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The High Metal Macronutrients Selectivity over Na^+ of *Puccinellia chinampoensis* Ohwi in the Rhizosphere of Sodic Soil

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Authors' contributions

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

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ABSTRACT

The uptake of metal macronutrients (K^+, Ca^{2+}, Mg^{2+}) and Na^+ of *Puccinellia chinampoensis* Ohwi (*P. chinampoensis*), a sodic tolerant plant, were investigated in both sodic and alkaline soil. In the first experiment, sodic soil was collected from Songnen Plain in Jilin Province in northeast China. *P. chinampoensis*, *Festuca arundinacea* Schreb. (*F. arundinacea*) and *Dactylis glomerata* L. (*D. glomerata*) were grown in the sodic soil in growth chamber under natural light, but the plants did not grow. Then, the plants were grown in sodic soil mixed with vermiculite (artificial soil). The plants grew, and *P. chinampoensis* and *F. arundinacea* showed better growth than *D. glomerata* in the artificial soil. *P. chinampoensis* showed higher K level than the other plants and maintained low Na level in the shoot. Besides, *P. chinampoensis* had tremendously low Na/K, Na/Ca, and Na/Mg ratios. In the properties of artificial soil, soil pH was similar to the original sodic soil which was over 10. However, the soil cation exchange capacity (soil CEC) was higher, and the soil electrical conductivity (soil EC) and exchangeable sodium percentage (ESP) were lower than the original sodic soil. In the second experiment, *P. chinampoensis* and *Leymus chinensis* [Trin.] Tzvelev (*L. chinensis*) were grown on natural alkaline area in the Songnen Plain. There were no significant differences of the Na, K, Ca, and Mg levels in the both plants. Especially, though the concentration of exchangeable K^+ was more than double, K level of *P. chinampoensis* in the alkaline soil was about one-tenth of that in the artificial soil. It was concluded that *P. chinampoensis* had high selectivity of metal macronutrients over Na^+ which functions in sodic soils. Besides, it seemed that high soil EC and exchangeable Na^+ were more harmful than high soil pH for plant growth on sodic soils.

Keywords: Sodic soil; alkaline soil; Songnen Plain; northeast China; Puccinellia chinampoensis Ohwi; sodium; potassium; soil EC.

1. INTRODUCTION

Desertification are acaused by accumulated salts is gradually spreading in arid or semi-arid areas in the world [1]. In cultivated lands of the world, about 23% are saline and another 37% are sodic soils [2,3]. Saline soils contain a high amount of neutral soluble salts enough to interfere with the growth of most plants, and the pH value of the soils are usually less than 8.5 [4,5,6]. Saline soils, however, do not contain enough exchangeable sodium ion (Na^+) to alter soil characteristics appreciably. On the other hand, sodic soils contain an excessive amount of exchangeable Na^+ which forms alkaline soluble salts such as Na_2CO_3 and $NaHCO_3$. Therefore, the pH of the sodic soils is raised to 10 [4,5,6].

Because of high pH and high concentration of exchangeable Na^+, sodic soils interfere with plant growth more severely than do saline soils [7,8]. Excessive Na^+ interfere with the transport of potassium ions (K^+), calcium ions (Ca^{2+}), and magnesium ions (Mg^{2+}) from the root to shoot [5,6,9,10,11]. Furthermore, in high pH conditions, the nutrient availability of Ca^{2+} and Mg^{2+} are extremely low [12]. Thus, the plants grown in sodic soils suffer from deficiency of metal macronutrients such as K^+, Ca^{2+}, Mg^{2+} more than those grown in saline soils.

In the Songnen Plain in northeast China, located between 42º30'-51º20'N and 121º40'-128º30'E, the increase of sodic soil areas has been a serious problem since the middle of the twentieth century [13], and approximately 70% of the natural grasslands have been facing soil salinization and sodification [6,14]. 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 causes such as population pressure, overgrazing, and improper agricultural and economic policy [13,15].

