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The Impact of Soil Dry–Wet Cycles on the Mineralization of Soil Organic Carbon and Total Nitrogen in Check Dams of the Loess Plateau

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Abstract: Frequent soil drying and wetting cycles significantly affect the mineralization processes of soil organic carbon (SOC) and total nitrogen (STN), impacting soil quality and contributing to nutrient loss. However, the effects of these dry–wet cycles on SOC and STN mineralization in dam soil are not well understood. This study simulated four consecutive wet–dry cycles under five soil moisture gradients of 0% (CK), 5%, 10%, 15%, and 100%, and 100%, across four cycles of 7, 14, 21, and 28 days, to investigate the effects on soil aggregates, enzyme activities, and the mineralization of SOC and STN. The results indicated that soil enzyme activity peaked after two dry–wet cycles and then began to decline. The dry–wet cycles reduced the proportion of soil macro-aggregates while also decreasing the proportions of small and micro-aggregates. In contrast, the 100% treatment conditions exhibited the opposite effect. Dry–wet cycles enhanced the mineralization rates of SOC and STN, with the average mineralization rates under the 10% soil moisture content being the highest—1.78 and 2.38 times greater than the CK treatment for SOC and STN, respectively. The impact of dry–wet cycles on SOC and STN mineralization through the enzyme pathway was greater than through the aggregate pathway. These research findings provide theoretical insights and scientific references for the efficient operation and ecological protection of sedimentation dams in the Loess Plateau.

Keywords: dry–wet cycle; mineralization; soil organic carbon; total nitrogen; aggregate

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1. Introduction

In recent years, global climate change has become increasingly evident, with frequent extreme rainfall and drought events. These phenomena have increased the frequency of soil drying and wetting cycles. This process accelerates the loss of soil nutrients, such as soil organic carbon (SOC) and soil total nitrogen (STN) [1], severely impacting soil fertility and crop growth. Field and laboratory experiments have shown that these cycles intensify the emission of greenhouse gases like CO_2, N_2O, and CH_4 [2]. This trend is worsening worldwide, significantly constraining agricultural development and ecological restoration [3]. However, the effects of dry–wet cycles at different soil moisture levels on the mineralization of soil organic carbon and nitrogen remain unclear.

Soil dry–wet alternation is a short-term hydrological variation in the soil system that can change soil physical, chemical, and biological properties to a certain extent [4,5]. By changing the soil water content and porosity around the soil aggregates, the dry–wet alternation causes the aggregates to shrink and expand, which affects their formation, particle size distribution, and structural stability [6]. The soil aggregate microstructure and stability changed after wetting and drying treatments, as evaluated by micro-computed tomography [7]. Denef et al. observed a significant decrease in water-stable micro-aggregates and particulate organic matter compared to the control after two dry–wet cycles [8]. Soil microorganisms are an important driving force in soil element cycles [9]. Soil moisture changes caused by alternating wet and dry conditions affect soil microbial activity and community structure [10]. In the process of soil drying, a rapid decrease in soil water potential leads to osmotic shock, which leads to cell rupture and death, and the microbial community consists mainly of aerobic microorganisms. With the rewetting of dry soil, soil microbial activity is enhanced at the beginning of the process, and the microbial community changes to mainly anaerobic microorganisms. Soil bacterial and fungal communities are sensitive to dry–wet cycles, and changes in soil microbial diversity affect the biogeochemical processes of soil organic carbon and nitrogen cycles [11].

SOC and STN mineralization are significantly affected by dry–wet alternation [12]. When the dry soil is wet, the capillary air in the soil is squeezed, which can produce "air explosions", causing the expansion and cracking of soil aggregates [13]. Stable organic carbon and nitrogen in soil aggregates promote SOC and STN mineralization [14]. Frequent changes in soil moisture increase soil microbial and enzyme activities, which accelerates SOC and STN mineralization. The transition of soil from dry to wet conditions stimulates the activity of microorganisms, resulting in a short-term peak of CO_2 and N_2O release in the soil [15]. Some studies have shown that SOC can be significantly decomposed by multiple dry–wet alternations, but the intensity of soil organic carbon mineralization decreases with successive dry–wet cycles [5,16]. Soil moisture variation caused by dry–wet alternation is an important factor affecting SOC and STN mineralization. However, the effect of different soil water contents on soil organic carbon and nitrogen mineralization during dry–wet alternation has not yet been studied.

