International Journal of Plant & Soil Science
5(3): 175-185, 2015; Article no.IJPSS.2015.0XX
ISSN: 2320-7035

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The Relationship between Electrical Conductivity and Growth of Gramineae with Varied Tolerance to Sodic Saline Condition-selectivity of K^+, Ca^{2+}, and Mg^{2+} over Na^+ in *Puccinellia chinampoensis* Ohwi

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Authors' contributions

This work was carried out in collaboration among the all authors. Authors TY, KN and SK designed the study, wrote the protocol, performed the statistical analysis and wrote the first draft of the manuscript. Authors LZ, HBW, AS, AKX, MQZ, BLQ and XMG gave the seeds of Puccinelli chinampoensis Ohwi and much essential information about the sodic soil in Songnen Plain in northeast China. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/IJPSS/2015/13699
Editor(s):
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(2) Francisco Cruz-Sosa, Biotechnology Department, Metropolitan Autonomous University Iztapalapa Campus, México.
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(6) Anonymous, China.
Complete Peer review History: http://www.sciencedomain.org/review-history.php?iid=781&id=24&aid=7429

Original Research Article

Received 29th August 2014
Accepted 11th December 2014
Published 19th December 2014

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ABSTRACT

The characteristics of metal macronutrients absorption (K^+, Ca^{2+}, Mg^{2+}) over Na^+ in the rhizosphere of sodic soils of *Puccinellia chinampoensis* Ohwi (*P. chinampoensis*) was investigated and compared with barley and oat. *P. chinampoensis* is a tolerant plant for sodic conditions. In the experiment, artificial sodic soil with several level of electrical conductivity (EC) values and high pH (pH 10) were made by adding 1mol/L Na_2CO_3-$NaHCO_3$ buffer (buffer for pH 10) to clay soil mixed with vermiculite. The plants were cultivated in a green house from September to October in 2009 in Iwate University, Morioka, Iwate pref., Japan. Root length, shoot dry weight, and root dry weight of the plants lowered with the increase of soil EC. However, *P. chinampoensis* showed higher root length and root dry weight as compared with those of the other plants. *P. chinampoensis* showed the lowest Na level and higher K, Ca, Mg levels in the shoots, which was not affected by the increase of soil EC under high pH condition around 10. Furthermore, *P. chinampoensis* showed the lowest values of cation level ratios of Na/K, Na/Ca and Na/Mg, and it was not also affected by the increase of soil EC. Therefore, it was suggested that *P. chinampoensis* had high selectivity of K^+, Ca^{2+} and Mg^{2+} over Na^+ in the rhizosphere of sodic soil. The plant with high root growth ability and high cation selectivity shown in the artificial sodic soils will have a higher ability to survive in the sodic soil. It was shown that *P. chinampoensis* is well adapted to the sodic conditions. Thus, *P. chinampoensis* would be useful and make meaningful contributions to recover vegetation of sodic soil.

Keywords: Sodic soil; soil EC; pH 10; songnen plain; northeast China; sodic tolerant plant; sodium; metal macronutrients.

1. INTRODUCTION

In the Songnen Plain located in the central part of northeast China, the land degradation caused by soil sodification has been a serious problem since the middle of twentieth century [1-3]. The causes of soil sodification in the Songnen Plain are natural factors such as parent materials of soil, topographic positions, arid/semi-arid climate and anthropogenic factors such as population pressure, overgrazing, and improper agricultural and economic policies [3]. The native dominant grass in the Songnen Plain is *Leymus chinensis*, but the dominance of *Leymus chinensis* has been partly replaced by sodic tolerant plants such as *Puccinellia chinampoensis* Ohwi (*P. chinampoensis*) because of the continual land degradation due to soil sodification [1].

P. chinampoensis, one of the sodic tolerant plants, makes a community in the natural sodic fields in the Songnen Plain [4]. The plant has high palatability and is ideal for animal grazing [4]. Thus, the Academy of Agriculture Science of Jilin Provinces in China has proceeded with a project for the utilization of the *P. chinampoensis* for recovery of vegetation in the Songnen Plain. There are some studies pertaining to the plant, but more research work is required [4,5].

The major salts in sodic soils are $NaHCO_3$ and Na_2CO_3 [1]. Once soil is affected by sodification, soil structure is destroyed and soil permeability is lowered [1]. Additionally, the soil pH raises to around pH 10 due to high concentrations of HCO_3^- and CO_3^{2-}, and a high amount of Na^+ accumulates in the soil [6]. Therefore, the plants grown in sodic soils suffer from the damaging effects of both alkaline stress and salt stress including Na^+ stress [7]. In sodic soils, plant growth is strongly repressed as compared with those in saline soil containing neutral salts like NaCl and/or Na_2SO_4 [7].

