Response of Soil Non-protected Organic Carbon to Desertification in Desert Steppe Postprint

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Abstract

The restoration and reconstruction of desertified grasslands constitute an important component of ecological construction in arid and semi-arid regions. Analyzing the variation patterns of soil non-protected organic carbon allocation ratios during desert steppe desertification holds significant theoretical value for exploring the restoration mechanisms of desertified grasslands. Using soils from desert steppe at different desertification stages in arid and semi-arid regions as the research object, this study analyzes the distribution characteristics of coarse particulate organic carbon, fine particulate organic carbon, and light fraction organic carbon content and allocation ratios, as well as the conversion rate from non-protected organic carbon to protected organic carbon. The results indicate that following reverse succession in desert steppe, soil fine particulate organic carbon content and allocation ratio exhibit the pattern: fixed sand > desert grassland > semi-fixed sand > mobile sand; coarse particulate organic carbon content shows the pattern: desert grassland > semi-fixed sand > mobile sand > fixed sand, while coarse particulate organic carbon allocation ratio shows the pattern: mobile sand > semi-fixed sand > desert grassland > fixed sand; and light fraction organic carbon content and allocation ratio decrease progressively. Particulate organic carbon, light fraction organic carbon, and soil organic carbon exhibit different sensitivities to grassland desertification, with particulate organic carbon being more sensitive than light fraction organic carbon and soil organic carbon, and fine particulate organic carbon being more sensitive than coarse particulate organic carbon. As the degree of grassland desertification intensifies, the allocation ratio of soil non-protected organic carbon shows a declining trend, indicating that grassland desertification reduces soil quality. The rate of conversion from soil non-protected organic carbon to protected organic carbon shows an overall increasing trend as desert grassland degrades to mobile sand.

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Preamble

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Response of Unprotected Soil Organic Carbon to Desertification in Desert Grassland

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Abstract

The restoration and reconstruction of desertified grassland in arid and semiarid regions are critical components of regional ecological construction. Changes in unprotected soil organic carbon across different desertification stages of desert grassland are important for understanding the mechanisms of grassland desertification. This study investigated the characteristics of coarse particulate organic carbon (CPOC), fine particulate organic carbon (FPOC), light-fraction organic carbon (LFOC), and the rate constant for carbon transfer from unprotected to protected soil pools in desert grassland at different desertification stages in arid and semiarid regions. Results demonstrated that during desert grassland desertification, the ranking of FPOC content and proportion was fixed dunes > grasslands > semi-fixed dunes > mobile dunes. CPOC content ranked as grasslands > semi-fixed dunes > mobile dunes > fixed dunes, while CPOC proportion ranked as mobile dunes > semi-fixed dunes > grasslands > fixed dunes. LFOC content and proportion decreased gradually during desertification. Particulate organic carbon (POC) was more sensitive to grassland desertification than LFOC and SOC, with FPOC showing greater sensitivity than CPOC, LFOC, and SOC. The proportion of unprotected soil organic carbon decreased gradually during desertification, indicating declining soil quality. The rate constant for carbon transfer from unprotected to protected pools increased gradually during desertification (from grasslands to mobile dunes).

Keywords: particulate organic carbon; light-fraction organic carbon; unprotected soil organic carbon; desertification; desert grassland

1. Study Area Overview

The study area was located in Wanjigou Village, Huamachi Town, Yanchi County, Ningxia Hui Autonomous Region (37°49 N, 107°27 E), in the transition zone from the Ordos Plateau to the Loess Plateau. The region has a typical continental monsoon climate with an average annual temperature of 8.2°C and average annual precipitation of 280 mm, which varies significantly between years. The hottest and coldest months are July (22.4°C) and January (-8.7°C), respectively. The frost-free period is 165 days, with prevailing wind speeds of 2.8 m/s and maximum wind speeds of 17 m/s. The terrain slopes from south to north at an elevation of 1411–1435 m. Soils are primarily zonal sierozem and light sierozem with loose structure, dominated by fine sand particles (50–100 m), silt (2–50 m), and clay (<2 m). Soil pH ranges from 8.94 to 9.22, with organic carbon content of 2.3 g/kg, total nitrogen of 0.2 g/kg, total phosphorus of 0.4 g/kg, available nitrogen of 9.0 mg/kg, and available phosphorus of 2.1 mg/kg. Vegetation consists mainly of desert and psammophytic species, with dominant plants including *Pennisetum centrasiaticum*, *Artemisia scoparia*, *Leymus secalinus*, *Aster altaicus*, *Corispermum hyssopifolium*, and *Sophora alopecuroides*. Due to drought and poor substrate conditions, plants grow stunted.

