

Effects of Alfalfa-Crop Rotation Patterns on Soil Aggregate Stability and Organic Carbon: Post-print

Authors: Song Liping, Luo Zhuzhu, Li Lingling, Cai Liqun, Zhang Renzhi, Niu Yining

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Abstract

This study investigated the effects of six rotation patterns—alfalfa-alfalfa (L-L), alfalfa-fallow (L-F), alfalfa-wheat (L-W), alfalfa-maize (L-C), alfalfa-potato (L-P), and alfalfa-millet (L-M)—on soil aggregate stability and total organic carbon content in rain-fed farmland on the Longzhong Loess Plateau. The results demonstrated that across different rotation patterns, mechanically stable aggregates were dominated by aggregates ≥ 0.25 mm, comprising over 72.17% of the total, whereas water-stable aggregates were dominated by aggregates < 0.25 mm, comprising over 95.18%. With increasing soil depth, the content of aggregates ≥ 0.25 mm and the mean weight diameter (MWD) increased for all treatments, while the content of water-stable macroaggregates and MWD values exhibited no discernible pattern. Compared with the L-L treatment, the L-C and L-P treatments increased the content of aggregates ≥ 0.25 mm in the 0–30 cm topsoil layer by 5.94% and 1.12%, respectively, with the L-C treatment showing the highest MWD, whereas other rotation treatments reduced the content of aggregates ≥ 0.25 mm and MWD to varying degrees. Soil organic carbon content in all six rotation patterns decreased progressively with soil depth; in the 0–30 cm topsoil layer, the L-W, L-C, L-P, and L-M treatments reduced soil organic carbon content to varying degrees relative to the L-L treatment, with the L-P treatment showing the lowest organic carbon content (18.68% reduction). Correlation analysis revealed that soil total organic carbon was extremely significantly positively correlated with the proportions of water-stable aggregates in the 2–5 mm, 1–2 mm, 0.5–1 mm, and 0.25–0.5 mm size fractions and with MWD, while being extremely significantly negatively correlated with water-stable aggregates < 0.25 mm. In conclusion, the alfalfa-maize rotation pattern significantly enhanced soil aggregate mechanical stability, whereas different alfalfa-crop rotation patterns had relatively minor effects on water stability of soil aggregates; soil organic carbon content substantially influences the formation and stability of water-stable

granular structure, with the two being closely correlated.

Full Text

Preamble

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Effects of Lucerne-Crop Rotation Patterns on Soil Aggregate Stability and Organic Carbon*

SONG Liping¹, LUO Zhuzhu^{1,2**}, LI Lingling², CAI Liqun^{1,2}, ZHANG Renzhi², NIU Yining²

¹College of Resources and Environmental Sciences, Gansu Agricultural University, Lanzhou 730070, China

²Gansu Provincial Key Laboratory of Arid Land Crop Sciences, Lanzhou 730070, China

Abstract

A field experiment was conducted on dry farmlands of the Loess Plateau in central Gansu Province to investigate the effects of six lucerne-crop rotation patterns on soil aggregate stability and total organic carbon content. The rotation patterns included lucerne-lucerne (L-L), lucerne-fallow (L-F), lucerne-wheat (L-W), lucerne-corn (L-C), lucerne-potato (L-P), and lucerne-millet (L-M). The results showed that mechanically stable aggregates were dominated by 0.25 mm aggregates, accounting for over 72.17% of the total, whereas water-stable aggregates were dominated by <0.25 mm aggregates, exceeding 95.18%. With increasing soil depth, the content of 0.25 mm aggregates and mean weight diameter (MWD) increased, while larger water-stable aggregates and MWD showed no consistent pattern. Compared with the L-L treatment, the L-C and L-P treatments increased the content of 0.25 mm aggregates in the 0-30 cm tillage layer by 5.94% and 1.12%, respectively, with L-C showing the highest MWD. Other rotation treatments reduced the content of 0.25 mm aggregates and MWD to varying degrees. Soil organic carbon content decreased gradually with soil depth across all rotation patterns. In the 0-30 cm layer, L-W, L-C, L-P, and L-M treatments all reduced soil organic carbon content compared with L-L, with L-P showing the lowest organic carbon content (18.68% reduction). Correlation analysis revealed that total soil organic carbon was significantly positively correlated with the proportions of water-stable aggregates in the 2-5 mm, 1-2 mm, 0.5-1 mm, and 0.25-0.5 mm fractions and with MWD, but significantly negatively correlated with the <0.25 mm fraction. In conclusion, the lucerne-corn rotation pattern significantly increased soil aggregate mechanical stability, while different lucerne-crop rotation patterns had minimal effects on water stability. Soil organic carbon content strongly influenced the formation and stability of water-stable aggregate structure, with the two factors being