Sodium ion (Na^+) is the major cation inimical to the growth and productivity of plants [8]. Because of competitive inhibition of Na^+, the uptake of metal macronutrients such as potassium ions (K^+), calcium ions (Ca^{2+}), and magnesium ions (Mg^{2+}) by the roots is interfered by Na^+ [9]. The hydrated Na^+ has a radius of 0.358 nm, whereas that of the K^+ is 0.331 nm [10]. It seems logical that some higher plants have developed high selectivity in the uptake of K^+ as compared with that of Na^+ [10]. There are some reports that investigate the physiological or genetic characteristics on cation selectivity of sodic tolerant plants [7,8,11-14]. However, several reports suggested the K^+ selectivity over Na^+ in some plants grown in neutral salts like NaCl. However, there are few comprehensive reports about metal macronutrients selectivity about not only K^+ but also Ca^{2+} and Mg^{2+} over Na^+ under high alkaline conditions with pH around 10. Also, there are few nutritional studies such as cation selectivity of *P. chinampoensis*, as far as we know, though attempts have been made to utilize the plant for improving revegetation of sodic soils. Clarification of the characteristics of cation selectivity in sodic tolerant plants such as *P. chinampoensis* and demonstration of the usefulness of the plants would make meaningful contributions for recovery of the vegetation of sodic soil.

The objectives of this study were to investigate the cation selectivity of plants under the sodic condition and to clarify the characteristics of *P. chinampoensis*. Our study is of importance for a better under standing of sodic tolerant plants and effective use of the plants for improving revegetation in sodic soils.

2. MATERIALS AND METHODS

2.1 Preparation of the Artificial Sodic Soil for Cultivation

Artificial sodic soil for cultivation was prepared as follows –clay soils were collected from Hachiro-gata polder which was reclaimed from old lake Hachiro 40 years ago [15]. The clay concentration of the soil in the area was approximately 50% [16]. This soil was put in a water permeable plastic sack which was washed in the tap water for 36 h to remove excess ions present in the clay. The 16 elements contained in the tap water were measured by ICP-OES (ICPE-9000, Shimadzu, Kyoto). Table 1 shows the amounts of the elements. The tap water contained B, Ca, Fe, K, Mg, Na and S. The amounts of Al, Cd, Co, Cr, Cu, Mn, Ni, P, and Zn were lower than detectable level of each element in ICP-OES and they were not detected by this determination. Hardness of the tap water was 34.1 (mg/L). The water contained little amount of minerals.

The washed clay soil was soaked in 1 mol/L Na_2CO_3-$NaHCO_3$ buffer (buffer for pH 10) for 24 h to allow Na^+ and CO_3^{2-}/HCO_3^- cation exchange to occur on the surface of clay soil. Then, the clay soil soaked in buffer was washed with the tap water for 24 h to remove the excess Na^+ and CO_3^{2-}/HCO_3^-. The clay soil was air-dried and mixed with vermiculite (v/v, 1: 8) to improve the soil permeability and physical characteristics. Vermiculilte ($Mg_{1.8}Fe^{2+}{}_{0.9}Al_{4.3}SiO_{10}\,(OH)_2{\bullet}4(H_2O)$) was purchased from Miyako Calcine Co. (Miyako). The alkalinized clay soil mixed with vermiculite was denoted as "artificial sodic soil".

The chemical properties of the artificial sodic soil were measured (pH, electrical conductivity (EC), and amount of exchangeable cations). The pH and EC of soil suspension were measured (soil: deionized water = 1: 2.5 for pH, soil: deionized water = 1: 5 for EC) by using a pH conductivity meter (D-54, Horiba Co., Tokyo). The amounts of exchangeable cations (K^+, Ca^{2+}, Mg^{2+}, and Na^+) were measured by using an extracting solution (1 mol/L NH_4-acetate) at pH 7 [17]. The cations in the extracted solution were analyzed by flame atomic absorption spectrometry (AA-6200, Shimadzu, Kyoto). The bulk density of the artificial sodic soil was calculated from the weight and volume of the soil.

The properties of the original artificial sodic soil used in the experiment are shown in Table 2. The pH value of the soil was 9.9 and similar to that of natural sodic soils [1]. The EC value of the soil was 1.0 dS/m and was a little lower than that of natural sodic soils [1]. Exchangeable Na^+ showed the highest level among the exchangeable cations. Exchangeable Mg^{2+} had the second highest level but it was about a quarter of the level of exchangeable Na^+. Exchangeable K^+ had the lowest level and exchangeable Ca^{2+} had the second lowest level among the exchangeable cations, and those levels were about one-fourteenth of that of exchangeable Na^+. It was shown that prepared artificial sodic soil had a high pH value and a high amount of exchangeable Na^+ similar to those of the natural sodic soil [1]. The bulk density of the soil was very low and the value was 0.181. It was shown that the main part of the artificial sodic soil was vermiculite. The artificial sodic soil was clarified as sand (S) and loamy sand (LS) in soil texture.

A different amount of 1 mol/L Na_2CO_3-$NaHCO_3$ buffer (buffer for pH 10) was added to 10 g of artificial sodic soils, and the soil EC was measured (1: 5 wt). Then, the calibration curve of EC value as a function of the amount of added buffer solution was constructed. The calibration curve is shown in Fig. 1.

