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The Edaphic and Vegetational Properties Controlling Soil Aggregate Stability Vary with Plant Communities in an Arid Desert Region of Northwest China

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Abstract: The stability of soil aggregates is the basis for supporting ecosystem functions and related services provided by the soil. In order to explore the mechanism of the influence of soil and vegetation properties on the stability of soil aggregates in desert communities, the particle size distribution and aggregate in different communities were compared, and the contribution of soil physical and chemical properties (soil salinity, soil water content, soil pH, soil organic carbon, soil total phosphorus, soil total nitrogen, etc.) and vegetation properties (species richness, phylogenetic richness, plant height and coverage, etc.) to the stability of soil aggregates was determined by using a structural equation model. The results show the following: Soil water content, organic carbon, and salt in river bank plant communities have significant direct positive effects on the mean weight diameter of soil, with path coefficients of 0.50, 0.11, and 0.24, respectively ($p < 0.01$). Water also indirectly affects soil stability by affecting plant height, soil salt, and soil organic carbon; species richness and vegetation coverage have significant direct positive effects on the soil stability index, with path coefficients of 0.13 and 0.11, respectively ($p < 0.01$). In the desert marginal plant community, the plant coverage and species richness have significant positive effects on soil stability, with path coefficients of 0.43 ($p < 0.001$) and 0.35 ($p < 0.001$), respectively. Phylogenetic richness has a significant direct negative effect on soil stability ($p < 0.05$), with an effect value of −0.27. Phylogenetic richness indirectly affects soil stability by adjusting the coverage, with an indirect effect value of 0.23. Moisture, ammonium nitrogen, and nitrate nitrogen have significant direct positive effects on soil stability, with effect values of 0.12, 0.09, and 0.15, respectively. Our research shows that the process of soil stabilization is mainly controlled by soil factors and vegetation characteristics, but its importance varies with different community types.

Keywords: soil aggregates; soil structure; soil properties; plant characteristics; arid desert region

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1. Introduction

Soil is the main component of the terrestrial ecosystem, and soil degradation leads to a decline in the ecosystem services provided by the soil. Soil degradation weakens the soil structure and reduces soil productivity [1], thus aggravating soil desertification [2,3]. The soil structure is considered to control many processes in soil, regulating water retention and infiltration, gas exchange, the dynamics of soil organic matter and nutrients, root infiltration, and sensitivity to erosion. The soil structure also constitutes the habitat of countless species and the diversity of soil organisms, thus promoting their diversity and regulating their activities [4]. The soil structure is actively shaped by these organisms, in that they change the distribution of soil moisture and air [5–7]. Many processes have been proved to be related to the soil structure. One of the most important indicators of soil degradation is aggregate stability [8,9]. The stability of soil aggregates is closely related to the soil structure and can affect some soil physical and biogeochemical processes, such as the ability of soil to resist erosion, soil atmospheric exchange, water permeability, and nutrient availability [10–12].

Soil agglomeration is a complex process that involves the dynamic interaction between soil organic matter and mineral components and assembles micro-aggregates into macro-aggregates [13]. It is well known that soil stability is influenced by abiotic factors (e.g., soil organic matter, soil water content) and biological factors (e.g., vegetation type, plant roots). Previous studies have shown that soil properties closely related to the stability of soil aggregates include soil texture, organic matter content, soil cations, pH, and microbial activity [13–15]. SOM acts as the main binder of soil particles, while the mineralogy, cation ratio, and binder are closely related to the stability of micro-aggregates [16,17]. In this dynamic aggregation process, clay particles form an organic–mineral combination as a binder during the interaction with soil organic matter, thus reducing the wettability of aggregates and affecting the mechanical strength of soil aggregates [15,18]. However, studies have found that biological factors also play an important role. Plant diversity can buffer the influence of physical disturbances (such as raindrops) on soil aggregates, which is due to the increase in aboveground biomass [19,20], and promote root activities to enhance soil aggregation [21]. However, there are complex interactions between biotic and abiotic factors that will affect soil stability. For example, plant communities with a large number of species have a positive impact on the stability of soil aggregates by affecting soil carbon dynamics, soil microbial activity, and plant growth [20]. Fine roots can increase soil agglomeration by increasing the soil organic matter content and the soil drying–wetting alternation effect [22]. The combination of root biomass and soil water potential affects the production of microbial polysaccharides, and then plays an important role in controlling the formation of water-stable aggregates [23]. Additionally, different vegetation types have different effects on the soil structure [24,25]. On the one hand, different vegetation types affect the chemical composition of soil organic carbon, while SOC plays a key role in soil agglomeration [26–28]. On the other hand, the differences in plant coverage and composition in different communities also affect the stability of soil aggregates [29]. For example, soil aggregate stability under different rain conditions showed the order: forest land > forest–grass land > grass land [25]. Dou et al. found that the aggregate stability of natural shrub was significantly higher than that of natural grass [30]. Although many studies have been carried out regarding the influence of abiotic factors (soil organic carbon, soil water content) and biological factors (plant coverage, plant richness, and root biomass) on soil stability, their relative contribution and mechanism of interaction remain controversial and need to be discussed.

