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Carbon sequestration and *Jerusalem artichoke* biomass under nitrogen applications in coastal saline zone in the northern region of Jiangsu, China

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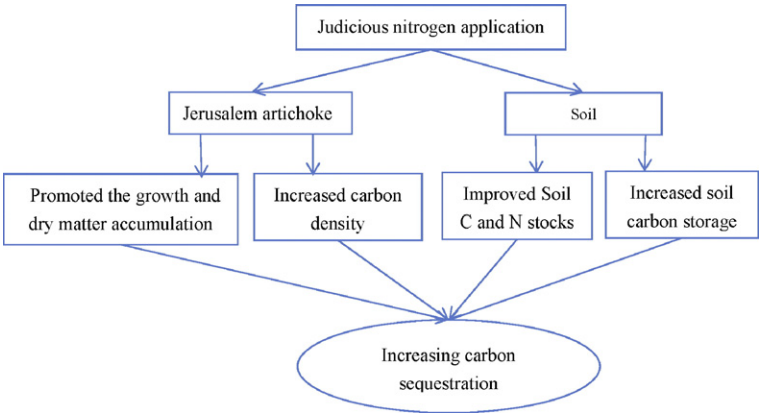
HIGHLIGHTS

- Dry matter accumulation increased under nitrogen fertilization application.
- Carbon density in Jerusalem artichoke ranged from 336 to 419 g C kg^{-1}.
- Soil carbon storage increased under nitrogen fertilizer application.
- Nitrogen application is effective in increasing carbon sequestration.

GRAPHICAL ABSTRACT



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ABSTRACT

Agriculture is an important source of greenhouse gases, but can also be a significant sink. Nitrogen fertilization is effective in increasing agricultural production and carbon storage. We explored the effects of different rates of nitrogen fertilization on biomass, carbon density, and carbon sequestration in fields under the cultivation of Jerusalem artichoke as well as in soil in a coastal saline zone for two years. Five nitrogen fertilization rates were tested (in g urea m^{-2}): 4 (N1), 8 (N2), 12 (N3), 16 (N4), and 0 (control, CK). The biomass of different organs of Jerusalem artichoke during the growth cycle was significantly higher in N2 than the other treatments. Under different nitrogen treatments, carbon density in organs of Jerusalem artichoke ranged from 336 to 419 g C kg^{-1}. Carbon sequestration in Jerusalem artichoke was higher in treatments with nitrogen fertilization compared to the CK treatment. The highest carbon sequestration was found in the N2 treatment. Soil carbon content was higher in the 0–10 cm than 10–20 cm layer, with nitrogen fertilization increasing carbon content in both soil layers. The highest soil carbon sequestration was measured in the N2 treatment. Carbon sequestration in both soil and Jerusalem artichoke residue was increased by nitrogen fertilization depending on the rates in the coastal saline zone studied.

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1. Introduction

The acceleration of greenhouse gas emissions is considered a global problem in the twenty-first century (Bolan et al., 2013). Increasing levels of atmospheric carbon dioxide (CO_2) and other greenhouse gases are thought to be contributing to an increase in atmospheric temperatures. During the past 250 years, the atmospheric concentrations of CO_2, CH_4 and N_2O have increased by 30, 145 and 15%, respectively (Mosier, 1998). Therefore, reducing greenhouse gas emissions and increasing carbon sequestration in terrestrial ecosystems have received widespread interest in the international community. Farmland ecosystems as one of the most active parts in the global carbon pool have equal and frequently greater net ecosystem production (NEP) than the natural ecosystems (Hollinger et al., 2004; Li et al., 2006). By 2030, farmland ecosystems have the potential to mitigate emissions of 5.5–6.0 Gt CO_2 per year, with 89% of this amount being due to soil organic carbon (SOC) storage (Häger, 2012). Many activities may affect farmland ecosystems, such as cultivation, irrigation and fertilization, resulting in significant variations in net ecosystem exchange (NEE) of CO_2. However, excessive fertilization can lead to soil degradation and water pollution, which may counteract the benefits of carbon sequestration (Zhang et al., 2002). Therefore, practical measures to improve carbon sequestration in farmland need to be characterized.

