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Assessment of Reclamation Treatments of Abandoned Farmland in an Arid Region of China

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Abstract: Reclamation of abandoned farmland is crucial to a sustainable agriculture in arid regions. This study aims to evaluate the impact of different reclamation treatments on abandoned salinized farmland. We investigated four artificial reclamation treatments, continuous cotton (CC), continuous alfalfa (CA), tree-wheat intercropping (TW) and trees (TS), which were conducted in 2011–2012 in the Manasi River Basin of Xinjiang Province, China. Soil nutrient, microorganism and enzyme activity were examined in comparison with natural succession (CK) in an integrated analysis on soil fertility improvement and soil salinization control with these reclamations. Results indicate that the four artificial reclamation treatments are more effective approaches than natural restoration to reclaim abandoned farmland. TW and CA significantly increased soil nutrient content compared to CK. CC reduced soil salinity to the lowest level among all treatments. TW significantly enhanced soil enzyme activity. All four artificial reclamations increased soil microbial populations and soil microbial biomass carbon. TW and CA had the greatest overall optimal effects among the four treatments in terms of the ecological outcomes. If both economic benefits and ecological effects are considered, TW would be the best reclamation mode. The findings from this study will assist in selecting a feasible method for reclamation of abandoned farmland for sustainable agriculture in arid regions.

Keywords: abandoned farmland; reclamation treatment; salinity; arid zone; sustainable agriculture

1. Introduction

Abandoned farmland is widespread over the world [1–3], in particular in arid and semi-arid regions. Primary causes of abandoned farmland in arid and semi-arid zones are soil fertility decline and soil secondary salinization. Abandoned farmland will gradually lose its soil nutrients [4], suffer degradation of soil physical characteristics [5], and eventually result in desertification [6]. Reclamation of abandoned farmland is an important practice to protect agricultural ecological systems, and is vital to a sustainable agriculture and a viable food security for a rapidly increasing world population.

Artificial reclamation, which involves efficient irrigation and fertilization, is more effective than natural recovery of an abandoned farmland. A process of vegetation recovery through natural succession will take much longer [7]. However, the effect of soil fertility improvement and soil salinization control using different artificial measures is significantly different [8–10]. For instance, different artificial vegetation recovery treatments will have a varied effect on the improvement of soil properties, such as soil nutrient, microbial biomass and enzyme activity [11,12]. Therefore, the study to assess different artificial reclamation treatments in a region will help with the selection of a proper reclamation mode for abandoned farmland.

The ecological effects of vegetation on soil nutrient content, such as carbon (C), nitrogen (N) and phosphorus (P), during the reclamation of abandoned farmland have drawn the attention of many researchers [13]. Studies have shown significant interactions between soil and vegetation during a reclamation process, such that soil and vegetation are constantly evolving and developing [14,15]. As vegetation recovers, soil nutrient contents will increase. These changes promote further recovery of vegetation.

Soil microorganisms drive soil structure formation, soil organic matter decomposition and soil nutrient transportation to plants. Therefore, it is essential to understand soil microbial sensitivity to environmental changes, including soil salinization and land reclamation. Saline stress may have a detrimental influence on microbial soil communities and their activities [16–18]. Since soil microbial biomass carbon (SMBC) and soil microbial nitrogen (SMBN) in microbial communities are important components of soil nutrient pools, changes of SMBC and SMBN may serve as pronounced indicators in soil microorganisms and may help to recognize the reclamation effect of abandoned farmland [19,20].

Soil enzymes are critical in soil biochemical transformations. Enzyme activity, the quantity of active enzyme present, is useful in assessing soil quality of reclamation land [21–23]. Soil enzymes come from living and dead microbes, plant roots and residues, and soil animals. They play an important role in maintaining healthy soil ecological conditions, such as both physical and chemical properties and fertility [24]. Soil enzyme activities catalyze several vital reactions in soils, such as decomposition of organic matter, formation of agglomerates and nutrient cycling [25–27]. They are important indicators for evaluating soil fertility levels in different reclamation treatments.

