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Impacts of Agricultural Land Reclamation on Soil Nutrient Contents, Pools, Stoichiometry, and Their Relationship to Oat Growth on the East China Coast

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Abstract: Agricultural land reclamation of coastal tidal land (CTL) with organic amendments may modulate the soil properties, and therefore promote crop growth. However, the linkages between soil nutrient contents, pools, stoichiometry, and crop growth under the supplement of organic amendments in CTL is limited. In this study, six treatments including the control (CK), organic manure (OM), polyacrylamide plus organic manure (PAM + OM), straw mulching plus organic manure (SM + OM), buried straw plus organic manure (BS + OM), and bio-organic manure plus organic manure (BM + OM) were conducted to explore these linkages in newly reclaimed CTL in Jiangsu Province, eastern China. The results showed that the application of different soil reclamation treatments increased soil nutrient contents, pools, and modulated their stoichiometric ratio, which thus promoted the growth of oat. Soil under all reclamation treatments increased the contents of surface soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP), and the BM + OM treatment had the highest increase, which increased by 11.7–182.4%, 24.3–85.7%, 3.2–29.4%, respectively. The highest soil C pools were observed in the oat heading stage (36.67–41.34 Mg C ha^{-1}), whereas the soil N and P pools were more stable during the oat growth period. Similarly, the highest surface soil C/N and C/P were observed in the oat heading stage (11.23–14.67 and 8.97–14.21), whereas the N/P in surface soil increased compared with the CK treatment during the oat growth period, with the exception of the filling stage. Land reclamation treatments significantly promoted oat growth by changing soil C, N, and P contents, pools, and stoichiometry, among which soil SOC, TN, TP, C/P, and N/P are more closely related to oat growth ($p < 0.05$).

Keywords: land reclamation; ecological stoichiometry; redundancy analysis; coastal tidal land

1. Introduction

With an increasingly prominent contradiction between human and land resources, the agricultural reclamation of coastal tidal land (CTL) has become an important approach to increase the cultivated land, as well as improve agricultural productivity and ensure food security [1–3]. However, soil salinization seriously limits the soil quality and inhibits the growth and yield of crops in newly reclaimed coastal tidal land [4]. For instance, the increase of the salt ions can lead to physiological water shortage of plants and inhibit nutrient absorption, thus resulting in dysplasia of plants and reduction in crop yields [5–7]. Earlier study indicated that the increase of Na^+ and Mg^{2+} ions may cause the structural damage and photosynthesis disorder of plant cells, and thus inhibit the production of chlorophyll [8]. Therefore, the physical (deep ploughing, straw/film mulching, etc.), chemical (macromolecular polymer, organic/inorganic fertilizer, biochar, gypsum, etc.), biological (bio-organic fertilizer, salt-tolerant plants, etc.), and engineering (irrigation and drainage system) improvement have been widely applied to reclaim the saline soil [9–12]. Many studies have confirmed that land reclamation apparently affected the contents of soil C, N, P, and their pools. For instance, straw returning can improve soil physical properties, inhibit soil salinity, and increase the content of soil organic carbon and total nitrogen [9,13]. Previous studies have indicated that application of organic and inorganic fertilizer can reduce soil salinity, improve soil nutrient content and pools, and promote crop yields [14,15]. For example, application of chemical fertilizer can accelerate the consumption of soil organic carbon, whereas the straw returning can offset the mineralization of organic carbon and increase the soil C pool [16]. Moreover, appropriate application of polyacrylamide (PAM) can improve the soil nutrient retention capacity [17]. Besides, the planting of salt-tolerant plants can improve the physicochemical properties, reduce the soil salinity, and increase the soil nutrient content of CTL [18]. For instance, oat (*Avena sativa* L.) cultivation is considered as an efficient reclamation approach to improve CTL due to its high capacity to accumulate salt ions in straw biomass [18].

Ecological stoichiometry deals with the balance of multiple chemical elements (mainly C, N, and P) in the process of ecologic interaction [19], which is used to track the changes of ecosystem structure and nutrient cycling [20]. Soil nutrient directly affects the growth and productivity of plant communities, and soil C/N/P stoichiometry is considered an important indicator of soil nutrient characteristics [21]. Therefore, the study of soil C/N/P stoichiometry can indicate soil nutrient status, which is conducive to a better understanding of soil limiting elements, and scientifically adjusts the fertilization type, so as to promote plant growth and improve crop productivity [22,23]. Large numbers of studies have demonstrated that land reclamation can affect the soil C/N/P stoichiometry. For example, intensive fertilization in farmland has led to a decrease in C/N and C/P, and the N/P was more sensitive to nitrogen addition [24]. Besides, deep plowing broke the nutrient fixation status, and significantly increased the soil C/N and reduced the C/P [25]. Straw mulching directly affected the rate of mineralization and decomposition of nutrients by the adjusted soil temperature and water content, which in turn caused the changes in soil C/N/P [26].

Although the impact of different land reclamation treatments on soil nutrients have been fully revealed, the linkages between soil nutrient contents, pools, stoichiometry, and crop growth under the supplement of organic amendments in CTL is limited. Therefore, we hypothesized that different soil reclamation treatments can increase soil nutrient content, pools, and modulate their stoichiometric ratio, thus promoting the growth of oat. Specifically, the objectives of this study were to: (1) identify the effect of different land reclamation treatments on C, N, and P contents, pools, stoichiometry, and oat growth; and (2) explore the linkages between soil C, N, and P contents, pools, stoichiometry, and oat growth parameters following the reclamation of CTL.