2. Methods

2.1 Plot Selection

Severe degradation and desertification of desert grassland result from human disturbances such as overgrazing and environmental factors like drought. Based on vegetation community characteristics and coverage changes, the desertification process follows a sequence: desert grassland → fixed dunes → semi-fixed dunes → mobile dunes. The study area contains grasslands at different desertification stages. Using vegetation indicators and coverage classification standards, we selected representative plots at each desertification stage (desert grassland, fixed dunes, semi-fixed dunes, and mobile dunes) as replicate sampling areas with consistent topography and environmental conditions. Desert grassland served as the control. Each plot measured 50 m × 50 m.

2.2 Soil Sampling

At the end of August 2015, five 1 m × 1 m quadrats were randomly established in each desertification stage. Soil samples were collected from three depths (0–10, 10–20, and 20–30 cm) using a 5 cm diameter soil auger. Samples from each quadrat were mixed, bagged, air-dried, sieved (2 mm), and cleared of visible roots and debris.

2.3 Soil Sample Analysis

Soil total organic carbon was determined by the potassium dichromate external heating method.

Particulate organic carbon (POC): Following Liu Mengyun [22], 20 g of air-dried soil was dispersed in 100 mL of 0.01 mol/L sodium hexametaphosphate solution on a reciprocating shaker (90 r/min) for 15 minutes. The suspension was wet-sieved through 250 m and 53 m sieves. The retained materials were separated into coarse particulate organic matter (CPOM, 250-2000 m) and fine particulate organic matter (FPOM, 53-250 m), oven-dried, weighed, and ground for organic carbon analysis. Coarse and fine POC contents were calculated by multiplying carbon concentration by mass percentage. The ratio of each fraction to total soil organic carbon represented its allocation proportion.

Light-fraction organic carbon (LFOC): Following Janzen et al. [23], 5 g of air-dried soil was placed in a 250 mL centrifuge tube with 40 mL of NaI solution (1.6 g/cm³ density). After ultrasonic dispersion (300 W, 15 min) and centrifugation (3500 r/min, 15 min), the supernatant was vacuum-filtered through a 0.45 m membrane. The residue was washed with 100 mL of 0.01 mol/L CaCl and 200 mL of distilled water, then dried and analyzed for organic carbon content. LFOC proportion was calculated as the ratio of LFOC to total organic carbon.

Unprotected organic carbon proportion: Since POC and LFOC are both non-protected components of soil organic carbon, their average allocation proportion was used to represent the unprotected organic carbon proportion [24].

Sensitivity index: Calculated following Bremner et al. [25] as: (Maximum value - Minimum value) / Minimum value.

Transformation rate constant: The rate constant for carbon transfer from unprotected to protected pools was calculated following Garten et al. [24] as: (Protected organic carbon content) / (Unprotected organic carbon content × Protected carbon turnover time (100 years)).

2.4 Data Analysis

SPSS 19.0 was used for statistical analysis. One-way ANOVA and LSD tests were performed to analyze differences among desertification stages at $P < 0.05$ significance level.

3. Results

3.1 Coarse Particulate Organic Carbon Content and Allocation

Grassland desertification significantly affected soil coarse particulate organic carbon (CPOC) content and allocation ($P < 0.05$). In the 0-30 cm layer, CPOC content in semi-fixed dunes, fixed dunes, and mobile dunes decreased by 5.3%, 5.1%, and 15.9% compared to desert grassland, respectively. In the 0-10 cm layer, desert grassland had significantly higher CPOC content than fixed, semi-fixed, and mobile dunes. No significant differences were observed among stages in the 10-20 and 20-30 cm layers. Vertical distribution patterns varied by desertification stage: semi-fixed and fixed dunes showed increasing CPOC with depth, while desert grassland showed a decrease followed by increase, reaching minimum at 10-20 cm. Differences among soil layers within each stage were not significant.