Before the increase of sodic soil areas, *Leymus chinensis* [Trin.] Tzvelev (*L. chinensis*) was the dominant grass in the Songnen Plain and was ideal for forage because of its high palatability [16,17,18]. The grasslands of the *L. chinensis*, however, have degraded due to the soil sodification with high pH around 10 [19,20,21,22]. Since then, the dominance of the *L. chinensis* has been replaced, depending on soil conditions by grasses which have sodic tolerance such as *Puccinellia chinampoensis* Ohwi (*P. chinampoensis*) [22]. The *P. chinampoensis* has also high palatability and was ideal for animal grazing [23]. Thus, Academy of Agriculture Science of Jilin Provinces in China has proceeded with the project for the utilization of the *P. chinampoensis* to recover vegetation in the Songnen Plain. There are a few studies about the plant, but more research work is required [23,24]. There are also some genetic studies about sodic tolerant plants such as *Puccinellia tenuiflora* or *Chloris virgate* [23,25]. However, to our understanding, the research about mineral nutrients of sodic tolerant plants in the actual field is not sufficient for revealing the characteristics of nutrient uptake.

Further study about the characteristics of nutrient uptake in sodic tolerant plants such as *P. chinampoensis* and a demonstration of the usefulness of these plants could make meaningful contributions to improvement of the revegetation of sodic soil. Therefore, the focus of this study was to understand the uptake of metal macronutrients such as K^+, Ca^{2+}, Mg^{2+} of *P. chinampoensis* in the rhizosphere of sodic soils. In fact, *P. chinampoensis* is widespread on sodic grasslands and forms communities in the Songnen Plain [23]. Therefore, it is considered that *P. chinampoensis* would have some superior ability in nutrient uptake to survive on sodic soils, though physiological activity has not been well investigated. Furthermore, there is no research about the characteristics of the nutrient uptake of *P. chinampoensis* related to the differences of soil types such as sodic soil or alkaline soil.

Thus, we studied the nutrient uptake ability of *P. chinampoensis* compared with other grasses growing in sodic soil or alkaline soil. The aim of this study was to reveal the superior characteristics in nutrient uptake of *P. chinampoensis* grown in sodic soils and to show the usefulness of the plant for improving revegetation in sodic soil.

2. MATERIALS AND METHODS

2.1 Cultivation of *P. chinampoensis* in Sodic Soil in Growth Chamber under Control Conditions

Sodic surface soil of 10 kg was collected in the Songnen Plain: suburbs of Dàān, Jilin Prov., China. This area has suffered from severe soil sodification [15]. In the site from where soil was collected, there were several grasses present, such as *P. chinampoensis* and *Chloris virgate* which have sodic tolerance [3,25]. The collected soil was air-dried and passed through a 2 mm sieve. Then, chemical properties were measured (soil pH, soil electrical conductivity (soil EC), the cation exchange capacity (CEC), amounts of exchangeable cations, and exchangeable sodium percentage (ESP)). The pH and EC of soil suspension were measured (soil: deionized water = 1: 2.5 for pH, soil: deionized water = 1: 5 for EC) with a pH conductivity meter (D-54, Horiba Co., Tokyo). The amounts of exchangeable cations and cation exchange capacity (CEC) were measured by the semi-micro Schollenberger's method using an extracting solution (1 mol/L NH_4-acetate) at pH 7 [26]. The metals in the extracted solution were analyzed by flame atomic absorption spectrometry (AA-6200, Shimadzu, Kyoto). The ESP was calculated by the values of exchangeable Na^+ and CEC.

