

Suaeda salsa/*Zea mays* L. intercropping in saline soil on plant growth and rhizospheric physiological processes

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Abstract

Background and aims

Halophytes possess the capacity to uptake high levels of salt through physiological processes and their root architecture. Here, we investigated whether halophyte/non-halophyte intercropping in saline soil decreases the soil salt content and contains root-dialogue.

Methods

Field and pot experiments were conducted to determine the plant biomasses and salt and nutrient distributions in three suaeda (*Suaeda salsa*) / maize (*Zea mays* L.) intercropping systems. The three treatments were set up by non-barrier, nylon barrier and plastic barrier between plant roots.

Results

The biomass of the non-barrier-treated maize was significantly lower than that of the nylon barrier-treated maize, whereas the suaeda root biomass showed a limited increase. The soil salt content negatively affected the non-barrier group's roots compared with those in the nylon and plastic barrier-treated groups, and it was also higher on the maize side of the nylon-barrier treatment. There were higher available nitrogen and phosphorus contents in the soil of the non-barrier- and nylon barrier-treated groups compared with the plastic barrier-treated group. In addition, the pH was lower, and the available potassium content was higher, which suggested that rhizospheric processes occurred between the two species.

Conclusions

The suaeda/maize intercropping would decrease the soil salt content, and they also revealed potential rhizospheric effects though the role of root, which provides an effective way for the improvement of saline-alkali land.

Introduction

Salt stress is an abiotic factor that limits crop productivity and agricultural development worldwide. A halophyte is a plant that can complete its entire life cycle on a high-salt soil owing to a series of adaptive strategies in its coordinated evolution with the environment (Bennett et al. 2013; Shabala et al. 2014; Yuan et al. 2016). Halophytes developed special mechanisms to resist and alleviate salinity stress over evolutionary time (Tian and Zhang, 2017; Chaudhary et al. 2018). The efficient use of halophytes helps decrease the salt concentrations of saline soils. Halophytes exposed to salt stress are subject to the base ions (Na^+ and Cl^-) responsible for the resulting osmotic stress. They can survive in media containing

more than 200 mM NaCl and direct root damage in the surficial soil (Munns et al. 1983; Matsushita and Matoh 1991; Flowers and Colmer 2008; Byrt et al. 2014; Tian et al. 2016). Thus, roots may produce excretions in response to the environment, which effectively associate with soil salt, microbes and nutrients (Song and Wang 2014; Tian and Zhang 2017). Sufficient transformational levels of nitrogen (N), phosphorus (P) and potassium (K) are necessary simultaneously to drive vegetative growth that promotes further nutrient acquisition in a plant–root system (Sashidhar and Podile, 2010; Lamers et al. 2012). The effects of rhizospheric processes on soil nutrients are also important aspects of intercropping systems. Thus, whether the substantial capabilities of halophytes to absorb salt may be used to decrease the salt content of saline soil to promote non-halophyte growth in a suaeda/maize intercropping system should be investigated.

Higher yields of non-halophytes, such as legumes, have occurred after halophytes were initially cultivated in virgin saline soil (Wang et al. 2021). This implies that halophyte roots and salinity-tolerant microorganisms improve non-halophyte adaptability to saline soils (Dodd and Pérez-Alfocea 2012; Etesami and Beattie 2018). Rhizospheric and physiological processes provide ways to investigate the salt-tolerance mechanisms belowground and to improve non-halophyte production through intercropping (Gitari et al. 2019). Generally, intercropping or crop rotations have greatly induced the growth rates of plants and stable food crops that have nutrient competitive advantages and significantly superior yield levels (Li et al. 2001, 2003; Zhang et al. 2016; Bi et al. 2019). The intercropping of water spinach/corn not only significantly weakened the toxic action of nitrate in the water spinach, also reduced the nitrate accumulation in the soil (Vandermeer 1989; Fang et al. 2014; Wang et al. 2003). Legumes promote P nutrition in non-legume plants; thus, the absorption is significantly greater in intercropping than in sole cropping (Glyan'ko and Ischenko, 2017). These intercropping patterns all include rhizospheric dialogues, in which root exudates play important roles in delivering soil nutrients (Shabala et al. 2015; Lv et al. 2020; Tian et al. 2020). Halophyte root excretions are necessary for altering, and adapting to, salt conditions to enhance the availability of soil nutrients and microbial activities (Barhoumi et al. 2015; Zhao et al. 2018). Thus, the salt-tolerance of non-halophytes may be improved by row intercropping. However, it is difficult to extrapolate the promotive effects on non-halophytes in intercropping systems that contain distinct species.

Consequently, we hypothesized that suaeda/maize intercropping would decrease the soil salt content on the maize side, and increase nutrient movements through root interactions. The objectives of this study were as follows: (a) to analyze the differences in biomasses and root characteristics; (b) to investigate the variations in pH and salt in horizontal directions between the two root systems; and (c) to assess the movement of, and interspecific competition or cooperation for, nutrients (available N, P and K) in the suaeda/maize intercropping system.

Materials And Methods

Field experiment

The study was conducted at the Salt Farm Botanical Garden in Karamay (45°28'6.38" N, 84°59'41.61" E), Xinjiang Province, China. The annual mean temperature and precipitation are 8.1°C and 108.9 mm, respectively, and the light and heat are sufficient in this region, with 2,734 h of sunshine, 200 frost-free d, and effective and accumulated temperatures of up to 3,968.1°C. The experimental soil was classified as lightly salinized, and the soil chemical and physical properties were measured, as indicated in Table 1.

Table 1
The field soil's chemical and physical properties.