The CPOC allocation proportion in the 0-30 cm layer ranged from 7.7% to 33.4% across stages, showing a decreasing then increasing trend with desertification, with minimum values in fixed dunes. In the 0-10 and 10-20 cm layers, mobile and semi-fixed dunes had significantly higher CPOC proportions than fixed dunes and desert grassland. With increasing depth, mobile and semi-fixed dunes showed decreasing CPOC proportions, while fixed dunes showed a decrease then increase pattern. The 10-20 cm layer had significantly higher CPOC proportion than the 20-30 cm layer.

3.2 Fine Particulate Organic Carbon Content and Allocation

Desertification stage significantly affected fine particulate organic carbon (FPOC) content and allocation ($P < 0.05$). In the 0-30 cm layer, FPOC content in desert grassland, semi-fixed dunes, and mobile dunes decreased by 17.4%, 59.0%, and 63.6% compared to fixed dunes, respectively. In all three layers (0-10, 10-20, 20-30 cm), desert grassland and fixed dunes had significantly higher FPOC content than semi-fixed and mobile dunes. Vertical distribution varied: mobile and fixed dunes showed an increase then decrease pattern with depth (minimum at 10-20 cm, maximum at 20-30 cm), while semi-fixed dunes showed a decrease then increase pattern, and desert grassland showed a consistent decrease.

The FPOC allocation proportion in the 0-30 cm layer ranged from 64.2% to 77.5%. Semi-fixed and mobile dunes had significantly lower FPOC proportions than fixed dunes. No significant differences were found among stages in the 10-20 and 20-30 cm layers. With increasing depth, fixed dunes showed decreasing FPOC proportion, while mobile and semi-fixed dunes showed increasing trends. Desert grassland showed a decrease then increase pattern, reaching minimum at 10-20 cm.

3.3 Light-Fraction Organic Carbon Content and Allocation

Desertification significantly affected light-fraction organic carbon (LFOC) content and allocation ($P < 0.05$). In the 0-30 cm layer, LFOC content in semi-fixed dunes and mobile dunes decreased by 7.1% and 42.8-51.0% compared to desert grassland, respectively. In all layers, desert grassland and fixed dunes had significantly higher LFOC content than semi-fixed and mobile dunes. LFOC content in semi-fixed and fixed dunes decreased with depth, with 10-20 cm layer significantly lower than 0-10 and 20-30 cm layers.

The LFOC allocation proportion in the 0-30 cm layer ranged from 60.4% to 81.1%, decreasing with desertification. Desert grassland and fixed dunes had significantly higher LFOC proportions than semi-fixed and mobile dunes. In the 0-10 and 10-20 cm layers, proportions were significantly higher than in mobile dunes. Vertical distribution showed a decrease then increase pattern with depth, reaching minimum at 10-20 cm for most stages.

3.4 Sensitivity of Soil Organic Carbon Fractions to Desertification

As components of the soil active organic carbon pool, POC and LFOC are sensitive to management practices. However, their responses to grassland desertification were inconsistent. Sensitivity analysis showed that across all three layers, FPOC had the highest sensitivity index while CPOC had the lowest, indicating FPOC best reflects soil carbon pool changes during desertification.

3.5 Unprotected Organic Carbon Proportion and Transformation Rate

Desertification stage significantly affected unprotected organic carbon proportion ($P < 0.05$). In the 0–10 cm layer, proportions in fixed dunes, semi-fixed dunes, and mobile dunes decreased by 3.5%, 0.6%, and 5.9% compared to desert grassland, respectively. In the 10–20 and 20–30 cm layers, proportions decreased by 3.5% and 0.6%, respectively. The proportion generally decreased with desertification, indicating reduced soil quality.