Table 1. Amount of elements in tap water

Al (mg/L)	B (mg/L)	Ca (mg/L)	Cd (mg/L)	Co (mg/L)	Cr (mg/L)	Cu (mg/L)	Fe (mg/L)
LD	0.0272	9.87	LD	LD	LD	LD	LD
K (mg/L)	**Mg (mg/L)**	**Mn (mg/L)**	**Na (mg/L)**	**Ni (mg/L)**	**P (mg/L)**	**S (mg/L)**	**Zn (mg/L)**
0.922	2.36	LD	5.37	LD	LD	5.51	LD

LD indicated the data was lower than detectable level of each element. Detectable level of each element in ICP-OES used in this study: Al, Ca, Cu, Fe, Zn> 42.1 (µg/L), B, Cd, Co, Cr, Mg, Mn, Ni> 10.5 (µg/L), K, Na< 105 (µg/L), P, S> 210 (µg/L)

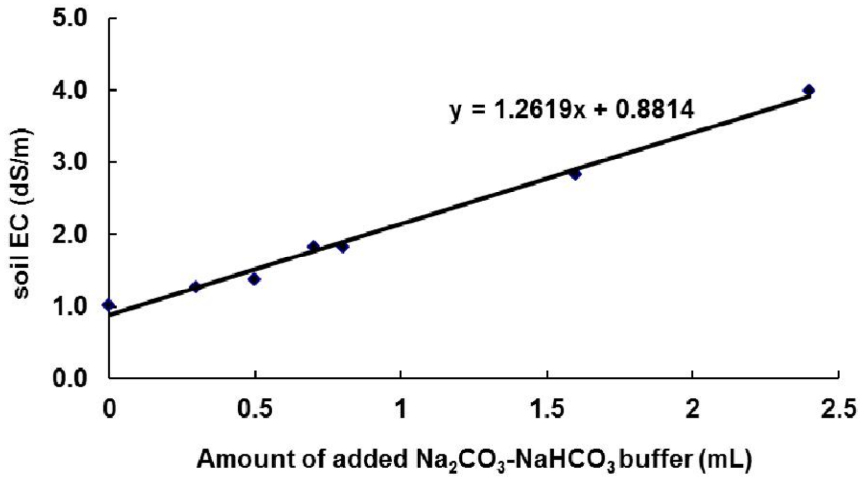

Fig. 1. The calibration curve between the EC and the amount of Na_2CO_3-$NaHCO_3$ buffer (1 mol/L) added to 10 g of the artificial sodic soil

Table 2. Properties of original artificial sodic soil

pH	9.9
EC (dS/m)	1.0
Bulk density (g/mL)	0.181
Exchangeable Na^+($cmol_c$/kg)	42.0
Exchangeable K^+($cmol_c$/kg)	3.02
Exchangeable Ca^{2+}($cmol_c$/kg)	3.42
Exchangeable Mg^{2+}($cmol_{c/}$/kg)	10.7

2.2 Cultivation of *P. chinampoensis* in Artificial Sodic soils

This experiment was conducted in a greenhouse from September to October in 2009 in Iwate University, Morioka, Iwate pref., Japan. Each pot (volume= 360 mL, height= 76 mm, size= 9.0 cm, root diameter= 64 Φmm) was prepared containing 180 g of the artificial sodic soils. In order to adjust the EC value of the artificial sodic soils, a buffer solution was added. One mol/L Na_2CO_3-$NaHCO_3$ buffer (pH 10) was added to the pots in the following amounts: 9.1 mL, 16.4 mL, and 23.8 mL according to the calibration curve (Fig. 1). With this procedure, the soil EC of the artificial sodic soils was adjusted to 1.5, 2.0, or 2.5 dS/m, maintaining pH value around 10. The original artificial sodic soil was used as control. The same amount (0.3 g) of chemical fertilizer with a concentration of nitrogen, phosphate and potassium of 10% each was added to the pots.

The seeds of *P. chinampoensis* were obtained through a grant from the Academy of Agriculture Science of Jilin provinces in China. Then, 0.01 g of the seeds of *P. chinampoensis*, 6 seeds of *Hordeum vulgare* L. cv. Minorimugi (Barley) which is a halophyte, or 6 seeds of *Avena sativa*. cv. Onward (Oat) which is a glycophyte were sown to each pot containing the original artificial sodic soil and artificial sodic soils whose EC values were adjusted to 1.5, 2.0, and 2.5 dS/m by adding the 1 mol/L Na_2CO_3-$NaHCO_3$buffer. The experiment was conducted in triplicate. In the cultivation, the tap water was added to the each pot without leaching of the elements from the lower part of the pots.

One month after sowing, the cultivated barley and oat were harvested. The roots were carefully washed with deionized water, and each root length was measured. Because of the late growth rate, *P. chinampoensis* was grown for two months and harvested. The root length of the plant was measured using similar methods. The plants were separated into shoots and roots and dried at +70ºC for 24 h. Then, dry weights of the plant parts were measured. The shoots of each plant were digested with a mixture of HNO_3 and $HClO_4$ (v/v, 5: 1), and the contents of Na^+, K^+, Ca^{2+}, Mg^{2+} in the shoots were measured by flame atomic absorption spectrometry (AA-6200, Shimadzu, Kyoto).