Oasis agriculture has developed rapidly in Xinjiang during the past 60 years. This region is now an important grain and cotton production area of China. As a marginal region with a fragile ecological balance, irrigation, fertilization and other human activities altered regional soil properties [28]. In particular, the irrational use of land and water resources has caused secondary salinization of farmland, such as intensive irrigation, overuse of fertilizers and inappropriate planting patterns. More than one-third of the total farmland was abandoned in Xinjiang [29]. With the wide-spread adoption of drip irrigation technology since 1996, large areas of farmland have been reclaimed in the region. However, there is a debate about which fit-for-purpose reclamation method should be adopted. Little is known about the influence of these methods on soil quality. In this study, a field experiment of four artificial reclamation treatments and one natural succession was designed to explore the best reclamation mode by assessing and comparing the effects of different reclamation treatments in abandoned farmland in Xinjiang. There are two major steps in this study: (1) analysis of the difference in soil nutrient, microorganism and enzyme activity under different reclamation treatments; (2) a comprehensive assessment on the most optimal reclamation treatment. The outcome of this study will provide a much needed reference framework for future studies of reclamation in abandoned farmland, adjustment of cropping pattern and sustainable utilization of salinized farmland.

2. Materials and Methods

2.1. Study Area

The Manasi River Basin is located at the center of the Eurasian continent, along the southern margin of the Junggar Basin in Xinjiang (44°33′ N, 85°37′ E, 378 m above sea level, Figure 1). The basin has an arid, continental climate [30]. The average annual rainfall is 153 mm and the average annual potential evapotranspiration is 1521 mm (1956–2010). The frost-free period is 168–171 days. Halosols are the dominant soils in the basin. The main plant species are *Tamarix ramosissima*, *Salsola collina*, *Kalidium foliatum*, *Halostachys belangeriana*, and *Limonium* spp. Vegetative cover on the abandoned land was 20%–30% before reclamation. Irrigation water in the basin comes mainly from snowmelt in the Tianshan Mountains. Since 1948, about 400,000 ha of farmland have been cultivated in the Manasi River Basin. This basin has become Xinjiang's largest oasis agricultural area and the fourth largest national agricultural irrigation area in China. Long-term flood irrigation has caused the groundwater table to rise in Manasi River Basin. Drip irrigation under plastic film has replaced the original drainage system (alkali drainage canal) since 1996. Adoption of drip irrigation in the region has accelerated secondary salinization and abandonment of nearly 130,000 ha of farmland in the basin. This amount is equivalent to about one-third of the basin's total cultivated land.

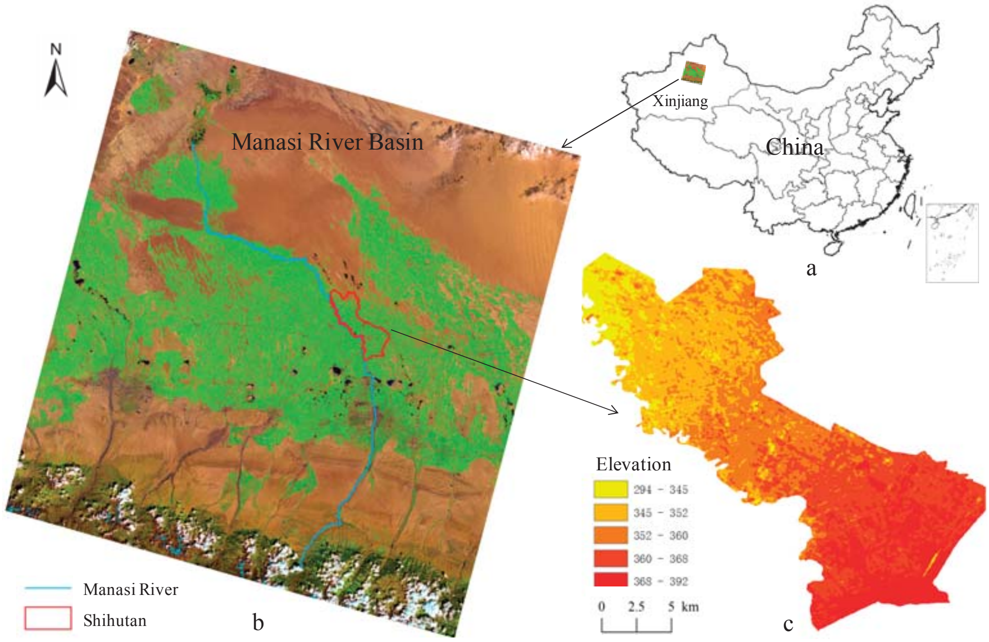

Figure 1. Manasi River Basin and study area.