closely interrelated.

Keywords: Lucerne-crop rotation; Rotation pattern; Soil aggregate; Mechanical stability; Water stability; Soil organic carbon

Introduction

Soil aggregates are the fundamental units of soil structure, and their abundance largely reflects the capacity of soil to store nutrients, retain water, and maintain permeability [1]. Different aggregate size fractions play distinct roles in nutrient retention, supply, and transformation [2]. Good soil structure requires not only adequate aggregate quantity and appropriate size distribution but also sufficient stability, particularly water stability, to maintain multi-level pore structure without rapid deterioration under tillage, fertilization, irrigation, or raindrop impact [2]. Soil aggregates reveal soil structural conditions and serve as important indicators of soil fertility. Aggregate stability is primarily influenced by soil organic carbon content, fertilization practices, cropping systems, and rotation patterns [3].

Soil aggregates and soil organic carbon (SOC) are inseparable [4]; aggregation provides physical protection for SOC [5–7], while SOC promotes aggregate formation and stabilization [8]. Aggregates provide the habitat for SOC, and SOC acts as the cementing material for aggregates [4]. Soil organic carbon content significantly influences the formation and stability of water-stable aggregate structure and is a critical determinant of soil nutrient supply, fertility retention, tillage quality, and buffering capacity [9].

The lucerne (*Medicago sativa*)-crop rotation system is a long-established farming practice. The Loess Plateau is one of the most severely eroded regions globally, with an extremely fragile ecological environment [10–12]. Its unique topography and precipitation characteristics cause substantial soil loss, particularly of nutrient-rich surface soil. Lucerne roots possess strong nitrogen-fixing capacity, and the humus left by root nodules and extensive fibrous roots after lucerne cultivation increases soil organic matter and improves aggregate structure [13–15]. As an excellent legume for rotation and soil fertility restoration, lucerne is well-suited for rotation with grain crops to improve their quality and yield [16–17]. In crop cultivation, rational rotation utilizing the stubble characteristics of different crops can improve soil moisture, nutrient, aeration, and thermal conditions, maintaining soil fertility while preventing pests, diseases, and weeds, thereby achieving both yield increase and soil conservation [18]. Research indicates that in lucerne-crop rotation systems, biological nitrogen fixation by lucerne generally eliminates soil fertility constraints and continuously enhances soil fertility levels when converting farmland to lucerne pasture [19–21]. However, soil fertility typically declines when converting lucerne pasture back to cropland. Current research on lucerne-crop rotation systems has focused primarily on soil dry layer formation, water recovery effects, water use efficiency,

and impacts on yield and soil nutrients [16,22-23], with limited studies on soil aggregates and organic carbon.

This study investigated a lucerne-crop rotation experiment in a typical semi-arid rainfed agricultural region of the central Loess Plateau with severe soil erosion, examining the effects of different lucerne-crop rotation patterns on soil aggregate stability and organic carbon content. The objective was to identify rational rotation patterns to effectively improve soil quality, reduce soil erosion, and maintain sustainable soil productivity, providing a theoretical basis for sustainable lucerne pasture utilization and stable crop production in semi-arid regions of the Loess Plateau.