2.3 Statistical Analyses

Experiments were conducted in triplicate. Data was subjected to an ANOVA test using "HP proLiant DL320 G6" computer in Iwate University, Japan [18]. Differences between means were statistically evaluated using the Ryan-Einot-Gabriel-Welsch multiple range test ($p < 0.05$).

3. RESULTS

Fig. 2 shows the root length of the plants. Root length of the barley and oat decreased significantly according to the increase of soil EC (Fig. 2). In the soil with EC value 2.5, barley and oat could not develop roots substantially though they were grown in the soil only for a month. The root length of *P. chinampoensis* did not decrease according to the increase of soil EC (Fig. 2). The plant could form roots even 2 months growing in the soil with high EC value 2.5.

Dry weights of the plant parts are shown in Fig. 3. Dry shoot weight of each plant lowered with the increase of soil EC. Dry root weight of each plant also lowered with the increase of soil EC. Dry root weight of the barley and oat in EC2.5 treatment were lower than 0.1 mg though they were grown there only for a month. However, *P. chinampoensis* could grow the roots even 2 months growing in EC2.5 treatment.

Cation levels of the shoots of each plant are shown in Fig. 4. In barley and oat, there were no significant differences in Na levels among the plants of the control, EC1.5, and EC2.0 treatments (Fig. 4a). Na levels of both plants lowered significantly in the EC2.5 treatment. *P. chinampoensis* maintained a low Na level consistently which was less than half of the other plants and there were no significant differences among the treatments (Fig. 4a). Potassium levels of barley lowered significantly with the increase of soil EC (Fig. 4b). Oat maintained low K level and there were no significant differences among the treatments. Potassium level of *P. chinampoensis* was more than three times than the other plants in all treatments and lowered significantly with the increase of soil EC (Fig. 4b). Barley maintained a low Ca level and there were no significant differences among the treatments (Fig. 4c). Oat also maintained a low Ca level. However, in oat there was significant increase of Ca levels in EC2.5 treatment as compared with that of EC1.5 and EC2.0 treatments (Fig. 4c). *P. chinampoensis* maintained a Ca level much higher than those of the other plants and there were no significant differences among the treatments (Fig. 4c). In barley and oat, Mg levels lowered significantly with the increase of soil EC (Fig. 4d). On the other hand, *P. chinampoensis* maintained high Mg level and there were no significant differences among the treatments (Fig. 4d).

Ratios of cation levels in the shoots of each plant are shown in Fig. 5. In barley, the Na/K ratio increased with the increase of soil EC and there were significant differences between the control and EC2.0 treatment. However, in the EC2.5 treatment, the Na/K ratio was lower and it was similar to that of the control. The Na/K ratio of oat was lower with the increase of soil EC and there were significant differences between the control and the EC2.5 treatment. On the other hand, in *P. chinampoensis*, the Na/K maintained less than one-tenth ratio of the other plants and there were no significant differences among the treatments. In the Na/Ca ratio of barley, it tended to increase with the increase of soil EC. However, in the EC2.5 treatment, the Na/Ca ratio was also lower and it was similar to that of the control. In the Na/Ca ratio of oat, there were no significant differences among the control, EC1.5, and EC2.0 treatments. In the EC2.5 treatment, the Na/Ca ratio in oat was significantly lower as compared with that of the control. On the other hand, in Na/Ca ratio of *P. chinampoensis*, the Na/Ca maintained less than one-tenth ratio of the other plants except for that of oat in EC2.5 treatment and there were no significant differences among the treatments. The Na/Mg ratio of barley increased with the increase of soil EC and there were significant differences between those of the control and the EC2.5 treatment. In oat, there were no significant differences of the Na/Mg ratio among the treatments. The Na/Mg ratio of *P. chinampoensis* maintained a much lower level and there were no significant differences among the treatments.

4. DISCUSSION

The root growth of barley and oat were repressed with the increase of soil EC, but *P. chinampoensis* could develop their roots under high soil EC and pH 10 conditions (sodic conditions) (Fig. 2). The results suggest that high EC values may be very harmful for the growth of barley and oat, especially in root growth, because the plants cannot grow under pH 10 and high-EC condition higher than 2.0 (Fig. 2). Maas reported that the maximum soil salinity which does not reduce yield of barley is 8.0 dS/m [10,19]. However, the barley did not grow well under high-EC condition higher than 2.0 (Fig. 2) in our experiment. The difference of our results from that of Maas [19] may be due to the fact that our condition was alkaline condition with high concentration of HCO_3^-/CO_3^{2-}. Generally, the plants grown in sodic soils suffer from the damaging effects of both alkaline stress and salt stress including Na^+ stress [7]. The barley grown under sodic conditions suffered from the damaging of high pH around 10 and HCO_3^-/CO_3^{2-}. Therefore, soil EC may affect plant growth such as barley more sensitively in sodic conditions. This may be the reason why the barley grown in sodic conditions did not grow well under high-EC condition more than 2.0 in this experiment.