Nitrogen (N) is one of the macronutrients needed for plant growth. In the 1950s, before the development and worldwide application of the Haber-Bosch process, most agricultural systems were nitrogen (N)-limited (Ma et al., 2016). However, judicious application of N fertilizers can improve the quantity and quality of crop yields, which can be used to offset increased CO_2 emissions into the atmosphere (Liu et al., 2015; Kowalenko and Ivarson, 1978) and return assimilated CO_2 to the soil organic carbon (SOC) pool through the production and turnover of belowground biomass (Jung et al., 2011). Nevertheless, excessive application and inefficient use of N fertilizer are not only costly, but also contaminate surface and groundwater, acidify soil (i.e. ammonium-containing N fertilizers) and increase greenhouse gas emissions (Zhang et al., 2015a, 2015b).

Jerusalem artichoke (*Helianthus tuberosus* L.) (family Asteraceae) is a perennial, temperate-zone plant, native to North America (Li et al., 2015; Yang et al., 2015). This is an agricultural crop with a great potential for food, and production of fuels and industrial products (Kosaric et al., 1984). Compared with the traditional agricultural crops, Jerusalem artichoke has advantages in high growth rate, good tolerance to salt, frost, drought and infertile soils, strong resistance to pests and diseases, and the minimal-to-zero fertilizer requirements (Afoakwah et al., 2015). Jerusalem artichoke could produce large biomass and is a potentially useful crop for producing biofuel, such as bioethanol (Long et al., 2014; Krivorotova and Sereikaite, 2014). It produces high yield of edible tubers, which are rich in inulin (10–20% of fresh tuber weight) (Gunnarsson et al., 2014; Panchev et al., 2011). Inulin from Jerusalem artichoke tubers can be used as raw material for bioethanol production (Zhang et al., 2010).

Many studies on the effect of nitrogen fertilizer on Jerusalem artichoke were conducted with respect to growth, physiological and biochemical characteristics (Long et al., 2008). However, very few studies have been performed to characterize the effects of nitrogen fertilizer on biological carbon sequestration by Jerusalem artichoke and soil carbon storage in coastal saline zone. In order to fully utilize saline soils, we hereby propose to grow *Helianthus tuberosus*, which could be of particular importance in countries with scarce arable land and fresh water resources (Long et al., 2014). The aim of this study was to investigate the effects of different N fertilization rates on biomass, carbon density and carbon sequestration of Jerusalem artichoke together with soil carbon storage, thus providing a basis for research on optimizing fertilizer management of Jerusalem artichoke in coastal saline zone.

2. Materials and methods

2.1. Site description

The experiment was conducted at the "863 Program" Research Station of Dafeng, Jiangsu, China (32.59°N, 120.50°E, 4 km away from the Yellow Sea). The area has the typical monsoon climate transitioning from warm-temperate zone to north subtropical zone (Zhou et al., 2003), with mean annual temperature of 14.0 °C, mean annual precipitation of 1068 mm (most occurring from late June to August). The average salt contents at depths 0–20, 20–40 and 40–60 cm were 1.2, 3.1 and 5.0 g kg^{-1}, respectively. The basic soil properties before the study were pH 7.45–8.15 (Jenway 3540, Bibby Scientific Limited, UK), 1.1 g total nitrogen kg^{-1}, 19 mg available P kg^{-1} (extractable in 0.5 mol L^{-1} sodium bicarbonate), 212 mg available K kg^{-1} (extractable in 1 mol L^{-1} ammonium acetate) and an average pH of 7.47 (in 1:5, soil/water, w/w).