Check dams are important water and soil conservation measures for controlling soil erosion in the Loess Plateau of China. More than 5000 large check dams and 50,000 small- and medium-sized check dams have been constructed in the Loess Plateau [17]. Check dams can effectively prevent soil erosion by local retention of the sediment brought by a flood, making full use of the water and soil resources by forming a dam floor. Check dams were built in the channel, and the flooding process caused frequent alternations of dry and wet conditions in the dam soil. Prolonged drought and extreme rainfall events also intensify the drying and wetting cycles in check dam soils. However, there has been limited research on the mineralization of SOC and STN in dam soils during dry–wet cycles, and the extent to which different soil moisture levels impact this mineralization remains unclear.

Therefore, this study conducted laboratory-based simulations to investigate the characteristics of SOC and STN mineralization in sedimentation dams on the Loess Plateau under varying soil moisture gradients during drying–rewetting cycles. In parallel, we measured soil enzyme activity and changes in soil aggregate proportions to quantitatively analyze the contributions of soil moisture, aggregates, and enzyme activity to SOC and STN mineralization under these conditions. The findings provide theoretical and scientific support for the effective management and ecological restoration of check dams in the Loess Plateau.

2. Materials and Methods

2.1. Study Area

The experimental site is located at the check dam upstream of Dam No. 3 in the Xindiangou watershed in Suide County, Yulin City, Shaanxi Province, with coordinates 110°17′23″~110°17′29″ E and 37°30′59″~37°46′19″ N (Figure 1). Established in 1953, the

Xindiangou experimental site is situated on the left bank of the midstream section of the Wuding River, a primary tributary of the Yellow River, and comprises 24 silt dams covering a total area of 1.44 km^2. The elevation ranges from 800 m to 1100 m, typical of the hilly and gully region of the Loess Plateau, with a gully density of approximately 7.26 km/m^2. The site experiences an average annual temperature of 9.7 °C and a long-term average precipitation of about 486 mm. The study plot covers approximately 6000 m^2 and is divided into main and tributary gullies. The slope of the left bank of the main gully is about 60° and is covered with vegetation, with forests at the base, while the right bank is nearly vertical and predominantly exposed loess. The pH of the soil at a depth of 0–10 cm is 8.53 ± 0.01, while the pH at a depth of 10–20 cm is 8.72 ± 0.01. The bulk density of the soil at 0–10 cm depth is 1.21 ± 0.07 g/cm^3, and at 10–20 cm depth, it is 1.29 ± 0.04 g/cm^3. The vegetation distribution in the dam area varies; low shrubs dominate near the dam, trees are prevalent in the central part, and herbaceous plants are mainly found at the dam's end [18].

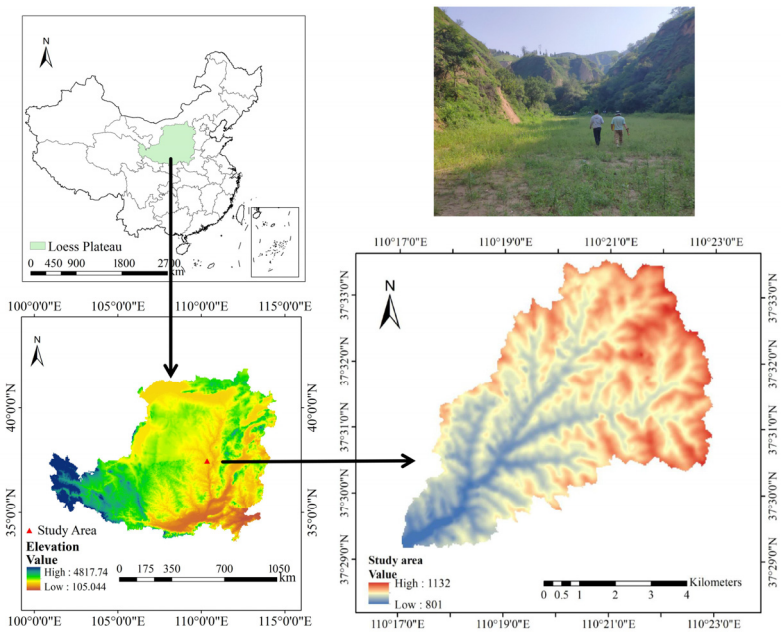


Figure 1. Study area.

2.2. Dry–Wet Cycle Experiment

In this study, undisturbed soil samples were collected from the top 20 cm of the main channel area at the dam site of the Xindiangou watershed. In the main channel area of the Xindiangou watershed, we collected 15 undisturbed surface soil samples (0–20 cm depth) using aluminum boxes, with three replicates set for each soil moisture gradient. After transporting the samples to the laboratory, stones, weeds, roots, and other debris were removed, and the soil was air-dried for future use.