1.1 Study Area Description

The experiment was conducted in Mazichuan Village, Lizhuang Town, Anding District, Dingxi City, Gansu Province, located in the semi-arid hilly and gully region of the central Loess Plateau. The area has an average elevation of 2,000 m, mean annual solar radiation of $592.9 \text{ kJ} \cdot \text{cm}^{-2}$, sunshine duration of 2,476.6 h, mean annual temperature of $6.4 \text{ }^\circ\text{C}$, annual accumulated temperature $0 \text{ }^\circ\text{C}$ of 2,933.5 $^\circ\text{C}$, annual accumulated temperature $10 \text{ }^\circ\text{C}$ of 2,239.1 $^\circ\text{C}$, and a frost-free period of 140 days. Mean annual precipitation is 390.9 mm, with annual evaporation of 1,531 mm, aridity index of 2.53, guaranteed precipitation of 365 mm, and a variation coefficient of 24.3%, characterizing it as a typical rainfed dryland farming region. The soil is typical loessial soil (Huangmian soil), with soft texture, deep profile, uniform 质地, and good water storage capacity. The average soil bulk density in the 0-200 cm layer is $1.17 \text{ g} \cdot \text{cm}^{-3}$, wilting water content is 7.3%, and saturated water content is 21.9%.

1.2 Experimental Design

This study utilized a lucerne-crop rotation experimental field with six treatments and three replications arranged in a randomized block design. Each plot measured $3.0 \text{ m} \times 7.0 \text{ m}$. The test crops included alfalfa (*Medicago sativa*), spring wheat (*Triticum aestivum*), corn (*Zea mays*), potato (*Solanum tuberosum*), and millet (*Setaria italica*). Detailed descriptions of each treatment are provided in .

** Descriptions of different rotation patterns in the experiment**

Rotation Pattern	Description
Lucerne-lucerne (L-L)	Lucerne was continuously planted from 2003 to 2015.

Rotation Pattern	Description
Lucerne-fallow (L-F)	Lucerne was planted for 8 years from 2003, then grubbed up in March 2012 (before rainy season). The field was kept fallow until 2015.
Lucerne-wheat (L-W)	Lucerne was planted for 8 years from 2003, then grubbed up in March 2012. Spring wheat was planted in spring 2013 and continued until 2015.
Lucerne-corn (L-C)	Lucerne was planted for 8 years from 2003, then grubbed up in March 2012. Corn was planted in spring 2013 and continued until 2015.
Lucerne-potato (L-P)	Lucerne was planted for 8 years from 2003, then grubbed up in March 2012. Potato was planted in May 2012 and continued until 2015.
Lucerne-millet (L-M)	Lucerne was planted for 8 years from 2003, then grubbed up in March 2012. Millet was planted in April 2012 and continued until 2015.

1.3.1 Soil Aggregates

Aggregate soil samples were collected after crop harvest (October 2014) using the five-point method with a shovel at three depths: 0-10 cm, 10-30 cm, and 30-50 cm, with three replicates per layer. Disturbance was minimized during collection and transport to preserve aggregate structure. Samples were air-dried in the laboratory and broken into approximately 1 cm clods along natural structural planes for aggregate stability determination. Manual dry and wet sieving methods [24-25] were used to obtain aggregate contents across size fractions. Both methods employed five sieve levels with apertures of 5 mm, 2 mm, 1 mm, 0.5 mm, and 0.25 mm. The content of 0.25 mm aggregates ($R_{0.25}$) and mean weight diameter (MWD) were calculated.

1.3.2 Soil Organic Carbon

Organic carbon soil samples were collected after crop harvest (October 2014) using the S-shaped sampling method with a soil auger at three depths: 0-10 cm, 10-30 cm, and 30-50 cm. Stones and plant residues were removed, and samples

were mixed and reduced to approximately 1 kg using the quartering method, with three replicates per treatment. Samples were air-dried, ground, and passed through a 1 mm sieve for analysis. Soil organic matter was determined using the potassium dichromate oxidation method [26].