Soil depth (cm)	pH	EC	Total salt (g·kg ⁻¹)	available N (mg·kg ⁻¹)	Olsen-P (mg·kg ⁻¹)	available K (mg·kg ⁻¹)
0–10	7.247	1.260	1.308	7.556	5.282	2.858
10–20	7.403	1.027	2.567	13.208	5.369	3.099
20–30	7.383	0.616	1.833	7.032	4.876	2.336
30–50	7.373	0.691	2.025	6.308	4.110	2.448
50–100	7.490	0.582	1.570	4.964	4.683	2.691

Field experimental methods were used to analyze the effects of halophyte (*suaeda*)/non-halophyte (maize) intercropping systems on plant growth and soil physiology. Additionally, the root systems of the two species were separated by placing different materials between them, as follows: (1) roots separated by a 30- μ m nylon mesh (nylon-barrier treatment): there were no interactions between the roots of the two species; (2) roots separated by a plastic film (plastic-barrier treatment): the transmission of energy, soil nutrients and microbial products could proceed belowground; and (3) the control; not separated (non-barrier treatment): the root systems of the different plants coexisted, allowing direct competitive and promotive effects. These conditions would expose the regulatory mechanisms behind the interactions at the root–soil interface of halophytes and non-halophytes.

The experiment had a split-plot design, with nine plots, and three replicates. The area of each individual plot was 6 m \times 5.6 m. To satisfy nutrient requirements, the site was treated with 0.5 kg urea, 1.0 kg potassium sulfate and 0.55 kg superphosphate per plot. The nylon and plastic barriers were placed in the soil at 1-m depths, and the inter-row distance was 40 cm.

Suaeda was sown in May 2019, and maize was sown 15 d later. Each intercropped plot included four rows of *suaeda* and three rows of maize. The harvesting and gathering of root and soil samples were completed in August 2019. During the growth period, the plots were manually irrigated and weeded regularly.

The shoot biomasses of the two species were determined by harvesting from the intercropping systems. To clearly determine the root spatial distributions and correlations with soil properties, the soil was stratified in the vertical direction to acquire the roots. At each plot, two 30 \times 30 \times 50-cm soil samples were excavated for *suaeda* and for maize in the adjacent row. The samples were stratified every 5 cm and then

divided into 10 parts. The roots were obtained from the soil samples and washed free of soil. All the samples were killed by treating at 105°C for 30 min and then dried at 65°C for 48 h.

The potential deliveries of soil substances and signals were investigated between the two species by horizontal soil stratification. The junction between the two root systems was determined to occur at a 10-cm depth in the middle of the plants. The 5-cm topsoil layer was initially removed and then the soil was divided into 10 1-cm thick layers (Fig. 1).

The soil pH was measured using a pH meter. The soil conductivity (EC) was measured using a conductivity meter (10 g soil in 50 ml water). The available N was measured using the alkali hydrolysis diffusion method (5 g soil in 50 ml solution). The available P (Olsen-P) was measured using the molybdenum antimony anti-colorimetric method (2.5 g soil in 50 ml solution). The available K was measured using an atomic absorption spectrophotometer (2.5 g soil in 50 ml solution).

Pot experiment

A greenhouse experiment was conducted in 2019 to verify the field results. Saline soil was collected from the experimental station at Changji, Xinjiang Province, China (44°09'59" N, 87°04'56" E). Then, the soil was air-dried and passed through a 2-mm sieve. The soil properties were as follows: pH, 7.75; EC, 1.32 mS; total salt, 0.50%; available N (NO_3^- and NH_4^+), 33.68 $\text{mg}\cdot\text{kg}^{-1}$; Olsen-P, 4.62 $\text{mg}\cdot\text{kg}^{-1}$; and available K, 0.25 $\text{g}\cdot\text{kg}^{-1}$.

To identify variations in plant growth in the suaeda/maize field intercropping, the pot experiment was established using three inter-species root treatments. The intercropping system's equipment was shown in Fig. 2b. The pot tube had an inner length of 20 cm, width of 10 cm and height of 25 cm. The suaeda seeds were gathered in October 2018 from a botanical garden in Karamay, Xinjiang Province, China.

To ensure an adequate nutrient supply for plant growth, the soil was fertilized with 3.36 g KH_2PO_4 per pot and 3.79 g urea per pot. The pot was filled with 8.0 kg of air-dried soil, which was divided using a nylon or plastic barrier. Then, the appropriate amount of water was added, and the soil was allowed to stand for 5 d. In July 2019, on one side per pot, 20 suaeda seeds were sown and grown to 4 cm before thinning. After 15 d, on the other side of each pot, four maize seeds were sown. To reduce the influence of water on plant growth, the weighing method was used to determine the amount of water used for replenishment.

The aboveground parts of suaeda and maize were harvested during maturity at approximate 45 d after sowing. All the samples were killed by treating at 105°C for 30 min and then dried at 65°C for 48 h.

Statistical analyses

An analysis of variance was used to determine the differences in the shoot and root biomasses among the three treatments with SPSS statistical software (SPSS version 19.0, IBM SPSS Inc, Chicago, IL, USA) and R software (version 4.0.3-win). Significant differences among means were separated using least-

significant difference (LSD) at the $P < 0.05$ probability level. Using the smooth fit method, we also detected spatial (vertical and horizontal) variations in the soil pH, salt content and nutrients to explore the potential rhizospheric processes of the two species.

Results

Plant shoot and root biomasses

The suaeda/maize shoot biomasses and N absorptions were determined in the three intercropping systems (Fig. 2). The non-barrier treatment inhibited maize growth in the field experiment (Fig. 2a). Compared with the plastic-barrier treatment, the maize biomass in the non-barrier treatment was 11.2% lower, and the shoot biomasses of suaeda and maize were significantly greater in the nylon-barrier treatment. The plant development observed in the pot experiment was consistent with that observed in the field experiment, whereas there was not a significant difference in the suaeda biomasses (Fig. 2b). The N absorption showed a trend similar to the biomass (Fig. 2c, d). In the pot experiment, the N absorption levels per maize plant in the nylon- and plastic-barrier treatments were 73 g and 64 g greater than in the non-barrier treatment.

