Postprint: Soil Quality Assessment of Retired Farmland in the Manas River Irrigation District Under the Water Resources "Three Red Lines" Constraints

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Abstract

The "Three Red Lines" constraints on water resources have prompted regions primarily reliant on agricultural water use to gradually implement farmland retirement and water reduction measures, which effectively ensure compliance with total water use control targets but also lead to soil quality degradation issues from abandoned farmland. This study examines retired farmland soil in the Manas River Irrigation District of Xinjiang under the "Three Red Lines" water resource constraints, analyzing and comparing seven soil quality indicators between retired farmland (RF) and adjacent cultivated land (CK): pH, total dissolved solids (TDS), organic matter (OM), total nitrogen (TN), total phosphorus (TP), alkaline-hydrolyzable nitrogen (AN), and available potassium (AK). A fuzzy comprehensive evaluation model was constructed to calculate the soil fertility indices of RF and CK, thereby assessing soil quality in the Manas River Irrigation District under water resource constraints. The results indicate: (1) pH values between RF and CK ranged from 7.18 to 8.78, showing an overall positive correlation with soil depth. The salt content in retired farmland was 10.84% higher than in adjacent cultivated land overall, with salts primarily distributed in the 40-100 cm layer. (2) Soil nutrients in retired farmland were generally lower than in adjacent cultivated land, with alkaline-hydrolyzable nitrogen showing the largest difference at 22.15% lower. (3) The soil fertility evaluation indices for both retired and adjacent cultivated land ranged from 0.49 to 0.77, with soil quality being medium to high; the mean fertility index of adjacent cultivated land was 6.67% higher than that of retired farmland. The research findings provide a theoretical basis for implementing farmland retirement plans and protecting soil quality under total water resource constraints in irrigation districts.

Full Text

Soil Quality Evaluation of Returning Farmland in the Manas River Irrigation Area Under the Constraints of Water Resources "Three Red Lines"

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Abstract

The constraints of the water resources "Three Red Lines" policy have prompted regions dominated by agricultural water use to gradually implement farmland retirement and water reduction measures, which effectively ensures compliance with total water consumption control targets but also leads to soil quality degradation in abandoned farmland. This study examines retired farmland soil in the Manas River irrigation area of Xinjiang under the "Three Red Lines" constraints, analyzing and comparing soil pH, total dissolved salts, organic matter, total nitrogen, total phosphorus, alkali-hydrolyzable nitrogen, and available potassium between retired farmland (RF) and adjacent cultivated plots (CK). A fuzzy comprehensive evaluation model was constructed to calculate the soil fertility index. The results indicate: (1) The salt content in RF plots is 10.84% higher overall than in CK plots, with salts mainly accumulating in the 40–100 cm layer; (2) Soil nutrients in RF plots are generally lower than in CK plots, with alkali-hydrolyzable nitrogen showing the largest difference at 22.15% lower; (3) The soil fertility evaluation index for both treatments ranges from 0.49 to 0.77, indicating moderately high soil quality, with CK plots showing a 6.67% higher fertility index than RF plots. These findings provide a theoretical basis for implementing farmland retirement schemes and protecting soil quality under total water resource constraints in irrigation areas.

Keywords: farmland retirement and water reduction; soil quality; fuzzy comprehensive evaluation; soil fertility index; Manas River irrigation area

1 Materials and Methods

1.1 Study Area Overview

The study area is located in the Manas River irrigation area of Xinjiang, with geographic coordinates of 84°98 -86°39 E and 44.04 -45°19 N. The region features a dry to semi-arid climate with annual precipitation of 125–200 mm and annual evaporation of 1700–2200 mm. Total water resources amount to approximately

20.92$×10^{8}$ m^{3}, with available water resources of 22.91$×10^{8}$ m^{3} and groundwater resources of about 11.97$×10^{8}$ m^{3}. Soils are predominantly gray desert soil, fluvo-aquic soil, and meadow soil, with textures mainly gravelly and sandy. Since 2015, the irrigation area has implemented farmland retirement and water reduction measures, with cumulative retired farmland reaching 2.49$×10^{4}$ hm^{2}, reducing total water consumption by 2.14$×10^{8}$ m^{3}. Agricultural water use has decreased from 12.09$×10^{8}$ m^{3} (accounting for 95.3% of total water use) to 9.01$×10^{8}$ m^{3}, a reduction of 3.08$×10^{8}$ m^{3}. An additional 2.14$×10^{4}$ hm^{2} of farmland requires retirement to meet the "Three Red Lines" control targets.