A 500 g sample of air-dried soil was placed in a light-excluded incubator set to 25 °C to begin the dry–wet cycle experiment. The experiment established five soil moisture gradients: 0% (CK), 5%, 10%, 15%, and 100%, with CK serving as the control group, which remained dry throughout the experiment. The 100% treatment group was maintained under prolonged flooding conditions, with deionized water replenished every 24 h. On days 0, 7, 14, and 21 of the cultivation period, deionized water was used to saturate the soil to the specified moisture levels, followed by a 7-day natural drying period. Destructive sampling of the cultivated soil was conducted before the experiment began and after completing the full drying and wetting cycles (on days 7, 14, 21, and 28), measuring soil organic carbon (SOC), total nitrogen (STN), soil enzyme activity, and the composition ratios of soil aggregates.

2.3. Sample Determination and Analysis

This study employed the microplate fluorescence labeling method using the SpectraMax iD3 to measure the activity of enzymes related to soil carbon and nitrogen cycling, particularly leucine aminopeptidase and β-glucosidase. Although alkaline phosphatase has a strong correlation with phosphorus cycling, it was included due to its close association with soil microbial mineralization rates [19]. SOC was measured with a TOC analyzer (Elementar, Hanau, Germany), and STN was determined using a Kjeldahl nitrogen analyzer. The Yoder method [20] was used to determine soil aggregates during each dry–wet cycle, resulting in three aggregate size classes: macro aggregates (>5 mm), small aggregates (0.25–5 mm), and micro aggregates (<0.25 mm). Soil moisture content was measured with a portable soil moisture meter. A portable soil moisture meter was used to determine whether each experimental group achieved the predetermined soil moisture content.

2.4. Mineralization Calculation

SOC and STN cumulative mineralization and mineralization rates were calculated using Equations (1) and (2):

$$CSM_i = SMC_0 - SMC_i \tag{1}$$

$$RSM_i = \frac{CSM_i - CSM_{i-1}}{\Delta T} \tag{2}$$

where CSM_i is the total cumulative mineralization from the start of incubation to moment i; SMC_0 is the initial soil SOC or STN content before the start of incubation; SMC_i is the SOC or STN content at moment i after the start of incubation; RSM_i is the rate of soil mineralization at moment i after the start of incubation; CSM_{i-1} is the cumulative soil mineralization at moment $i-1$; and ΔT is the time difference between moments i and $i-1$.

The equation for calculating soil enzyme activity is

$$A_b = \frac{1000FV}{eV_1tm} \tag{3}$$

$$F = \frac{f - f_b}{q} - f_s \tag{4}$$

$$e = \frac{f_r}{C_sV_2} \tag{5}$$

$$q = \frac{V_q - V_b}{f_r} \tag{6}$$

where A_b represents the calculated enzyme activity (μmol/g/h); F is the corrected fluorescence value; V is the volume of the soil suspension (125 mL); V_1 is the volume of the added suspension (0.2 mL); t is the incubation time in the dark; m is the mass of dry soil; f is the fluorescence value of the sample well; f_b is the fluorescence value of the blank well; q is the quenching factor; f_s is the fluorescence value of the negative control well; e is the fluorescence release coefficient; f_r is the fluorescence value of the reference standard well; C_s is the concentration of the reference standard well (10 μmol/L); V_2 is the volume of the standard reference (0.05 mL); and V_q is the fluorescence value of the quenching standard well.

2.5. Statistical Analyses

The Shapiro–Wilk test was used to determine normality, and all data showed a normal distribution ($p > 0.05$). A one-way ANOVA was used to identify the effects of dry–wet cycles and soil moisture on SOC and STN mineralization. Pearson's correlation analysis was conducted to analyze the relationships between environmental factors and SOC and STN mineralization. A structural equation model (SEM) was used to evaluate the direct and indirect effects of dry–wet cycles and soil moisture on SOC and STN mineralization.

3. Results

3.1. Effects of Dry–Wet Cycles on Soil Aggregates

The dry–wet cycle process significantly alters the composition ratio of soil aggregates. Soil macro- (>5 mm), small (0.25–5 mm), and micro-aggregates (<0.25 mm) in the no dry–wet cycle treatment (CK) were 76.38%, 13.52%, and 10.09%, respectively (Table 1). Under the dry–wet cycle of 5%, the soil macro-, small, and micro-aggregates were 55.61%, 22.03%, and 22.36%, respectively. With the dry–wet cycle of 10%, soil macro-aggregates decreased to 55.41%, and soil small and micro-aggregates decreased to 18.89% and 25.70%, respectively. The average proportions of soil macro-, small, and micro-aggregates under the dry–wet cycle of 15% were 57.25%, 21.19%, and 21.56%, respectively. The submergence treatment (100%) increased the proportion of soil macro-aggregates to 93.88% and decreased soil small and micro-aggregates.