The vertical distributions of the suaeda/maize roots in the three systems are presented in Fig. 3. The maize root biomasses were significantly greater than those of suaeda under the three root-partitioning conditions ($P < 0.05$). Furthermore, the growth of the maize root system was more conducive to separation by a nylon or plastic barrier, whereas the root biomass of suaeda remained high in the non-barrier treatment, especially at the 0–20-cm soil depth.

The vertical distributions of soil salt and nutrients

The spatial soil salt distributions in the three intercropping systems are shown in Fig. 4. The salt contents in the different suaeda-associated soil layers in the non-barrier treatment were obviously lower than those in the nylon- and plastic-barrier treatments, as measured in the 5–15-cm and 20–50-cm soil layers. Compared with the plastic-barrier treatment, the nylon-barrier treatment resulted in a significantly higher soil salt concentration on the suaeda side compared with on the maize side, which indicated that the nylon barrier was more beneficial to the absorption of salt by halophytes.

Differences in the available N and Olsen-P contents in the three intercropping systems existed to a certain extent (Fig. 5). The soil available N content in the non-barrier treatment was significantly lower than in the nylon-barrier treatment, and it was also $10.36 \text{ mg}\cdot\text{kg}^{-1}$ lower than in the plastic-barrier treatment, indicating that the suaeda/maize intercropping system increased nutrient competition. The higher available N content in the nylon-barrier treatment than in the plastic-barrier treatment also confirmed the possibility of synergy in suaeda/maize intercropping through the physiological root-dialogue process. The Olsen-P content in the plastic-barrier treatment was significantly lower than in the non-barrier and nylon-barrier treatments ($P < 0.05$). The content at the 0–20-cm soil depth was relatively lower on the

maize side in the non-barrier treatment, whereas on the suaeda side the content was higher in the nylon-barrier treatment. This suggested that the suaeda/maize intercropping system resulted in underlying interspecific competition and synergetic mechanisms.

Horizontal variations in soil properties

An increasing trend in soil pH was found in the horizontal direction from suaeda to maize under non-barrier treatment conditions (Fig. 6a). Comparably, the EC values and salt contents on the suaeda sides were higher than on the maize sides under nylon- and plastic-barrier treatment conditions. In addition, the pH value was lower, and the EC and salt contents were higher at the interface near the nylon barrier (Fig. 6b, c).

In the horizontal direction, an increasing trend in available N developed from suaeda to maize in the non-barrier and nylon-barrier treatments (Fig. 7a). In the vertical distribution, the available N content was lower in the plastic-barrier treatment than in the other treatments. As a whole, the Olsen-P in the nylon-barrier treatment was significantly greater than in the non-barrier and plastic-barrier treatments (Fig. 7b). The available K level was significantly greater, with an increasing trend from suaeda ($96.9 \text{ mg}\cdot\text{kg}^{-1}$) to maize ($126.6 \text{ mg}\cdot\text{kg}^{-1}$), in the non-barrier treatment compared with in the nylon- and plastic-barrier treatments (Fig. 7c). Higher available N, P and K levels were found at the interface near the nylon barrier.

Discussion

The effects of intercropping systems on biomass and root distribution

The promotion of non-halophyte growth was not found in the suaeda/maize intercropping systems, which was inconsistent with the results of a previous study (Latati et al. 2017; Ling et al. 2020). In this study, the non-barrier treated maize biomass was lower than that during the plastic-barrier treatment. Intertwining roots of the different plants may have restrained each other's growth in the intercropping systems. Roots of the halophyte have their own adaptive strategy-related responses to saline-alkali soil, and physiological responses to the nylon barrier may also exist. A greater salt content near suaeda roots influences maize belowground growth and suppresses the shoot biomass (Radhakrishnan and Baek 2017). Inhibitory effects during the intercropping are greatly affected by the planting distance and density, as well as the plant species (Song et al. 2020). Even though the shoot biomasses of suaeda/maize intercrops were not greater in the non-barrier treatment, suaeda root development was induced, especially in the 0–20-cm soil layer. This might be explained by the mutual actions of roots and photosynthetic product distributions. In maize, well-developed root architectures are preferable for growth and P content accumulations under drought and low P conditions (Klamer et al. 2019).

The soil salt's spatial variations in the intercropping systems

The study was conducted to determine whether salt migrated from non-halophytes to halophytes in the intercropping systems (Figs. 5 and 7). The salt level variation in the horizontal direction was not significant in the non-barrier and nylon-barrier treatments, but the salt content was higher at the 20-cm soil depth on the suaeda side compared with on the maize side (Fig. 5). Salt-tolerance has evolved in a variety of vegetative types over long periods, during which non-halophytes might have lost their genetic variation and developed special traits related to high salt-tolerance, such as in crop plants (Bennett et al. 2013; McDonald et al. 2013; Bian et al. 2015). Some glycophytes, such as maize and wheat, also tend to remove Na⁺ from roots (Ilangumaran and Smith, 2017). Suaeda appears to gather and uptake salt into the root zone (Byrt et al. 2014; Alharby et al. 2018), which reduces the salt injury level and improves the saline-related root environment for maize. Additionally, the salt flow and diffusion may impact salt accumulation levels in the root zone (Alharby et al. 2018).

Variations in nutrient responses to the suaeda/maize intercropping systems

The variations in the available N were obvious among the three intercropping systems. In the non-barrier treatment, compared with the other treatments, the soil available N was lower, which suggests that suaeda/maize intercropping increases the nutrient-use-efficiency, which promotes root architecture through interspecies competition (Li et al. 2003; Nafi et al. 2019). Root interactions in an intercropping system may improve resource acquisition and adaptation to nutrient constraints (Li et al. 2005).

