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Field performance of sweet sorghum in salt-affected soils in China: A quantitative synthesis

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ABSTRACT

Sweet sorghum is a high-yield crop with strong resistance, which has the potential to support the development of the forage farming industry in China where vast salt-affected lands are potentially arable. Nutrient management is imperative for sweet sorghum growing on salt-affected lands. Although nitrogen (N) synthetic fertilizers have long been recognized as a key factor for increasing crop yields, their effects on sweet sorghum cultivation are under debate. Consequently, this study integrated the current available observations of yield (n = 255) and partial factor productivity of nitrogen (NPFP, n = 242) of sweet sorghum in salt-affected lands, which included both inland (n = 189) and coastal (n = 66) areas. We quantitatively analyzed the effects of climatic, soil properties and management measures on biomass yield and NPFP of sweet sorghum, comparing the differences between inland and coastal salt-affected lands. We found that average biomass yield and NPFP of sweet sorghum in coastal areas were 19,082.48 ± 8262.75 kg/ha and 107.29 ± 51.44 kg/kg respectively, both significantly lower than that in inland areas ($p < 0.05$). The N application rate did not have significant promoting effect on the biomass yield of sweet sorghum in inland salt-affected areas ($p > 0.05$), whereas in coastal salt-affected areas, N application significantly increased the biomass yield of sweet sorghum. Increasing soil organic matter content could promote NPFP in inland areas. The recommended N application rate for inland salt-affected and coastal salt-affected areas were 100 kg/ha and 150 kg/ha respectively. The results indicate that it is crucial to apply nutrient management measures based on the local climatic and soil conditions, since the causes of salinity differ in coastal and inland salt-affected lands. More systematic field studies are required in the future to optimize the management of water and nutrients for sweet sorghum planting in salt-affected lands.

1. Introduction

In China, 1.23×10^7 ha of the total 3.6×10^7 ha salt-affected lands are potentially arable, which account for about 4.88% of exploitable lands in total (Yang, 2008). However, constrained by the water and salt stress in these areas, traditional crops can not generate satisfying grain production even with high nutrient input. It is documented that the reduction in wheat yield caused by salt stress can be up to 10%–90% (Eynard et al., 2005). Comparing to grain crops, forage grass production requires less coordination of climatic and soil properties, making it an effective and economic way to utilize salinized soils in China today. It has been showed that planting forage grass can not only enrich soil nutrients but decrease salinization as well (Xie et al., 2019). Despite the positive effect of developing forage grass on land use and livestock industry in salt-affected regions, studies focus on nutrient management in salt-affected regions are still limited.

Plants growing in salt-affected areas tend to exhibit nitrogen deficiency, which is partly due to the impact of salt content on nitrogen effectiveness and this has been verified in sorghum plants (Esmaili et al., 2008, 2008de Souza Miranda et al., 2016; Smith et al., 2020). Sweet sorghum is a variant of *Sorghum bicolor* (L.) Moench with the capacity of tolerance to salt, drought and flood (Almodares et al., 2008). It is now considered as a promising emerging crop for forage, sugar and energy production in China (Tang et al., 2018). Sweet sorghum is highly

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recommended for marginal land utilization in recent years. It shares similar properties with corn silage (*Zea mays* L.) and can be used for bioethanol and fodder production. However, corn silage is merely mildly salt tolerant (Farooq et al., 2015). When the salt content is up to 1 g/kg, its biomass will be limited remarkably (Sheng et al., 2010), whereas sweet sorghum has the capacity to less yield loss under stress conditions (Reyes-Cabrera et al., 2017). Comparing to silage, sweet sorghum can produce more dry matter than silage corns with less fertilizer inputs, thus costing less while the crude protein production is similar to the former one (Qu et al., 2014; Tang et al., 2018). It is reported that the yield of sweet sorghum was satisfying when the irrigation was around 250 mm, which is almost half of the amount maize requires, thus rain feed cultivation can be applied in many parts of China (Marsalis et al., 2010). Moreover, it can also accumulate more dry matter than grain sorghum (Murray et al., 2009; Diallo et al., 2019). Despite its advantages in yield and cost, it has not been widely grown in China. Comparing to forage grasses like silage corn and alfalfa (*Medicago sativa*), research information about planting and management practices of sweet sorghum is still scanty, limiting the spread of sweet sorghum in China. In the past few years, some experts proposed the shortage of forage in China could be alleviated by taking sweet sorghum as an alternative to silage corn (Qu et al., 2014; Tang et al., 2018). Thus, further studies should be conducted to promote the planting of sweet sorghum under salt stress.

Current studies focus on selective breeding and the adaptability of cultivars of sweet sorghum, but the responses of its biomass accumulation and fertilizer use efficiency to climate and soil conditions have not been well explored, given that the relationship between agriculture management and the environment is complex (Li et al., 2021). The climate and soil properties vary significantly across these regions for the causes of salinization differ in different bio-climatic zones. Seawater intrusion results in the dominant role of sodium chloride (NaCl) in coastal salt-affected soils in eastern China, whereas in the wider inland saline areas, the higher amount of evaporation than precipitation generates salt accumulation in the soil surface, and chloride, sulphate and carbonate are the main components. Thus, management and development of sweet sorghum cultivation differ in the two kinds of saline regions. Factors like the recommended planting density and fertilizer and water requirement have been broadly studied to determine their effects on biomass yield of sweet sorghum (Cosentino et al., 2012; Sawargaonkar et al., 2013). Among all the factors, nitrogen application has always been a focus in agriculture because it is one of the key factors that determines the yield of plants. Partial factor productivity of nitrogen (NPFP) is an indicator for nitrogen use efficiency of plants. Despite its strong correlation with N application, it is also regulated by other factors such as water availability and plant density (Ren et al., 2020; Xie et al., 2017). The overuse of nitrogen not only leads to decreasing nitrogen use efficiency (NUE), but also causes serious environmental problems as the result of leaching. However, a reasonable N application rate for sweet sorghum is still under debate. Some researchers pointed out that the optimum application rate was about 90 kg N/ha, while some proposed a high level of application rate ($>$200 kg N/ha) would contribute to high biomass accumulation (Marsalis et al., 2010). There are even evidences show that N application has no effects on sweet sorghum biomass (Sawargaonkar et al., 2013; Kurai et al., 2015; Tang et al., 2018). Consequently, a comprehensive understanding of how sweet sorghum responds to environmental factors and agricultural management in different salt-affected soils is crucial for optimization of cultivating techniques and enhancement of production efficiency.