2. Materials and Methods

2.1. Study Area

This experiment was carried out in Tongzhou Bay (32°11′ N, 121°22′ E), Nantong City, Jiangsu Province, eastern China (Figure 1). The region has a subtropical monsoon climate, with an average annual temperature of about 14–15 °C. The average annual rainfall is about 1000–1080 mm, which is relatively concentrated from June to September. The area was reclaimed for marine aquaculture in 2008, and the experiment field was established in 2016. The groundwater depth is 1.2–1.8 m. The soil is characterized by a sandy loam texture, high bulk density, salinity, and sodicity, and has low nutrients (Table 1).

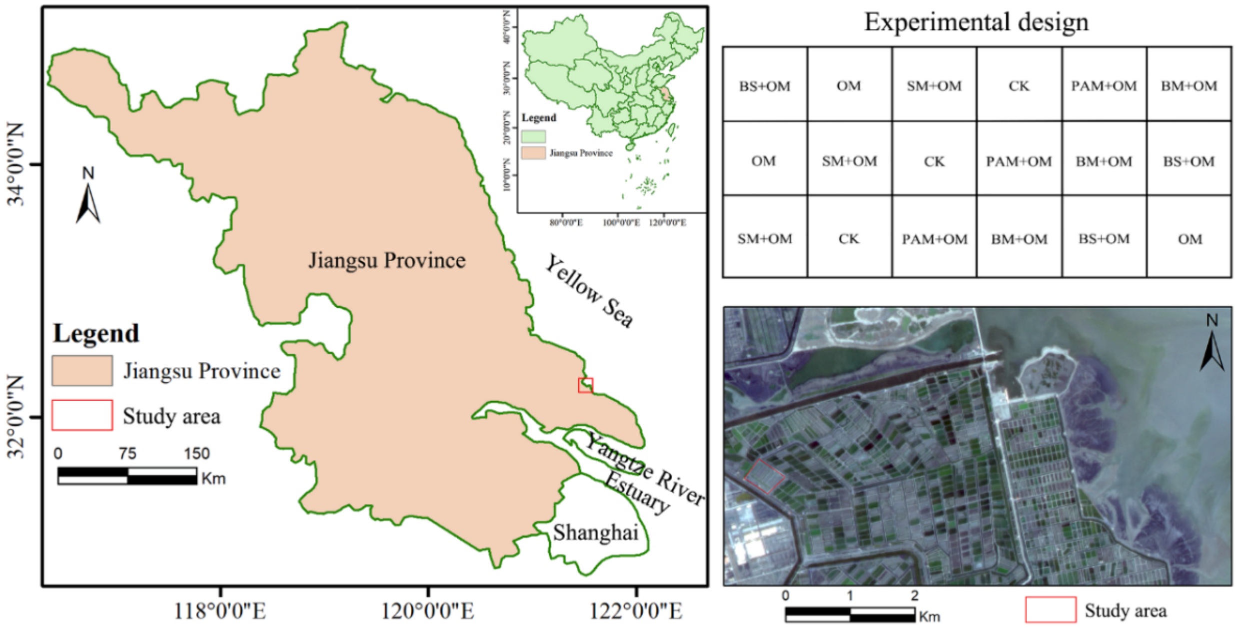

Figure 1. Location of the study area.

Table 1. Soil properties before field experiment.

Soil Depth (cm)	Sand (%)	Silt (%)	Clay (%)	BD (g cm^{-3})	$EC_{1:5}$ (dS m^{-1})	$pH_{1:2.5}$	SOC (g kg^{-1})	TN (g kg^{-1})	TP (g kg^{-1})
0–10	79.35	17.45	3.19	1.49	1.82	8.06	4.13	0.55	0.73
10–20	79.01	17.72	3.26	1.53	1.43	8.16	4.04	0.54	0.69
20–40	80.54	16.37	3.08	1.52	2.32	7.98	3.69	0.47	0.67

Note: BD, bulk density; EC, electrical conductivity; SOC, soil organic carbon; TN, total nitrogen; TP, total phosphorus.

2.2. Experimental Design

In this experiment, 18 plots (3 × 2 m) were insulated by double-layer plastic sheets buried to 60 cm deep and 50 cm wide to the soil surface to reduce interference between the plots. Due to the high soil bulk density, all plots were plowed to 20 cm deep before the experiment. The following 6 reclamation treatments were applied: (1) control (CK); (2) organic manure (OM); (3) polyacrylamide plus organic manure (PAM + OM); (4) straw mulching plus organic manure (SM + OM); (5) buried straw plus organic manure (BS + OM); and (6) bio-organic manure plus organic manure (BM + OM). All treatments were randomly designed and repeated three times, and the specific measures of each treatments are shown in Table 2. The physicochemical properties of all applied amendments are presented in Table 3. All treatments were conducted in September 2016. Oat seed was sown in drill (drill spacing 60 cm) with 90 kg ha^{-1} on 3 November 2016, and the urea (46% N) was sprayed with 180 kg ha^{-1} on the soil surface at the jointing stage (March 2017). The field management practices were consistent with local farmers, and the crop was harvested on 2 June 2017. The oat growing period can be divided into the seedling stage (0–60 days), jointing stage (60–90 days), heading stage (90–120 days), filling stage (120–150 days), and maturation stage (150–210 days).

Table 2. Experimental treatment design and specific measures.