However, the trends in the soil available P in the intercropping system were not similar to those of the available N. The soil available P levels in the non-barrier and nylon-barrier treatments were less than in the plastic-barrier treatment (Fig. 6), which indicates that P release and absorption were accelerated by root interactions in the suaeda/maize intercropping systems. The significantly higher available N and P levels in these systems indicated that intercropping may increase the available nutrient levels, but these results were not consistent with those of previous studies (Hinsinger et al. 2011; Wang et al. 2015; Gitari et al. 2018). The prominent impact of pH on soil available P in the rhizosphere has been demonstrated previously (Mai et al. 2018). Furthermore, the Olsen-P increase during intercropping (non-barrier) may be a result of a well-developed suaeda root at the 20-cm depth in response to increasing enzyme activities and a P deficiency, to a certain extent. Alternatively, the higher P level on the suaeda side of the nylon barrier, compared with the maize side, may be attributed to maize excretions that acidize the salt. Potassium is a major nutrient and a common essential element for plant growth and development (Li et al. 2010; Mai et al. 2018). The high level of available K on the maize side of the non-barrier treatment might be explained by maize's greater need for growth compared with the neighboring plant. The K flow in the xylem increases from root to shoot, maintaining sufficient K levels to alleviate Na toxicity (Wang et al. 2016). A high nutrient availability was displayed at the interface near the nylon barrier, and this was coincident with the low pH value. This suggested that suaeda/maize intercropping shifted nutrients and ions between the inter-species roots, as reported in previous research (Song et al. 2007; Li et al. 2003; Latati et al. 2017).

Conclusions

Our results showed that suaeda/maize intercropping inhibited the growth and N absorption of maize in the non-barrier treatment, but it significantly promoted growth in the nylon-barrier treatment. The soil salinity and nutrient availability levels were also reduced in the non-barrier treatment, whereas the nylon-barrier treatment obviously increased the salt content on the suaeda side. In addition, a higher salinity level and a greater nutrient content occurred at the nylon mesh junction, which indicated that rhizospheric processes existed in the two species. This study on suaeda/maize intercropping may provide new insights into the amelioration of saline soil.

Abbreviations

N: Nitrogen; P: Phosphorus; Olsen-P: Available Phosphorus; pH: Pondus Hydrogenii; EC: Electrical Conductivity.

Declarations

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Compliance with ethical standards

Competing interests: The authors declare that they have no competing interests.

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Figures

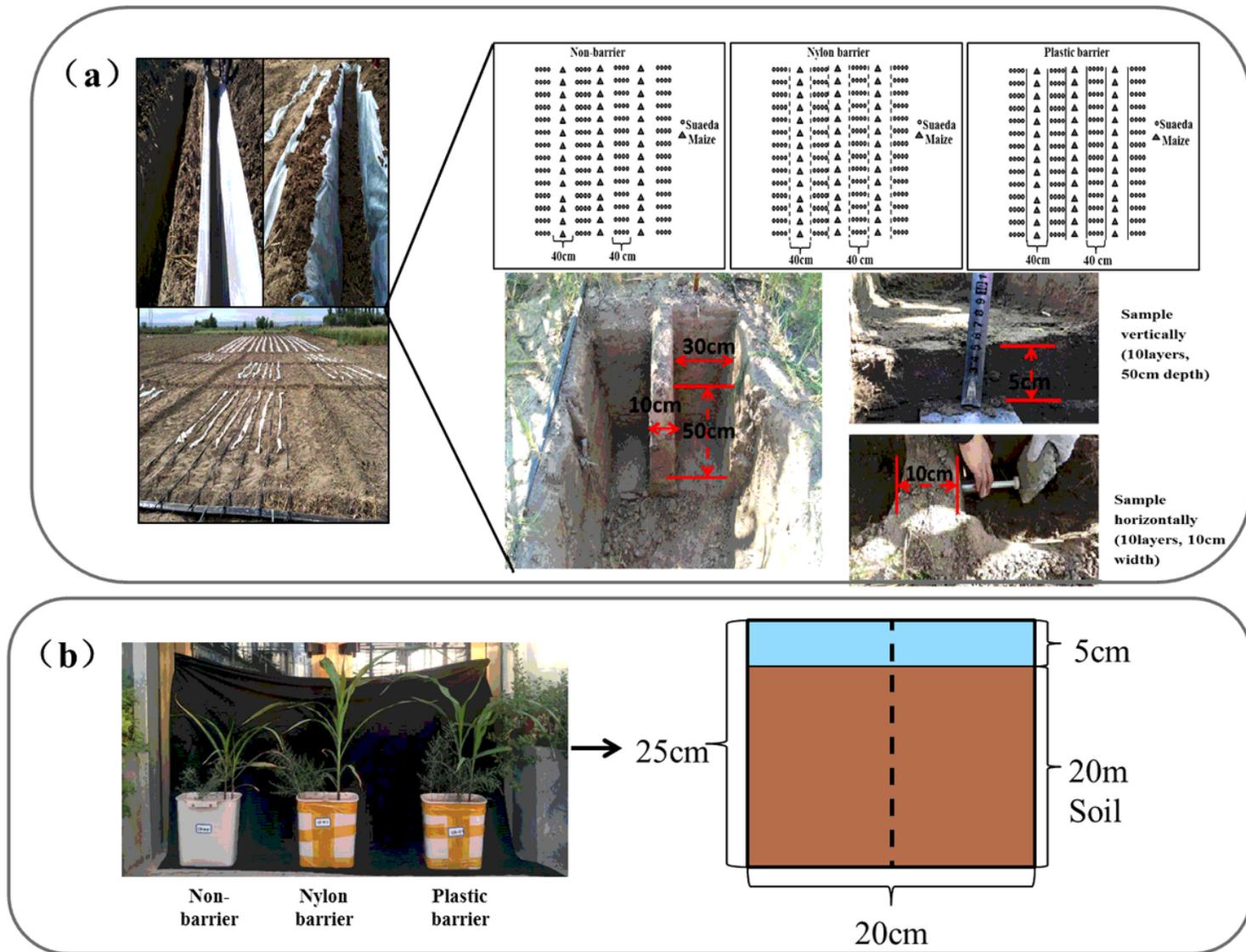


Figure 1

Soil samples from the suaeda/maize intercropping systems. (a) In the field experiment, soil samples were collected horizontally at 5-cm depths and vertically at 1-cm depths. (b) The pot experiment was conducted in concert with the field experiment.