At present, no integrated study is available concerning planting techniques for sweet sorghum. Therefore, we conducted a synthesis integrating literature data from different kinds of salt-affected areas to provide an insight into the nutrient management for sweet sorghum. The objectives of this study were (1) to investigate the dominant factors impacting the yield and NUE of sweet sorghum in inland and coastal salt-affected areas; (2) then, to evaluate which management methods are effective for sweet sorghum production in salt-affected lands. We hypothesized that: (1) the dominant factors for inland and coastal regions were different because of the environment conditions varied in the regions; (2) the responses of sweet sorghum to nutrient management also differed in the regions.

2. Materials and methods

2.1. Data compiling

Data were collected from published peer-reviewed research articles during 1990–2021 from CNKI (China National Knowledge Infrastructure, https://www.cnki.net/) and Web of Science database (http://apps.webofknowledge.com), using keywords and terms like “sweet sorghum”, “salinized”, “salinity”, “salt stress”, “saline-alkali” and a combination of them. The articles should meet with the following criteria.

1. The studies were conducted on croplands or marginal lands in mainland China. Pot studies were not included in our database.
2. Soil salinity concentration of the study field before the growing season should be available. Salinity level signified as EC w excluded to avoid inappropriate transformation.
3. Studied only lasted for a short period were omitted from the database.
4. Fertilization management methods should be clearly clarified in the study.

2.2. Definitions

According to the above criteria, space variables of the study site (i.e., longitude, latitude and elevation), climate conditions (i.e., mean annual precipitation (MAP) and temperature (MAT)), soil properties (i.e., pH, SOM, soil total nitrogen concentration (TN), salt content), agricultural management methods (i.e., N application rate, P application rate, K application rate, density, growth days) and aboveground biomass were extracted from the selected articles. In the case when only soil organic carbon was presented, SOM was estimated using the equation $\mathrm{SOM}=\mathrm{SOC}/0.58$. Data presented in figures were extracted via the Graph Digitizer software GetData (Version 2.24, http://getdata-graph-digitizer.com). While the climate data were not available, we used longitude and latitude to extract the relative variables from 1 × 1 km WorldClim database (Version 2.1, http://www.worldclim.org/). As TN and SOM in 2 sites were not found in the original literature, we supplemented them from the 1 × 1 km China Dataset of Soil Properties (Shangguan et al., 2013) (http://data.tpdc.ac.cn/zh-hans/data/).

In order to better indicate the hydrothermal conditions of the study sites, the humid index was calculated using the equation: $\text{Humid Index} = \mathrm{MAP}/(\mathrm{MAT}+10)$ (Zhang and Wang, 2015).

NUE was determined as NPFP, which was calculated as the crop yield per unit of N fertilizer applied, i.e., $\mathrm{NPFP}=\mathrm{Yield}/\mathrm{N}$. Yield is the reported aboveground biomass of sweet sorghum and N means N application rate.

2.3. Data assembly and analyses

In total, 255 observations of biomass yield and 242 observations of NPFP (N application rate >0) were compiled from the published papers.

The descriptive statistical analysis was applied on all variables. Since variables were not normally distributed, biomass and NPFP were Ln-transformed and other variables were Z-score normalized for later analysis. Then, linear mixed effect models were employed on inland and coastal saline regions respectively to examine how biomass and NPFP respond to climatic variables, soil properties and management methods. First, full models were built. Then, the collinearity between variables was addressed by removing factors which variance inflation factor (VIF) values were >10. Cities were set as random effects in the model. These steps were performed in R program (R ×64 4.1.1) using package “lme4” and “car”.

To further investigate the effects of environmental and management factors on sweet sorghum in different salt-affected regions, structural equation models (SEM) were built based on the previous bivariate relationships. Model fitness was indicated by χ^2 test, low root square mean error of approximation (RMSEA) and goodness-of-fit index (GFI). $P > 0.05$ indicates the model can be accepted. Standardized total effect was calculated to indicate the importance of factors. SEMs were constructed and adjusted in the statistical software SPSS Amos 22.0.

3. Results

3.1. *Overview of climate conditions, soil properties and agriculture management*

The distribution of study sites ranged from 81.18 to 126.50°E and 33.01 46.75°N, covering 5 types of salt-affected regions in China, i.e. northwest, northeast, central north, north and coastal saline regions (Table 1, Fig. 1). Except for the last one, the other four kinds could be defined as inland salt-affected regions. Apart from TN, the other environmental and management variables were significantly different between inland and coastal salt-affected regions. Management methods in inland areas also varied a lot from that in coastal areas, including NPK application rate and planting density (Table 1).