2.2. Experimental Design and Sample Collection

Under the pressure of an increasing population and a growing demand for agricultural products, reclaiming abandoned farmland has been a research priority in the region and has gained much support from local government. In 2008, 2000 ha salinized soil near Shihutan in the Manasi River Basin was investigated. The land had been abandoned for approximately 20 years. Cotton is widely planted as a saline-tolerant crop, and alfalfa which has a short growth period can tolerate high salinity levers. Although trees can maintain lower groundwater level and decrease soil salinity, their economic payback period is too long. Tree-wheat intercropping can achieve better benefits than trees only. Four artificial reclamation treatments were designed and implemented: (i) 15 ha of continuous cotton (CC); (ii) five ha of continuous alfalfa (CA); (iii) 50 ha of tree–wheat (*Populus afghanica*) intercropping (TW); and (iv) 15 ha of trees (*Populus afghanica)* (TS). The spacing is 1.75 m × 1.75 m in the TS treatment. The spacing of trees is 1 m × 1 m, and 2 m trees and 8 m wheat were arranged between rows in the TW treatment. In addition, two ha of abandoned farmland with natural vegetation succession was used as a control treatment (CK) (Figure 2, Table 1). Five treatments were randomly distributed over the study area. Three plots were surveyed in each reclamation treatment for plant density, irrigation times and quantity, fertilizer amount and mode. A summary of each reclamation treatment is given in Table 1.

Soil samples were collected during the period of 2011–2012. The samples were taken in an "S-shaped" pattern (0–40 cm) from five points within each reclamation treatment plot. The five samples were mixed and three 1 kg subsamples were extracted for analysis using the "quartering" method [31]. Soil biological properties were determined from fresh soil samples. Soil physical and chemical properties were determined from air-dried soil samples.

Table 1. Plant density, irrigation practices, and fertilizer practices under different reclamation treatments. Irrigation water and fertilizer were evenly distributed according to irrigation times, irrigation quantity and fertilizer mode throughout the whole growth period.

Reclamation Treatment	Plant Density (Plants ha^{-1})	Irrigation			Fertilizer	
		Type	Times	Quantity ($m^3 \cdot ha^{-1}$)	Fertilizer Amount (ha^{-1})	Mode
Natural succession (CK)	2.89×10^4	No irrigation	0	0	No fertilizer	—
Continuous alfalfa (CA)	5.5×10^6	Drip irrigation	8–10	4500	300 kg N	Drip fertigation
Continuous cotton (CC)	1.95×10^5	Drip irrigation under plastic mulch	8–10	4500	300 kg N, 120 kg P_2O_5, 60 kg K_2O	Basal application + drip fertigation
Trees (TS)	3.3×10^3	Drip irrigation	6	300	270 kg N	Drip fertigation
Tree-wheat intercropping (TW)	$1.02 \times 10^3 + 4.8 \times 10^6$	Drip irrigation	2 + 6	5250	300 kg N, 120 kg P_2O_5, 60 kg K_2O	Basal application + drip fertigation

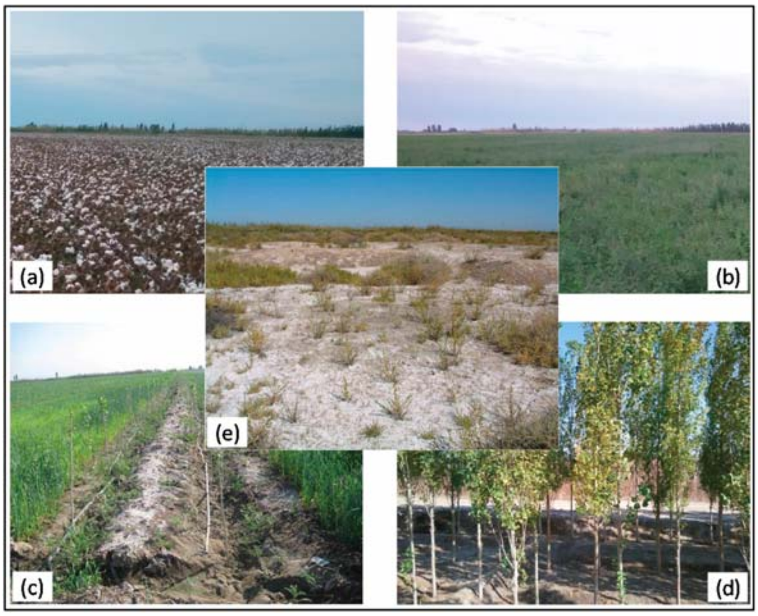

Figure 2. Four artificial reclamation treatments and natural vegetation succession. (**a**) Continuous cotton (CC); (**b**) continuous alfalfa (CA); (**c**) tree-wheat intercropping (TW); (**d**) trees (TS); and (**e**) natural vegetation succession (CK).

2.3. Soil Sample Test Indicators and Methods

Three key indicators of soil quality, namely soil nutrient, microorganism and enzyme activity, were used to gauge different soil reclamation treatments.