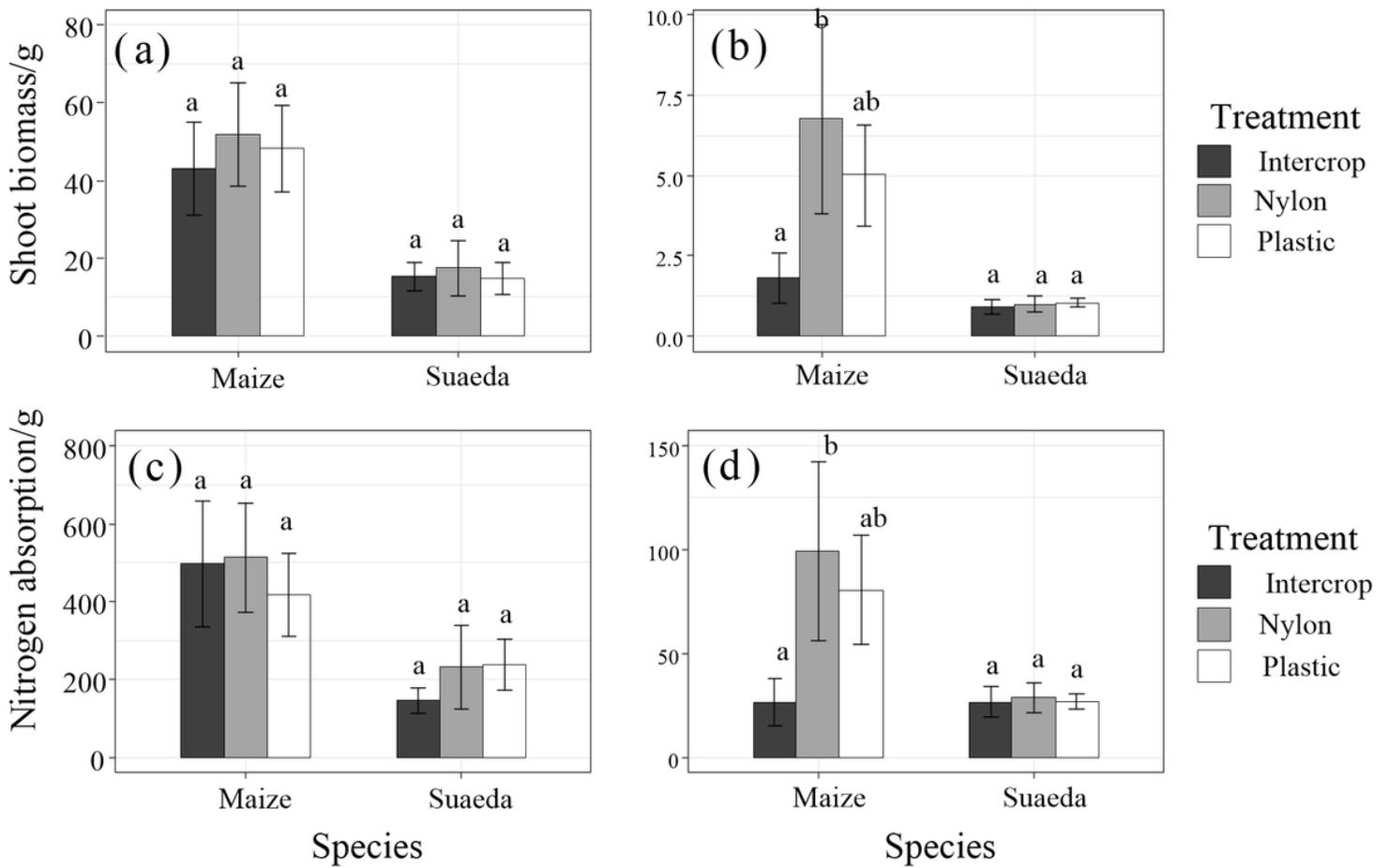


Figure 2

The shoot biomasses and nitrogen absorptions of plants in the different suaeda/maize intercropping systems. (a, c) Field experiments; (b, d) Pot experiments.