Treatment	Specific Measures	References
CK	No application of amendments.	
OM	Chicken manure was evenly applied at soil surface at 15 ton ha^{-1}, then the plot was ploughed and harrowed to a depth of 10–15 cm with a physically acceptable evenness and mellowness.	[27]
PAM + OM	Both nonionic polyacrylamide (5%, approximately 2 ton ha^{-1}) and chicken manure (15 ton ha^{-1}) were evenly applied at soil surface, then the plot was ploughed and harrowed to a depth of 10–15 cm with a physically acceptable evenness and mellowness.	[28]
SM + OM	Chicken manure (15 ton ha^{-1}) was evenly applied at soil surface, and the plot was ploughed and harrowed to a depth of 10–15 cm with a physically acceptable evenness and mellowness, then the wheat straw (15 ton ha^{-1}) was cut to 10 cm long and evenly mulched.	[29]
BS + OM	Wheat straw (15 ton ha^{-1}) was cut to 10 cm long and evenly buried nearly 20 cm underground after removal of soil, followed by the addition of chicken manure (15 ton ha^{-1}); thereafter, the plot was ploughed and harrowed to a depth of 10–15 cm with a physically acceptable evenness and mellowness.	[30]
BM + OM	Both Jiahua (a compound bio-organic manure made from cow dung and crushed corn straw by deep fermentation and decomposition of *Bacillus* and *Saccharomyces*, containing approximately 2.0×10^8 CFU of viable bacteria g^{-1}) and chicken manure were evenly applied at soil surface at a rate of 15 ton ha^{-1}, and the plot was ploughed and harrowed to a depth of 10–15 cm with a physically acceptable evenness and mellowness.	[28]

Note: CK, control; OM, organic manure; PAM + OM, polyacrylamide plus organic manure; SM + OM, straw mulching plus organic manure; BS + OM, buried straw plus organic manure; BM + OM, bio-organic manure plus organic manure.

Table 3. Physicochemical properties of soil amendments.

Amendment	TOC (%)	TN (%)	TP (%)
Chicken manure	13.14	1.42	0.87
Polyacrylamide	–	0.07	–
Wheat straw	16.53	0.62	0.23
Jiahua bio-organic manure	27.10	4.58	3.63

Note: TOC, total organic carbon; TN, total nitrogen; TP, total phosphorus; "–", not determined.

2.3. Soil Sampling and Determination

After the oats were sown, a composite soil sample was randomly collected at 0–10 cm (surface layer), 10–20 cm (subsurface layer), and 20–40 cm (deep layer) in each plot with five replicates at 30-day intervals. A total of 432 soil samples were collected during the whole oat growing period. All samples were stored in polyethylene bags and brought back to the laboratory. After removing all visible plant roots, stones, and organisms, soil samples were naturally air-dried and passed through a 0.149 mm sieve to measure physicochemical properties. All methods applied for measuring the soil physicochemical properties have been described in detail by Lu [31]. Briefly, soil bulk density (BD) was determined by oven drying to constant mass at 105 °C for 48 h; soil organic carbon (SOC) was determined by potassium dichromate oxidation-spectrophotometry; soil total nitrogen (TN) was determined by the Kjeldahl method; soil total phosphorus (TP) was determined by the colorimetric method after digestion with hydrofluoric and perchloric acid. The pools of SOC, TN, and TP were calculated using the following equation:

$$Y_P = \sum_{i=1}^{n} X_i \times BD_i \times D_i \times 0.1 \quad (1)$$

where Y_P is the pools of SOC, TN, and TP; X_i is the concentration of SOC, TN, and TP in the ith layer; BD_i is the bulk density of the ith layer; D_i is the depth interval of ith layer; and 0.1 is the conversion factor from g cm^{-2} to kg m^{-2}.

2.4. Determination of Oat Growth Parameters

During the oat growing period, 5 oat plants were randomly selected from each plot, and the plant height and stem diameter were recorded every 30 days. The plant height was determined by measuring the absolute height from the ground to the highest position of the main stem with a steel tape, and the stem diameter was measured by vernier caliper from the internode position at the base of the main stem.

2.5. Statistical Analysis

The measured soil properties and oat growth parameters were analyzed with one–way ANOVA to test the significant differences among the different reclamation treatments, and the means comparisons were separated using the Fisher's least significant difference (LSD) test at $p = 0.05$. Redundancy analysis (RDA) was applied to clarify the relationship between oat growth, soil C, N, and P content, pools, and stoichiometry. All data analyses were carried out in SPSS 20.0 for Windows software package and Canoco 4.5 for Windows software package.

3. Results

3.1. Soil C, N, and P Content

During the oat growing period, the content of SOC under different reclamation treatments in all soil layers showed a trend of first increasing and then decreasing with the highest content observed in the heading stage (Figure 2). In the surface layer, compared with the CK treatment, the SOC content of each reclamation treatment gradually increased, especially under the BM + OM treatment, which increased by 11.7–182.4%. However, compared with the CK treatment, the content of SOC in the subsurface layer increased by 0.0–40.0% during the entire growing season, except for the SM + OM treatment. Additionally, no significant differences were observed in SOC content between different treatments during the entire growing season in the subsurface layer, except for the heading stage; whereas no significant differences were found in the SOC content in the seedling, heading, and maturation stage among different treatments in the deep layer. The content of TN in all soil layers remained relatively stable under different treatments during the oat growing season, except for the BM + OM treatment (Figure 2). In the surface layer, the content of TN under the PAM + OM treatment was slightly lower than that of the CK treatment (decreased by 9.1%) during the filling stage, whereas soils under the BM + OM, BS + OM, SM + OM, and OM treatments were higher than that of the CK treatment, and increased by 24.3–85.7%, 9.1–47.2%, 12.1–25.0%, and 1.2–22.9%, respectively. Besides, there were no significant differences in TN content between different reclamation treatments in subsurface and deep layers during the oat growing season, except for the heading stage in the subsurface layer and the filling stage in the deep layer, respectively. The dynamics of TP content in all soil layers were similar to that of TN content (Figure 2). Throughout the oat growing season, BM + OM, BS + OM, OM, SM + OM, and PAM + OM treatments increased surface layer TP content by 3.2–29.4%, 0.5–17.4%, 3.8–14.8%, 4.9–10.4%, and −0.5–13.6% compared with the CK treatment. In general, there were no significant differences in TP content between different reclamation treatments during the jointing, heading, and filling stages in the surface layer, whereas no significant differences were observed in TP content during the middle and later stages of oat growth in subsurface and deep layers.