We have reported that *P. chinampoensis* grew well in sodic soil when the soil EC was lowered but soil maintained a high alkaline pH of around 10 [20]. Also, Liu et al. [21,22] reported that the drip irrigation of sodic-saline soils in the Songnen Plain leached the salts in the rhizosphere and reduced the soil EC and soil pH. The soil EC values of experimental land were reduced from the value greater than 15 dS/m to less than 6 dS/m after the first drip irrigation [22]. Subsequently, the soil pH value was reduced from 9.8 to 9.6 [22]. Then, *Puccinellia tenuiflora* (*P. tenuiflora*), one of the sodic tolerant plants, showed better growth in the irrigated soil than in the sodic-saline soils [22]. This report suggested the importance of salts removal from sodic soils for plant growth. Also, it suggested that reducing rate of the soil EC value for recovery vegetation in sodic soil may be faster when the soil was washed with water [22]. To our understanding, high EC value might be more harmful than high pH value for the plant growth. It is known that soil structure is destroyed and soil permeability is lowered in sodic soils [1]. High root growth activity under sodic conditions in plants will be advantageous in absorbing water and essential nutrients.

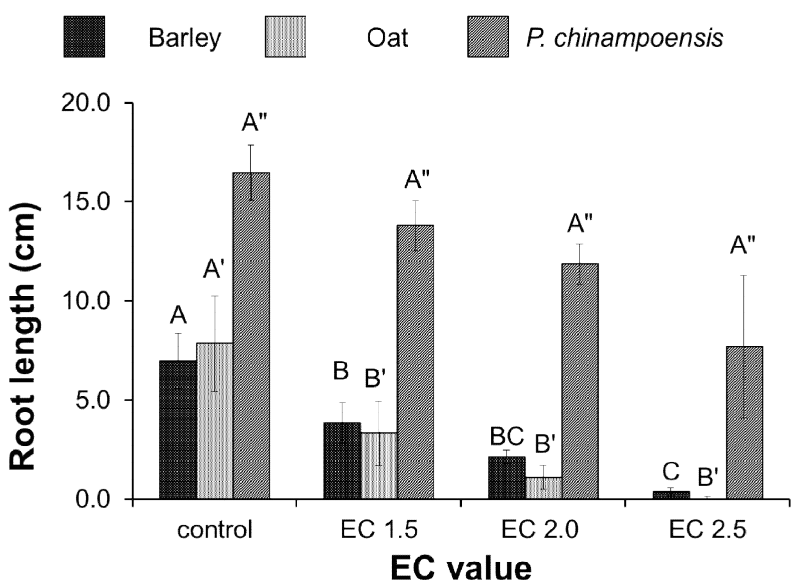

Fig. 2. Root length of the plants under the different soil EC values

Barley and oat were grown for 1 month and P. chinampoensis was grown for 2 months. Each value represents the mean ± SD (n = 3). Different letters at the top of each column indicate significant differences (p< 0.05) according to the Ryan-Einot-Gabriel-Welsch multiple range test. Barley: F = 31.08, p< 0.001. Oat: F = 16.45, p< 0.001. P. chinampoensis: F = 2.94

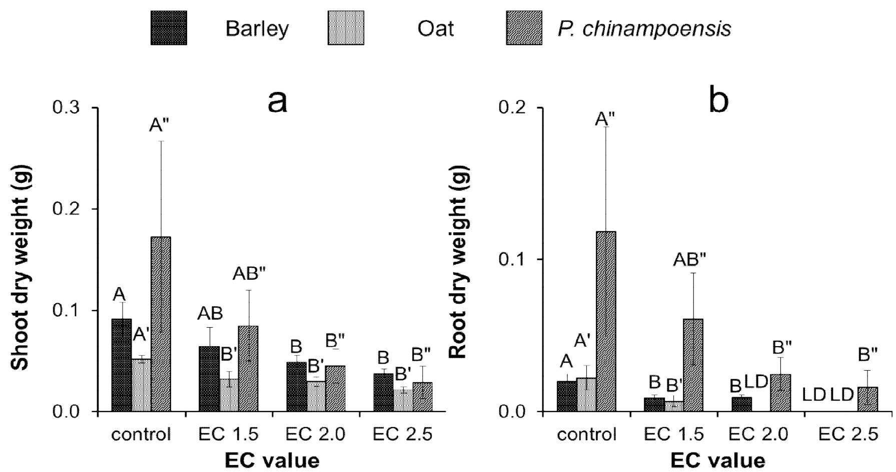

Fig. 3. Dry weight of the plants under the different soil EC values (a) Dry shoot weight, (b) Dry root weight