Arid and semi-arid areas are an important part of the global land area, accounting for approximately 20–25 percent of the total global land area, with scarce precipitation and a lack of water resources, and the areas are most sensitive to global climate change [31]. In arid areas, the change in the soil structure has a particularly significant impact on the change in the plant community, which can also improve the soil stability. Yang et al. [32] compared the differences in soil aggregate under four typical halophyte communities (*Karelinia caspia*, *Bassia dasyphylla*, *Haloxylon ammodendron*, and *Tamarix ramosissim*) in an arid area, and found that the percentage of soil aggregate in the >0.25 mm fraction is significantly higher under the *H. ammodendron* community. Abdi et al. [33] found that soil fixation and erosion are controlled by *Haloxylon persicum* roots in arid lands. However, these studies only focused on the percentage of aggregate under different communities and the contribution of roots to soil fixation. There are relatively few studies on the stability of soil aggregates in arid areas, and there are few reports on the relationship between soil aggregate stability and plant community characteristics, structure, and function. Studying the relationship between soil stability and plant distribution and composition and analyzing the mechanism of influence to improve community resistance have become problems to be solved. Based on this, we selected one plant community on the river bank and the desert margin in the Ebinur Lake Wetland National Nature Reserve to compare the differences in soil physical and chemical properties and vegetation properties under different community types, as well as the changes in the stability of aggregates with different community types. In this study, we tried to clarify the direct and indirect roles of abiotic and biological factors in determining the stability of soil aggregates under different vegetation types in arid areas (the plant communities of the river bank and desert margin). In order to verify this hypothesis, this study aimed to: (1) quantify the contribution of abiotic factors (soil physicochemical properties) and biological factors (vegetation properties) to the stability of soil aggregates; and (2) describe the complex interaction between these factors.

2. Materials and Methods

2.1. Study Area, Sample Layout, and Plant Sample Collection

The study area is located in the Ebinur Lake Wetland National Nature Reserve in the northwest of Jinghe County, Xinjiang and the southwest of Junggar Basin (Figure 1). It is the lowest depression and the center of water and salt collection in the southwest margin of Junggar Basin. The basin has a typical temperate continental arid climate [34], with an annual evaporation of over 1600 mm, an annual rainfall of approximately 100 mm, annual sunshine of approximately 2800 h, an extreme maximum temperature of 44 °C, and an extreme minimum temperature of −33 °C [35]. There are various types of sandy vegetation, mesophytic vegetation, and aquatic vegetation in the area. The main dominant plants in the sample plot were *Populus euphratica*, *Haloxylon ammodendron*, *Halimodendron halodendron*, *Alhagi sparsifolia*, *Reaumuria soongarica*, *Nitraria roborowskii*, *Apocynum venetum*, *Seriphidium terrae-albae*, *Phragmites australis*, *Halocnemum strobilaceum*, *Salsola collina*, and *Suaeda glauca*.

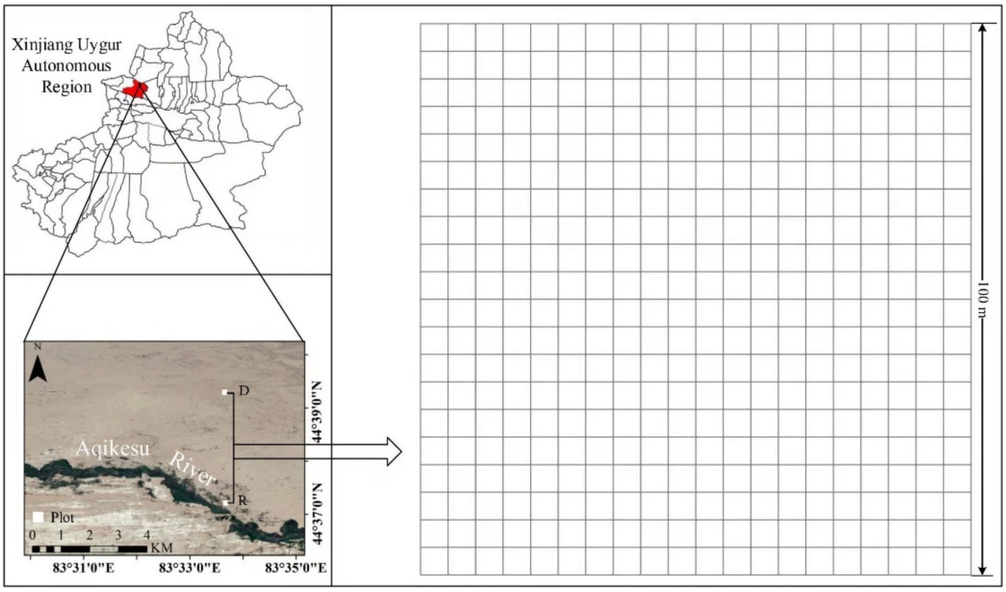

Figure 1. The study area and location of the plots. Note: R and D represent the plant communities of the river bank and desert margin, respectively.

Two large sample plots of 1 hm^2 (100 m × 100 m) (Figure 1) were set up on the river bank and in the desert margin to the north of Aqiksu River near the East Bridge Management and Protection Station in the reserve. Based on a scale of 5 m × 5 m, we studied the community, and each sample plot had 400 quadrats (totaling 800 quadrats). After the establishment of the quadrats, we investigated plant community characteristics in each quadrat, including species composition, species abundance, plant crown, and plant height.