Three major soil nutrient components and other two soil properties were measured. They are soil electrical conductivity (EC), pH, soil organic matter (SOM), available N and available P. Soil EC was measured using the electrical conductivity method (DDSJ-308A conductivity meter, water-to-soil ratio 5:1, $dS \cdot m^{-1}$). Soil pH was measured by an Ampholine (LKB Producter AB, Stockholm, Sweden) pH meter (3310, water-to-soil ratio 2.5:1). Soil organic carbon (SOC) was determined using the potassium dichromate oxidation method (Vance et al., 1987). SOM was estimated according to Equation (1). Available N (alkali-hydrolyzable N) was determined using the alkaline solution diffusion method. Available P was extracted using 0.5 $mol \cdot L^{-1}$ $NaHCO_3$.

$$SOM(\%) = \frac{SOC(\%)}{58\%} \tag{1}$$

Two key parameters of soil microorganisms, soil microbial populations and soil microbial biomass, were selected. Soil microbial population indicators were bacteria, actinomycetes and fungi. They are sensitive indicators of changes in both soil organic matter and the soil environment. Soil samples were serially diluted and plated on Thornton's agar, Czapek-Dox agar and Kenknight media for bacteria, fungi and actinomycetes, respectively. They were incubated at 30 °C and counted [32]. Quantity of microbial populations is the sum total of bacteria, actinomyces and fungi. Soil microbial biomass includes SMBC, SMBN and entropy of soil microbial biomass carbon (qSMBC). SMBC and SMBN were determined by chloroform fumigation-extraction, and *qSMBC* was calculated according to Equation (2).

$$qSMBC = \frac{SMBC}{SOC} \tag{2}$$

Three major parameters of soil enzyme activity were investigated. They were urease activity, sucrase activity and phosphatase activity. Urease activity was determined using phenol-sodium hypochlorite colorimetry, sucrase activity by 3,5-dinitrosalicylic acid colorimetry and phosphatase activity by aminoantipyrine-potassium ferricyanide colorimetry, respectively.

2.4. Statistical Analyses

The descriptive statistics of the data (soil pH, EC, soil organic matter, available N and P, SMBC, SMBN, SOC, qSMBC, urease, sucrose and phosphatase) from laboratory experiments were performed using the SPSS statistical software (Statistical Package for Social Sciences, version 20.0, IBM, Armonk, NY, USA). All data were expressed as the mean ± standard error. Least significant difference (LSD) multiple range tests were employed to compare and rank the reclamation treatments [33]. The letter-marking method was used in the comparison of different treatments. Statistically significant differences between different individual reclamation treatments were indicated using different lowercase letters ($p < 0.05$).

3. Results

3.1. Soil Nutrients

Soil nutrient content varied significantly among the reclamation treatments (Figure 3). Soil organic matter content was 10.54 g·kg^{-1} for TW, significantly higher than those from other reclamation treatments. Soil-available N and available P followed the order of TW > CC > CA > TS > CK, as shown in Table 2. All four artificial reclamation treatments significantly reduced soil salinity compared with CK.