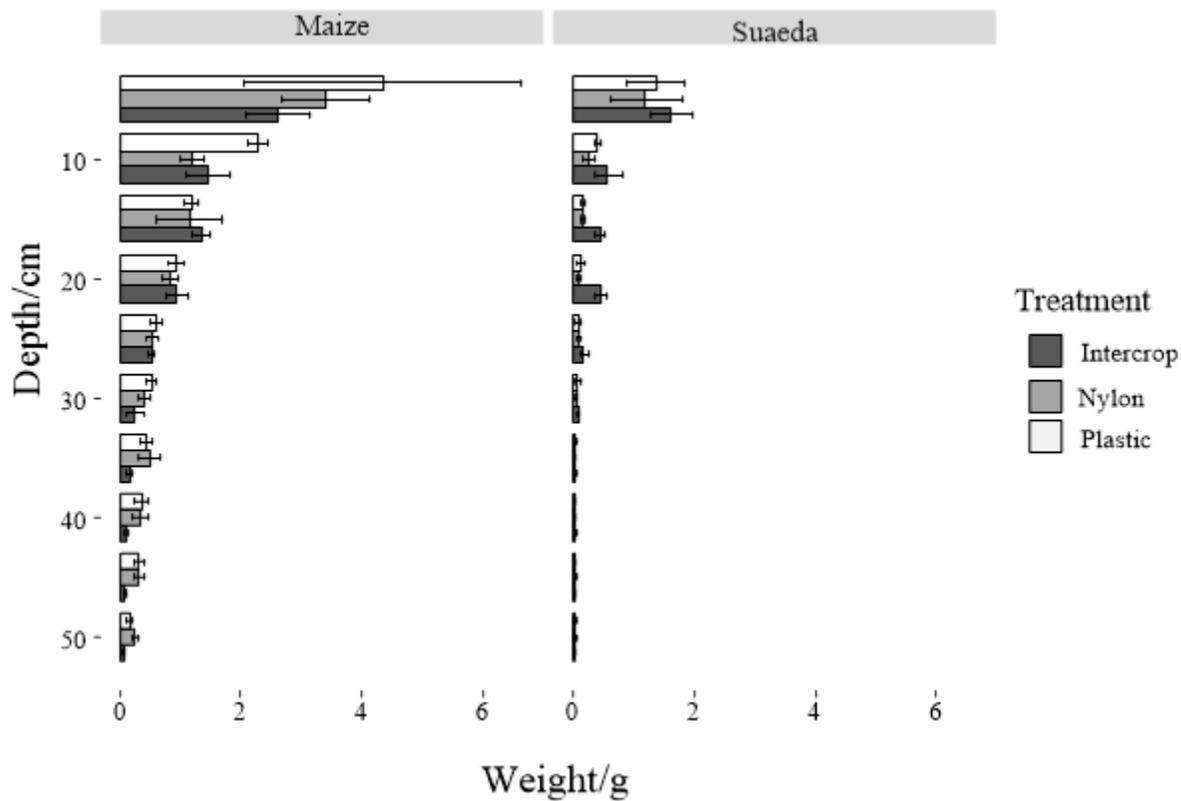


Figure 3

The distributions of root biomasses in the different suaeda/maize intercropping systems.

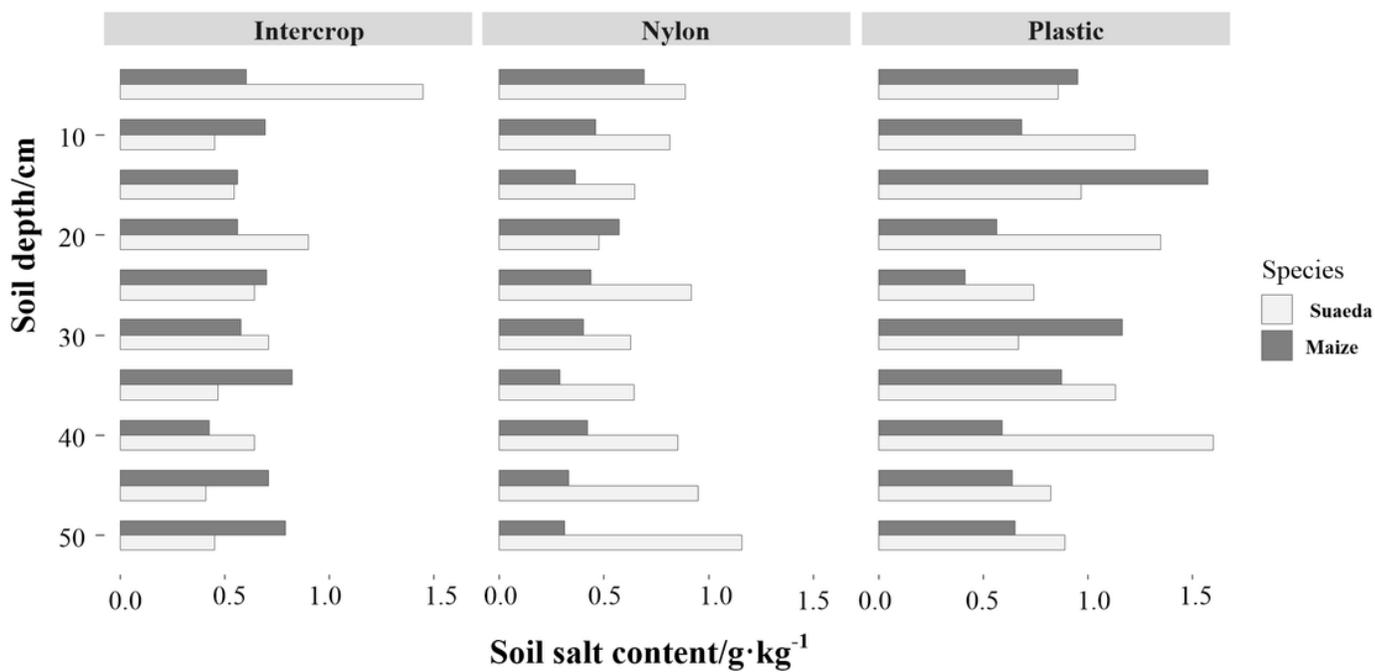


Figure 4

The vertical distributions of soil salt in the different suaeda/maize intercropping systems.