2.2. Collection and Measurement of Soil Samples

Within each sample plot of 5 m × 5 m, the diagonal method was used to select the center point, and 0–20 cm of topsoil was taken in two soil samples. Each soil sample was collected in an aluminum box (the quality of the aluminum box was determined in advance).

The aluminum box was numbered after the sample was collected, and the sample's fresh weight was measured. Then, the sample was taken back to the laboratory and dried in an oven in order to calculate the soil water content (SWC). In addition, undisturbed soil samples were taken and brought back to the laboratory. The soil samples were peeled into small clods with a diameter of about 1 cm, and the visible pebbles and animal and plant residues were picked out. Each sample was then air-dried indoors and, after being mixed evenly, one part (kept the same) was classified as aggregate, and the other part was ground with a 100-mesh nylon sieve and naturally air-dried for later soil index determination.

The collected soil samples were measured in the laboratory, and SWC was determined by the drying method at 105 °C for 48 h to a constant quality [36]. Soil salinity content (SA) was determined by the weight method, soil pH value was determined by potentiometry, soil organic carbon (SOC) was determined by the potassium dichromate dilution heat method, and AN was determined by indophenol blue colorimetry [37]. NN was determined by dual-wavelength ultraviolet spectrophotometry [38]. Total nitrogen (TN) in the soil was determined by the Kjeldahl digestion method [39]. The soil's total phosphorus (TP) and available phosphorus (AP) were determined by the Mo-Sb anti-spectrophotography method [40]. The particle size distribution and stability of soil aggregates were measured by the dry screening method and the wet screening method, respectively [41].

2.3. Calculations for Soil Aggregates and Plant Diversity

2.3.1. Calculations for Soil Aggregates

The following formulas were used to calculate the mean weight diameter (MWD), the percentage of soil aggregates with a particle size larger than 0.25 mm (WSR), and the percentage of aggregate destruction (PAD).

The formula for the mass percentage of aggregate content at all levels is as follows [42,43]:

The mass percentage of aggregates in each grade = the mass of aggregates in this grade/the total mass of soil samples × 100%.

The average mass diameter was calculated using the formula:

$$\mathrm{MWD} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}} X_i W_i}{\sum_{\mathrm{i}=1}^{\mathrm{n}} W_i}$$

where n is the number of particle size groupings; X_i is the average diameter of this particle size component; and W_i is the mass fraction of this size aggregate.

The percentage of soil aggregates with a grain size greater than 0.25 mm was calculated using the formula:

$$\mathrm{WSR} = \frac{\mathrm{M_{r>0.25}}}{\mathrm{M_t}}$$

where WSR is the percentage of soil aggregates with a particle size greater than 0.25 mm, Mr > 0.25 is the cumulative mass of aggregates with a particle size greater than 0.25 mm, and Mt is the sum of the masses of aggregates with different particle sizes.

We used the following formula to calculate the aggregate failure rate:

$$\mathrm{PAD} = (W_d - W_w)/W_d$$

where PAD is the aggregate failure rate, W_d is the sum of the mass percentages of aggregates with particle sizes larger than 0.25 mm in the dry screening method, and W_w is the sum of the mass percentages of aggregates with sizes larger than 0.25 mm in the wet screening method.

2.3.2. Calculation of Plant Diversity

The vegan package was used to calculate the weighted average of the plant community species diversity index and plant height. The picante package was used to calculate the phylogenetic richness index. The above-mentioned index calculations were all performed in R version 4.1.1.

2.4. Data Analysis

In R version 4.1.1, the t-test was used to analyze the differences in the proportion and stability of soil aggregates in different vegetation communities, and the cor.test function was used to analyze the correlation between vegetation and soil characteristics and soil stability. In SPSS Amos version 24.0, the structural equation model was used to analyze the relative effects of soil factors (soil water content, salt content, organic carbon, pH, and total nitrogen) and plant characteristics (species richness, phylogenetic richness, plant height, and plant coverage) on the stability of soil aggregates in different plant communities.

3. Results

3.1. Differences in the Proportion and Stability of Soil Aggregates in Different Community Types

A t-test showed that the percentages of soil water-stable large aggregate (>2 mm) and middle aggregate (2–0.25 mm) fractions in the river bank were larger than those in the desert margin, and the percentage of micro-aggregate fractions (<0.25 mm) on the river bank was lower than that on the desert margin (Figure 2). The MWD of the soil and the WSR in the desert margin plant community were significantly smaller than those in the river bank plant community. However, the river bank plant community had a significantly lower aggregate destruction rate than the desert margin plant community (Figure 3).