1.2 Experimental Design

Soil sampling was conducted in mid-May 2021. Sampling sites were located in key farmland retirement areas of the Manas River irrigation area, with geographical positions shown in [Figure 1: see original paper]. Two treatments were established: adjacent cultivated plots (CK, cotton fields under mulched drip irrigation) and retired farmland plots (RF, abandoned for 3-5 years). Five sampling points were set up for each treatment, totaling ten sampling points. Using the plum-blossom sampling method, each plot was divided into five 5 m × 5 m rectangular subplots for soil profile sampling. Soils were collected at depths of 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm using a soil auger. Soils from the same depth across five subplots were mixed, then reduced using the quartering method to obtain one sample per depth per plot, as illustrated in [Figure 2: see original paper].

Soil samples were analyzed for pH, total dissolved salts, organic matter, total nitrogen, total phosphorus, alkali-hydrolyzable nitrogen, and available potassium following the methods of Qiao Shengying. Specifically: pH was measured using a 1:2.5 soil-water ratio pH meter method; total dissolved salts by 1:5 soil-water ratio electrical conductivity method; organic matter by potassium dichromate external heating method; total nitrogen by Kjeldahl method; total phosphorus by sodium hydroxide-molybdenum antimony colorimetry; alkali-hydrolyzable nitrogen by alkali diffusion method; and available potassium by ammonium acetate extraction-flame photometry.

1.3 Soil Quality Evaluation

The fuzzy comprehensive evaluation method was employed to assess soil quality in RF and CK plots. Based on the relationship between fertility indicators and crop growth, membership functions were constructed: parabolic functions for organic matter, alkali-hydrolyzable nitrogen, available potassium, total nitrogen, and total phosphorus; and decreasing functions for total dissolved salts and pH. Turning point values for each indicator' s membership function curve are presented in and .

The correlation coefficient method was used to assign weights to each evaluation indicator, objectively reflecting their influence on soil fertility. After determining membership values and weight coefficients, the fuzzy comprehensive evaluation method calculated the soil fertility index (IFI) through weighted summation:

$$IFI = \sum_{i=1}^{n} f_i \times w_i$$

where n is the number of evaluation indicators, f is the membership value of the ith indicator, and w is the weight coefficient of the ith indicator. The IFI ranges from 0 to 1, with higher values indicating better soil fertility. Based on regional characteristics, soil fertility was classified into five levels: high (0.8-1.0), relatively high (0.6-0.8), moderate (0.4-0.6), relatively low (0.2-0.4), and low (0-0.2).

2 Results

2.1 Soil Fertility Characteristics

Statistical analysis revealed that pH values for both treatments ranged from 7.18 to 8.78, showing no significant difference and generally increasing with soil depth. Total dissolved salts ranged from 0.22 to 12.47 $g \cdot kg^{-1}$ (mean 2.49 $g \cdot kg^{-1}$) in CK and 0.48 to 7.97 $g \cdot kg^{-1}$ (mean 2.76 $g \cdot kg^{-1}$) in RF, indicating moderate salinization with strong variability (CV = 107.01% for CK, 73.06% for RF). Alkali-hydrolyzable nitrogen, organic matter, and total nitrogen contents were relatively low in both treatments, while available potassium and total phosphorus were high.

Nutrient contents varied significantly with depth. Alkali-hydrolyzable nitrogen, organic matter, and total nitrogen showed surface accumulation, decreasing with depth. Total phosphorus decreased with depth, with reduced change rates below 60 cm. Available potassium was negatively correlated with depth, with highest contents in surface soil (262.53 $mg \cdot kg^{-1}$ in CK, 243.16 $mg \cdot kg^{-1}$ in RF). RF plots showed 10.84% higher salinity overall than CK plots, with salts accumulating mainly at 40-100 cm depth. Nutrient contents in RF plots were generally lower than CK, with alkali-hydrolyzable nitrogen showing the largest difference (22.15% lower).