The biomass yield of sweet sorghum ranged from 3852.50 to 97,450.00 kg/ha from all sites, with an average of 25,029.35 ± 16,162.20 kg/ha. Except for the significant difference in the biomass yield of sweet sorghum between North China and Northeast salt-affected areas, there was no difference between other regions. Conversely, NPFP varied greatly among regions, ranging from 31.61 to 5568.26 kg/kg. The average NPFP was 107.29 ± 51.44 kg/kg in coastal saline-alkali regions, which was the lowest of all 5 regions and significantly lower than that in North, Northwest and Central North China. Overall, both biomass yield and NPFP of sweet sorghum were significantly higher in inland areas comparing to that in coastal salt-affected regions ($p < 0.05$) (Fig. 1).

3.2. *Factors influencing yields and NPFP of sweet sorghum in inland and coastal salt-affected region*

A distinct control pattern for biomass yield and NPFP of sweet sorghum was found between inland and coastal salt-affected regions (Figs. 2–4; Table 1). The biomass yield and NPFP of sweet sorghum did not vary across spatial distribution in inland salt-affected areas, where climatic variables were also not correlated with the biomass yield and NPFP. However, the biomass yield and NPFP increased with mean annual temperature (MAT) in coastal salt-affected regions.

Soil salinity can lead to a decline in biomass yield and NPFP of sweet sorghum in both inland and coastal salt-affected regions. The stimulating effects of soil organic matter (SOM) on the biomass yield and NPFP significantly were found in inland areas, where soil pH was also moderately correlated with the biomass yield ($p < 0.1$) (Fig. 2a and c). In coastal salt-affected regions, the effects of TN and SOM could not be tested because of homogeneity among study sites.

The responses of the biomass yield to nutrient application rate were not significant in inland salt-affected areas. In coastal salt-affected areas, higher N application rate tended to significantly increase the biomass yield of sweet sorghum (Fig. 2a, b and 3g). However, P application rate, K application rate, growth days and density appeared to have no impacts on the biomass yield of sweet sorghum in both inland and coastal salt-affected areas. NPFP of sweet sorghum significantly decreased with N application rate, in inland salt-affected areas ($p < 0.05$) (Figs. 2–4). However, the relationship between N application rate and NPFP was not significant in coastal salt-affected areas.

3.3. *Contribution of factors to biomass yield and NPFP variation of sweet sorghum in coastal and inland salt-affected land*

In inland salt-affected regions, the results of SEMs revealed that MAT was the most important factor in determining the biomass yield of sweet sorghum, including both direct and indirect negative effects, in which the normalized coefficient of direct effects was −0.49 ($p < 0.001$) (Fig. 5a). The indirect effects were regulated by soil salinity, pH and SOM. Coupled with MAP, the variables explained 15% of the total variation of biomass yield. In coastal areas, N application rate contributed the most to the biomass yield of sweet sorghum (Fig. 5b).

MAT, soil salinity, pH and SOM influenced NPFP of sweet sorghum in different extent in inland salt-affect regions, explaining 29% of the total variation (Fig. 5c). The influence of SOM was the most (standardization coefficient 0.37, $p < 0.001$), whereby higher SOM increased the NPFP of sweet sorghum. Soil pH also played a role in promoting NPFP while salt was the second dominant factor, which negatively correlated with NPFP with the standard coefficient value being −0.34 ($p < 0.001$). Similar to that of biomass yield, MAT had a direct effect on NPFP and NPFP was indirectly influenced through soil pH, salinity and SOM. For the coastal salt-affected areas, although we tried to build an SEM to explain the path of NPFP, a suitable model ($P < 0.05$) could not be acquired, so we did not present the model here.

Table 1
Climatic conditions, soil properties and management methods in inland and coastal salt-affected areas.

	Inland Salt-affected Land				Coastal Salt-affected Land				P
	Mean	SD	Min	Max	Mean	SD	Min	Max	
Latitude/°N	39.5	3.28	36.2	46.8	35.2	2.02	33	38.9	***
Longitude/°E	109	8.97	81.2	126	120	0.972	117	121	***
Elevation/m	948	585	20	2090	13.7	8.34	6	27	***
Precipitation/mm	297.69	126.73	150	518	822.54	199.29	536	1005	***
Temperature/°C	8.89	2.46	5.08	14.71	14.63	0.9	12.5	15.71	***
Humid Index	16.31	8.04	7.9	33.14	33.25	7.42	22.5	40.77	***
pH	8.5	0.58	7.12	9.43	8.07	0.22	7.5	8.38	***
Soil Organic Matter/(g kg^{-1})	16.03	17.01	0.7	88.5	7.22	1.95	2.41	9.30	***
Total N	0.8	0.3	0.34	1.49	0.95	0.43	0.41	1.65	0.084
Salinity	1.99	1.94	0.22	5.97	2.88	0.69	1.82	4	***
N application rate/(kg/ha)	89.7	71.2	0	300	198	125	0	389	***
P application rate/(kg/ha)	51.7	38.6	0	151	82.9	68.8	0	294	***
K application rate/(kg/ha)	46.0	51.1	0	249	78.7	39.8	0	137	***
Growth days	136	23	71	172	138	24.9	79	165	0.349
Density/(plants per ha)	82,100	19,500	66,700	160,000	109,000	33,300	66,000	210,000	***
Biomass/(kg ha)	27,106.03	17,679.49	4468.75	97,450.00	19,082.48	8262.75	3852.50	39,640.48	**
NPFP/(kg kg^{-1})	609.07	730.85	31.61	5568.26	107.29	51.44	41.18	226.63	***