2.2. Experimental design

There were a total of 15 treatments with 3 replications, and a completely randomized distribution in this field. The size of each plot was 25 m^2 (5 m × 5 m). Urea (N content = 46%) was commercially available. The plot was provided with nitrogen fertilizer rate of urea at five levels: 0 g m^{-2} (CK), 4 kg m^{-2} (N1), 8 g m^{-2} (N2), 12 g m^{-2} (N3) and 16 g m^{-2} (N4). The soil was ploughed in winter using a conventional mould board plough and was then tilled twice more prior to sowing tubers. N fertilizer was applied at the seedling stage. The date of sowing seeds was on March 27, 2014 and March 20, 2015. Disease- and injury-free tubers of Jerusalem artichoke (cv Nanyu No. 1) were cut into pieces with one to two buds each, and sown at 60-cm row spacing and 50-cm intra-row spacing. The harvest date was on December 15, 2014 and December 10, 2015. The rainfall amounted to 580 mm and 610 mm for the Jerusalem artichoke growing season, respectively.

2.3. Plant and soil analyses

Plant samples were taken in September, July and December. In each plot nine plants were selected randomly, the whole plants were dug out with a spade, and transported to the Laboratory. The stem height was measured by a ruler. Plants were divided into roots, stems, leaves and tubers, and fresh weight was recorded after roots and tubers were washed thoroughly with tap water and rinsed with deionizer water. For determination of dry weight, roots, stems and leaves were first oven-dried at 105 °C for 15 min and then at 65–75 °C until constant weight was obtained. Carbon content in different plant organs was determined by the potassium dichromate oxidation method (Lister and Jones, 2003).

Soil samples were collected using a 6-cm-diameter soil auger to determine the physico-chemical properties at depths of 0–10 and 10–20 cm. These soil samples (1–2 kg each) were packed into self-sealing plastic bags for transport and then air-dried and passed through a 0.25-mm sieve for measuring SOC and total N contents. The SOC concentration was determined with the dichromate oxidation method (Walkley and Black, 1934), and total soil N was analyzed by Kjeldahl method (Qiu et al., 2015). Soil bulk density was calculated by dividing the oven-dried soil mass by the volume. The SOC density (g C m^{-2}) was calculated as follows: $SOC = \sum (Ci \times \rho i \times Hi \div 1.724 \div 100)$ where SOC, Ci, ρi and Hi represent the soil organic carbon storage (t ha), layer *i* soil organic matter content (g kg^{-1}), bulk density (g cm^{-3}), and soil thickness (cm), respectively. 1.724 represents a conversion coefficient for organic matter and organic carbon (Ma et al., 2016).