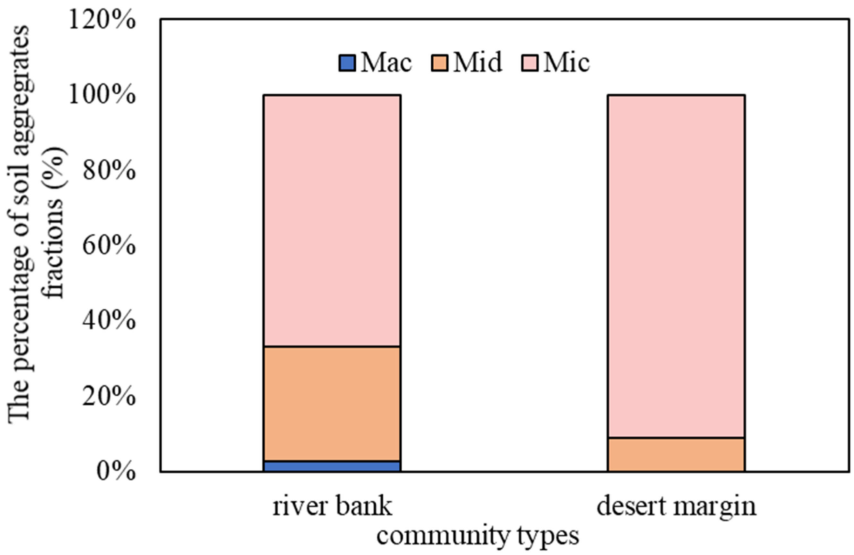

Figure 2. The difference in the soil water-stable aggregate proportion of different communities. Note: Mac, Mid, and Mic represent soil macro-aggregates, intermediate aggregates, and micro-aggregates, respectively.

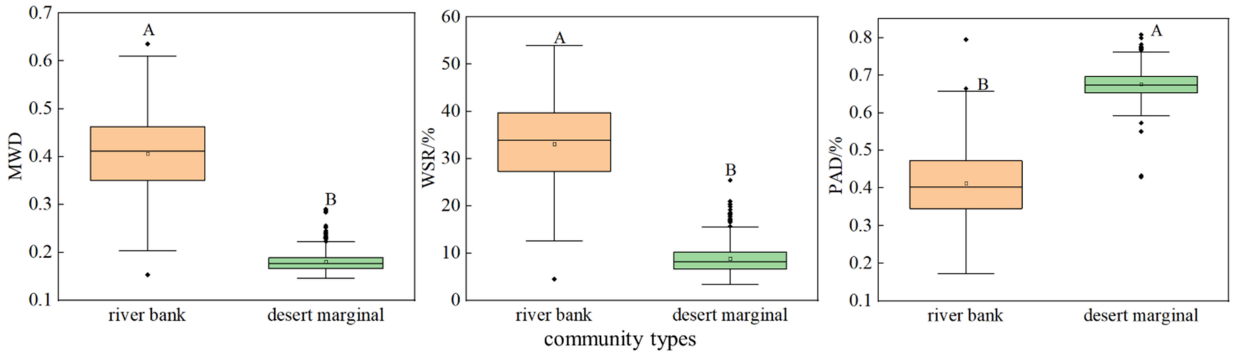

Figure 3. The difference in the soil aggregate stability of different community types. Note: MWD, mean weight diameter; WSR, the percentage of soil aggregates with a particle size larger than 0.25 mm; PAD, the percentage of aggregate destruction. The different letters (A and B) indicate statistically significant differences between the two communities ($p < 0.05$).

3.2. Influencing Factors of Soil Aggregates

Soil physicochemical and vegetation properties (species richness, phylogenetic richness, plant height, etc.) varied in the different communities (Table 1). There were 14 species in the river bank community, with a height range of 4–1350 cm, and 10 species in the desert margin community, with a height range of 3.5–420 cm. The Maglef species richness index of the river bank plant community was significantly larger than that of the desert margin plant community, while the Simpson and Shannon–Weiner indices showed no significant differences. The plant phylogenetic richness was significantly larger in the river bank plant community than in the desert margin plant community. The soil pH, water content, salt content, organic carbon, total nitrogen, total phosphorus, available phosphorus, nitrate nitrogen, and ammonium nitrogen of the river bank plant community were significantly higher than those of the desert margin plant community.

Table 1. The vegetation and soil characteristics.

	River Bank	**Desert Margin**
Vegetation		
Plant height/cm	4–1350	3.5–420
Species number	14	10
Simpson	$1.52 \pm 0.03\ ^a$	$1.54 \pm 0.03\ ^a$
Maglef	$0.59 \pm 0.02\ ^a$	$0.53 \pm 0.02\ ^b$
Shannon–Weiner	$0.52 \pm 0.02\ ^a$	$0.50 \pm 0.02\ ^a$
Phylogenetic richness	$384.24 \pm 0.09\ ^a$	$187.82 \pm 0.11\ ^b$
Soil		
pH	$8.07 \pm 0.02\ ^a$	$7.38 \pm 0.02\ ^b$
SWC %	$13.12 \pm 0.19\ ^a$	$1.04 \pm 0.02\ ^b$
SA (g/kg)	$5.58 \pm 0.12\ ^a$	$1 \pm 0.02\ ^b$
SOC (g/kg)	$9.57 \pm 0.28\ ^a$	$1.35 \pm 0.03\ ^b$
TN (g/kg)	$1.31 \pm 0.01\ ^a$	$0.59 \pm 0.01\ ^b$
AP (g/kg)	$38.19 \pm 0.75\ ^a$	$7.96 \pm 0.18\ ^b$
TP (mg/kg)	$2.05 \pm 0.04\ ^a$	$0.63 \pm 0.01\ ^b$
AN (mg/kg)	$2.47 \pm 0.06\ ^a$	$1.39 \pm 0.03\ ^b$
NN (mg/kg)	$12.51 \pm 0.36\ ^a$	$2.76 \pm 0.06\ ^b$

Note: The different letters indicate statistically significant differences between the two plant communities ($p <$ 0.05). SWC, SA, SOC, TN, AP, TP, AN, and NN represent soil water content, soil salinity content, soil organic carbon, soil total nitrogen, soil available phosphorus, soil total phosphorus, soil ammonium nitrogen, and soil nitrate nitrogen, respectively.