This experiment was conducted in a growth chamber under sunlight conditions with the adjusted temperature (12 h daytime at +25ºC and 12 h nighttime at +15ºC) from December in 2009 to January in 2010. Each pot (200 ml) was prepared containing 200 g of the sodic soil or 200 g of the sodic soil mixed with vermiculite (v/v, 1: 1).Vermiculilte was purchased from Miyako Calcine Co. (Miyako). This soil mixed with vermiculite was denoted as "artificial soil". The chemical properties of the artificial soil were also measured by the similar methods as described above (soil pH, soil electrical conductivity (soil EC), the cation exchange capacity (CEC), the amounts of exchangeable cations, and exchangeable sodium percentage (ESP)).The seeds of *P. chinampoensis* were granted from the Academy of Agriculture Science of Jilin provinces in China. Then, seeds of *P. chinampoensis*, *Festuca arundinacea* Schreb. (*F. arundinacea*; Tall fescue), or *Dactylis glomerata* L. (*D. glomerata*; Orchard grass) were sown in 6 pots, three pots contained the collected sodic soil and the other 3 pots contained artificial soil. The same weight of each seed was sown into the pots: 0.01 g of *P. chinampoensis*, 0.1 g seeds of *F. arundinacea*, and 0.5 g seeds of *D. glomerata*. Therefore, experiments were conducted in triplicate. *F. arundinacea* is one of the alkaline tolerant plants, and *D. glomerata* is one of the glycophytes. It was considered that the experiment was meaningful to compare the results among the plants having different tolerance. After two months when the plants grew enough for analysis, the shoots of cultivated plants were harvested and dried at +80ºC to a constant weight. Then, the dry weight of the shoots was measured. The shoots were digested with a mixture of HNO_3 and $HClO_4$ (v/v, 5: 1), and the contents of Na, K, Ca, Mg in the shoots were measured by the flame atomic absorption spectrometry (AA-6200, Shimadzu, Kyoto).

2.2 Cultivation of *P. chinampoensis* in Alkaline Soil in Songnen Plain

This experiment was conducted from middle June to middle August in 2012 in alkaline soil in the experimental field, which did not suffer from sodification, of Jilin Agricultural University in the Songnen Plain. The area is under the continental monsoon climate, and seasonal temperatures vary from −34ºC to +37ºC. From middle April to early June, there is distinct drought period. The annual precipitation ranges from 300-600 mm, and it has rain mainly from June to September (from 70% to 80% of the total rain fall of one year) [15,23].

The experimental site was prepared, and the surface soil sample in the site was collected. The soil was air-dried and passed through a 2 mm sieve. Then, chemical properties (soil pH, soil electrical conductivity (soil EC), the cation exchange capacity (CEC), the amounts of exchangeable cations, and exchangeable sodium percentage (ESP)) were measured. The pH and EC of soil suspension was measured (soil: deionized water = 1: 2.5 for pH, soil: deionized water = 1: 5 for EC) with a pH conductivity meter (D-54, Horiba Co., Tokyo). Amounts of exchangeable cations and cation exchange capacity (CEC) of the soil sample were measured by the semi-micro Schollenberger's method using an extracting solution (1 mol/L NH_4-acetate) at pH 7 [26]. The metals in the extracted solution were analyzed by flame atomic absorption spectrometry (AA-6200, Shimadzu, Kyoto). The ESP was calculated by the values of exchangeable Na^+ and CEC.

The experimental site was divided into two, each part was a 9.0 m^2 (3.0 m × 3.0 m) area. The seeds of *L. chinensis*or *P. chinampoensis* were sown in two sites, respectively. Comparison of both plants will provide us one of the reasons why *P. chinampoensis* cannot dominate on alkaline soils, but only on sodic soils. The plants were grown by rainwater in the natural climate of the Songnen Plain. About two months later (from middle June to middle August), the shoot of cultivated plants were harvested and dried at +80°C to a constant weight. Three samples (five plants per sample) were selected, and the dry weight of samples was measured. Those samples were digested with a mixture of HNO_3 and $HClO_4$ (v/v, 5: 1), and the contents of Na, K, Ca, Mg in the plant tissues were analyzed by the flame atomic absorption spectrometry (AA-6200, Shimadzu, Kyoto).