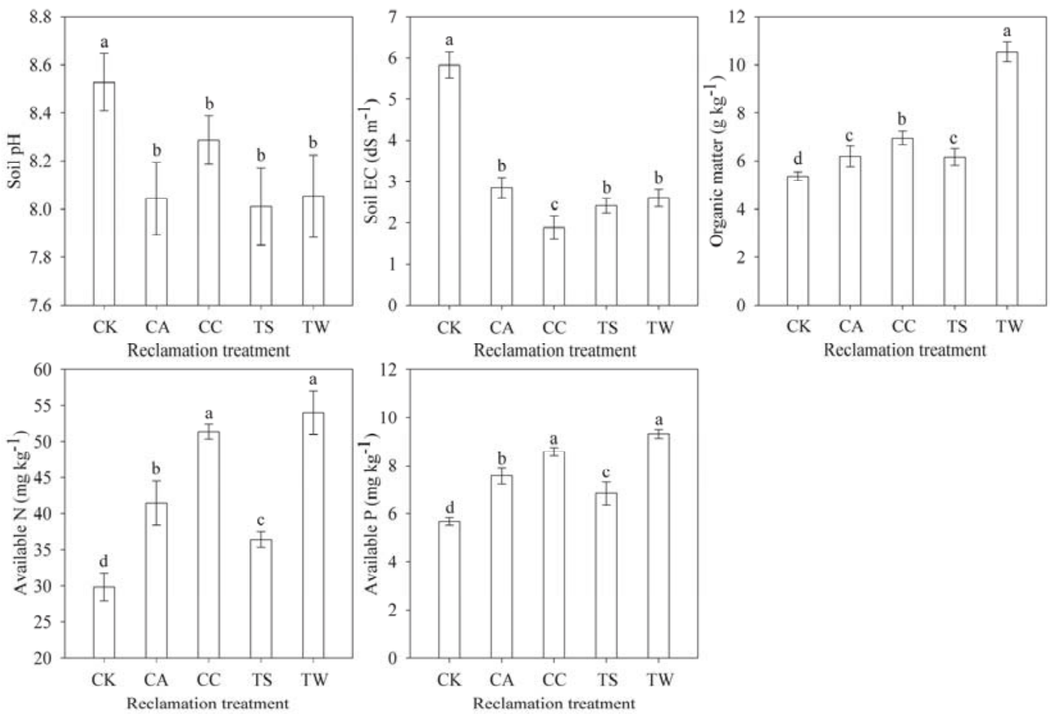

Figure 3. Difference analysis of pH, EC, soil organic matter, available N and available P in five land reclamation treatments. Data show mean ± standard error (n = 5). Significant differences ($p < 0.05$) among treatments are indicated by different lowercase letters.

Table 2. Soil nutrient change compared with natural succession (%)

Indicator	Continuous Alfalfa (CA)	Continuous Cotton (CC)	Trees (TS)	Tree–Wheat Intercropping (TW)
Soil pH	−4.7	−1.8	−5.1	−4.6
Soil EC	−51.1	−67.6	−58.5	−55.4
Soil organic matter	26.6	42.1	26.0	115.5
Available N	39.1	72.2	22.1	81.1
Available P	33.2	51.0	20.4	63.8

3.2. Soil Microbial Population and Biomass

(1) Soil microbial population

The composition of the soil microbial communities was similar among the four artificial reclamation treatments and the CK treatment (Figure 4a). Bacteria were present in the largest numbers followed by actinomycetes and then fungi. In terms of the total microbial population, there were some differences among the reclamation treatments. Specifically, total microbial population followed the order of TW > CA > CK > CC > TS, as shown in Table 3. The results in Figure 4b show that the CK treatment was good for bacterial growth, the CC treatment was beneficial to actinomycetes, and the TS treatment was conducive to fungi.

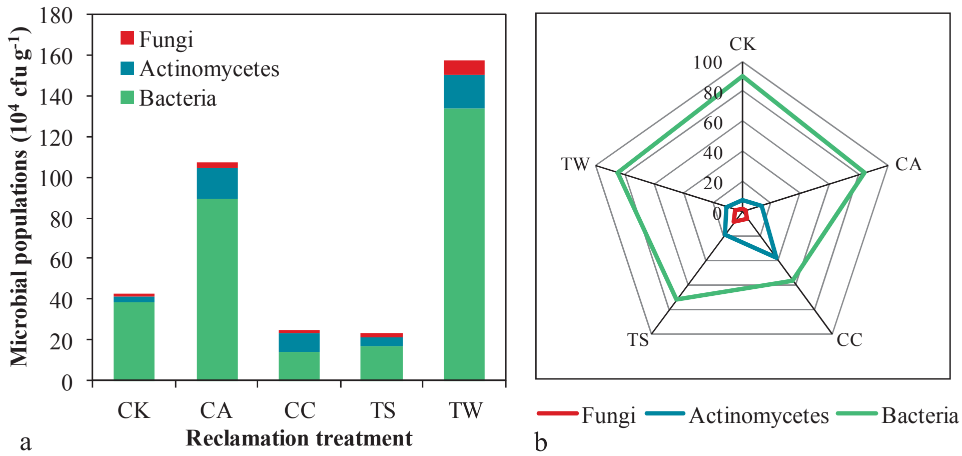

Figure 4. Difference analysis of soil microbial populations in five land reclamation treatments. (**a**) Data show means (n = 3), unit cfu means colony forming units; (**b**) Percentage of each microorganism in total microbial population (%).

(2) Soil microbial biomass

All four artificial reclamation treatments significantly increased SMBC and SMBN in comparison with the CK treatment (Figure 5). SMBC was 42% higher under TW, 36% higher under continuous alfalfa, 26% higher under continuous cotton, and 23% higher under TS than CK. SMBC and SMBN both followed the order of TW > CA > CC > TS > CK, as shown in Table 3. The qSMBC followed the order of CA > TS > CK > CC > TW (Figure 5). The highest qSMBC was observed under the CA treatment, at 17.6% higher than under the CK treatment.