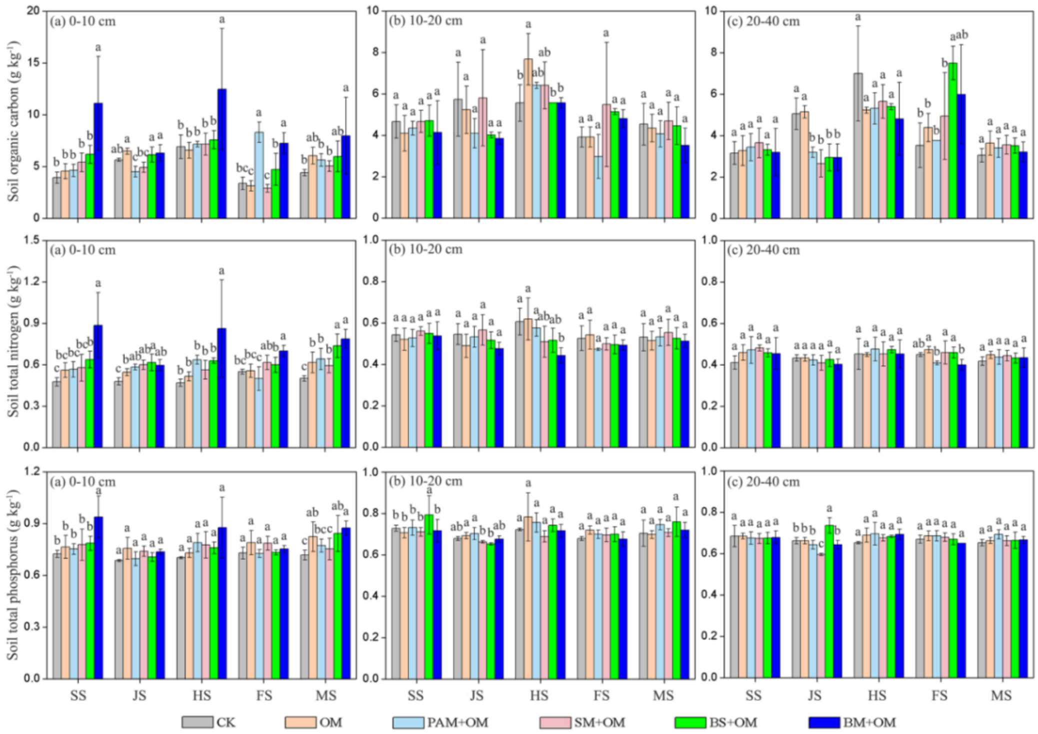

Figure 2. Dynamics of soil organic carbon, total nitrogen, and total phosphorus contents under different oat growth stages in 0–10 cm (**a**), 10–20 cm (**b**), and 20–40 cm (**c**). SS: seedling stage; JS: jointing stage; HS: heading stage; FS: filling stage; MS: maturation stage. Values are means of three replicates ± SD; error bars refer to standard deviation; values having different lowercase letters on the bars indicate significant differences among different treatments (least significant difference (LSD), $p < 0.05$).

3.2. Soil C, N, and P Pools

During the oat growing period, the soil organic carbon pools (SOCP) under different reclamation treatments in the 0–40 cm soil layer showed a trend of first increasing and then decreasing (Figure 3). Except for the BS + OM treatment (filling stage), the highest SOCP under different treatments were found in the heading stage. Compared with the CK treatment, the SOCP increased to different degrees under different reclamation treatments in seedling, filling, and maturation stages. Among them, the BM + OM and BS + OM treatments showed significant differences in SOCP in seedling and filling stages, respectively, whereas there were no significant differences between the treatments in the heading and maturation stage. In the jointing stage, the SOCP in OM treatment was significantly higher than other treatments.

Generally, soil total nitrogen pool (TNP) under the BS + OM treatment was slightly higher than that of other treatments (Figure 3). In the seedling and maturation stages, the TNP under different reclamation treatments increased by 6.5–19.9% and 6.0–11.2%, respectively, compared with the CK treatment. However, no significant differences were observed in TNP under different treatments at jointing and heading stages. Besides, the TNP under the PAM + OM treatment was significantly lower than CK, OM, SM + OM, and BS + OM treatments.

During the oat growing season, soil total phosphorus pool (TPP) remained relatively stable under different reclamation treatments, and no significant differences were observed between different treatments in seedling and heading stages (Figure 3). The TPP in the jointing stage was similar to the maturation stage, with the highest value in the BS + OM treatment, whereas the lowest value was in the SM + OM treatment. Additionally, TPP under the SM + OM treatment in the filling stage was significantly lower than that of CK, OM, PAM + OM, and BS + OM treatments.