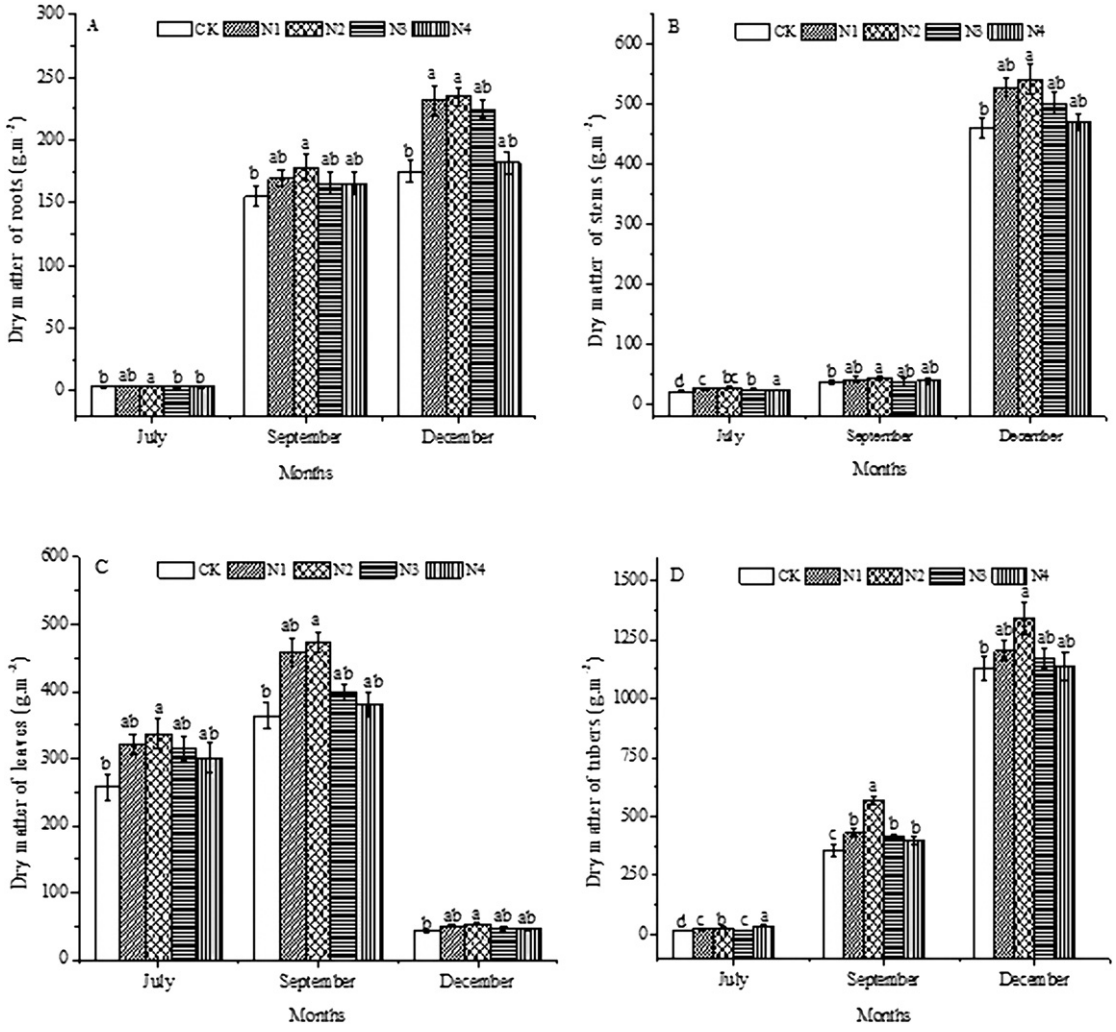

Fig. 1. The influence of nitrogen fertilization on dry matter accumulation by *Helianthus tuberosus* (A: roots; B: stems; C: leaves; D: tubers). The scale of the Y-axis differs in different graphs. Different letters in a particular month in each graph denote significant differences among nitrogen fertilization treatments ($P \leq 0.05$).

2.4. Statistical analysis

The mean values of two years were calculated, and the standard errors of the means were determined. Data were analyzed by one-way ANOVA. The mean differences were compared by Duncan's new multiple range test (SPSS 19.0). Difference between individual means was tested using the least significant difference test at $P \leq 0.05$ significance level.

3. Results

3.1. Dry matter accumulation

Dry matter of roots, stems and tubers increased with an increase in N fertilization and the growth stage (Fig.1). Dry matter of roots was higher than control in different growth stages of Jerusalem artichoke and increased rapidly from July to September. Dry matter of roots reached maximum under different treatments in December and increased in the order: N2 > N1 > N3 > N4 > CK.

Dry matter of stems grew slowly at first (from July to September) and then increased rapidly (Fig.1b). It was higher in the N2 than the other treatments.

Dry matter of leaves increased slowly from July to September and then decreased in December (Fig.1c). With an increase in N fertilization, dry matter of leaves increased first and then decreased, reaching the maximum under N2.

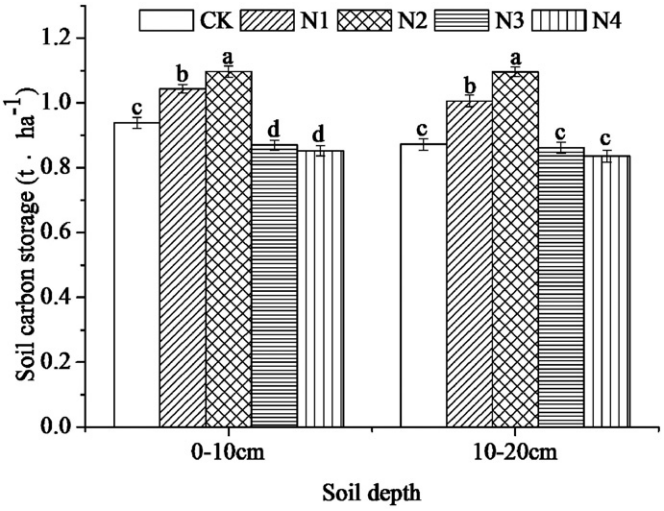

Fig. 2. Soil organic carbon storage as influenced by soil depth and different nitrogen fertilization. Different letters in a particular month in each graph denote significant differences among nitrogen fertilization treatments ($P \leq 0.05$).