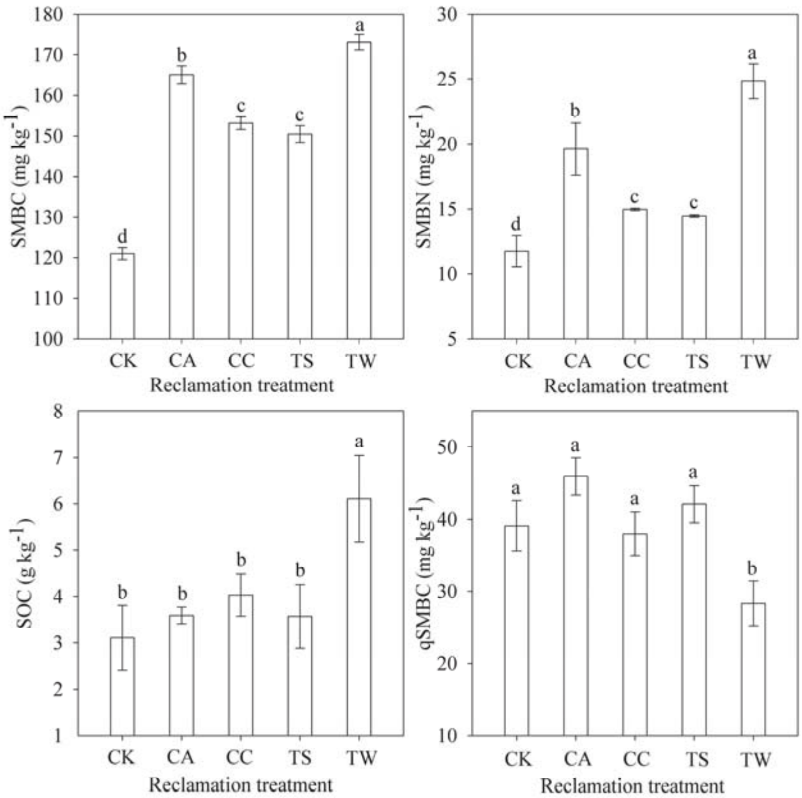

Figure 5. Difference analysis of SMBC, SMBN, SOC and qSMBC in five land reclamation treatments. Data show mean ± standard error (n = 5). Significant differences (p < 0.05) among treatments are indicated by different lowercase letters.

Table 3. Soil microbial indicator change compared with natural succession (%).

Indicator	Continuous Alfalfa (CA)	Continuous Cotton (CC)	Trees (TS)	Tree–Wheat Intercropping (TW)
Fungi	172.3	38.6	95.1	572.5
Actinomycetes	359.4	196.9	37.5	428.1
Bacteria	134.2	63.2	55.3	250.0
SOC	15.4	29.6	14.8	96.5
SMBC	36.4	26.4	24.0	43.0
SMBN	48.5	13.6	9.8	88.6
qSMBC	17.6	2.8	7.7	27.6

3.3. Soil Enzyme Activity

Soil urease activity followed the order TW > CA > CC > TS > CK (Figure 6). It was significantly higher in TW than in any other treatments. Sucrase not only increased the soluble nutrient content of soil, but also had a role in soil C cycle. Compared with CK, sucrase activity increased by 105% under CA, 97.8% under TW, 44.5% under CC, and 21.2% under TS. Soil phosphatase facilitated the decomposition of soil organic P compounds and played a role in the transformation of soil P. Soil phosphatase activity followed the order TW > TS > CC > CA > CK, as show in Table 4. Soil phosphatase activity was significantly higher under TW than under any other reclamation treatments.

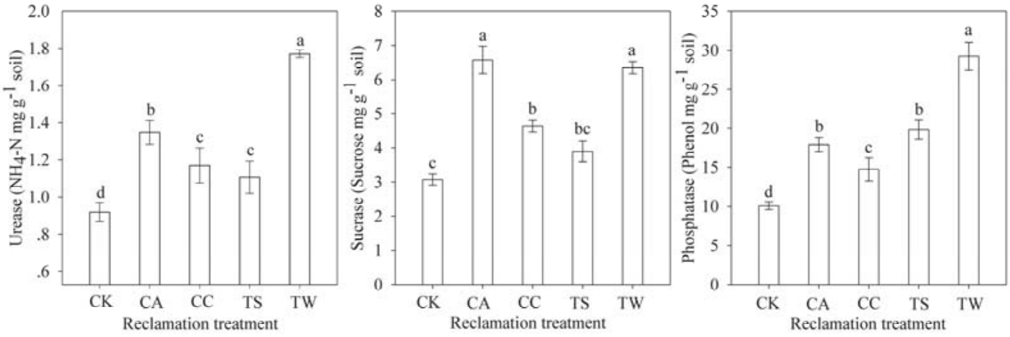

Figure 6. Analysis of three enzyme activities (urease, sucrose and phosphatase) in five land reclamation treatments. Data show mean ± standard error (n = 5). Significant differences ($p < 0.05$) among treatments are indicated by different lowercase letters.