Correlation analysis showed that the factors that determine the stability of soil aggregates were significantly different among the different vegetation types (Figure 4). Soil aggregates in the river bank community were jointly influenced by soil physical and chemical properties (SWC, salinity, organic matter, total nitrogen, nitrate nitrogen, and soil pH), plant coverage, and plant diversity (plant species richness, plant height, and phylogenetic richness). The intermediate aggregates were not significantly affected by ammonium nitrogen, water, total phosphorus, and soil pH, while soil water, salt, organic matter, total nitrogen, nitrate nitrogen, plant coverage, species richness, plant height, and phylogenetic richness were negatively correlated with micro-aggregate content and aggregate destruction rate and positively correlated with the mass fraction of soil aggregates with a particle size larger than 0.25 mm. The mean weight diameter of soil had no significant correlation with ammonium nitrogen, available phosphorus, total phosphorus, or soil pH. Soil macro-aggregates in desert margin plant communities were significantly positively correlated with soil nitrate nitrogen and vegetation coverage, while soil moisture, total nitrogen, ammonium nitrogen, nitrate nitrogen, plant coverage, species richness, plant height, and phylogenetic richness were significantly positively correlated with the mass fraction of intermediate aggregates and soil aggregates with a particle size >0.25 mm, and significantly negatively correlated with the content of micro-aggregates. The destruction rate of soil aggregates was negatively correlated with species richness, phylogenetic richness, and soil available phosphorus.

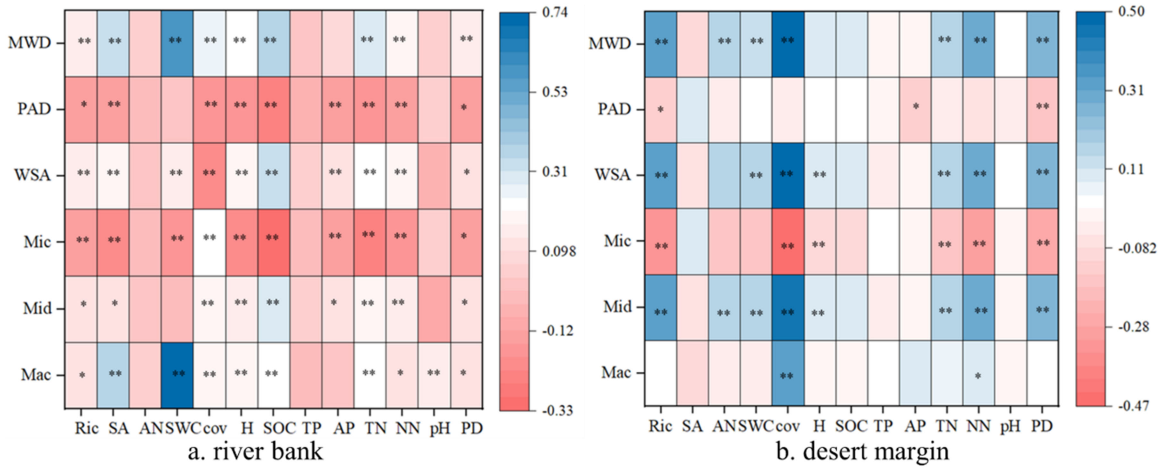

Figure 4. The correlation between vegetation and soil characteristics and soil stability in different communities. Note: MWD, PAD, and WSR represent mean weight diameter, the percentage of soil aggregates with a particle size larger than 0.25 mm, and the percentage of aggregate destruction, respectively. Mac, Mid, and Mic represent soil macro-aggregates, intermediate aggregates, and micro-aggregates, respectively. Ric, SA, AN, SWC, cov, H, SOC, TP, AP, TN, NN, pH, and PD represent species richness, soil salinity, ammonium nitrogen, soil water content, plant coverage, plant height, organic carbon, total phosphorus, available phosphorus, total nitrogen, nitrate nitrogen, soil acidity and alkalinity, and plant phylogenetic richness, respectively. * and ** represent $p < 0.05$ and $p < 0.01$, respectively. The blue grid represents a positive correlation and the red grid represents a negative correlation.