Table 1. Effects of dry–wet cycles on soil aggregate (%).

Dry–Wet Treatment	Soil Macro-Aggregates (>5 mm)	Soil Small Aggregates (0.25–5 mm)	Soil Micro-Aggregates (<0.25 mm)
CK	76.38 ± 4.23	13.52 ± 2.31	10.09 ± 2.21
5%	55.61 ± 5.89	22.03 ± 2.74	22.36 ± 5.52
10%	55.41 ± 4.69	18.89 ± 2.89	25.71 ± 1.89
15%	57.25 ± 11.79	21.19 ± 6.30	21.56 ± 5.63
100%	93.88 ± 6.79	4.84 ± 1.04	1.28 ± 0.09

3.2. Changes in Soil Organic Carbon Mineralization with Dry–Wet Cycles

SOC continuously decreased with an increasing number of dry–wet cycles. The soil organic carbon (SOC) content experienced the most significant decline during the first wet–dry cycle, after which the rate of decrease gradually slowed. After four cycles, the SOC content in the 5%, 10%, and 15% treatment groups decreased by 40.65%, 42.51%, and 37.43%, respectively, while the decrease in the CK and 100% treatment groups was less pronounced (Figure 2a). The SOC contents of the no dry–wet cycle treatment (CK) decreased from 16.28 g/kg to 12.40 g/kg after the 28d experiment, with a decline of 23.80%. The 100% treatment had a higher SOC content than the other dry–wet cycle treatments, and the decrease was 13.69% within the experiment.

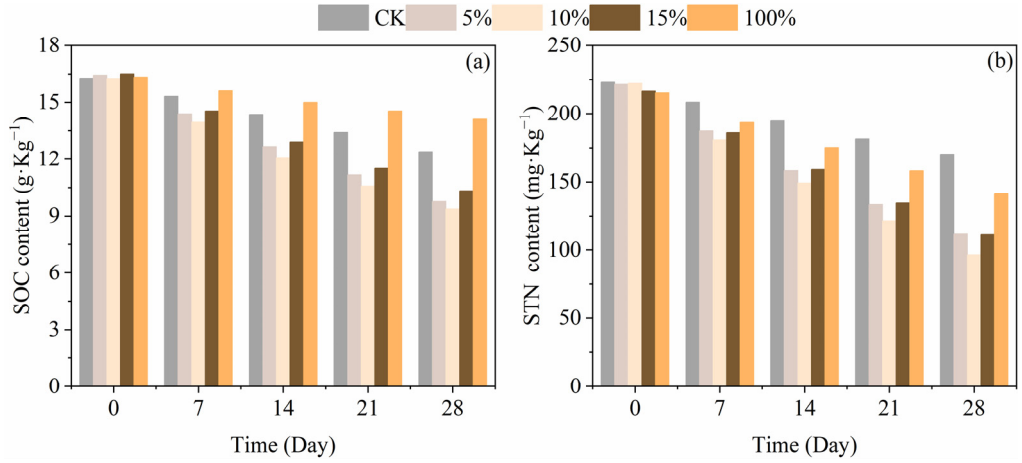


Figure 2. Changes in SOC and STN content with dry–wet cycles. (The data values represent the average from three replicates for each treatment, with n = 3). (**a**) represents SOC, and (**b**) represents STN.

After the dry–wet cycle treatments (5%, 10%, and 15%), both the SOC mineralization amount and rate were significantly higher than those in the CK and 100% treatments

(Figure 3a). The SOC mineralization rate exhibited a continuous downward trend. This may be related to the depletion of mineral substrates during the mineralization process. In the CK and 100% treatments, the rate remained relatively stable throughout the incubation period, ranging between 13.53 and 14.17 g/kg/d and 0.06 and 0.11 g/kg/d, respectively. The 10% treatment showed the greatest fluctuation in SOC mineralization rate, with the rate after the fourth dry–wet cycle being only 52.28% of that after the first cycle.