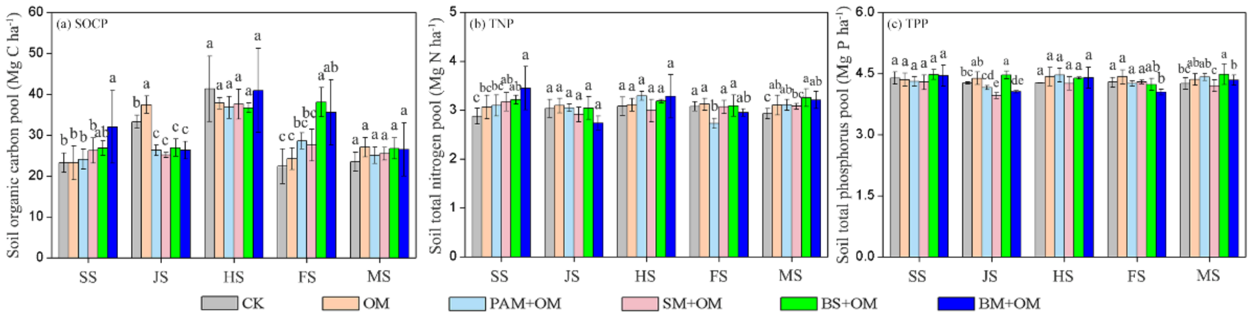

Figure 3. Dynamics of SOCP (**a**), TNP (**b**), and TPP (**c**) under different oat growth stages in 0–40 cm. SOCP: soil organic carbon; TNP: total nitrogen; TPP: total phosphorus pools; SS: seedling stage; JS: jointing stage; HS: heading stage; FS: filling stage; MS: maturation stage. Values are means of three replicates ± SD; error bars refer to standard deviation; values having different lowercase letters on the bars indicate significant differences among different treatments (LSD, $p < 0.05$).

3.3. Soil C, N, and P Stoichiometry

Soil C/N roughly increased first and then decreased with the growth of oat under different treatments and soil layers, and reached the highest value at the heading stage (Figure 4). In the surface layer, significant differences were found in soil C/N between different treatments in the seedling, jointing, heading, and filling stage, whereas no significant difference was found in the maturation stage. Among them, soil C/N of the BM + OM treatment was significantly higher than that of other treatments at the seedling stage, and the PAM + OM treatment had the lowest soil C/N at jointing and heading stages and the highest C/N at the filling stage. The C/N of the subsurface layer did not differ significantly under different treatments. Similarly, in the deep layer, there was no significant difference in C/N at seedling, heading, and maturation stages. The C/N of the deep layer under CK and OM treatments were apparently higher than that of other treatments at the jointing stage, whereas BS + OM and BM + OM treatments at the filling stage were notably higher than that of CK, OM, and PAM + OM.

The dynamic of soil C/P during the oat growing period was similar to that of C/N, with the highest value appearing at the heading stage (Figure 4). Overall, the BM + OM treatment had a significant impact on the C/P of different soil layers. In the surface layer, compared with the CK treatment, soil C/P under the BS + OM and BM + OM treatments increased by 1.0–44.5% and 28.0–126.3%, respectively, during the whole oat growth period. There was no significant difference between OM and CK treatments. Additionally, PAM + OM and SM + OM treatments were significantly lower than the CK treatment at the jointing stage, whereas they were significantly higher than the CK treatment at the filling stage and seedling stage, respectively. The reclamation treatments have little effect on the C/P in the subsurface layer. Except that the BM + OM treatment was significantly higher than other treatments at the heading stage, and there was no significant difference in C/P between different treatments at other growth stages. Soil C/P under different treatments in the deep layer is not significantly different at the heading stage. However, in the seedling and maturation stages, the C/P under BM + OM treatment was significantly higher than other treatments.

Soil N/P fluctuated slightly under different treatments during the oat growing season (Figure 4). In the surface layer, soil N/P under BM + OM and BS + OM (except the filling stage) treatments was significantly higher than the CK treatment throughout the oat growing season. Compared with the CK treatment, the N/P of the subsurface layer under BS + OM, PAM + OM, and OM treatments, respectively, decreased by 1.2–17.5%, 3.6–12.9%, 1.1–12.0%, and no significant differences were found between jointing and filling stages. Moreover, no significant differences were observed between reclamation treatments throughout the growth period in the deep layer.