Table 1
Effects of different nitrogen fertilization on carbon density in different organs of *Helianthus tuberosus* (g C kg^{-1}).

Treatment	Carbon density in different organs			
	Roots	Stems	Leaves	Tubers
CK	336 ± 3.9c	393 ± 13.0b	323 ± 12.8b	353 ± 7.8b
N1	354 ± 2.6ab	407 ± 7.5ab	327 ± 15.0ab	361 ± 5.1b
N2	363 ± 6.1a	419 ± 11.4a	332 ± 12.9a	386 ± 7.9a
N3	346 ± 6.2bc	418 ± 14.2a	329 ± 8.0ab	354 ± 10.7b
N4	340 ± 5.4bc	415 ± 9.6a	324 ± 13.7ab	364 ± 9.4b

Mean ± standard error, n = 36; different letters in the same column denote significant difference among nitrogen fertilization treatments (P ≤ 0.05).

Tubers accumulated more dry matter at the harvesting stage in December than in July and September (Fig.1d). In December, the highest dry matter of tubers was recorded in the N2 treatment, but difference was significant (P ≤ 0.05) only for the control.

3.2. Carbon density in different organs of Jerusalem artichoke

Carbon density in different organs of Jerusalem artichoke was higher with fertilization than in the control. The highest value of carbon density in different organs tended to be in the N2 treatment. Compared with control, root carbon density was increased by 5.1%, 7.5%, 2.9% and 1.3% in the N1, N2, N3 and N4 treatment, respectively. When nitrogen fertilization was >8 g urea m^{-2}, carbon density in different organs of Jerusalem artichoke tended to decrease.

3.3. Biomass accumulation and carbon sequestration in various organs of Jerusalem artichoke

Biomass of various organs of Jerusalem artichoke was lowest in the CK treatment (Table 2). With an increase in nitrogen fertilization, the biomass of each organ firstly increased and then decreased. Biomass of roots, stems, leaves and tubers in the N1 treatment increased by 0.57, 0.86, 0.1 and 0.64 t ha^{-1} compared with the CK treatment. Biomass of leaves and tubers reached the maximum in the N2 treatment. Carbon sequestration in Jerusalem artichoke was higher in treatments with nitrogen fertilization compared to the CK treatment. The range of total carbon sequestration in Jerusalem artichoke ranged from 6.72 to 8.89 t ha^{-1}.

3.4. Effect of nitrogen fertilization on soil carbon pool

As could be seen from Table 3, SOC concentration was significantly higher at 0–10 cm than 10–20 cm soil in the CK and various fertilization treatments. SOC concentration in CK, N1, N2, N3 and N4 at 0–10 cm depth was significantly higher by 9.3%, 5.9%, 0.51%, 3.3% and 4.4%, respectively, compared with the 10–20 cm layer (Table 3). The increases in mean SOC concentration (0–10 vs. 10–20 cm) were ranked in the order: N2 > N1 > CK > N3 = N4. Similar trends in SOC concentration were observed in both layers.

Concentration of soil total N (TN) decreased with an increase in soil depth, and ranged from 1.01 to 1.24 g kg^{-1}. At 0–10 cm depth, the concentrations of TN under N1, N2, N3 and N4 were significantly higher than at 10–20 cm depth. There was no significant difference in TN concentrations at 0–10 cm across various treatments.

