; a ratio higher than 20 indicates that there is a potential deficiency of soil mineralisation in relation to N needs. On the other hand, Figure 3 shows that higher MWD values were not observed for the lower C/N ratio. Therefore, the structure of the community and the activity of microorganisms seem critical to improve the understanding of the functional relationship between SOM content and structural stability [58].

When we analysed the results corresponding to land use, where Figure 3 presents a ranking according to this factor, it was seen that MWD values of fallow grasslands were significantly higher when compared that in both trellised (T-type) and gobelet vineyard

(G-type) units. Different land uses incorporate different agricultural practices, such as tillage and weed control practices. As identified during soil description, the superficial tilled horizon (Ap-horizon) was present in all soil trenches. However, in the fallow units (F1 and F2), there was no further disturbance of the topsoil due to tillage. This condition was reported by [59] as favourable for high stability of the soil aggregate. Additionally, in the fallow land, we also assumed that higher soil biological activities supported soil organic decomposition and soil aggregate formation [60]. Contrary to these fallow land conditions, actual vineyards (T- and G-type) were often tilled at various soil depths, with the deepest physical disturbance attributed to younger vineyards (T1 and T2), where deep mechanical ploughing was performed (pre-planting works). This comment, based on frequency and depth of soil tillage operation, is in agreement with the results of [53], who found that fallow grasslands had the largest aggregate stability compared to young and old cultivated vineyards. A previous study [61] also indicated that conventional tillage negatively affected soil aggregate stability compared to reduced tillage, which was ideal to preserve SOC [62]. The results showed that the length of time the soil was exposed to the tillage practice was also a crucial factor. Field G, which had been cultivated continuously for more than 50 years, showed the lowest values of structural stability, whereas stopping tillage for 3 years led to an increase in structural stability (Field T). Field T, which had been cultivated as a vineyard for less than 30 years and which had been fallow earlier, showed an intermediate status.

Moreover, depending on land use, soil horizons could be differently subjected to aggregate destruction and soil compaction [63]. Often, compaction begins with a reduction in the volume of macropores [64]. Thus, we can assume that the evolution of the macro-aggregate fraction along with soil bulk density can be a good indicator for both aggregation potential and potential for water flow (functional indicators). Gas transport and air permeability declines with compaction. Therefore, soil compaction negatively influences important soil functions.

4.2. Soil Structure Remediation

In salt-affected land, the priority for agriculture is to reduce the overall quantity of salts within the root-zone volume. Often, the rehabilitation strategy is based on salt leaching by optimising rainfall infiltration or by applying fresh water submersion (irrigation) [65]. Such a strategy is inefficient, as suggested by the presence of a compacted layer and low MWD value, physically associated with a low capacity of soil horizons for water fluxes (infiltration and lixiviation). In this context, the absolute priority seems to be the restoration of the soil structure at the soil profile scale, in order to restore the soil capacity for salt leaching. To evaluate an efficient structure rehabilitation strategy with time, once again, soil aggregate stability measurements seemed to be appropriate.

Degradation of soil structure could be attributed to several factors acting together as mentioned by Le Bissonnais [23]. To identify the origin of its degradation, ESP values can be inspected, as proposed by Rengasamy et al. [66]. In our study, most of the ESP values were lower than the threshold value of 15% [34], except that of field T1, but an impact on aggregate stability, particularly at deeper soils was still evident. This finding is in agreement with Crescimanno et al. [35], who reported that the destabilisation of soil aggregate was also observed at very low ESP values (2–5%). Moreover, a geochemical analysis (Table 1) suggested that much of the sodium was not present in the soil-exchangeable part; the quantity of sodium extracted by water was high, whereas the sodium saturation was low. We then assumed that salt ions (Na-Cl) might have been present and were crystallised in vadose zones during the dry period, and they would have been diluted during the wet period [67]. Therefore, it seems efficient to leach down the salt ions from the soil surface to the saturated zone, without preliminary cation substitution, e.g., the addition of a substitution cation to replace sodium in the exchangeable soil part, as conducted in many contexts [68]. The remediation strategy by applying additional fresh water (irrigation) requires a ditch network management to allow the soluble salt out from the agricultural system [8,65].

A way to restore soil structure could be to enhance other soil properties such as aluminium and iron content, bulk density, and soil pH that play a major role in soil aggregation potential. The results showed that salt-affected soil had a lower Al and Fe content; both were below 0.02 mg kg^{-1}. Such low Al and Fe content could not support soil aggregation and resulted in a low MWD value [69], since metal oxides have a positive relation with aggregate stability [70]. They coagulate with humid acid by covering the surface of metal oxides, forming micro-scale aggregates [39]. Duiker et al. [71] also suggested that the precipitation of Al/Fe-Oxide or Al/Fe-hydroxide become composite building units for small micro-aggregates (<20 µm). Moreover, soil pH is related to the concentration of solubility of metal oxides (Al and Fe). Generally, at pH > 7.0, the solubility of Fe and Al is very low. The soil pH of our sample was around 8.0 (Table 1), therefore, combined with low initial abundance of AL and Fe in soil parental material, these characteristics might be responsible for the low concentration of Al and Fe in soil, which influence aggregate stability.

Considering high bulk density, especially for a silty clay loam texture, values over the threshold of 1.58 g cm^{-3} [72] caused restrictions for root penetration because of compaction. Our results showed that the mean BD at the B-horizon was around 1.53 g cm^{-3}; thus, the restriction of root development may occur. This could be problematic for cultivated plants (such as a vine) but could also limit the development of weed roots and, in turn, have a negative effect on SOM content and soil properties related to hydrodynamics (water storage and permeability).

The highest MWD value observed for fallow land conditions (F1 and F2) suggested that the positive effect of crop services on soil structure need to be studied in the coastal zones affected by salinisation in the future [73].

5. Conclusions

This study assessed soil aggregate stability in various saline conditions by measurements at different soil depths for different land uses, and by investigating the relationships between aggregate stability and known aggregation factors. Soil aggregate stability appears as an interesting key to approach the understanding of soil functioning and to arrive at solutions to restore soil fertility. Soil aggregate stability was unstable and very unstable at the organo-mineral horizon and the mineral horizon, respectively. The destabilisation of soil aggregate in the top horizon was related to soil agricultural practices (in particular, tillage) and soil properties (SOM and clay content). Meanwhile, destabilisation of soil aggregate for subsoil horizons was related to the intrinsic soil properties, particularly soil salinity. The results indicate that salt (Na-Cl) may precipitate in the vadose (pore) zone instead of the exchangeable soil part. Therefore, there is a possibility to remediate the salt-affected soil by carrying out submersions with fresh water, if the soil structure allows for an effective leaching of the salts.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land11040541/s1, Figure S1: Gobelet-trained vines—picture by Aplena E.S. Bless; Figure S2: Trellised vines—picture by Aplena E.S. Bless; Figure S3: Degraded soil surface—picture by S. Follain; Figure S4: Hole drilling using the prospecting kit for geological surveys by Eijkelkamp (The Netherlands)—picture by A. Crabit.

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