Barley and oat were grown for 1 month and P. chinampoensis was grown for 2 months. Each value represents the mean ± SD (n = 3). Different letters at the top of each column indicate significant differences (p< 0.05) according to the Ryan-Einot-Gabriel-Welsch multiple range test. LD indicated the data was lower than detectable level of electronic balance used in this study. The detectable level of weight in the electronic balance: weight> 0.1 (mg) (a)Barley: F = 9.05, p< 0.01. Oat: F = 18.66, p< 0.001. P. chinampoensis: F = 4.63, p< 0.05 (b)Barley: F = 10.13, p< 0.05. Oat: F = 9.00, p< 0.05. P. chinampoensis: F = 4.65, p< 0.05

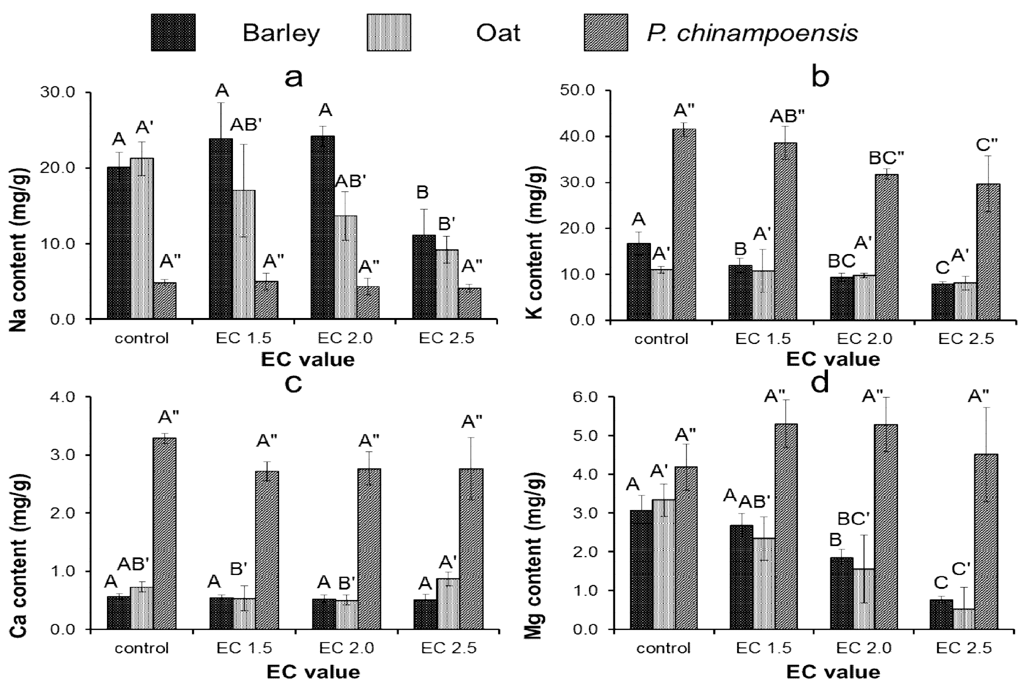

Fig. 4. Cation content of shoots of the plants under the different soil EC values (a) Na content, (b) K content, (c) Ca content, (d) Mg content

Barley and oat were grown for 1 month and P. chinampoensis was grown for 2 months. Each value represents the mean ± SD (n = 3). Different letters at the top of each column indicate significant differences (p< 0.05) according to the Ryan-Einot-Gabriel-Welsch multiple range test.

(a) Barley: F = 11.29, p< 0.005. Oat: F = 5.66, p< 0.05. P. chinampoensis: F = 0.49
(b) Barley: F = 18.74, p< 0.001. Oat: F = 0.86. P. chinampoensis: F = 7.24, p< 0.05
(c) Barley: F = 0.39. Oat: F = 4.77, p< 0.05. P. chinampoensis: F = 2.18
(d) Barley: F = 38.88, p< 0.001. Oat: F = 11.10, p< 0.005. P. chinampoensis: F = 1.36