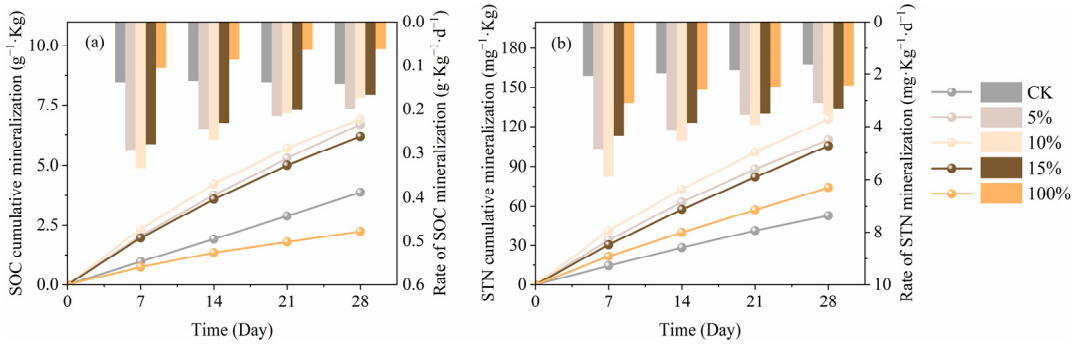


Figure 3. Mineralization of SOC and STN with dry–wet cycles. (The rate of mineralization is represented by a bar graph and the cumulative mineralization is represented by a point and line graph. The data values represent the average from three replicates for each treatment, with $n = 3$). (**a**) represents SOC, and (**b**) represents STN.

3.3. Changes in Soil Total Nitrogen Mineralization with Dry–Wet Cycles

Similar to SOC, the STN content decreased as the number of dry–wet cycles increased. After four cycles, the 10% treatment exhibited the lowest STN content, at only 96.67 mg/kg, representing a reduction of 56.5% (Figure 2b). The STN content in the 5% and 15% treatments decreased by 49.59% and 48.61%, respectively, after four cycles. In contrast, the CK and 100% treatments, which were not subjected to dry–wet cycles, experienced less STN loss, with reductions of 23.62% and 34.47%, respectively, by the end of the incubation period compared to initial conditions.

Compared to the CK and 100% treatments, the drying–rewetting cycles led to higher cumulative mineralization and mineralization rates of STN. The average mineralization rates across treatments followed this order: 10% > 5% > 15% > 100% > CK (Figure 3b). The mineralization rate of STN decreased over time, with the 10% treatment showing the largest decline (39.43% reduction from the initial rate), followed by the 5% and 15% treatments with reductions of 36.26% and 24.10%, respectively. In contrast, the CK and 100% treatments, which were not subjected to drying–rewetting cycles, exhibited smaller changes in mineralization rates, ranging from 1.62 to 2.07 mg/kg/d and 2.43 to 3.10 mg/kg/d, respectively.

3.4. Effects of Dry–Wet Cycles on Soil Enzyme Activities

The activities of leucine aminopeptidase, β-1,4-glucomannase, and alkaline phosphatase were highest in 10% in the 28d experiment, followed by 5% and 10%, with the lowest values in 100% (Figure 4). Soil enzyme activities of 5%, 10%, and 15% increased during the first and second dry–wet cycles and then decreased. The activity of β-1,4-glucomannase and alkaline phosphatase decreased more rapidly after the second wet–dry cycle, while the decline in leucine aminopeptidase activity occurred more gradually. The activity of leucine aminopeptidase ranged from 8.12 to 11.89 μmol/mg/h, which was highest after the second dry–wet cycle of 10%. Leucine aminopeptidase activity in the different dry–wet treatments followed the order: 10% > 5% > 15% > CK > 100%. The activities of β-1,4-glucomannanase and alkaline phosphatase were similar to that of leucine aminopeptidase.

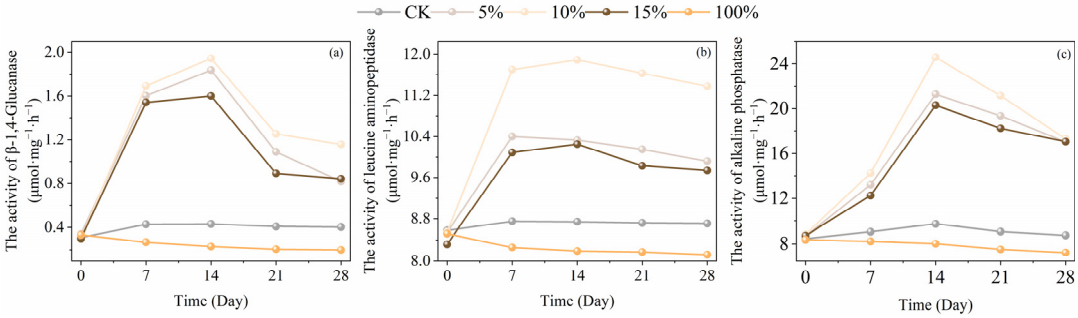


Figure 4. Changes in soil enzyme activities with dry–wet cycles. (The data values represent the average from three replicates for each treatment, with n = 3). (**a**) represents The activity of β -1,4-Glucanase, (**b**) represents leucine aminopeptidase, and (**c**) represents alkaline phosphatase.