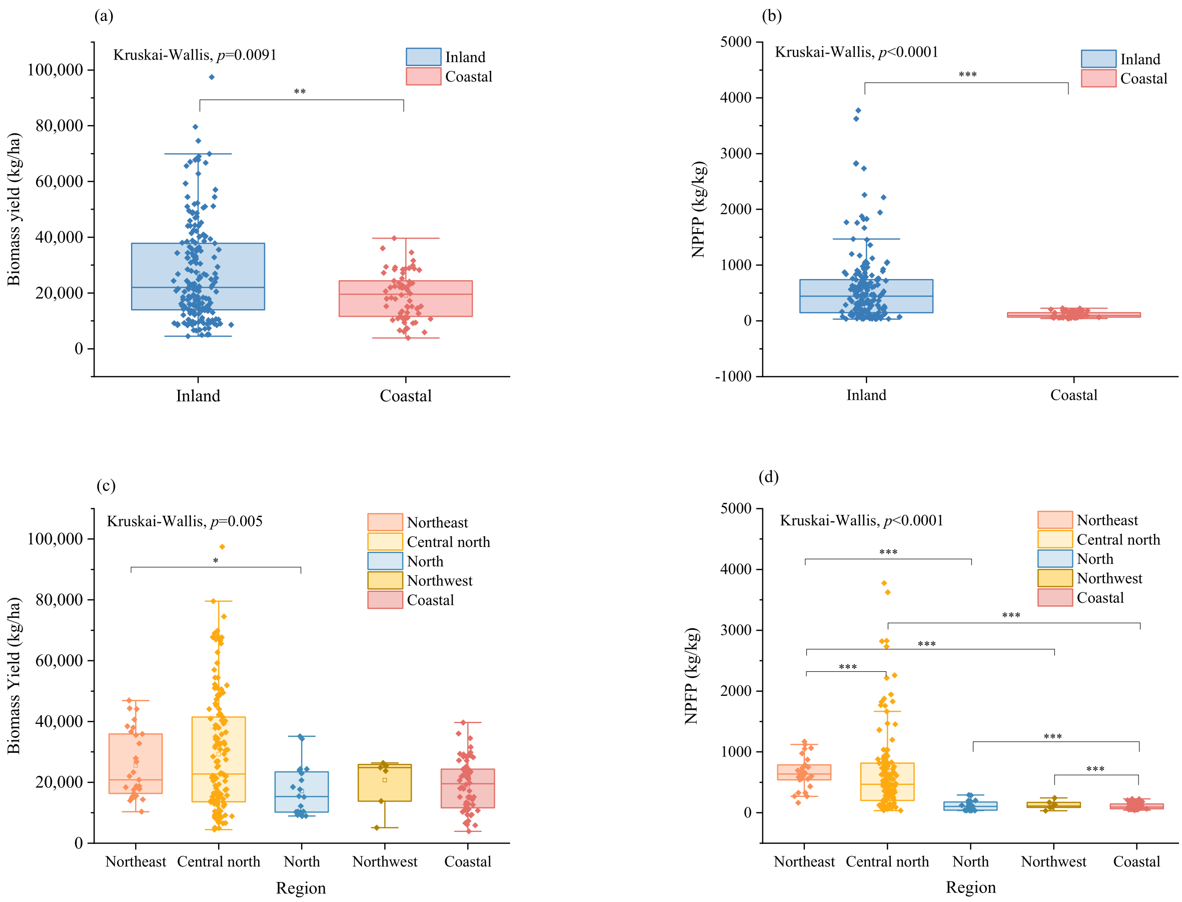

Fig. 1. Comparisons of biomass yield (a, c) and nitrogen partial factor productivity (NPFP) (b, d) of sweet sorghum between inland and coastal salt-affected regions.

4. Discussion

4.1. Differences between inland and coastal salt-affected regions

Despite better hydrothermal conditions and higher nutrient inputs in coastal areas, the biomass yield and NUE performance of sweet sorghum in inland salt-affected areas were higher than those in coastal areas. This may be caused by the different soil chemical properties in the two regions. In inland salt-affected areas SOM was significantly higher than that in coastal salt-affected areas, thus it can provide more available N for plants through mineralization (Li et al., 2019).

The biomass yield of sweet sorghum in the inland salt-affected areas was less sensitive to nutrient input but more sensitive to climate conditions (Fig. 5). This might be due to the large longitude span of the inland regions which caused great variations of hydrothermal conditions in different study sites. Coastal salt-affected areas locate in the eastern part of China where MAP is similar among observations, thus MAT instead of MAP played important role in sweet sorghum production. The results supported our first hypothesis that the determinants differed in the two regions.

The N application rate is the pivotal driver for biomass yield under limited levels of salinity in coastal salt-affected zones. Comparing to the coastal salt-affected areas, the N application rate did not significantly stimulate the biomass yield of sweet sorghum in the inland salt-affected areas, indicating that the effect of N input in the salt-affected land was regulated by soil salinity and other conditions (Smith et al., 2020). Sweet sorghum is a kind of C4 plants with extremely high nutrient utilization efficiency. Cushioned by the SOM content, the positive effects of nitrogen application on biomass yield weakened. The significant negative correlation between N application rate and NPFP was observed (Fig. 2) also implied that there may be excess N input than sweet sorghum requires in inland salt-affected areas. In coastal salt-affected areas where the content of TN and SOM were too limited, N input could rapidly enhance the content of inorganic N which was available to plants in soil, thus the biomass yield increased significantly. This was in line with the previous study that N input promoted soil fertility in coastal areas (Yao et al., 2021). Previous debate about the effects of N input on sweet sorghum may be due to the fact that various climatic and soil conditions in the study sites were overlooked, which resulted in different responses of sweet sorghum to N fertilizers.