2.3 Statistical Analyses

Experiments were conducted in triplicate. Data was subjected to an ANOVA using computer of "HP proLiant DL320 G6" in Iwate university, Japan [27]. Differences between means were evaluated using the Ryan-Einot-Gabriel-Welsch multiple range test (p< 0.05).

3. RESULTS

3.1 Cultivation of *P. chinampoensis* in Sodic Soil in Growth Chamber under Control Conditions

The soil pH of sodic soil or artificial soil was higher than 10 (Table 1). The soil EC and ESP of artificial soil containing vermiculite was lower than those of sodic soil. The soil CEC of artificial soil was higher than that of sodic soil. The amount of exchangeable Na^+ of artificial soil was lower than that of sodic soil. However, the amount of K^+, Ca^{2+} and $Mg^{2+}$of artificial soil was higher than that of sodic soil. According to the definition of sodic soil by Bear [4], soils which has a pH higher than 8.5, EC less than 4, and ESP value higher than 15 is defined as sodic soil. Thus, by definition, both the sodic soil obtained from Dàān, Jilin prov., China and the artificial soil were sodic soils (Table 1) [4].

Table 1. Chemical properties of sodic and artificial soil

	Sodic soil	Artificial soil
pH	10.6± 0.012	10.1± 0.042
EC (dS/m)	2.76± 0.026	1.77± 0.072
CEC (cmol/kg)	20.9± 3.4	41.3± 0.86
ESP (%)	55.1± 3.9	18.2± 0.57
Exchangeable Na^+ (cmol/kg)	11.5± 0.81	7.52±0.24
Exchangeable K^+ (cmol/kg)	0.14±0.016	0.17±0.0033
Exchangeable Ca^{2+} (cmol/kg)	2.58±0.16	3.56±0.14
Exchangeable Mg^{2+} (cmol/kg)	0.10± 0.012	0.29±0.037

EC: electrical conductivity, CEC: cation exchange capacity, ESP: exchangeable sodium percentage, Data are shown as mean ±standard error (SE)

In the pots containing sodic soil, *F. arundinacea* and *D. glomerata* did not germinate. However, only *P. chinampoensis* could germinate on the sodic soil but it could not grow enough for the measurement of dry weight and cation contents. The results of the shoot dry weights of plants grown in the artificial soil are shown below (Fig. 1). *F. arundinacea* showed the highest shoot dry weight, and *P. chinampoensis* showed the second highest. However, *D. glomerata* showed the lowest shoot dry weight and did not grow well in the artificial soil. The results of the levels of Na, K, Ca and Mg per shoot dry weight of each plant are shown in Figs. 2a, 2b, 2c, and 2d.The highest level of Na was found in *D. glomerata*. Compared with other elements, Na levels were much higher. *P. chinampoensis* and *F. arundinacea* had low Na levels, and there were no significant difference between those of both plants. With respect to K levels, *P. chinampoensis* showed the highest level among the plants. The K level of *P. chinampoensis* was more than double of those of the other plants, and there was no significant difference between *F. arundinacea* and *D. glomerata*. With respect to Ca levels, *F. arundinacea* showed the lowest level among the plants. The Ca level of *F. arundinacea* was less than one-tenth of those of the other plants, and there was no significant difference between *P. chinampoensis* and *D. glomerata*. With Mg levels, there were no significant differences among the plants.