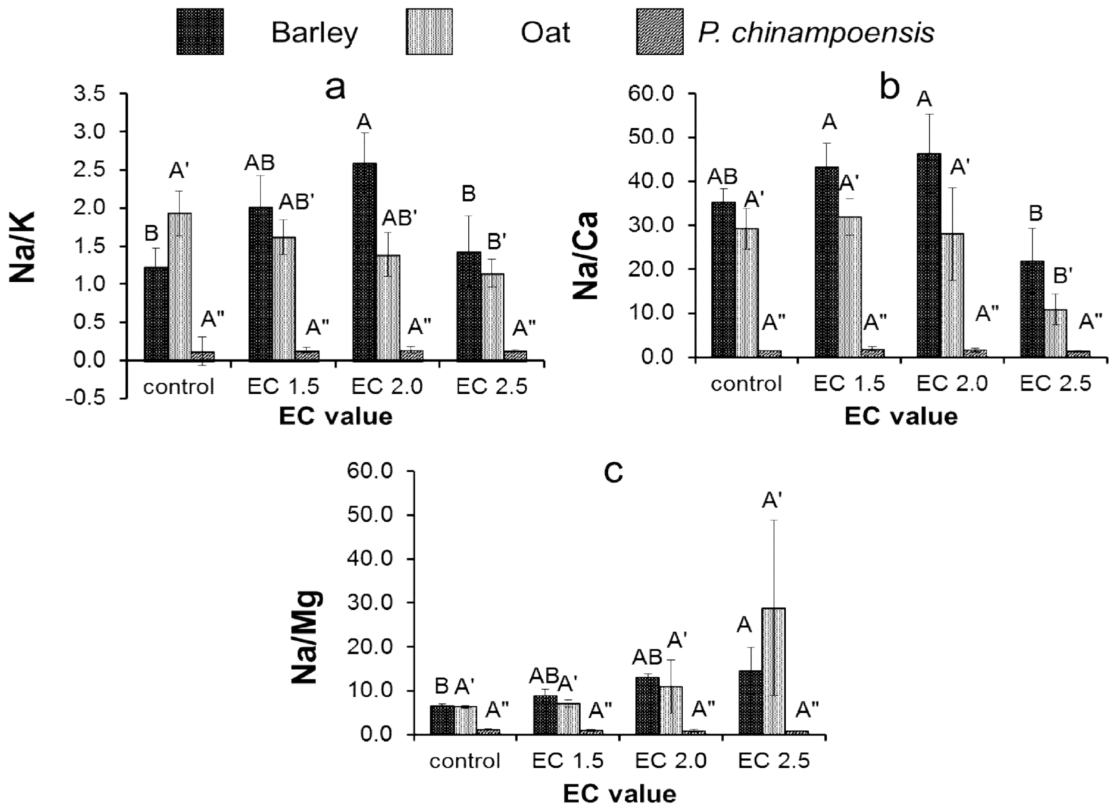

Fig. 5. Cation content ratio of shoots of the plants under the different soil EC values (a) Na and K ratio, (b) Na and Ca ratio, (c) Na and Mg ratio

Barley and oat were grown for 1 month and P. chinampoensis was grown for 2 months.
Each value represents the mean ± SD (n = 3). Different letters at the top of each column indicate significant differences ($p< 0.05$) according to the Ryan-Einot-Gabriel-Welsch multiple range test.
(a) Barley: $F = 7.52$, $p< 0.05$. Oat: $F = 5.29$, $p< 0.05$. P. chinampoensis: $F = 0.27$
(b) Barley: $F = 8.26$, $p< 0.01$. Oat: $F = 6.80$, $p< 0.05$. P. chinampoensis: $F = 0.91$
(c) Barley: $F = 5.18$, $p< 0.05$. Oat: $F = 3.04$. P. chinampoensis: $F = 1.16$

Dry shoot weight of the plants lowered with the increase of soil EC (Fig. 3a). In barley and oat, dry root weight also lowered and there was no growth at EC2.5 (Fig. 3b). However, growth rate of roots of *P. chinampoensis* was maintained up to EC2.5 (Fig. 3b). The high maintaining activity in root growth of *P. chinampoensis* may confer an advantage to it to survive under the sodic condition.

P. chinampoensis showed the lowest Na level and higher K, Ca, Mg levels in the shoots among the plants, and it was not affected by the increase of soil EC (Figs. 4a, 4b, 4c, and 4d). The sodic soils used in this study contained a much higher amount of exchangeable Na^+ than the other exchangeable metal macronutrient ions (Table 1). Especially, the amounts of exchangeable K^+ and Ca^{2+} were about one-fourteenth that of exchangeable Na^+. Generally, in sodic conditions, the nutrient availability of Ca^{2+} and Mg^{2+} are extremely low [23]. This result indicated that *P. chinampoensis* had high selectivity of K^+, Ca^{2+}, Mg^{2+} over Na^+ in the rhizosphere of sodic soils. Furthermore, *P. chinampoensis* showed the lowest values of cation level ratios of Na/K, Na/Ca, and Na/Mg among the plants (Figs. 5a, 5b and 5c). This result also indicated the high cation selectivity of *P. chinampoensis* in rhizosphere of sodic soils. The activity to maintain a lower Na level relative to K, Ca, and Mg must be advantageous for survival activity of *P. chinampoensis* under sodic conditions in the Songnen Plain. Cation selectivity under high pH conditions around 10 is indispensable for living plants in sodic soils. It is considered that *P. chinampoensis* is well adapted to the sodic conditions. We reported that

P. chinampoensis showed the high metal macronutrient selectivity in sodic soil collected from Songnen Plain [20]. However, the Na level (mg/g) of shoots of *P. chinampoensis* was around 40 mg/g when grown in the sodic soil where EC was 1.77 dS/m [20]. The Na level of *P. chinampoensis* grown in the sodic soil was 10 times higher than that in this experiment (Fig. 4a), though the other cation levels were similar to those in our previous report. The artificial sodic soils used in this experiment contained much amount of vermiculite (clay soil: vermiculte=v/v, 1: 8). Vermiculite has high cation exchangeable capacity (CEC). The greater part of Na^+ in Na_2CO_3-$NaHCO_3$ added to the artificial sodic soils was adsorbed to the vermiculite Na^+ absorption by the plants may be lowered compared with the condition in natural sodic soil. The raising EC value by adding Na_2CO_3-$NaHCO_3$ buffer was resulted from the much amount of CO_3^{2-}/HCO_3^-. In sodic soil in natural field, the much amount of free Na^+ and CO_3^{2-}/HCO_3^- exists in soil solutions, and availability of Na^+ in natural sodic soil may be much higher than that in the artificial sodic soil used in this experiment. This may be the reason why the plant shoots had large difference in Na^+ level between the soils. There are possibilities that unknown factors other than Na^+ availability may exist in sodic soils.