The soil C:N ratio at 10–20 cm depth was slightly (non-significantly) higher than that at 0–10 cm depth regardless of the nitrogen treatments (Table 3). The soil C:N ratio in the 0–10 cm soil layer under CK, N1, N2, N3 and N4 fell by 0.49%, 4.2%, 2.5%, 3.4% and 0.15% compared to that at 10–20 cm depth. Significant difference was observed among different treatments (P ≤ 0.05).

3.5. Soil organic carbon storage after Jerusalem artichoke growth

In the 0–10 cm layer, soil carbon stocks first increased with increasing amount of nitrogen fertilization and then decreased (Fig. 2). The highest soil carbon storage (1.10 t ha^{-1}) was found in the N2 treatment. The carbon storage was higher in N1 and N2 soils than in control, increasing by 0.10 and 0.16 t ha^{-1}, respectively. The carbon storage in N3 and N4 was lower than the control, reduced by 0.07 and 0.09 t ha^{-1}, respectively. There were significant differences in soil carbon storage among CK, N1 and N2 (but not between N3 and N4) in both layers. The trends of carbon storage in the 10–20 cm soil layer were the same as those in the surface layer.

4. Discussion

Nitrogen fertilizer is one of the most important practices to increase and maintain crop production and quality in modern crop management (Gao et al., 2015). In the present study, nitrogen fertilization promoted the growth and dry matter accumulation of Jerusalem artichoke and increased tuber yield (Fig. 1), which was consistent with earlier studies (Fontes et al., 2010; Zhou et al., 2006). However, an excess nitrogen application increased the risk of degradation of soil, air and water resources (Bhattacharyya et al., 2010). In addition, the present study showed that dry matter accumulation in Jerusalem artichoke showed a decreasing tendency when an excess of nitrogen fertilizer was applied.

The carbon density in plant biomass influences C sequestration (Rajput et al., 2015). Our study showed that nitrogen application could increase carbon density in various Jerusalem artichoke organs, but a decreasing trend was shown with nitrogen fertilization above 8 g urea m^{-2}, particularly for roots and tubers (Table 1). Previous studies have reported similar effects of fertilizer applications on carbon storage in plants (Gao et al., 2015).

Soil increased sequestration of carbon in agricultural lands (Su et al., 2006). Soil organic carbon is an important component of the carbon pool and part of the global carbon cycle (Yigini and Panagos, 2016). The accumulation of soil organic carbon in agriculture can be achieved through some management measures (Haynes and Naidu, 1988). Soil C and N stocks were significantly higher with N fertilization (Wilson et al., 2009). Nitrogen fertilizer application (up to 80 kg hm^{-2} in the N2 treatment) increased soil carbon storage compared to the CK,

Table 2
Effects of different nitrogen fertilization rates on carbon sequestration in different organs of Jerusalem artichoke (t ha^{-1}).

Treat-ment	Carbon sequestration in different organs									
	Roots		Stems		Leaves		Tubers		Total	
	Biom-ass	Carbon stock	Biom-ass	Carbon stock	Biom-ass	Carbon stock	Biom-ass	Carbon stock	Biom-ass	Carbon stock
CK	1.74 ± 0.29b	0.63 ± 0.06c	4.61 ± 0.68b	1.75 ± 0.22b	0.43 ± 0.11c	0.15 ± 0.03b	10.33 ± 1.00b	4.19 ± 0.54b	18.06 ± 1.94c	6.72 ± 0.49b
N1	2.31 ± 0.24a	0.76 ± 0.1bc	5.47 ± 0.40a	1.96 ± 0.18b	0.53 ± 0.08b	0.15 ± 0.03b	10.97 ± 1.16b	4.65 ± 0.73b	20.13 ± 2.01b	7.53 ± 0.37b
N2	2.37 ± 0.46a	0.81 ± 0.06a	5.57 ± 0.28a	2.21 ± 0.35a	0.62 ± 0.07a	0.18 ± 0.02a	12.86 ± 0.84a	5.70 ± 0.72a	21.72 ± 1.84a	8.89 ± 0.47a
N3	1.95 ± 0.30b	0.75 ± 0.01b	5.29 ± 0.18a	1.81 ± 0.37b	0.51 ± 0.05b	0.17 ± 0.02ab	10.82 ± 1.26b	4.42 ± 0.47b	19.41 ± 2.33b	7.16 ± 0.49b
N4	1.82 ± 0.15b	0.78 ± 0.04c	4.65 ± 0.67b	1.77 ± 0.18b	0.45 ± 0.03c	0.17 ± 0.01ab	10.37 ± 1.85b	4.60 ± 0.62b	18.36 ± 2.02c	7.32 ± 0.38b

Mean ± standard error, n = 36; different letters in the same column denote significant difference among nitrogen fertilization treatments (P ≤ 0.05).