3.3. Effects of Soil Factors and Plant Characteristics on the Stability of Soil Aggregates

The results of the structural equation model show that under different vegetation types, the effects and mechanisms of soil factors and plant characteristics on the stability of soil aggregates were different (Figures 5 and 6). Soil water content, organic carbon, and salt in the river bank community had significant direct positive effects on the mean weight diameter of soil, with path coefficients of 0.50, 0.11, and 0.24, respectively ($p < 0.01$). Water also indirectly affected soil stability by affecting plant height, soil salt, and soil organic carbon. Species richness and vegetation coverage had significant direct positive effects on MWD, with path coefficients of 0.13 and 0.11, respectively ($p < 0.01$). However, the effect of vegetation height on soil stability was not significant. The effect of soil factors on the soil stability of the river bank plant community was significantly greater than that of plant characteristics. In the desert margin plant community, compared with the river bank plant community, the effect of soil factors on soil stability was weaker, and the effect of vegetation characteristics was stronger. Plant coverage and species richness had significant positive effects on soil stability, with path coefficients of 0.43 ($p < 0.001$) and 0.35 ($p < 0.001$), respectively. Phylogenetic richness had a significant direct negative effect on soil stability ($p < 0.05$), with an effect value of −0.27. Phylogenetic richness indirectly affected soil stability by adjusting the plant coverage, with an indirect effect value of 0.23. Moisture, ammonium nitrogen, and nitrate nitrogen all had significant direct positive effects on soil stability, with effect values of 0.12, 0.09, and 0.15, respectively.

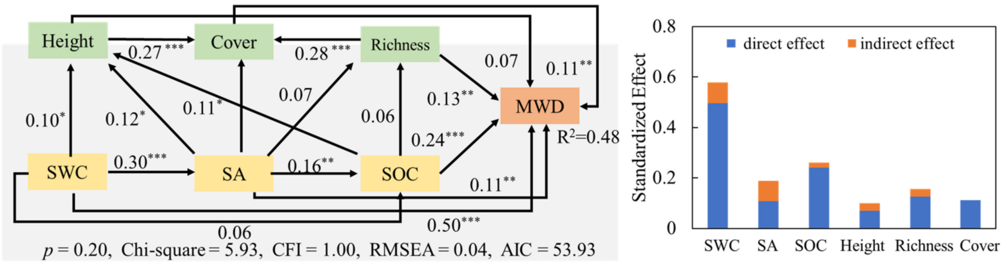

Figure 5. Effects of plant characteristics and soil factors on soil aggregate stability in the river bank. Note: SWC, SA, SOC, Height, Richness, and cover represent soil water content, soil salinity, soil organic carbon, plant height, species richness, and plant coverage, respectively. Black solid lines indicate a positive effect and red dashed lines indicate a negative effect. Values on lines denote the standardized effect size and significance (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$).

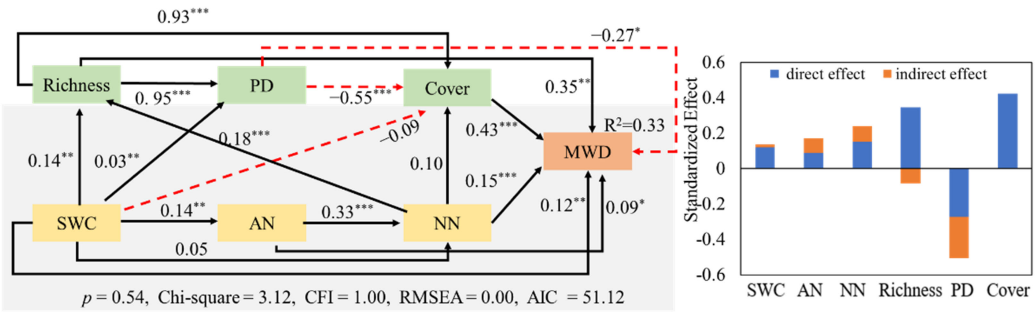

Figure 6. Effects of plant characteristics and soil factors on soil aggregate stability in the desert margin. Note: SWC, AN, NN, Richness, PD, and cover represent soil water content, soil ammonium nitrogen, soil nitrate nitrogen, species richness, phylogenetic richness, and plant coverage, respectively. Black solid lines indicate a positive effect and red dashed lines indicate a negative effect. Values on lines denote the standardized effect size and significance (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$).

4. Discussion

4.1. Differences in the Proportion and Stability of Soil Aggregates in Different Community Types

Soil structure stability is an important foundation for the maintenance of soil functions and the growth of animals and plants, and the water stability of soil aggregates is an important index that reflects the stability of the soil structure [26]. Macro-aggregates are the basis for maintaining the stability of the soil structure, and their content can reflect the quality of the soil structure to a certain extent. MWD has been widely used to measure the stability of aggregates, and it is acknowledged that a larger MWD value indicates higher aggregate stability [28]. In this study, the percentage of water-stable aggregates with a particle size >0.25 mm in the river bank was found to be significantly higher than that in the desert margin, and the aggregate destruction rate was lower than that in the desert margin. Although the MWD values in both locations were small, the soil of the river bank showed higher water stability. The reason for this result may be that the soil of the river bank had high soil water content and a large amount of organic matter. Higher soil water content can increase the content of large aggregates that improve the soil stability [10], so the soil stability in the river bank is higher. The reason for this result may be the high degree of vegetation coverage on the river bank, which may promote soil agglomeration by increasing the input of organic matter above and below the ground, reducing the erosion due to wind and rain, and protecting the stability of soil aggregates [44]. It can be seen that the different vegetation types will significantly change the aggregate content, but the particle size and stability of soil aggregates are affected by many factors, such as soil physical and chemical properties, plant characteristics, and climate factors, and show different distribution characteristics. Therefore, further research is needed on the influence of different soil conditions on aggregate properties.