Table 4. Soil enzyme activities change compared with natural succession (%).

Indicator	Continuous Alfalfa (CA)	Continuous Cotton (CC)	Trees (TS)	Tree–Wheat Intercropping (TW)
Urease	51.7	31.5	24.7	98.9
Sucrase	105.0	44.5	21.2	97.8
Phosphatase	73.8	42.7	92.2	183.5

4. Discussion

The results of this study indicate that four artificial reclamation treatments significantly altered the physicochemical properties of abandoned farmland (Figure 3). Soil salinity, which is the major concern in this region, declined most in CC treatment. Cotton could remove between 80 and 120 kg NaCl ha^{-1} from the soil during a growing season [34]. If the soluble salt content of the soil was 0.6% (moderate salinization), there would be 15,000 kg salt ha^{-1} in the 0–20 cm soil depth. This means the uptake of salt by cotton would account for a very small part of the soluble salt content in the soil. It was more likely that soluble salt concentrations declined due to leaching by irrigation water in four artificial reclamation treatments. This was supported by our observation that soil EC increased with soil depth in each treatment (Figure 7). The four artificial reclamation treatments not only significantly reduced soil pH and soil salinity, but also significantly increased soil nutrient content. The increase in soil organic matter, available N, and available P varied among the four artificial reclamation treatments. Soil organic matter content under TW was nearly twice that under CK. One possible explanation for this is the treatment used in natural resources (e.g., light, water, and nutrients) more efficiently than the other artificial reclamation treatments. It should also be noted that the amount of irrigation water was highest in the TW treatment. This could have contributed to the accumulation of soil organic matter.

Vegetation cover varied among four artificial reclamation treatments, leading to the differences in both mineralization of soil organic matter and soil nutrient content. These differences had a significant impact on soil microbial populations, especially in the TW treatment. The TW treatment also increased nutrient exchange between plant and soil. These conditions drove soil microbial populations to rise. Both TW and CA could be recommended for reclamation of abandoned, salinized farmland. The artificial reclamation treatments also increased soil microbial populations (Figure 4), SMBC and SMBN (Figure 5). Among all the treatments, TW had the best performance, increasing SMBC by 43.0% and SMBN by 88.6% compared with CK. The results indicate both TW and CA provided soil microorganisms with sufficient organic C and N. This improved soil physicochemical properties and increased soil microbial populations. The use of fertilizers increased the decomposition of soil organic C and reduced the ratio of soil carbon and nitrogen. A reduction in the availability of soil organic C decreased not only microbial activity but also soil microbial biomass C and N [35]. Therefore, TW seems to be an optimal reclamation method to increase soil quality.

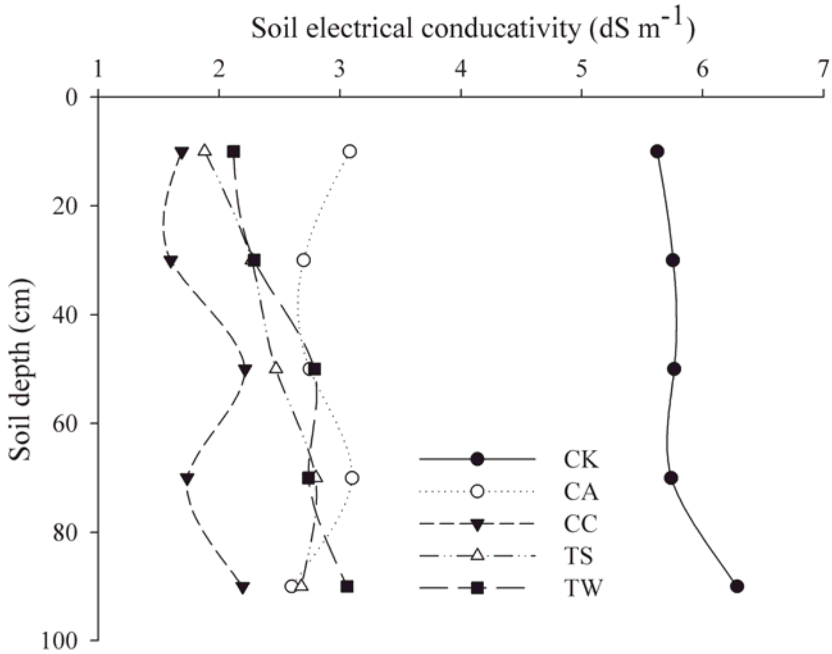

Figure 7. Soil EC of different soil depths in five land reclamation treatments.