4.2. The positive and negative factors for biomass yield and NPFP of sweet sorghum

In inland salt-affected regions, MAP's negative effect on NPFP of sweet sorghum was in line with the drought-tolerant characteristics of sweet sorghum. Other studies have also documented that forage sweet sorghum had higher protein yield and feeding value under mild drought conditions (Jahanzad et al., 2013). Excessive water reduced the germination rate and root growth of sweet sorghum in the early growth stage, thus impeding in biomass accumulation of sweet sorghum; and it also made seedlings more vulnerable to diseases and pests, resulting in reduced biomass yield (Carmi et al., 2006; Reyes-Cabrera et al., 2017). The hydrothermal conditions at different sowing periods may influence the biomass yield of sweet sorghum by changing the photoperiod and reproductive period of plants (Teetor et al., 2011; Houx and Fritschi, 2013). Most rain falls in July and August in temperate regions, which supports the finding that the best sowing date for sweet sorghum was in late May in temperate regions (Bonin et al., 2016). Earlier sowing extended the growth season for plants, therefore promoting biomass accumulation of sweet sorghum (Wannasek et al., 2017).

Soil properties are the most direct factors affecting water and

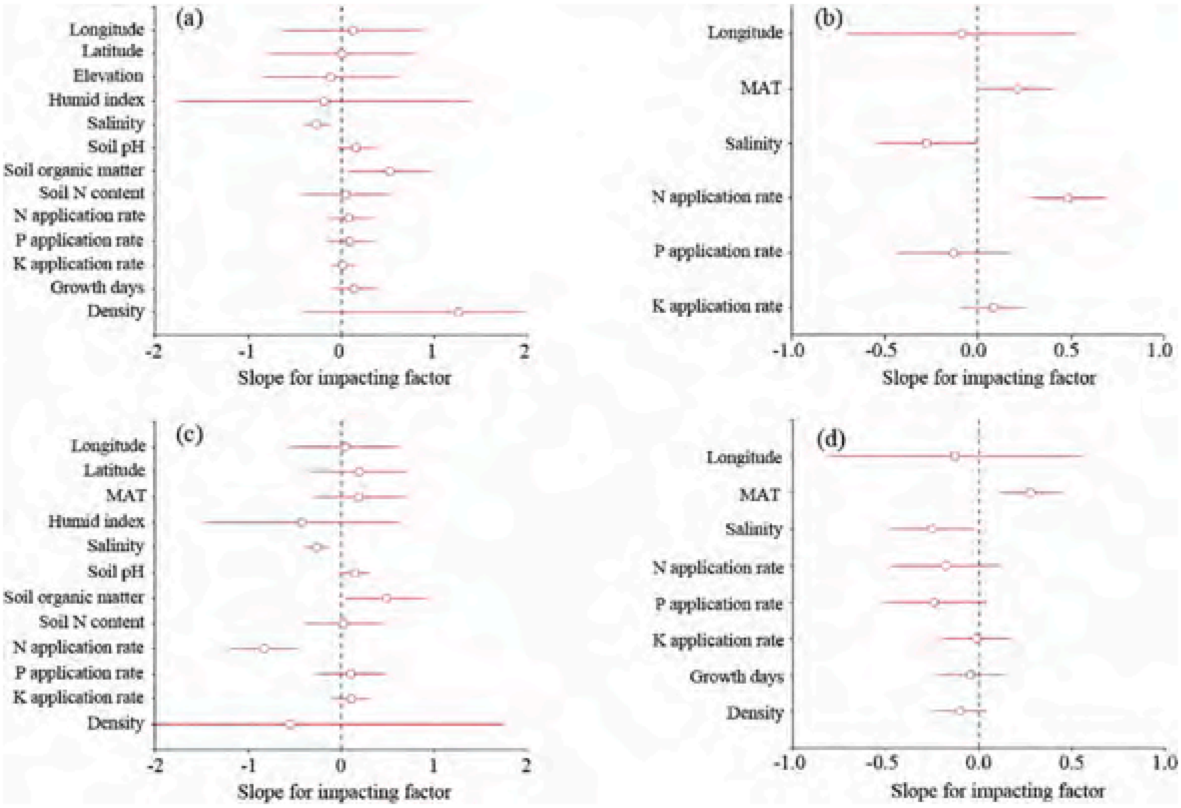

Fig. 2. Effects of different factors on biomass and NPFP of sweet sorghum in inland and coastal salt-affected regions. (a) biomass yield in inland areas; (b) biomass yield in coastal areas; (c) NPFP in inland areas; (d) NPFP in coastal areas.