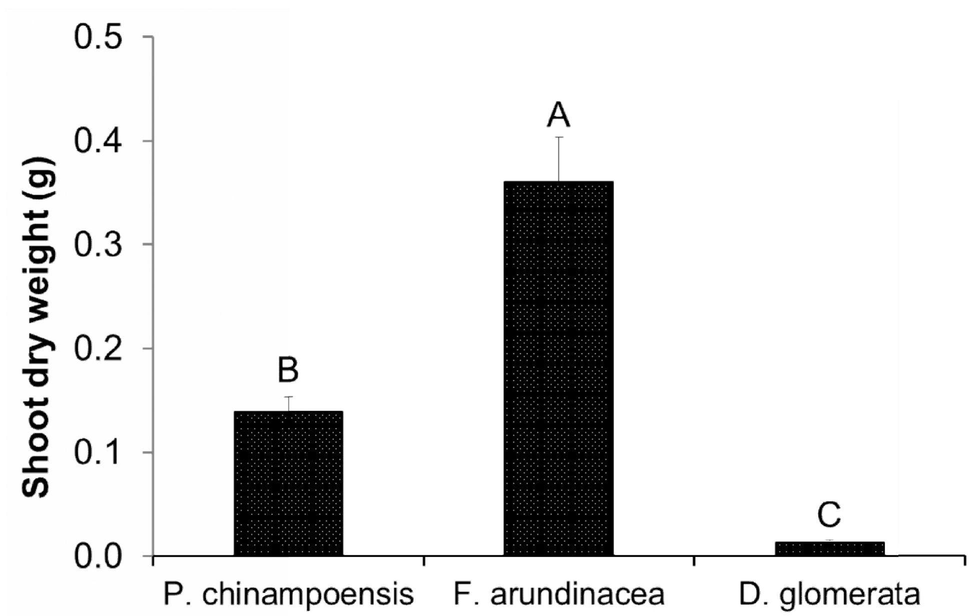

Fig. 1. Shoot dry weight of plants

Each value represents the mean ± SD (n = 3). Different letters at the top of each column indicate significant differences (p< 0.05) (F = 130.45, p< 0.001), according to the Ryan-Einot-Gabriel-Welsch multiple range test

The results of the cation levels ratio of the plants are shown in Figs. 3a, 3b, and 3c. *P. chinampoensis* showed the lowest values of Na/K, Na/Ca, and Na/Mg. *F. arundinacea* showed the highest value of Na/Ca, and the values of Na/K and Na/Mg were the second highest among the plants. *D. glomerata* showed the highest values of Na/K and Na/Mg, and that of Na/Ca was the second highest among the plants.

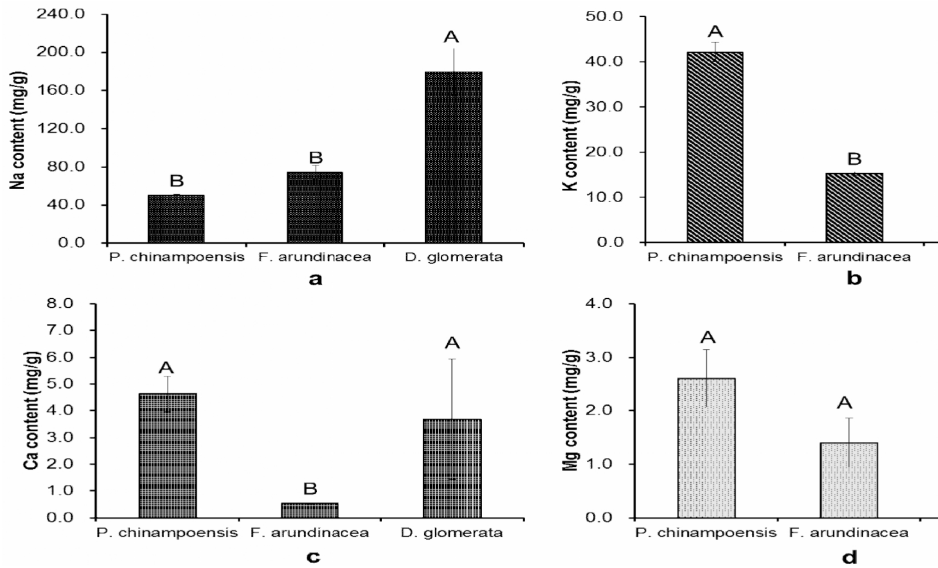

Fig. 2. Cation contents of plants (a) Na content (mg/g), (b) K content (mg/g), (c) Ca content (mg/g), and (d) Mg content (mg/g)