Soil qSMBC and SMBC responded differently to four artificial reclamation treatments (Figure 5). Specifically, CA and TS significantly increased qSMBC. A possible explanation was that legume roots secrete large amount of sugars, amino acids, and other low-molecular organic compounds. These compounds could stimulate the growth of microorganisms in the rhizosphere [36]. If legumes were planted on abandoned farmland, the mass fraction of soil organic C would increase significantly. High soil organic matter content would provide sufficient C, N, and energy for microbial growth. The soil microbial quotient was significantly higher in TS than in the other treatments. One explanation was that trees can pull more water from the soil and reduce the groundwater level. TS significantly reduced soil salinity [37]. Furthermore, the soil in TS was less disturbed than in CC, CA, and TW. Land use type had less influence on qSMBC than on SMBC, which was consistent with the observations by Zeller et al. [38], but different from the report of Saggar et al. [39], which stated that qSMBC was more sensitive than SMBC to changes in cultivation. Overall, the results indicate that the turnover of SMBC was highest under CA. This would promote the conversion of SOC into SMBC. Studies on the variation of SMBC and qSMBC during the reclamation process of abandoned salinized farmland could either directly or indirectly reflect the improvements in soil quality under different reclamation practices.

Soil nutrient availability to plants was directly related to soil enzyme activity. Mineralization of soil nutrients increased as soil enzyme activity increased. Nutrient recycling in the soil increased as mineralization increased [40]. Compared with CK, four artificial reclamation treatments increased the activity of urease, sucrase and phosphatase (Figure 6). Urease and phosphatase activity were highest under TW, suggesting that this treatment would increase both N use efficiency and available soil P content. Sucrase activity increased most under either CA or TW. Overall, these results indicate that soil quality increased more rapidly under human management than under CK.

Economic profit is an important benchmark to evaluate reclamation treatments. Cotton was widely grown in this region. The economic value of wood production in both TS and TW should not be overlooked. Trees will take 12–20 years before they mature. However, when calculated on annual basis, the estimated economic returns were as follows: 92,500 Chinese Yuan (CNY) ha^{-1}·year^{-1} for TS, 71,000 CNY ha^{-1}·year^{-1} for TW, 13,500 CNY ha^{-1}·year^{-1} for CC, and 7,500 CNY ha^{-1}·year^{-1} for CA (the exchange rate of CNY against US Dollar (USD) is 6.75 and the exchange rate of CNY against Euro (EUR) is 7.47 on 2 November 2016). If both economic benefits and ecological effects are considered, then TW was the best means for reclamation. The findings of this study have demonstrated the variation of different reclamation treatments in abandoned, salinized farmland. Four artificial reclamation treatments resulted in an improvement in soil quality and ecological environment, which was conducive to the sustainable development of the farmland ecosystem.

5. Conclusions

The focus of this study is to assess the effect of soil fertility improvement and soil salinization control under different reclamation treatments. Results show that all four artificial reclamation treatments significantly increased soil nutrient content. The magnitude of soil nutrient content followed the order of TW > CC > CA > TS > CK. Soil microbial population and biomass were highest under TW and CA. The activities of soil urease, sucrase, and alkaline phosphatase were higher under the four artificial reclamation treatments than under CK. Overall, TW and CA were the preferred treatments for reclaiming abandoned farmland. In terms of the ecological benefits, TW and CA were the best treatments. If both economic effects and ecological benefits are considered, then TW was the best means for reclamation. The integration of soil ecological environment and economic benefits can provide a comprehensive assessment and a guide for decision makers to achieve sustainable land resource utilization in arid areas.

Although this study demonstrates that an optimal reclamation treatment can be selected based soil nutrient, microorganism and enzyme activity, further research is needed to focus on investigating other reclamation treatments to ensure an adequate and detailed abandoned land reclamation assessment. These include the assessment of agricultural water resource management, sustainable land use and the ecological environment.

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Conflicts of Interest: The authors declare no conflict of interest.

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