3.5. The Impacts of Environmental Factors Associated with the Dry–Wet Cycle on SOC and STN Mineralization

SOC mineralization was significantly correlated with soil moisture, the dry–wet cycle, soil enzyme activity, and soil aggregates ($p < 0.01$). The correlation coefficient was the highest between SOC mineralization and the dry–wet cycle, followed by soil moisture (Table 2). STN mineralization was significantly correlated with the dry–wet cycle, soil enzyme activity, and soil aggregates ($p < 0.01$). The correlation coefficient was highest between SOC mineralization and the dry–wet cycle, followed by soil aggregates. Soil moisture and soil aggregates were negatively correlated with STN mineralization. In contrast, the dry–wet cycle and soil enzyme activity were positively correlated with SOC and STN mineralization.

Table 2. Relationships between environmental factors and SOC and STN mineralization.

Group	Soil Moisture	Dry–Wet Cycle	Soil Enzyme Activity	Soil Aggregate
SOC mineralization	−0.319 **	0.613 **	0.423 **	−0.433 **
STN mineralization	0.016	0.457 **	0.290 **	−0.416 **

Note: ** The relationship was significant at 0.01 level.

SEM analysis (Figure 5) showed that dry–wet cycles had significantly positive effects on SOC (with a direct effect of 0.51) and STN (a direct effect of 0.65) mineralization ($p < 0.05$). Soil moisture had a negative effect on SOC mineralization (a direct effect of −0.18), whereas it had a positive effect on STN mineralization (a direct effect of 0.30). The cycles of dry–wet alternation had significantly positive effects on soil enzyme activities ($p < 0.001$), with direct effects of 1.07 and 1.04 for pathways from SOC and STN mineralization, respectively. In contrast, the cycles of dry–wet alternation had significantly negative effects on soil aggregates, with direct effects of −1.12 and −1.17 for pathways from SOC and STN mineralization, respectively. Dry–wet cycles and soil moisture had significant indirect effects on SOC (with an indirect effect of 0.50) and STN (an indirect effect of 0.71) mineralization through the soil enzyme pathway ($p < 0.05$). Similarly, dry–wet cycles and soil moisture had indirect effects on SOC (an indirect effect of 0.39) and STN (an indirect effect of 0.45) mineralization through the pathway of soil aggregates.

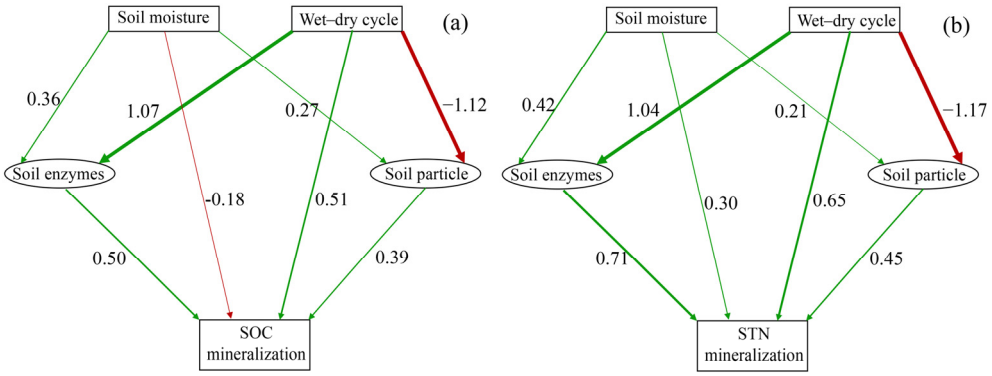


Figure 5. Describing the effects of dry–wet cycles on SOC and STN mineralization based on structural equations (SEM). (**a**) represents SOC, and (**b**) represents STN. The red line represents the negative impact, the green line represents the positive impact, and the line width represents the absolute value of the impact.

4. Discussion

4.1. Changes in Soil Aggregate Composition Drive the Mineralization of SOC and STN

The dry–wet alternation causes the pulse effect of SOC and STN mineralization and significantly increases the cumulative carbon and nitrogen release [16]. This phenomenon is called the "Birch Effect", named after H.F. Birch, who reported humus decomposition and nitrogen availability peaks upon rewetting soils in East Africa [21]. Although we lack a complete mechanistic understanding of this effect, the major drivers include soil porosity, aggregate dispersion, and soil biogeochemical cycling [5,9].