At present, there are several studies about Na^+ tolerant mechanisms of sodic tolerant plants. For example, *P. tenuiflora* and *Chloris virgata*, which are sodic tolerant plants, show preferential absorption of K^+over Na^+ [8,14,24]. It has also been revealed that *P. tenuiflora* had the plasma membrane localized Na^+/H^+ anti-porter (*PtSOS1*) and a high-affinity K^+ transporter (*PutHKT2;1*) which could function in preferential absorption of K^+ and exclusion of Na^+ transporter [11,12]. Furthermore, it has been indicated that *P. tenuiflora* has the casparian bands of the endodermis as an apoplastic barrier and this barrier leads to the high levels of K^+ in the shoot and a large Na^+ gradient between the root and the shoot [13]. *P. chinampoensis* also would have the ability to select K^+ over Na^+ in the rhizosphere of sodic soils similar to *P. tenuiflora*. It is suggested, however, that there are some different physiological characteristics between *P. chinampoensis* and *P. tenuiflora* [4]. Besides, the selectivity of Ca^{2+} and Mg^{2+} of *Puccinellia* genus has not been well documented. Preferential absorption of Ca^{2+} and Mg^{2+} over Na^+ in *P. chinampoensis* may be new evidence, as far as we know. These metal macronutrients may be also essential for Na^+ tolerance. For example, it is shown that Na^+ can replace Ca^{2+} in cell membranes [9]. Therefore, not only K^+ selectivity, but also high Ca^{2+} selectivity over Na^+ may be similarly important.

In the rhizosphere of sodic soils with a high soil pH around 10, it is thought that metal micronutrients such as Fe, Cu, Mn, Zn and other cations are precipitated. Therefore, absorption of the metals by plants would be repressed [23]. For example, it is common knowledge that Fe is precipitated as $Fe(OH)_3$ in alkaline soils. Therefore, Fe or Zn deficiency may be one of the inhibitory factors in plant growth on alkaline soils [25]. Therefore, Fe or Zn absorption ability is also indispensable in the rhizosphere of sodic soils for sodic tolerant plants such as *P. chinampoensis*. Thus, there is a possibility that *P. chinampoensis* has superior mechanisms to absorb metal micronutrients. Further work is required to reveal the mechanisms to absorb not only metal macronutrients but also metal micronutrients.

Land desertification caused by accumulated salts is gradually spreading in arid or semi-arid areas in the world [26]. In cultivated lands, about 23% suffer from soil salinization and another 37% suffer from soil sodification [27]. Preventing land desertification is an important global issue for food production in the 21st century. Therefore, clarification of the properties of plants having tolerance to survive in desolated soils is needed. Soil sodification to cause land desertification is a serious problem in the world. Thus, in order to prevent soil sodification, further work is required to investigate the mechanism of the sodic tolerant plants such as *P. chinampoensis* to utilize for the improvement of sodic soils in the future.

5. CONCLUSION

The growth and absorption of metal macronutrients (K^+, Ca^{2+}, Mg^{2+}) over Na^+ in the rhizosphere of sodic soil of *P. chinampoensis*, a sodic tolerant plant, were investigated. *P. chinampoensis* showed the ability to develop roots even under the condition with EC value 2.5 in artificially made sodic soil of pH 10. *P. chinampoensis* showed the lowest Na level and higher K, Ca, Mg levels in the shoots among the plants, and it was not affected by the increase of soil EC. Furthermore, *P. chinampoensis* showed the lowest values of cation level ratios of Na/K, Na/Ca, and Na/Mg among the plants. Therefore, *P. chinampoensis* had high selectivity of K^+, Ca^{2+}

and Mg^{2+} over Na^{+} in the rhizosphere of sodic soil. It is considered that plants with higher activity to maintain root growth and high cation selectivity in artificial sodic soils will have the ability to live in the sodic soil. It was concluded that *P. chinampoensis* was well adapted to the sodic conditions.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge a Grant-in-Aid for Scientific Research (C) from the Japan Society for Promoting of Science (No. 21580074). The authors thank Mr. Mark De Boer of Iwate University for correction of the English in the manuscript. The authors also thank Dr. Takashi Sato in Akita prefectural university, Japan, for giving us information about the spot of clay soils in old lake Hachiro.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sciencedomain.org/review-history.php?iid=781&id=24&aid=7429