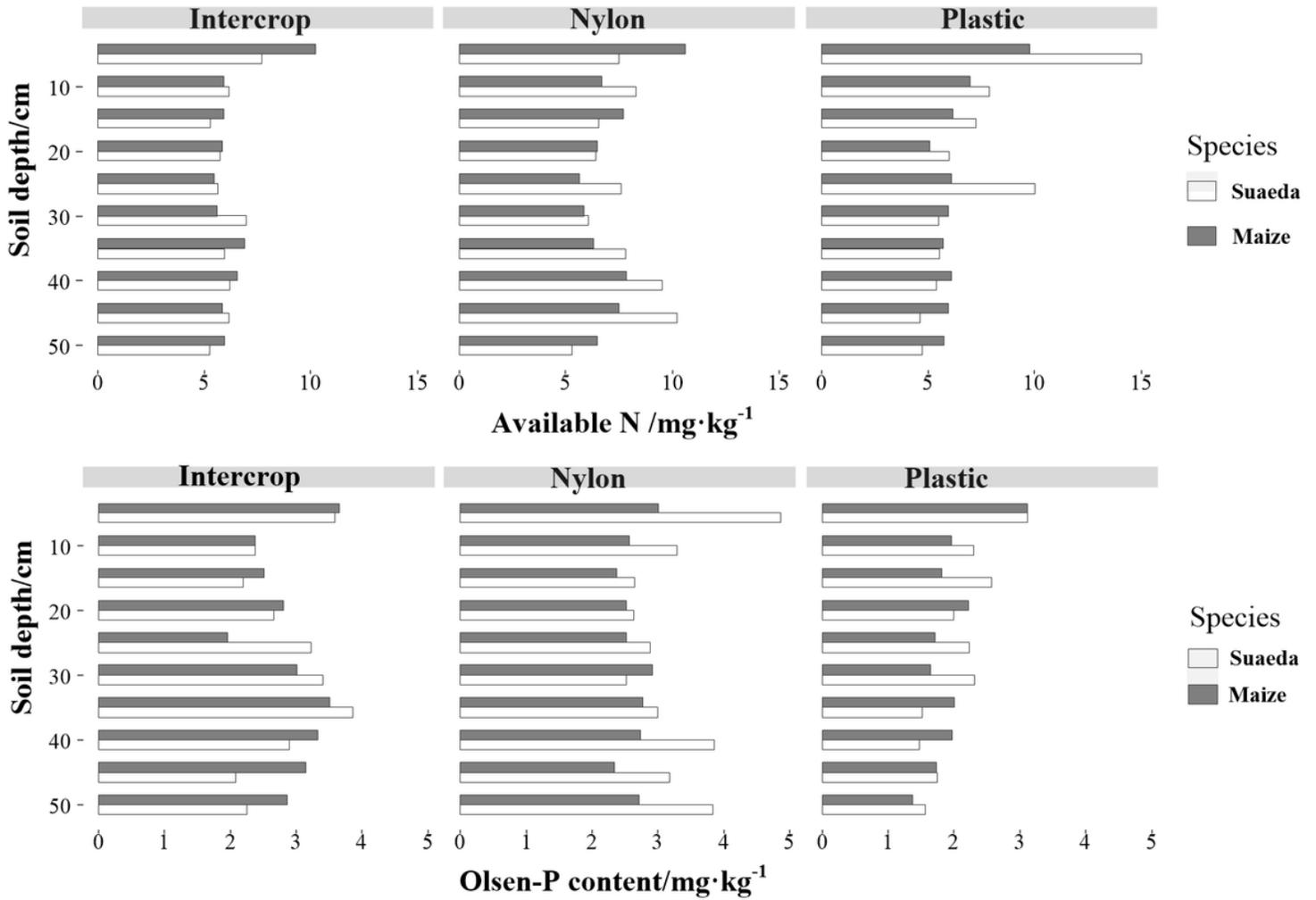


Figure 5

The vertical distributions of available nitrogen and phosphorus in the different suaeda/maize intercropping systems.