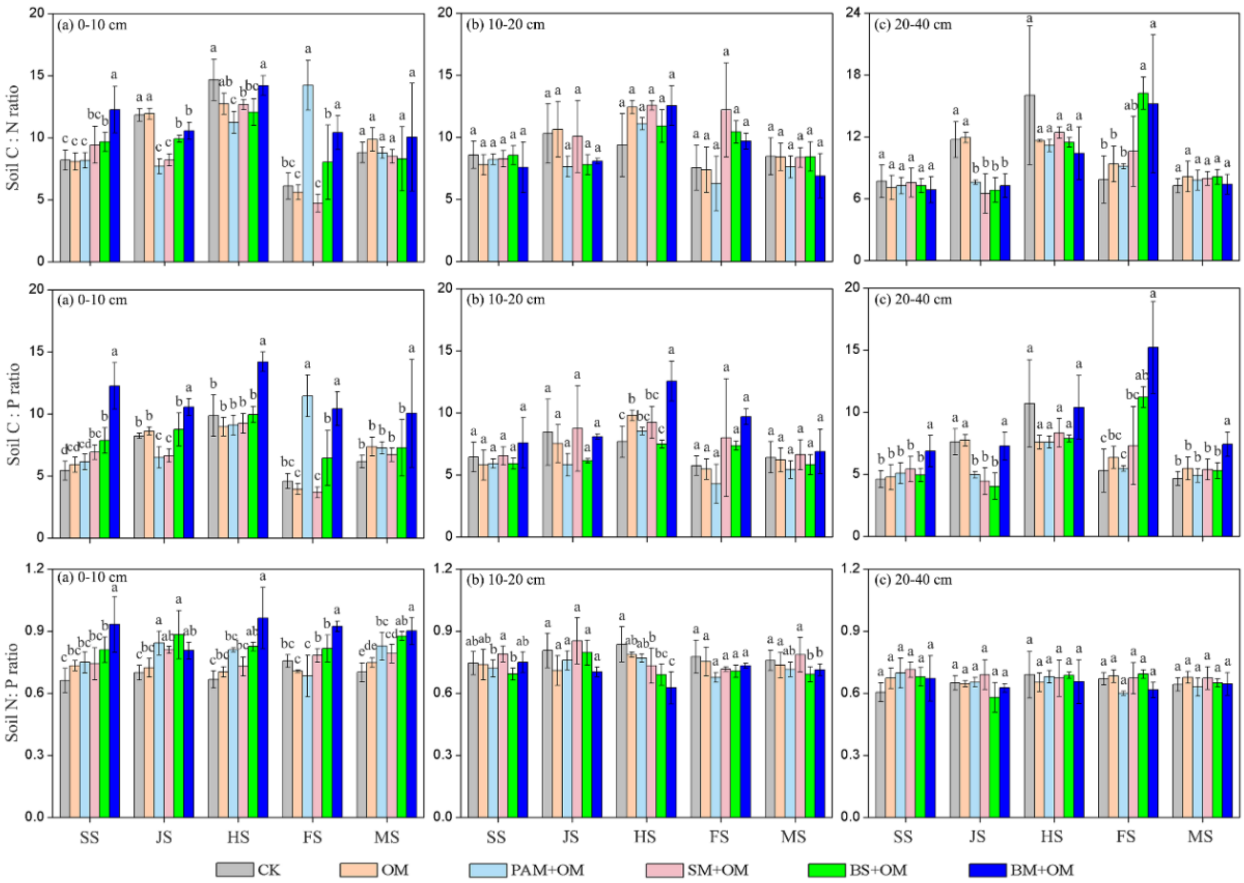

Figure 4. Dynamics of soil C/N, C/P, and N/P under different oat growth stages in 0–10 cm (**a**), 10–20 cm (**b**), and 20–40 cm (**c**). SS: seedling stage; JS: jointing stage; HS: heading stage; FS: filling stage; MS: maturation stage. Values are means of three replicates ± SD; error bars refer to standard deviation; values having different lowercase letters on the bars indicate significant differences among different treatments (LSD, $p < 0.05$).

3.4. Oat Growth Parameters

During the growth period of oat, all reclamation treatments can increase the stem diameter and plant height of oat in varying degrees (Figure 5). The stem diameter and plant height of oat under the BM + OM treatment was much higher than that of other treatments. As the growing season progressed, there were no significant differences in stem diameter under BS + OM, SM + OM, and PAM + OM treatments except for the maturation stage. Similarly, the plant height under PAM + OM, SM + OM, and BS + OM treatments were significantly higher than that of the OM treatment in the heading, filling, and maturation stage.

3.5. Redundancy Analysis

In this study, RDA was performed to explore the relationship between oat growth parameters and soil C, N, and P indicators at each oat growth period. As shown in Figure 6, the first two axes in the seedling, jointing, heading, filling, and maturation stages cumulatively explained 75.4%, 96.9%, 98.8%, 76.9%, and 63.0% of the variation of oat growth, which indicates that the first two axes can fully explain the relationship between oat growth and soil C, N, and P indicators. During the oat grown season, soil C, N, and P contents and their stoichiometry are positively correlated with oat growth parameters, whereas soil N and P pool in jointing and filling stages are negatively correlated (Figure 6).

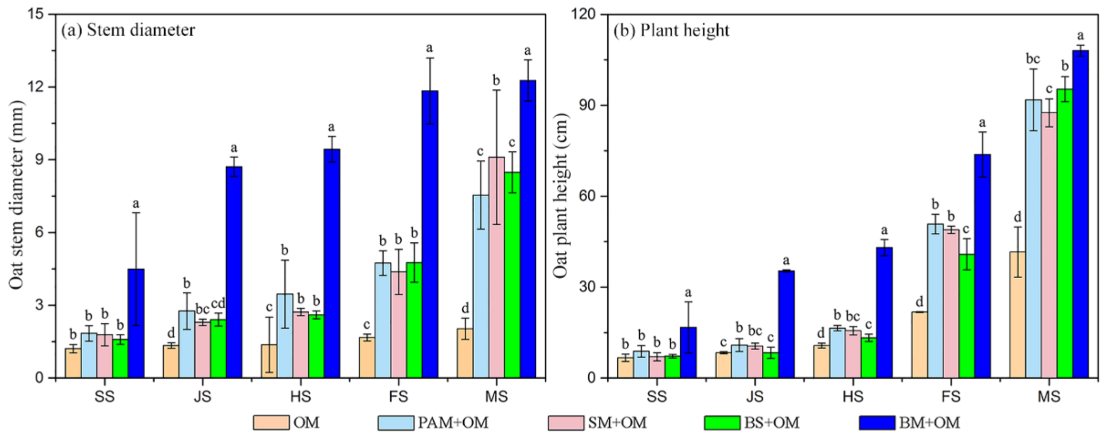

Figure 5. Dynamics of oat stem diameter (**a**) and plant height (**b**) under different growth stages. SS: seedling stage; JS: jointing stage; HS: heading stage; FS: filling stage; MS: maturation stage. Values are means of three replicates ± SD; error bars refer to standard deviation; values having different lowercase letters on the bars indicate significant differences among different treatments (LSD, $p < 0.05$).