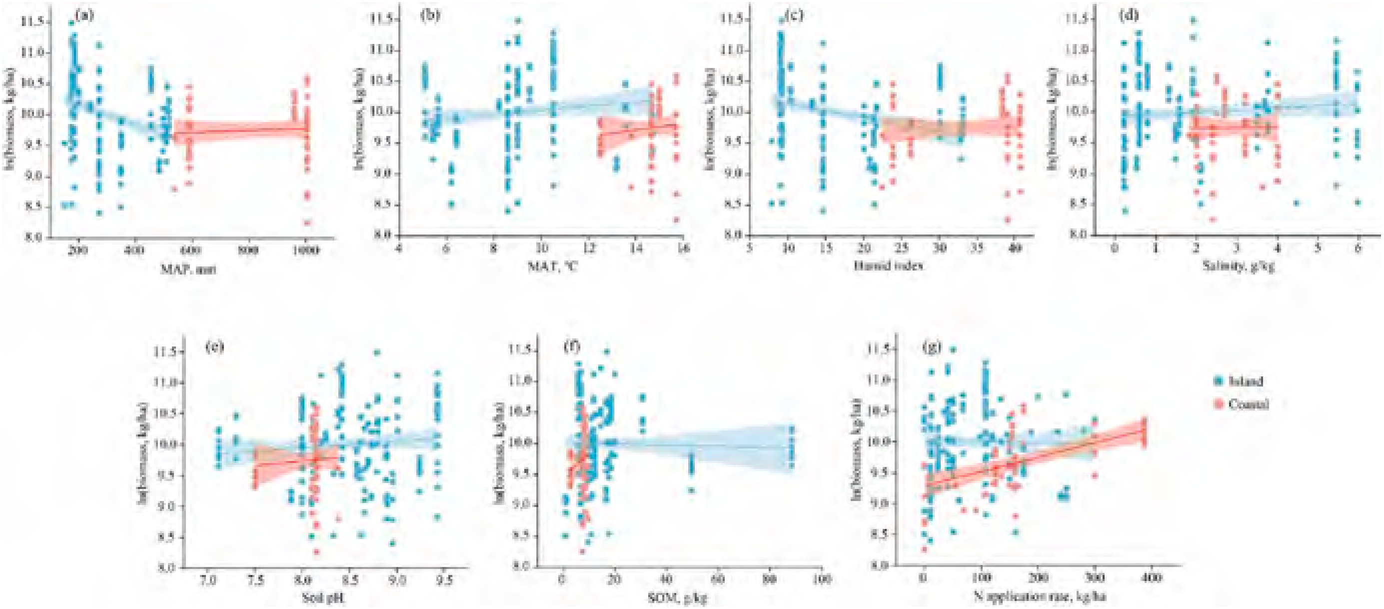

Fig. 3. Bivariate relations of sweet sorghum yield with mean annual precipitation (a), temperature (b), humid Index(c), soil N content(d), salinity(e), soil pH(f), soil organic matter(g) and N application rate in China.

nutrient uptake. The negative impacts of salt on plant production have been well studied. On the one hand, the salt-resistant strategy of plants decreased aboveground biomass yield. Sweet sorghum tends to allocate higher proportion of biomass to roots to retain Na+ in the root system, preventing the harm of Na + to the aboveground parts (Chaugool et al., 2013). On the other hand, excessive Na + hampers the absorption of water and other nutrients of plants (Dai et al., 2014). By disintegrating soil aggregates, Na^+ results in the reduction of effective soil porosity and deficit of oxygen in the soil, thus restraining the growth of plants (Dong et al., 2019).

SOM-derived N provided more than half of the N uptake of plants (Carter and Schipanski, 2022; Ju and Zhang, 2017). This could be supported by the positive relationship between SOM and yield in this study. Besides being a nutrient supplier, SOM improves the resistance of plants

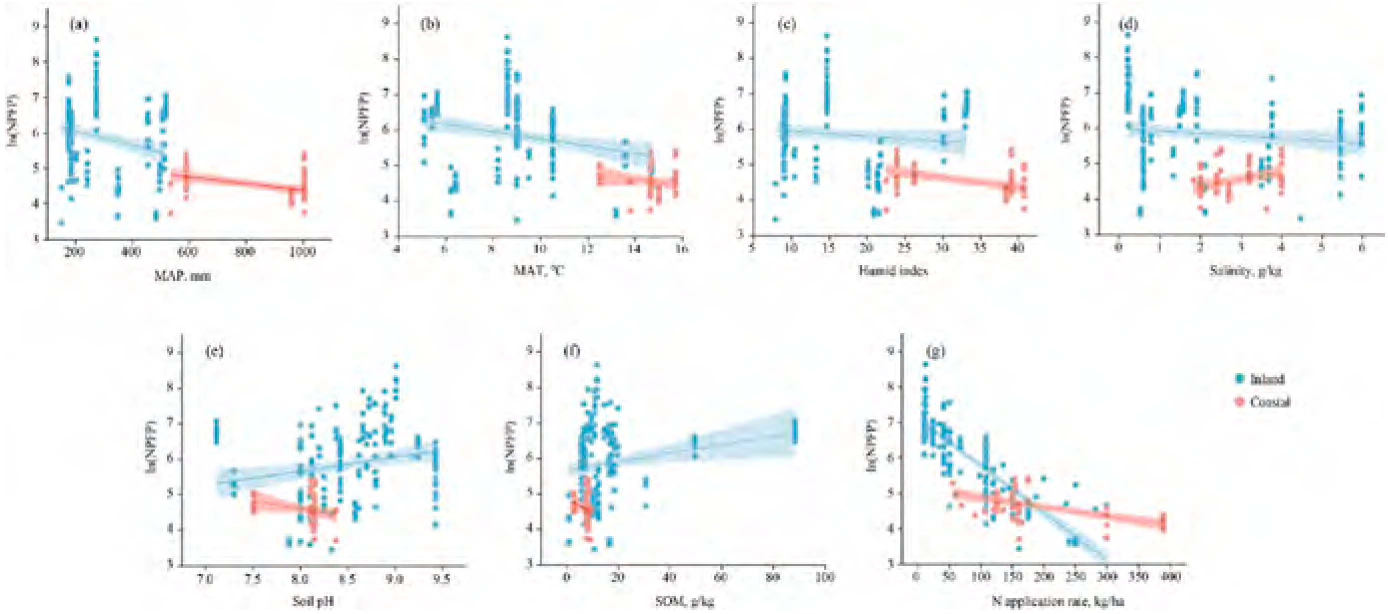

Fig. 4. Bivariate relations of partial factor productivity from N(PFP) with mean annual precipitation (a), temperature (b), humid Index(c), soil N content(d), salinity (e), soil pH(f), soil organic matter(g) and N application rate in China.