The correlation between SOC content and MWD, WSA, and PAD was significant in the plant community of the river bank, indicating that soil organic carbon content affects the stability of soil aggregates in the river bank (Figure 4). This finding is consistent with the research results of Zhao et al. (2018) and Wang (2019) on soil aggregates and their stability in different plant communities [45,46]. The correlation between SOC content and WSR showed that the soil organic carbon content had a significant influence on the formation of soil aggregates in the river bank, which promoted the formation of large aggregates as SOC is the main cementing material of large aggregates. This is because, in general, large aggregates (>2 mm) can accumulate more carbon than micro-aggregates (<0.25 mm) [1]. Micro-aggregates form large aggregates through organic matter bonding, and an increase in the soil organic carbon content creates favorable conditions for smaller particles in the soil to bond into larger aggregates [13]. The content of intermediate aggregates and MWD were significantly correlated with pH, SWC, NN, TN, and AP, indicating that soil water content, nutrient content, and acid–base level had an important influence on the formation of large aggregates and the stability of the soil structure in the river bank. The relationship observed between soil water-stable aggregates and soil total nitrogen content was consistent with the research results of An et al. This is because the addition of N aided the chemical reaction inside the aggregates to form a stable soil structure, and the smaller aggregates re-cemented to form larger aggregates [47]. The pH mainly affected the decomposition of soil organic matter by affecting the type, quantity, and activity of soil microorganisms [48], and changed the content of soil aggregates. In alkaline soil, with an increase in the pH value, the mineralization intensity gradually weakened, while the nitrification intensity gradually strengthened, which led to a decrease in the amount of ammonium nitrogen generated by mineralization in the soil, and, at the same time, more ammonium nitrogen was converted into nitrate nitrogen. Finally, under alkaline conditions, the amount of ammonium nitrogen in the soil decreased [49], which led to ammonium nitrogen having an insignificant effect on aggregates in the alkaline soil, while the effect of nitrate nitrogen was more significant. Soil available phosphorus in the river bank had a significant effect on the stability of soil aggregates, while soil phosphorus in the desert margin had no significant effect on the soil stability. This may be because a high pH value can enhance the fixation of soil phosphorus, and more phosphorus can promote the aggregation of soil particles [50]. Plant species richness had a significant positive impact on the stability of soil aggregates; for example, a *Robinia pseudoacacia* community with an abundance of species was found to be beneficial for the stability of soil aggregates [51].

4.2. Influence of Soil Factors on the Stability of Soil Aggregates

Water is an important factor affecting soil aggregates. Water can better promote the formation of soil aggregates, while less or excess soil water will destroy the formation of aggregates. At the same time, the formation of aggregates is also beneficial to the maintenance of soil moisture [52]. The results of the two structural equation models show that water had a significant impact on soil aggregates (Figures 5 and 6), but the mechanisms and sizes of action were different, which may have been caused by different water and nutrient levels and microbial environments under different vegetation types. Water is an important factor affecting the soil structure and function in arid areas. A change in soil moisture will also cause a series of changes in plants and microorganisms [53]. Plants and microorganisms are important factors affecting soil aggregates. The effects of various factors on soil aggregates are superimposed, and it is often difficult to distinguish the effects of water alone. Soil water content had a significant direct positive effect on the MWD of soil in the two communities, with path coefficients of 0.50 and 0.12, respectively. In the river bank, soil water also indirectly affected soil stability by affecting soil organic carbon, because water addition can increase the content of soil organic carbon. SOC can enhance the agglomeration of aggregates and promote the formation of an aggregate structure [54,55], which led to the increase in large soil aggregates. Soil moisture in the desert margin affected the soil stability by adjusting the nitrogen content. This may be because soil moisture is also an important factor affecting soil nitrogen mineralization. Soil moisture can regulate the population of nitrifying bacteria. Moreover, in a certain range of soil moisture values, an increase in soil moisture is beneficial to the growth of nitrifying bacteria, but not conducive to the growth of denitrifying bacteria, which makes the amount of ammonium nitrogen that is retained less than the amount of nitrification that occurs, and then increases the content of nitrate nitrogen [56] and promotes the stability of soil aggregates.

In the river bank, salt had significant direct and indirect effects on soil aggregates. The direct mechanism may be that the river bank had relatively high soil salt, and its soil contains more calcium ions and magnesium ions. Ca^{2+} has a strong ion bridge function, which is beneficial to the combination of soil clay and organic matter [57]. The soil salinity had an indirect effect on the soil stability. This may be because the river bank had higher soil salinity, which slowed down the decomposition rate, improved the accumulation and storage of soil organic carbon [58], and promoted the adsorption of more soil particles [58] as the accumulation of organic carbon content promotes the adsorption of soil particles. These two aspects jointly promote the formation and stability of aggregates, so the content of soil aggregates in a riparian forest is significantly positively correlated with salt. Yu et al. (2016) also pointed out that the content of water-stable aggregates in salinized soil increased significantly [59]. Soil salinity is also one of the important factors that control the changes in plant diversity in arid areas, and plant diversity is closely related to the accumulation of soil organic carbon. Therefore, soil salinity can indirectly affect soil aggregates by controlling the decomposition rate of soil organic carbon, vegetation distribution, and plant diversity.