Swelling and shrinkage often occur during soil wetting and drying, which changes the porosity distribution and results in soil volume. In particular, alternating soil wetting and drying mainly changes the pore structure between aggregates or within aggregates, shrinks and expands aggregates, and changes the particle size of soil aggregates [22]. Dry–wet cycles change the aggregate size through two stages: during the drying process, the soil moisture evaporates, the outside air enters the soil pores, the bubbles between the pores of the aggregates expand, the aggregates are squeezed and shrink, and their particle size decreases; during the wetting process, water enters the soil pores, and the bubbles between the pores of the aggregates are squeezed [23]. At the same time, the aggregates have a certain hydration resistance and expand due to water absorption, resulting in an increase in the particle size of the aggregates. Degens and Sparling found a rapid decline of 48–65% in soil macro-aggregates after the first two dry–wet cycles [24]. Denef et al. observed that the first drying and wetting event reduced the amount of macro-aggregates from 30 to 21% of the total soil weight [8]. Similar results were found in this study, where dry–wet cycles promoted the breaking of macro-aggregates into smaller aggregates. After four soil dry–wet cycles, the percentage of soil macro-aggregates decreased to 55.61%, 55.41%, and 57.25% in the 5%, 10%, and 15% treatments, respectively (Table 1), while the percentage of soil small and micro-aggregates increased to varying degrees. Soil aggregates have a physical protective effect on SOC and STN in aggregates [25], and spatial isolation between organisms and organic carbon and nitrogen is an important mechanism affecting nutrient cycles [26].

The results of the SEM analysis indicated that the indirect effects of dry–wet cycles on SOC and STN mineralization through the pathway of soil aggregates were 0.39 and 0.45, respectively. Macro-aggregates provide substantial physical protection for organic matter, reducing the likelihood of degradation due to direct contact with microbes and soil enzymes [25]. The results of this study show that after four dry–wet cycles, the content of macro-aggregates decreased significantly, while small and micro-aggregates increased. The breakdown of large aggregates exposed previously protected SOC and STN to external conditions, making them more susceptible to microbial decomposition, which indirectly increased SOC and STN mineralization. Compared to macro-aggregates, small and micro-

aggregates are less stable and more prone to fragmentation and reformation. Although the organic matter within these aggregates is closely bound to minerals, this protective effect is weakened under dry–wet cycles, making the carbon and nitrogen in small and micro-aggregates more susceptible to mineralization.

Additionally, the results of this study indicate that under conditions of prolonged drought (CK) and long-term flooding (100% soil moisture), the proportion of macro-aggregates remained relatively high, and the mineralization rates of SOC and STN were low. In the CK treatment, due to consistently low soil moisture and the absence of human disturbance, soil cementing substances gradually solidified, resulting in tightly bound soil particles. This characteristic contributed to the relative stability of soil aggregates, especially macro-aggregates, with fewer instances of physical breakdown. On the other hand, prolonged water deficiency resulted in reduced microbial activity and soil enzyme activity (Figure 4), leading to a slower decomposition rate of organic matter and, consequently, lower SOC and STN mineralization rates. Under long-term waterlogged conditions, the soil remains continuously saturated. Although excessive moisture may weaken the structural stability, the soil does not shrink due to drying. This prevents aggregates from undergoing the intense physical stress and breakdown caused by dry–wet cycles, thereby maintaining their structural integrity. Moreover, the waterlogged environment leads to anaerobic conditions, inhibiting the metabolic activity of most microbes, which in turn reduces the mineralization of SOC and STN.

4.2. The Interaction Between Soil Enzyme Activity and the Mineralization of SOC and STN

Soil enzymes are the main participants in soil biochemistry and play an important role in the SOC and STN cycles. Soil enzyme activities increased after the first and second dry–wet cycles in this study. Similar results were found by [10], where drying–rewetting treatment increased β-glucosidase activity by 10–13%. Drought inhibits soil enzyme activity, and this phenomenon has been attributed to the limitation of ion diffusion in soil water and a reduction in the accessibility of soil microbes to their substrates [27]. Rewetting of dried soils accelerates microbial exoenzymatic activity and results in a flush of soil mineralization. The dry–wet pulses may be attributed to several processes: (1) dry–wet processes can damage soil microbial and root cells, releasing organic carbon and nitrogen into the soil solution, which may directly affect soil organic matter decomposition and nutrient cycling [3]; (2) drying and wetting cycles increase visible macroporosity, thus improving soil oxygen content [28]; and (3) more substrates become available through the disruption of aggregates [29]. However, the stimulating effects on enzyme activities decreased gradually with an increase in dry–wet cycles. The third and fourth dry–wet cycles had lower enzyme activities than that of the first and second cycles, which may be the reason for material decomposition and substrate reduction. Soil nutrients and organic carbon are fundamental for microbial mineralization activities. The content of SOC influences microbial activity and community structure involved in nitrogen transformation, thereby regulating the rate of STN mineralization [30].