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)F = 66.11, p< 0.001, (b) F = 452.13, p< 0.001, (c) F = 7.49, p< 0.05, (d) F = 4.35

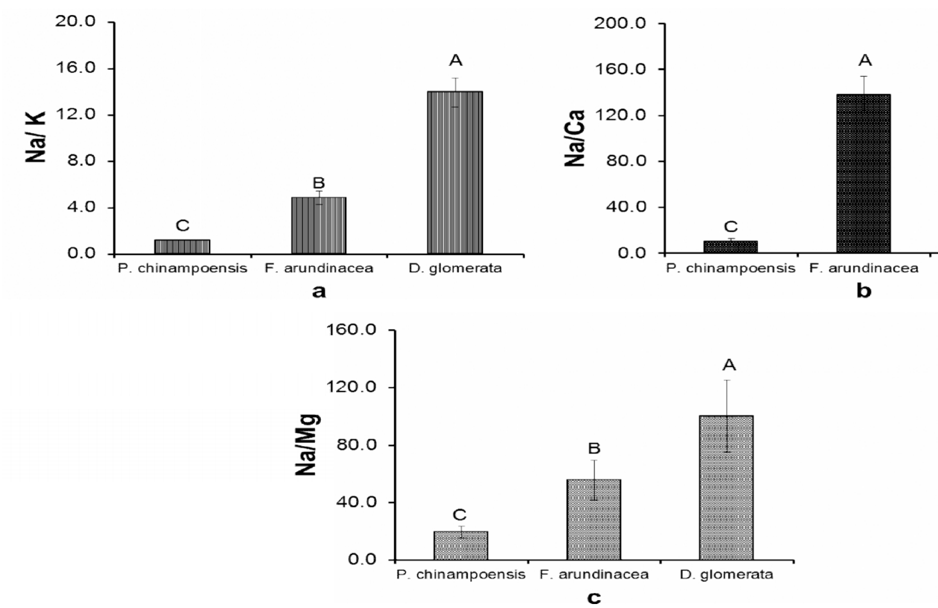

Fig. 3. Cation content ratio of plants (a) Na and K ratio, (b) Na and Ca ratio, and (c) Na and Mg ratio

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) F = 207.95, p< 0.001, (b) F = 27.90, p< 0.001, (c) F = 17.79, p< 0.05

3.2 Cultivation of *P. chinampoensis* in Alkaline Soil in Songnen Plain

The chemical properties of experimental soil can be seen in Table 2.The soil pH alkaline value was higher than 8.5, but it was lower than that of the sodic soil used in the experiment in the growth chamber. The soil EC and ESP were much lower but CEC was higher than that of the sodic soil. This soil had EC value 0.60 and ESP value 5.38. Therefore, this soil was not defined as saline or sodic soil [4,5]. The amount of exchangeable Ca^{2+} of this soil was more than ten times higher than that of sodic soil. The amount of exchangeable Na^{+} was much lower than that of the sodic soil. The exchangeable K^{+} and Mg^{2+} were more than double than those of the sodic soil. Thus, it seemed that this soil was rich in Ca and had the characteristics of fertile soil such as chernozem (Table 2) [28].

Table 2. Chemical properties of the soil in experiment field

	Alkaline soil
pH	8.57± 0.0050
EC (dS/m)	0.60± 8.1
CEC (cmol/kg)	28.3± 2.0
ESP (%)	5.38± 0.15
Exchangeable Na^{+}(cmol/kg)	1.52± 0.15
Exchangeable K^{+}(cmol/kg)	0.40± 0.033
Exchangeable Ca^{2+}(cmol/kg)	32.7± 1.7
Exchangeable Mg^{2+}(cmol/kg)	1.24± 0.032

EC: electrical conductivity, CEC: cation exchange capacity, ESP: exchangeable sodium percentage, Data are shown as mean ± standard error (SE)