4.3. Effects of Plant Characteristics on the Stability of Soil Aggregates

Soil aggregates are the basic units of the soil structure and an important factor in the maintenance of soil fertility. A stable soil aggregate is beneficial to the balance between soil nutrient retention and release, while the stability of a soil aggregate is positively influenced by the characteristics of plant communities. Plant characteristics are particularly important for soil aggregation in ecosystems that have been seriously disturbed by the external environment [51,60]. Some studies that have reported on how plant characteristics influence soil aggregation emphasized the important roles of root traits, shoot biomass, and niche complementarity [61–63]. In this study, we found that species richness has a positive effect on soil stability. This finding is in line with the insurance hypothesis. Higher biodiversity ensures that the ecosystem is protected from environmental fluctuations and maintains its functions [64]. However, in this study, plant diversity, including species richness and phylogenetic richness, was found to have different impacts on soil stability (Figures 5 and 6). In the correlation analysis, the species richness and phylogenetic richness in the plant communities of the river bank and desert margin had significant impacts on the soil stability; however, in the comprehensive analysis of soil factors and plant characteristics, phylogenetic richness did not enter into the structural equation model. However, phylogenetic richness had a negative effect on soil stability in the desert margin plant community, which may be due to the fact that when soil factors and plant characteristics were integrated, the influence of genealogy on plants was genetically different from the level of conservation of plant characteristics [65], which means that when plants and soil are combined, genealogy may not play a significant role, or it may play an opposing role. Phylogenetic richness in the desert margin plant community had a negative effect on soil stability, which shows that the closer the phylogenetic distance between species is, the more stable the soil structure can be. This means that plants belonging to the same family and genus can promote soil stability to a greater degree than a diversity of plant families and genera. For example, Leguminosae plants have higher rhizosphere microbial biomass than non-Leguminosae plants, thus improving soil stability [66], and the glommycin-related proteins secreted by arbuscular mycorrhizal fungi (AMF) have a 3–10 times stronger ability to adhere soil particles than other sugar substances [67]. Inoculation with rhizobia and mycorrhizal fungi can significantly increase the proportion of macro-aggregates [66]. Studies have also shown that the mechanism by which plants increase the stability of soil aggregates may be their roots [68]. Roots play a key role in soil aggregation because they transform loose soil particles into stable aggregates through root exudates. The fine roots of plants affect soil aggregation through the entanglement of fine root hyphae. The growth of fine roots and hyphae can stimulate microbial activity and promote the formation of large soil aggregates [69].

Most studies regard plant coverage as the key factor in soil stability [70]. A dense plant canopy will increase the surface roughness, act as a windbreak net and sediment trap, intercept raindrops, and reduce the evaporation of soil moisture [71]. In this study, we found that the coverage of plant communities can promote the stability of soil, and the intensity of the effect varies with different communities. This may be due to the increase in the surface vegetation coverage, which can reduce the damage to the soil epidermis and the loss of surface soil and nutrients, increase the organic matter input into the soil by litter, underground roots, and root exudates, and significantly increase the soil organic carbon and total nitrogen content [72–74], which in turn leads to an increase in the number of large soil aggregates. However, our findings indicate that, besides plant coverage, biodiversity may play a key role in the stability of soil aggregates. However, it is difficult to distinguish causality among these correlations. It is hard to say whether soil with high aggregate stability supports more species, or vice versa.

Wind-blown sand deposition is a common phenomenon in arid and semi-arid ecosystems. A large number of field observations and indoor simulation experiments have proved that plants are a necessary condition for wind-blown sand deposition. It has been shown that tufted plants can effectively influence the near-surface airflow and cause sedimentable particles carried in the wind-blown sand flow to be deposited among the plants [75,76]. The main component of the sedimentable particles carried by the wind-blown sand flow is soil clay particles [77]. Plants will lose water during transpiration and other processes, and some of the water may be dispersed among the soil clay particles at the base of plants, where it will act as an adhesive to bind the clay particles together and gradually form large-particle aggregates.

We preliminarily explored the mechanism of the influence of soil and vegetation properties on the stability of soil aggregates in desert plant communities. However, we did not include some of the important factors in this research. Vegetation roots contribute to soil fixation and reinforcement in arid areas, thus improving the soil's resistance to erosion [33]. Studies have shown that microbial diversity can promote soil stability [66,67]. Soil microbial diversity and plant roots also jointly influence soil aggregates. Our future studies on soil aggregates in arid regions will incorporate these two factors, helping us to better understand the plant–soil–microbe relationship.

5. Conclusions

The proportion and stability of soil aggregates in different plant communities were found to be obviously different. Soil physicochemical properties and vegetation properties varied in the different plant communities. Soil water content in the river bank and desert margin had a significant and direct positive effect on the MWD of the soil. The soil moisture also indirectly affected the soil stability by affecting the plant height, soil salinity, and organic carbon in the river bank. Salt and organic carbon had significant direct effects on soil aggregates, and soil salinity was found to indirectly affect soil aggregates by controlling the decomposition rate of soil organic carbon, vegetation distribution, and plant diversity. Phylogenetic richness had a negative effect on soil stability in the desert margin plant community, and plant community coverage had a positive effect on soil stability. The effect's intensity varied with the different communities, and the coverage of the plant communities had a greater effect on the soil stability in the desert margin plant community. In short, both soil properties and plant diversity had a significant impact on the soil stability of desert margin plant communities, but the mechanism of action changed with the type of plant community.

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