to salt. Increasing organic matter input is thought to be a fundamental method to amend salt-affected lands (Dong et al., 2019). Incorporation of organic manure into the rhizosphere can not only improve soil fertility, but also alleviate secondary salt damage by promoting the formation of soil aggregates, enhancing soil carbon sequestration, and decreasing exchangeable sodium percentage (García-Orenes et al., 2005; Liang et al., 2005; Xie et al., 2020). In salinized soils, the application of organic materials can hamper the movement of capillary water, thereby reducing the accumulation of salt in the topsoil (Zhang et al., 2014). Organic material input can also increase soil pH and the mineralization rate of SOM, which in turn lead to enhancement of nutrient availability in the soil (Wang et al., 2017). Our study also found the positive effect of soil pH on sweet sorghum. This may be due to the preference of soil microorganisms and enzymes which supply mineral nutrients. In general, bacteria and actinomycetes prefer a neutral to slightly alkaline environment (Rousk et al., 2010). When soil pH changes from acid to neutral, microbial biomass, microbial carbon and nitrogen increased (Kemmitt et al., 2006), thus SOM will be enhanced in the field.

4.3. *Implications for sweet sorghum planting in the future*

This study disclosed the possibility of increasing the yield of sweet sorghum by proper nutrient management, through sorting out the effects of climatic factors and soil properties on sweet sorghum in coastal and inland salt-affected lands in China. As precipitation had a negative effect on sweet sorghum in inland salt-affected areas, it is crucial to identify the suitable sowing date for sweet sorghum to obtain higher yield and nitrogen use efficiency. In inland salt-affected regions, especially where clay particles dominate, sowing before the rainy season and improving the drainage system in the field can help avoid waterlogging of sweet sorghum seedlings in summer, which might increase the biomass yield.

The greater effect of fertilization than MAT and soil salinity on biomass yield in coastal salt-affected areas indicated the great potential of coastal areas to improve the productivity of sweet sorghum by optimizing nutrient management. For inland salt-affected regions, even though the application of N fertilizers contributed less to biomass yield, considering that the growth of sweet sorghum consumes nitrogen pool of the soil, the supplement of N nutrient is still needed for sweet sorghum cultivation and the amount of N input should be based on the soil conditions. It is generally believed that the optimal N application rate for sweet sorghum is about 90 kg/ha, which can generate the highest nitrogen use efficiency and economic benefits, and the increase of biomass yield will slow down if it is higher than that rate (Sawargaonkar et al., 2013; Ameen et al., 2017). The biomass yield tended to be flat when the N application rate reached 100 kg/ha and above in inland salt-affected areas in this study. In coastal areas, the N application rate was about 150 kg/ha to get the maximum yield. Consequently, a recommended threshold of N application rate for sweet sorghum planting in China is 100 and 150 kg/ha for inland and coastal salt-affected regions respectively. This was quite lower than the recommended application rate for coastal salt-affected land for environmental benefit (Xie et al., 2021).

In inland salt-affected regions, exogenous input of organic matter in saline-alkali lands could be an promising way to improve soil properties and increase the biomass yield of sweet sorghum. It has been supported by the previous study that rational application of synthetic fertilizers or organic materials can improve crop yield in salt-affected areas; furthermore, the combined use of the two fertilizers generated better effect on increasing yield than the use of any one of them alone (Meena et al., 2016). However, the current studies of nutrient management of sweet sorghum shown less details during the experiment, which limits us to optimize the agronomic management measures to improve soil nutrients in salt-affected lands and production of sweet sorghum as well. Future studies should pay more attention to the water and nutrient uptake during the growing season, which plays an important role for the foundation of a high-yield sweet sorghum planting system.

In addition, the salinity in inland salt-affected areas was still not the most important limiting factor for biomass accumulation, though the soil salinity ranged from 0 to 5.7 g/kg in this study, covering the classification from mild salt stress to severe salt stress. For coastal areas, the range of salt content is relatively limited, ranging from 1.82 to 4 g/kg, which also implied that sweet sorghum might be able to grow in areas with higher salinity. Moreover, the effects of sweet sorghum on soil amendment should also be tested.

At present, the research on sweet sorghum planting in China is still limited. A cropping system guided by scientific planting techniques still requires further development by recognizing potential factors and their synergetic effects on sweet sorghum. Influenced by the accessibility and availability of previous research data, the studies involved in this analysis only focused on the effect of nutrients or salt on the growth of