The results of the shoot dry weight of plants can be seen in Fig. 4. The shoot dry weight of *L. chinensis* was significantly higher than that of *P. chinampoensis* (Fig. 4).The results of the levels of Na, K, Ca and Mg per shoot dry weight of each plant are shown in Figs. 5a, 5b, 5c and 5d. Sodium levels of the plants were much lower than those of the plants grown in the artificial soil. Potassium levels of *P. chinampoensis* were about 10 times lower than those grown in the artificial soil. There were no significant differences in the levels of Na, K, Ca and Mg between *L. chinensis* and *P. chinampoensis.*

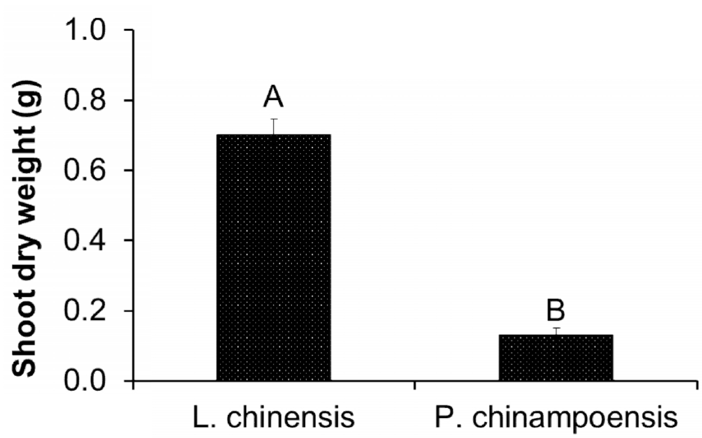

Fig. 4. Shoot dry weight of plants

Each value represents the mean ± SD (n = 3), Different letters at the top of each column indicate significant differences (p < 0.05) (F = 438.24, p< 0.001) according to the Ryan-Einot-Gabriel-Welsch multiple range test

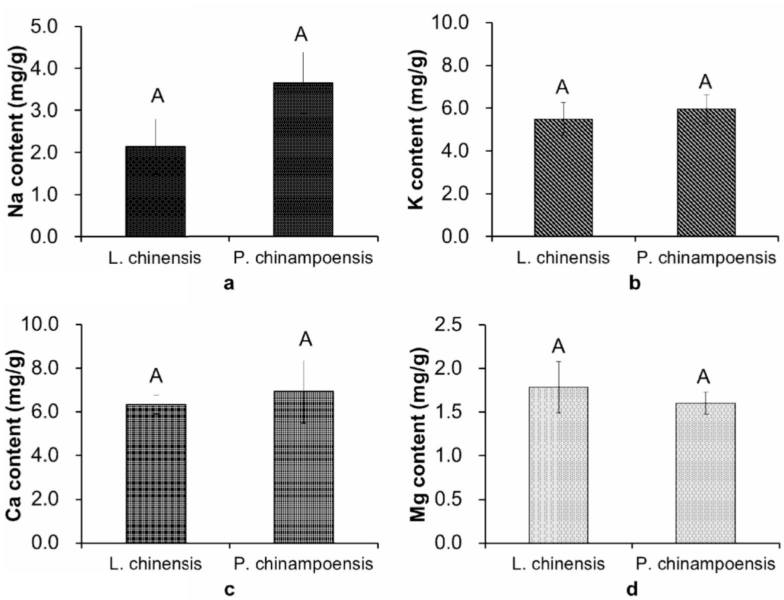

Fig. 5. Cation contents of plants (a) Na content (mg/g), (b) K content (mg/g), (c) Ca content (mg/g), and (d) Mg content (mg/g)

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) F = 7.17, (b) F = 0.59, (c) F = 0.51, (d) F = 0.99