The transformation rate constant from unprotected to protected carbon pools increased gradually with desertification across all stages except semi-fixed dunes, which showed minor fluctuations. Both the unprotected carbon proportion and transformation rate constant reached minimum values in the 10–20 cm layer across all desertification stages.

4. Discussion

Soil particulate organic carbon (POC) serves as an intermediate between organic and mineral substances with rapid turnover, representing non-protected soil organic carbon [26]. Li et al. [27] reported that both CPOC and FPOC contents decreased significantly under different land uses and fertilization management in northeast China black soils, consistent with our findings. Root-derived organic carbon contributes more to POC than plant residues, forming coarse POC (>250 m) from root carbon and fine POC (53–500 m) from root and residue decomposition [28, 29]. POC changes are closely related to soil aggregates, as POC binds soil particles into aggregates or serves as nuclei for aggregate formation [30–32]. Soil fungi and microorganisms preferentially utilize coarse POC within aggregates, which further decomposes into fine POC [27].

As desertification intensifies, removal of dominant species like *Pennisetum centrasiaticum* reduces POC input while diminishing protection against wind erosion, accelerating POC loss. Soil microbial biomass and enzyme activity decline significantly during desertification [33], reducing fine POC formation. In fixed dunes, dominant species (*Pennisetum centrasiaticum* and *Sophora alopecuroides*) with larger biomass and stronger competitiveness affect soil structure more substantially and enrich organic carbon [34–36], resulting in minimum CPOC but maximum FPOC content. Differences in vegetation, soil moisture, and porosity explain the inconsistent vertical patterns of POC among desertification stages.

Light-fraction organic carbon (LFOC), like POC, is non-protected and sensitive to environmental changes, consisting mainly of microorganisms such as actinomycetes [6]. Desert grassland and fixed dunes had significantly higher LFOC content than semi-fixed and mobile dunes. Grazing reduces vegetation productivity and LFOC input [37, 38], with moderate grazing decreasing LFOC by 23.7-42.2% in Inner Mongolia *Stipa grandis* steppe [39]. Additionally, soil microbial populations decline during desertification [40], reducing LFOC input. While some studies show LFOC decreasing with depth [10], our results lacked consistent patterns, likely due to the fragile nature of arid desert grassland ecosystems with complex microbial communities and soil structures.

Soil organic carbon content changes primarily through alterations in protected and unprotected carbon fractions [11]. POC (53-2000 m) and LFOC represent the unprotected fraction [8] with varying sensitivity to environmental change. Our results show POC was more sensitive than LFOC and SOC to desertification, with FPOC (53-250 m) more sensitive than CPOC (250-2000 m). This contrasts with some land use studies [22], possibly because initial desertification stages involve weak wind erosion and strong dust deposition, minimizing loss of fine particles that readily form FPOC [41, 42]. As desertification progresses, enhanced wind erosion causes greater FPOC loss than CPOC loss.

Unprotected organic carbon is crucial for energy transformation in grassland ecosystems. Its decline during desertification indicates reduced soil quality. The transformation from unprotected to protected carbon pools is key for long-term soil carbon stabilization [24]. While vegetation restoration in pine plantations enhances this transformation [44], our study found desertification also promotes conversion of unprotected to protected carbon, representing a shift from unstable to stable states as grassland degrades to mobile dunes. This transformation may reflect deteriorating chemical properties and reduced fresh organic matter input, though the extreme environment of mobile dunes limits vegetation utilization.

5. Conclusion

As grassland desertification intensified: - CPOC content and allocation proportion in the 0-30 cm layer showed a decreasing then increasing pattern, reaching minimum values in fixed dunes. - FPOC content and allocation proportion in the 0-30 cm layer showed an increasing then decreasing pattern, reaching maximum values in fixed dunes. - LFOC content and allocation proportion in the 0-30 cm layer decreased, reaching maximum values in desert grassland. - Sensitivity to desertification differed among carbon fractions, with POC > LFOC > SOC, and FPOC > CPOC within POC. - Unprotected organic carbon declined overall during desertification, indicating reduced soil quality as desert grassland degraded to mobile dunes. - Unprotected organic carbon gradually transformed to protected carbon pools during desertification.

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Note: Figure translations are in progress. See original paper for figures.