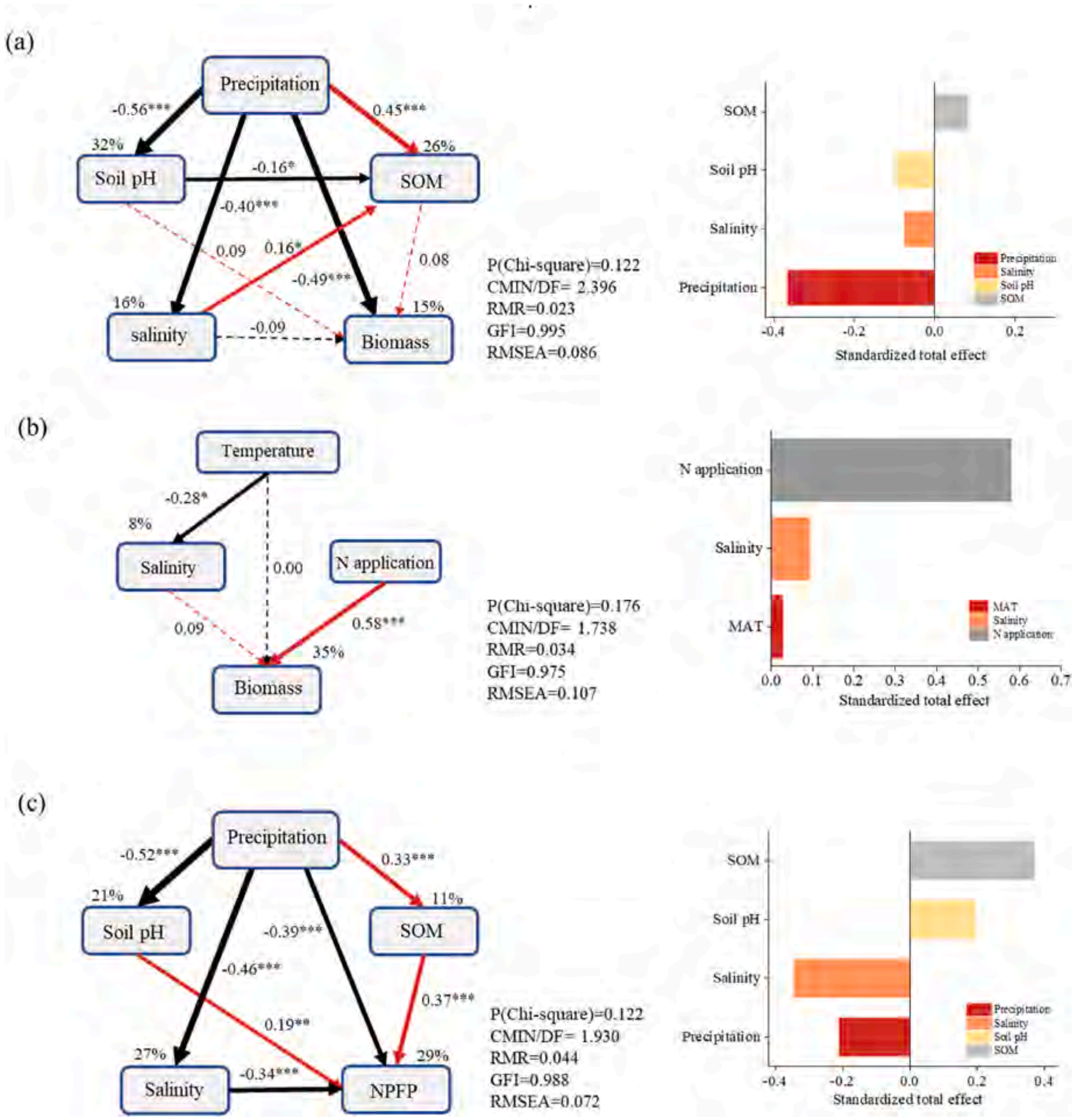

Fig. 5. Structural equation models (SEMs) for biomass yield and NPFP of sweet sorghum in inland and coastal salt-affected regions. (a) biomass yield in inland areas; (b) biomass yield in coastal areas; (c) NPFP in inland areas.

sweet sorghum instead of the combined effects of the two factors, which made us unable to quantify the optimal N application rate for sweet sorghum under different salinity conditions through further analysis. It also led to the insufficient evaluation of some factors. Moreover, the research on the cultivation of sweet sorghum is particularly insufficient in coastal areas, resulting in the impossibility to quantitatively evaluate the relative importance of each variable to sweet sorghum. Our research provides more intuitive views for understanding the factors affecting the planting of sweet sorghum in different salt-affected areas in China. It is still challenging work in the future to study the responses of sweet sorghum to water, nutrients and salt under specific climatic conditions, which contribute to the exploration of biological amelioration and further development in the salt-affected regions in China.

5. Conclusion

This study integrated the current available observations of sweet sorghum in salt-affected lands in China, giving evidence that the effects of climatic factors, soil properties and nutrient management measures on sweet sorghum planting varied in different salt-affected areas. Improving the nutrient conditions of inland and coastal salt-affected lands is the key process to promote the productivity and production efficiency of the lands. Enhanced SOM would increase biomass yield of sweet sorghum in inland regions. The recommended N application rate for inland salt-affected areas were 100 kg/ha while 150 kg/ha was recommended for coastal salt-affected areas. Our study highlights the differences of limiting factors for planting the salt-resistant sweet sorghum in inland and coastal salt-affected regions, which is cause by the formation of salinized soils. More systematic field studies are urgently needed in the future to optimize the management of water and nutrients for sweet sorghum planting in salt-affected lands.

Credit author statement

Jing Li: Conceptualization, Funding acquisition, Writing – review & editing, Supervision. Shanqing Lei: Conceptualization, Data curation, Formal analysis, Writing – original draft. Huarui Gong: Methodology, Data curation, Writing – review. Zhen Liu: Methodology. Yitao Zhang: Methodology. Zhu Ouyang: Conceptualization, Supervision.

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Declaration of competing interest

Data availability

Data will be made available on request.

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