The 10% treatment exhibited the highest SOC and STN mineralization rates, as well as cumulative mineralization amounts (Figure 3). The humidity environment provided by the 10% moisture content is relatively moderate, preventing limitations on microbial activity due to complete soil desiccation while also avoiding excessively low soil oxygen levels that can occur with higher moisture content [31]. Additionally, the three enzyme activities in the 10% treatment were also the highest (Figure 4), which further enhanced the decomposition rates of organic matter and nutrients such as nitrogen and phosphorus in the soil. The elevated enzyme activity levels are likely directly related to the highest proportion of small aggregates in the 10% treatment. These small aggregates create a more stable microenvironment, mitigating drastic changes in soil structure during the dry–wet cycles, thereby enabling the 10% treatment to maintain higher enzyme activity [32].

The results of the SEM analysis indicated that the indirect effects of dry–wet cycles on SOC and STN mineralization through the pathway of soil enzymes were 0.50 and 0.71,

respectively. Soil enzymes act as crucial catalysts in the mineralization process. Dry–wet cycles accelerate the turnover of soil organic carbon and nitrogen by influencing enzyme activity [20,33]. Leucine aminopeptidase is a hydrolase enzyme that primarily breaks down proteins and peptides, releasing amino acids. Higher activity of leucine aminopeptidase increases the rate at which proteins are degraded into amino acids, thereby enhancing the mineralization of STN. In the context of dry–wet cycles, the impact of soil enzyme activity on SOC mineralization involves the role of cellulose and hemicellulose, which are significant components of soil organic carbon. β-1,4-glucomannase degrades these macromolecules into simple sugars like glucose. Microbes metabolize these sugars, releasing carbon dioxide and thus increasing SOC mineralization [34]. Although alkaline phosphatase is most closely associated with phosphorus cycling, it also has an indirect impact on SOC and nitrogen mineralization. By breaking down organic phosphorus, it facilitates microbial utilization of organic matter, including carbon and nitrogen compounds, thereby increasing the rates of carbon and nitrogen metabolism and mineralization.

One of the primary functions of siltation dams is to prevent soil and water loss, which indirectly reduces the lateral loss of nutrients [30,35]. In areas where dams have already been constructed, frequent wet–dry cycles not only destabilize soil structure but also increase erosion during erosion events, leading to soil degradation. Additionally, the accelerated mineralization process can result in the rapid release of soil nutrients, negatively impacting crop growth and yield [28]. Furthermore, the significant greenhouse gas emissions (such as carbon dioxide) produced during mineralization can also have varying degrees of adverse effects on the environment. In summary, understanding the impact of dry–wet cycles on soil carbon and nitrogen cycling can provide valuable insights into the sustainable management of sedimentation dams [7]. Particularly in arid and semi-arid ecosystems, implementing water and soil conservation measures to artificially intervene and regulate soil moisture content can enhance soil resistance to erosion and effectively prevent significant losses of SOC and STN [6,34]. This approach can help mitigate agricultural ecological issues arising from land degradation.

Lastly, the results of this study were derived from laboratory-based simulations. However, the SOC and STN mineralization processes driven by soil dry–wet cycles are complex and influenced by multiple environmental factors. To better understand the impact of dry–wet cycles on the spatiotemporal patterns of SOC and STN in the sedimentation dams of the Loess Plateau, future research should include field observations. It is essential to account for factors such as rainfall and temperature while simultaneously monitoring the concentrations of greenhouse gases such as CO_2 and N_2O. This will allow for a more detailed description of the carbon and nitrogen cycling characteristics driven by the dry–wet cycles in the Loess Plateau check dams.

5. Conclusions

This study investigated the effects of dry–wet cycles on soil organic carbon (SOC) and total nitrogen (STN) mineralization by conducting simulated dry–wet cycle tests on soil from a check dam site. Soil enzyme activity exhibited a pattern of increasing initially, followed by a decrease during the dry–wet cycling process, with peak enzyme activity occurring after the second cycle. Dry–wet cycling increased the proportion of macro-aggregates and reduced the content of small and micro-aggregates in the soil. Increased soil enzyme activity and alterations in soil aggregate composition during dry–wet cycling collectively enhanced the mineralization of SOC and STN. The mineralization of SOC and STN was largest during the dry–wet cycles when the soil moisture content was 10%. Prolonged inundation minimized SOC mineralization, whereas prolonged drought led to the lowest STN mineralization.

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