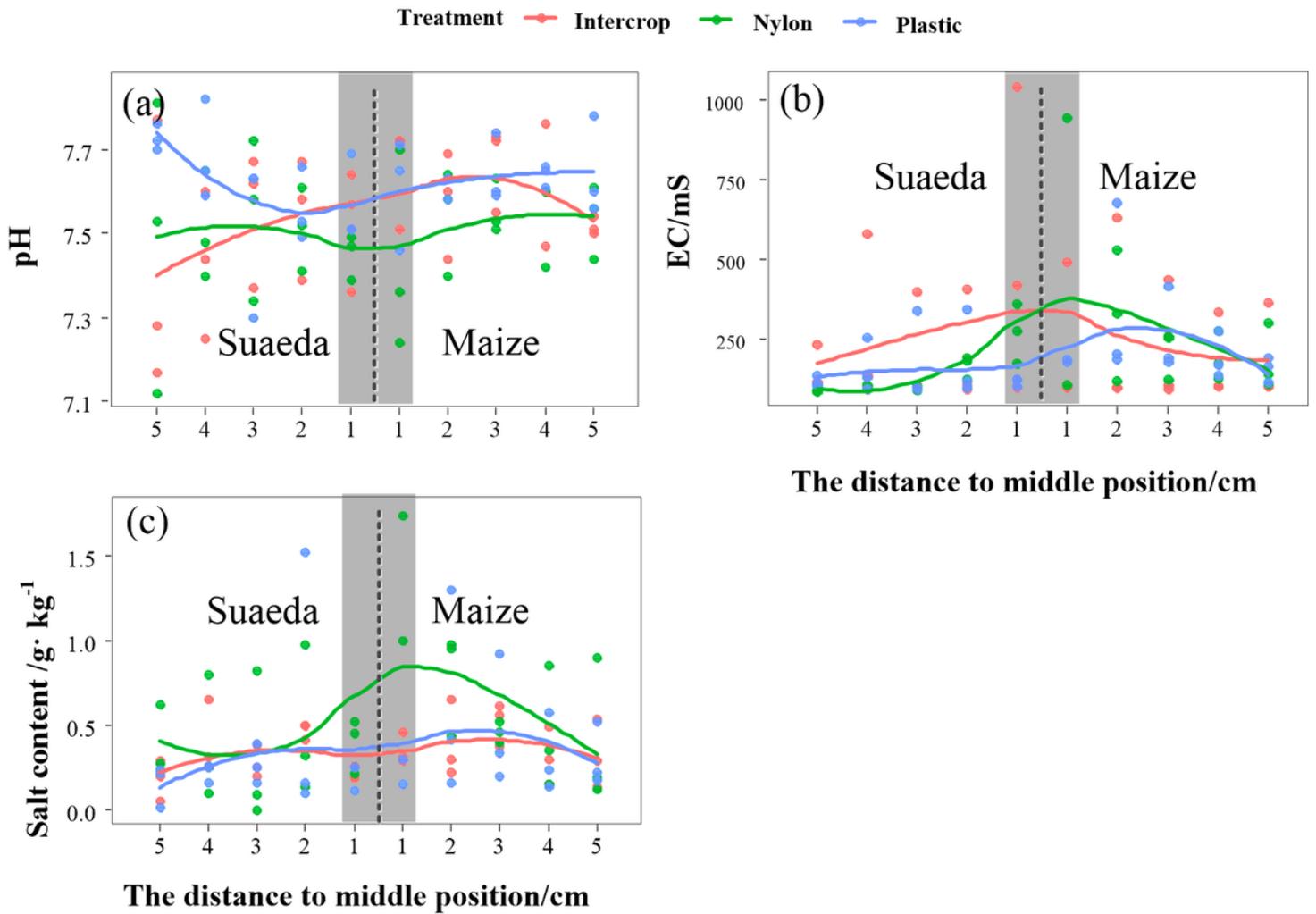


Figure 6

Variations in soil properties in the different suaeda/maize intercropping systems. (a) pH; (b) EC; and (c) salt content of the soil from the middle positions. Dotted black lines and gray shadowing represent the middle positions and the interfaces of the two species, respectively, in the different intercropping systems.

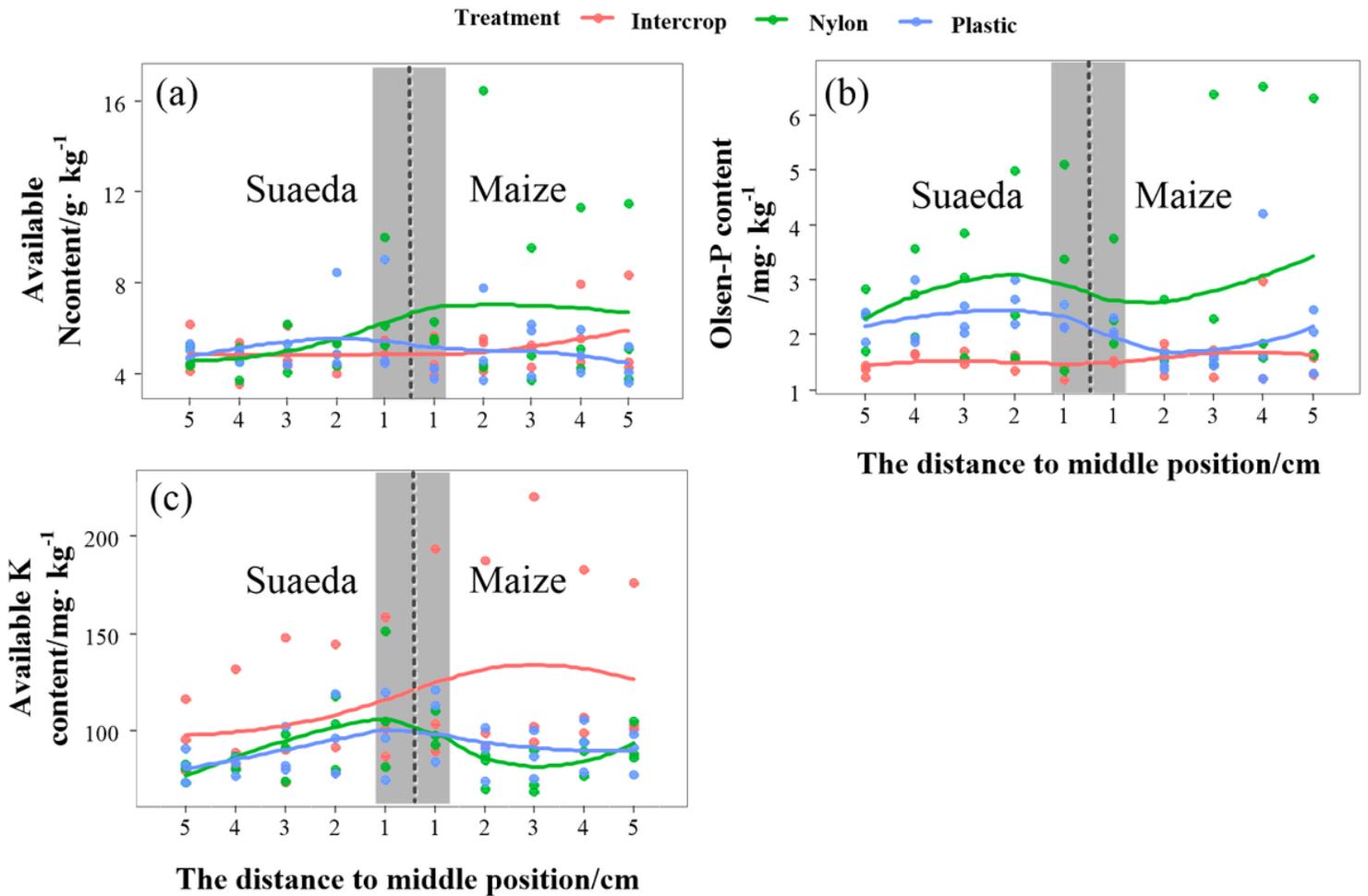


Figure 7

Variations in available nutrients in the different suaeda/maize intercropping systems. (a) Available N; (b) Olsen-P; and (c) available K contents of the soil at the middle positions. Dotted black lines and gray shadowing represent the middle positions and the interfaces of two species, respectively, in the different intercropping systems.