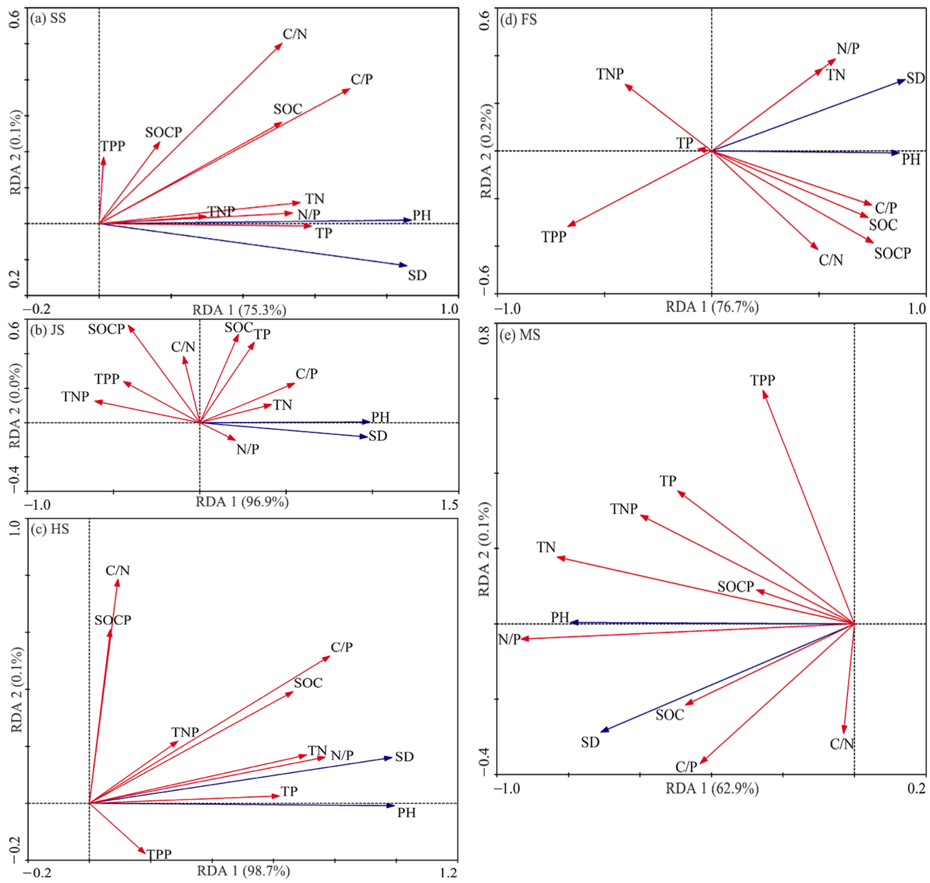

Figure 6. Coordination biplots of redundancy analysis (RDA) displaying the relationship between oat growth parameters and surface soil C, N, and P indicators in SS (**a**), JS (**b**), HS (**c**), FS (**d**), and MS (**e**). Oat growth parameters are response variables and soil C, N, and P indicators are explanatory variables. The positive and negative correlation between two soil properties depends on the same or opposite direction of arrows, and the correlation is determined by the projection length of the arrows of two soil properties. PH: plant height; SD: stem diameter; SOC: soil organic carbon; TN: total nitrogen; TP: total phosphorus; SOCP: soil organic carbon pool; TNP: total nitrogen pool; TPP: total phosphorus pool; SS: seedling stage; JS: jointing stage; HS: heading stage; FS: filling stage; MS: maturation stage.

4. Discussion

4.1. Response of Soil Nutrient Contents, Pools, and Stoichiometry Following Agricultural Land Reclamation

Land reclamation of CTL with organic and inorganic amendment may alter the mineralization and decomposition processes of soil nutrients [12,32]. In this experiment, soil C, N, and P contents, pools, and stoichiometry under different land reclamation treatments generally decreased with the increase of soil depth. This might be attributed to the various amendments that are mainly carried out in the upper soil layer, and the litter of oat plants is also concentrated on the soil surface. Earlier studies have indicated that organic manure was an efficient way to supplement the soil nutrients [11,33]. For example, the organic manure compost increased the cation exchange capacity, available macro-nutrient contents, and biological activities, whereas it decreased the soil salinity [11,14]. In the present experiment, application of chicken manure has increased the content of SOC, TN, and TP in the surface soil. Polyacrylamide changes the soil structure and improves soil water retention and corrosion resistance, which is conducive to maintaining soil moisture and fertility [34,35]. In this experiment, the content of SOC, TN, and TP in the surface layer under PAM + OM treatment basically increased during the oat growing period (Figure 1). Earlier studies have also shown that PAM as a structural modifier can effectively change the structure of soil aggregates, retaining soil water content and fertility, and reducing the loss of soil N, P, and other nutrient elements, and improving the stability of agricultural production [17]. Numerous studies have shown that straw is rich in organic matter and nutrient elements such as nitrogen, phosphorus, and potassium, and straw returning can increase the number and activities of microorganisms and promotes the decomposition of organic nutrients, resulting in the increase of soil nutrients [30,36]. In our study, the SOC, TN, and TP contents of the soil under treatments of SM + OM and BS + OM roughly increased, and the BS + OM is more conducive to the enhancement of deep soil fertility than that of SM + OM, which is consistent with Zhao et al. [13]. Many studies have shown that the bio-organic fertilizer provided a large amount of organic matter for microorganisms [12,37]. Similarly, the SOC, TN, and TP contents of the surface soil under the BM + OM treatment increased significantly in our experiment, which might be due to the bio-organic fertilizer used in this experiment containing the organic matter ≥45% and total nutrients (N + P + K) ≥12%, as well as containing a large number of microbial communities, which are beneficial to the release of available nutrients [28].

Application of organic amendment may also change the soil C, N, and P pools. In our study, the SOCP under different land reclamation treatments roughly increased from the seedling to heading stage, and then decreased from the heading to maturation stage, which is similar to the results of a previous study [21]. In addition, SOCP at the seedling, filling, and maturation stages increased significantly under different reclamation treatments, whereas at the jointing and heading stages it decreased (Figure 3). This may be owing to the gradual decomposition of organic amendment in the early oat growth period providing enough carbon source, while the oat grows rapidly at the heading stage, and the enhancement of photosynthesis improves the carbon fixation capacity of oat [38]. In this experiment, soil TNP and TPP basically remained stable throughout the growth period, which was not consistent with former studies that confirmed that the application of organic fertilizers can increase soil carbon and nitrogen pools [39]. It may be because nitrogen is usually present in organic matter in the form of organic nitrogen, which makes the changes in soil carbon and nitrogen more synchronized [40]. The decline in the phosphorus pool may be caused by the reduction in the fixation of inorganic phosphorus after the application of organic fertilizers, and part of the organic phosphorus in organic fertilizers is easily decomposed [41]. In general, fertilizers gradually dissolved and were slowly absorbed by the soil under different reclamation treatments. Therefore, the soil C, N, and P contents and pools increased in the early stage of oat growth, and the application of urea at the jointing stage further improved the soil N content and pool. After that, the oat enters the rapid growth stage and needs to absorb a large amount of soil nutrients to maintain growth, resulting in the decline of soil C, N, and P content and pools.