1.4 Data Processing and Analysis

Aggregate composition, structure, and stability were expressed using the percentage content of each aggregate fraction, R_i , and MWD. MWD reflects the size distribution of soil aggregates, with larger values indicating higher average aggregation [27]. The MWD calculation method is as follows:

Where: MWD is the mean weight diameter of aggregates; w is the weight proportion of aggregates in the i th size fraction; and x is the mean diameter of the i th aggregate fraction.

2.1 Mechanical Stability of Soil Aggregates Under Different Lucerne-Crop Rotation Patterns

Dry sieving provides the total quantity of aggregates in undisturbed soil, with the content of each size fraction reflecting mechanical stability. As shown in , in the 0-10 cm layer, aggregates measured by dry sieving were dominated by the <0.25 mm fraction (accounting for over 27% across treatments), except for L-C treatment where >5 mm aggregates were predominant, followed by <0.25 mm aggregates. In the 10-30 cm layer, all six rotation treatments showed >5 mm aggregates as the dominant fraction (average content 28.34%), followed by <0.25 mm aggregates (average 20.12%). In the 30-50 cm layer, similar patterns were observed.

2.4 Relationship Between Soil Organic Carbon Content and Water-Stable Aggregates

Soil aggregate formation depends on the cementing action of organic matter [30]. Stable aggregates can effectively protect the organic carbon they contain. Macro-aggregates (>0.25 mm) typically store more organic carbon but are vulnerable to disruption, forming micro-aggregates (<0.25 mm) that provide stronger physical protection for organic carbon and are considered the primary sites for carbon sequestration [31].

As shown in , soil organic carbon content under different lucerne-crop rotation patterns exhibited varying degrees of correlation with different aggregate size fractions. Significant positive linear correlations ($P < 0.01$) were observed with water-stable aggregates in the 2-5 mm, 1-2 mm, 0.5-1 mm, and 0.25-0.5 mm fractions, while a significant negative correlation ($P < 0.01$) was found with the <0.25 mm fraction. This indicates that higher total soil organic carbon content corresponds to greater macro-aggregate content and lower micro-aggregate content. Soil organic carbon also showed a highly significant positive correlation

with MWD ($P < 0.01$), demonstrating that higher organic carbon content increases mean aggregate weight diameter and water stability. Thus, soil organic carbon content is closely related to the distribution and stability of water-stable aggregates across size fractions.

** Correlations between total soil organic carbon and composition and mean weight diameter (MWD) of water-stable aggregates with different sizes**

Aggregate size (mm)	Regression equation	R ²
2-5	$Y = 6.131X + 8.360$	0.487**
1-2	$Y = 6.537X + 6.802$	0.551**
0.5-1	$Y = 2.664X + 7.875$	0.655**
0.25-0.5	$Y = 2.004X + 7.276$	0.628**
<0.25	$Y = -0.848X + 92.368$	0.645**
0.25	$Y = 0.848X + 7.577$	0.645**
MWD	$Y = 78.254X + 7.798$	0.621**

*Note: Y represents soil organic carbon content, X represents aggregate content of each size fraction and MWD. Sample size $n = 6$. ** indicates significant correlation at the 0.01 level.*

3 Discussion and Conclusion

In soil science, aggregates with equivalent particle diameters of 10–0.25 mm are classified as macro-aggregates. Higher macro-aggregate content indicates better soil aggregation, whereas <0.25 mm aggregates are mechanically unstable. A higher proportion of this fraction indicates greater soil dispersion, which can clog pores during rainfall and irrigation, reducing water infiltration, increasing surface runoff and soil erosion, and potentially causing dust storms [28]. MWD is a common indicator reflecting aggregate size distribution, with values increasing as large aggregate content increases. Larger MWD values signify higher average aggregate diameter and greater aggregate stability [32].