2.2 Soil Fertility Evaluation

Correlation analysis among soil fertility indicators is presented in [Figure 4: see original paper]. The absolute average correlation coefficient for each indicator was calculated, and its percentage of the total sum determined the weight coefficient. Alkali-hydrolyzable nitrogen and available potassium showed the highest correlation averages (0.76 and 0.79) and weight coefficients (0.19 each), indicating their greatest influence on soil fertility. Organic matter and total nitrogen had the lowest weight coefficients (0.11 each), reflecting lesser influence.

Membership values for individual fertility indicators across both treatments are shown in [Figure 5: see original paper]. Most indicators showed decreasing membership values with depth, indicating weaker soil fertility in deeper layers. The comprehensive soil fertility index (IFI) ranged from 0.49 to 0.77 for both treatments ([Figure 6: see original paper]). The IFI was negatively correlated with soil depth, decreasing by 32.89% in CK and 36.36% in RF from 0–60 cm to 60–100 cm depth. Surface soils (0–20 cm) and 20–40 cm layers in CK plots reached relatively high fertility levels (IFI = 0.70 and 0.64, respectively), while RF plots showed moderate fertility (IFI = 0.61 and 0.56). The mean IFI across 0–100 cm was 6.67% higher in CK (0.64) than in RF (0.60), indicating that both treatments maintained moderately high soil quality, with cultivated plots showing superior fertility.

3 Discussion

3.1 Impact of Farmland Retirement on Soil pH and Salinity

Irrigation water in the study area contains abundant soluble cations (Na^+, Ca^{2+}, Mg^{2+}). When soil colloids become saturated with adsorbed alkaline ions, hydrolysis of exchangeable cations occurs, generating OH^- and making soils alkaline. This explains the positive correlation between pH and soil depth, consistent with findings by Wang Yuanhua et al. The pH values showed no significant difference between treatments, indicating minimal impact from land retirement.

Total dissolved salts in RF plots were 10.84% higher than in CK plots overall. CK plots showed salt accumulation at 0–40 cm depth, while RF plots accumulated salts at 40–100 cm. During cultivation, irrigation leaches some salts to deeper soil layers following the principle of "salt moves with water." In contrast, RF plots experience salt accumulation at the surface due to soil evaporation and halophyte effects, consistent with Feng Xiaoping et al. Mulched drip irrigation in cotton fields facilitates salt leaching and prevents salinization.

3.2 Impact of Farmland Retirement on Soil Nutrient Content

Studies by Dong Lijun et al. show that organic matter loss is severe in surface soils during land degradation. In this study, RF plots had slightly higher organic matter content than CK plots at 0–20 cm depth because cotton cultivation depth does not exceed 20 cm, forming a compact plow layer that restricts root growth and nutrient absorption. Organic matter absorption concentrates in the 0–20 cm layer, where cotton uptake exceeds that of halophytes (e.g., *Kalidium foliatum*, *Halostachys caspica*) in RF plots. Below 20 cm, reduced human disturbance and similar halophyte root distributions resulted in comparable organic matter contents between treatments, consistent with Wang Shu et al.

Total nitrogen and alkali-hydrolyzable nitrogen contents were higher in CK than RF plots across 0–100 cm due to nitrogen fertilizer application during cultivation, increasing both total and mobile nitrogen. Total phosphorus content was lower in RF plots because phosphorus has poor mobility and high fixation rates (>95%), with minimal downward movement. Available potassium was high in both treatments, decreasing with depth as cotton and halophyte roots absorbed potassium mainly from 0–60 cm. CK plots showed higher available potassium due to fertilizer input and nutrient migration with irrigation water, while RF plots lacked nutrient replenishment and experienced consumption by halophytes, leading to severe degradation in deeper soils.

4 Conclusions

1. **pH and Salinity**: pH values for both treatments ranged from 7.18 to 8.78 with no significant difference, generally increasing with soil depth. RF plots had 10.84% higher salinity than CK plots, with salts mainly accumulating at 40–100 cm depth.

2. **Nutrient Content**: Both treatments showed surface accumulation of nutrients with large vertical variations. RF plots had 7.97% higher available potassium but lower contents of other nutrients compared to CK plots, with alkali-hydrolyzable nitrogen showing the greatest difference (22.15% lower).

3. **Soil Quality**: Both treatments maintained moderately high soil quality (IFI = 0.49-0.77). CK plots had a 6.67% higher mean fertility index than RF plots across 0–100 cm, indicating that farmland retirement leads to soil fertility decline while cultivated plots maintain favorable conditions for agriculture.

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