Land reclamation remarkably altered soil C/N/P stoichiometry, ascribing to the disproportionate increase of C, N, and P content. In our study, soil C/N, C/P, and N/P under different reclamation treatments were between 4.73–17.23, 3.69–15.22, and 0.58–0.96, respectively. SOC is a key factor to adjust soil C/N and C/P changes under different reclamation treatments, whereas soil N/P changes are mainly controlled by TN in this study. Generally, the soil C/N ratio is inversely proportional to its decomposition rate, and soil with a lower C/N ratio has faster mineralization [23]. The soil C/P ratio is considered an important indicator for assessing the mineralization ability of soil phosphorus, which can measure the potential of soil organic matter mineralization to release phosphorus or absorb and retain phosphorus [22,23]. In this experiment, soil C/N and C/P of each soil layer under different treatments generally increased first and then decreased, which might be due to the relatively high temperature in the seedling, filling, and maturation stages, and enhanced the soil microbial activities and accelerated the decomposition of organic matter, resulting from the decrease of SOC [42]. Simultaneously, the increase in precipitation can increase the mineralization rate of soil nitrogen, and ultimately lead to a decrease in soil C/N, which is consistent with the results of Yan [43]. The soil N/P ratio has been suggested to be useful for assessing N or P limitations [19,22]. Soil N/P in this study was much lower than the average level of Chinese national wetlands (13.6), which suggest that N is the main limiting element in this area [20].

4.2. Linkages between Soil Nutrient Contents, Pools, Stoichiometry, and Oat Growth Following Agricultural Land Reclamation

Land reclamation with organic amendments altered soil C, N, and P content, pools, and stoichiometry, thereby promoting the growth of oat. Our experiment indicated that the stem diameter and plant height of oat under BM + OM, BS + OM, SM + OM, and PAM + OM treatments were significantly higher than that of the OM treatment, while oat cannot germinate under the CK treatment due to high salinity. This is consistent with previous studies which demonstrated that the application of organic amendments in saline soils can improve soil structure, reduce soil salinity, increase nutrient contents, and thus promote the plant growth and crop yield [44,45]. However, the growth of oat in the middle and later stages of the OM treatment was slower than that of other treatments, which, due to the increase of soil salinity, inhibited the oat growth [28]. PAM modifier plays an important role in reducing nutrient loss [34] and can significantly promote oat growth (Figure 5). Straw returning to the field has been demonstrated to reduce soil water evaporation, regulate soil temperature, release a large amount of organic matter and nutrient elements during the process of decay, and promote crop growth and yield [9,13]. The effects of SM + OM and BS + OM treatments on oat growth are more obvious in the filling stage and maturation stage. This might be attributed to the slow decomposing rate of straw due to lower temperatures in the early stage (winter), and the accelerated decomposition of straw as the temperature rises in the later stage (spring) to release a large amount of nutrients, which ensures nutrient supply and enables rapid plant growth [46]. In this experiment, the BM + OM treatment significantly promoted the oat growth, which can be ascribed to the bio-organic fertilizer-enhanced soil microbial activity, and which continuously provides nutrients for plant growth [47].

Redundancy analysis revealed that soil SOC, TN, TP, C/P, and N/P is highly correlated with oat growth throughout the growth period of oat, indicating that soil C, N, and P content and their stoichiometric relationships are important factors affecting the growth of oat. Previous studies have shown that C, N, and P are essential nutrients for crop growth, and appropriate N and P content are beneficial to the increase of vegetation height, density, and biomass [48]. The phosphorus content in the study area was relatively low and stable under different soil reclamation treatments (Figure 3), and the fluctuation of C and N content led to changes in soil C/P and N/P, which ultimately affected the growth of oat. In this experiment, the correlation between SOCP, TNP, TPP, and oat growth are weak or even negatively correlated during oat growing season, which ascribes to the oat absorbing a large amount of N and P elements in the jointing and filling stages to meet the growth of oat, resulting in the decrease of N and P pools.

5. Conclusions

Our study revealed that the applied land reclamation treatments can be considered as an efficient approach to increase surface soil nutrients and pools. During the oat growth period, the BM + OM treatment significantly increased SOC, TN, and TP content, with the increasing rate of 11.7–182.4%, 24.3–85.7%, and 3.2–29.4%, respectively. The highest SOCP was observed in the oat heading stage (36.67–41.34 Mg C ha^{-1}), whereas the differences in TNP and TPP under all land reclamation treatments were not significant. The C/N and C/P ratio under different reclamation treatments showed a trend of increasing first and then decreasing, with the highest value in the oat heading stage (11.23–14.67 and 8.97–14.21), whereas the N/P fluctuates with the growth of oat. Simultaneously, the C/N/P ratio of all treatments indicated that the study area was regarded as N limited. Moreover, land reclamation treatments promoted the growth of oat, among which the highest stem diameter and plant height of oat were observed in the BM + OM treatment (12.27 mm and 108.06 cm). Furthermore, we observed soil C, N, and P contents and stoichiometry ($p < 0.05$) were more closely related to the oat growth compared with their pools. This study suggested that BM + OM can be recommended as priority agricultural management for reclamation of CTL.

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