The results indicate that soil aggregates obtained by dry sieving across all rotation treatments were dominated by macro-aggregates (>0.25 mm), while wet sieving yielded predominantly micro-aggregates (<0.25 mm). With increasing soil depth, the content of >0.25 mm aggregates and MWD values under dry sieving increased gradually, while <0.25 mm aggregates decreased—findings consistent with studies by Wu et al. [33–34]. Conversely, under wet sieving, >0.25 mm aggregates and MWD values decreased with depth, with no clear pattern in aggregate size distribution across layers, similar to results reported by Cai et al. [1]. This suggests that mechanical stability of soil aggregates increases with soil depth, while water stability decreases with depth.

Compared with the lucerne-lucerne (L-L) treatment, the lucerne-corn (L-C) rotation significantly increased the content of >0.25 mm aggregates and MWD values

in the 0–30 cm tillage layer. This may be attributed to plastic film mulching in the L-C system, which maintained adequate soil moisture while minimizing human disturbance and direct raindrop impact, effectively preventing soil crusting and preserving favorable soil structure. However, in the 0–10 cm layer, all other rotation treatments reduced the content of 0.25 mm water-stable aggregates compared with L-L, with lucerne-fallow showing the lowest values, while effects on MWD of water-stable aggregates were non-significant and irregular. Barber [35] found in Wisconsin that lucerne increased soil water-stable aggregate index, which increased with lucerne planting duration over a 4-year period. This suggests that compared with undisturbed lucerne-lucerne soil, other rotation treatments intensified tillage disturbance in the plow layer, destroying macro-aggregates, causing aggregate redistribution, accelerating aggregate turnover, and impairing soil self-regulation and recovery processes, thereby destabilizing soil structure. Although the lucerne-lucerne pattern maintained higher water stability than other rotations, its mechanical stability was lower than that of the lucerne-corn pattern, possibly due to differential crop effects on soil quality and influences from microorganisms, enzymes, and root exudates that require further investigation.

Soil organic carbon content varied significantly among rotation patterns and soil depths. Across the 0–50 cm profile, all six rotation patterns showed decreasing organic carbon content with depth. Compared with lucerne-lucerne, converting long-term lucerne fields to wheat, corn, potato, and millet rotations all reduced soil organic carbon content to varying degrees. In the 0–30 cm layer, lucerne-potato rotation exhibited the lowest organic carbon content, while continuous lucerne-lucerne and lucerne-fallow maintained relatively high organic carbon content. This is partly because lucerne's strong nitrogen-fixing capacity and the humus from root nodules and fibrous roots increase soil organic carbon [13–14], while the lucerne-fallow soil, without crop consumption, retained higher organic carbon. Additionally, the long-term undisturbed lucerne-lucerne soil experienced less aggregate disruption, maintaining higher stability. Stable aggregates effectively protect stored organic carbon, with macro-aggregates typically storing more organic carbon [30]. Zhang et al. [36] demonstrated that rotation systems involving leguminous forage lucerne increased soil organic carbon storage and activated soil organic matter. However, other studies indicate that tillage disturbance after converting lucerne pasture to cropland causes rapid declines in soil total nitrogen and organic matter, accelerating soil degradation [37], consistent with our findings.

Soil organic carbon resides within aggregates and substantially influences aggregate formation and stability. Our results show that organic carbon content was highly significantly positively correlated with water-stable macro-aggregates (2–5 mm, 1–2 mm, 0.5–1 mm, 0.25–0.5 mm, and 0.25 mm fractions) and MWD, but highly significantly negatively correlated with the <0.25 mm fraction. This demonstrates the close relationship between soil organic carbon content and water-stable aggregates, with organic carbon increasing as the proportion of water-stable macro-aggregates increases—findings similar to Jiang et al. [37] and

Chen et al. [30]. Therefore, selecting appropriate rotation patterns is necessary to improve soil quality while maintaining fertility balance. Due to certain limitations, this study can only provide a macro-level theoretical foundation for selecting rational rotation patterns in the future, lacking investigation into the water-fertilizer effect mechanisms and micro-level processes of lucerne-crop rotation systems.

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