Table 3
Effects of nitrogen fertilization rates on soil on SOC total N content and C/N ratio in different soil layer.

Analysis	Soil depths	Treatments				
		CK	N1	N2	N3	N4
SOC (g kg^{-1})	0–10 cm	7.75 ± 0.07c	8.62 ± 0.12b	9.07 ± 0.14a	7.19 ± 0.05d	7.05 ± 0.04d
	10–20 cm	7.03 ± 0.43c	8.12 ± 0.06b	9.02 ± 0.02a	6.95 ± 0.04c	6.74 ± 0.14c
Total N (g kg^{-1})	0–10 cm	1.09 ± 0.01a	1.10 ± 0.05a	1.24 ± 0.04a	1.11 ± 0.12a	1.12 ± 0.03a
	10–20 cm	1.15 ± 0.01ab	1.01 ± 0.06b	1.19 ± 0.02a	1.02 ± 0.11b	1.07 ± 0.03ab
C/N	0–10 cm	6.82 ± 0.12b	8.09 ± 0.39a	6.12 ± 0.30b	6.64 ± 0.69b	6.29 ± 0.17b
	10–20 cm	7.12 ± 0.39b	8.13 ± 0.39a	6.28 ± 0.13c	6.87 ± 0.74b	6.30 ± 0.09c

Mean ± standard error, n = 36; different letters in the same column denote significant difference among nitrogen fertilization treatments ($P \leq 0.05$).

which was consistent with related research (Li et al., 2013; Wang et al., 2012).

Soil C:N ratio has a direct relationship with the C:N ratio of the crop biomass that is added to the soil. In general, fertilizer rate and type, the amount of residue retention, and the decomposition rate of the residue also directly influence the biomass C:N ratio (Zhang et al., 2015a, 2015b). Therefore, appropriate soil and crop management strategies are crucial to C:N dynamics. In our experiments, soil C:N ratio in the 0–10 cm soil layer was slightly (but non-significantly) lower than that in the 10–20 cm soil layer. In contrast, other studies indicated that the soil C:N ratio tended to decline with depth (Zhang et al., 2015a, 2015b).

Soil is an important carbon sink in the biosphere (Jin et al., 2014). It is estimated that the reserves of soil C are approximately 2.5 to 3.0 times of the vegetation carbon reserve in terrestrial ecosystems and 2 to 3 times that of carbon pools in the atmosphere (Yang et al., 2010). The small changes in the carbon stocks of the soil organic carbon pool influence the atmospheric carbon dioxide concentrations (Hu et al., 2016). Nitrogen is required to support carbon storage in soils (Zhong et al., 2016). Our results showed that soil carbon storage showed a tendency to decrease with soil depth under different nitrogen fertilization in coastal saline zone. The results of this research on Jerusalem artichoke were consistent with those of previous studies that N applications increased soil carbon storage compared with CK (Bi et al., 2009; Wang et al., 2012). Recent studies suggested that excess soil N affects C degradation (Liu and Crowley, 2009; Manning et al., 2008); in agreement with those results, our study showed that soil organic carbon decreased when more 8 g urea m^{-2} nitrogen applied (Table 3).

5. Conclusions

Compared with the control treatment, applying nitrogen (up to 8 g urea m^{-2}) improved dry matter accumulation and carbon sequestration in Jerusalem artichoke as well as soil carbon storage. Judicious nitrogen fertilization can increase carbon sequestration in plants and soils. This study provided basic data for optimizing fertilization of Jerusalem artichoke in coastal saline zone.

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