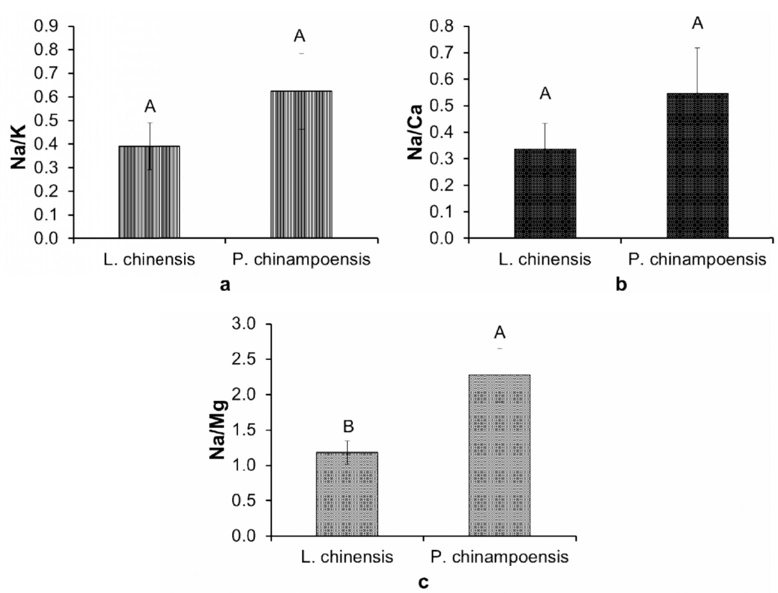

Fig. 6. Cation content ratio of plants (a) Na and K ratio, (b) Na and Ca ratio, and (c) Na and Mg ratio

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) F = 4.61, (b) F = 3.40, (c) F = 21.15, p< 0.01

The results of the cation levels ratio of plants are shown in Figs. 6a, 6b, and 6c. There were no significant differences in the values of Na/K and Na/Ca between *L. chinensis* and *P. chinampoensis.* The Na/K ratio of *P. chinampoensis* was 0.6 comparing with that grown on the artificial soil, 1.2 (Figs. 3a and 6a). *P. chinampoensis* showed significantly higher value of Na/Mg than that of *L. chinensis* (Fig. 6c).

4. DISCUSSION

In the experiment with sodic soil in growth chamber, *P. chinampoensis* only could germinate in the sodic soil though it did not grow well. There are some reports about the good germination ability of several plants in salt or sodic conditions [8,29,30], and *P. chinampoensis* may also have superior germination ability under sodic conditions which may be advantageous to its survival. Further investigation is needed to reach a conclusion.

Out of all the plants that grew in the artificial soil, *P. chinampoensis* and *F. arundinacea* showed a higher shoot dry weight compared with *D. glomerata* (Fig. 1), and *F. arundinacea* showed the highest shoot dry weight. It seemed that not only *P. chinampoensis* but also *F. arundinacea* had sodic tolerance and *F. arundinacea* may also be useful for revegetation of sodic soils. Further study is also required to investigate the usefulness of alkaline tolerant plants such as *F. arundinacea* for revegetation of sodic soil. In the artificial soil, the soil EC and exchangeable Na^+ levels were lowered though high soil pH was maintained even after the addition of vermiculite at pH higher than 10. Plant growth was improved by the addition of vermiculite. It was shown that plants grown in sodic soils suffer from both alkaline stress and salt stress [7,8,27,30,31]. This result indicated that excessive Na levels were more harmful than high soil pH for the growth of sodic tolerant plants. Thus, it is considered that reduction of exchangeable Na^+ and EC value could be an essential procedure for the revegetation of sodic soil. Liu et al. reported that the irrigation of sodic-saline soils in the Songnen Plain reduced the soil EC but soil pH maintained a high alkaline pH of around 10 [32,33]. Additionally, *Puccinellia tenuiflora* (*P. tenuiflora*), one of the sodic tolerant plants, and *L. chinensis,* showed better growth in the irrigated soil than those in the sodic-saline soils [32,33]. This report supports our indication of the importance of reducing the exchangeable Na^+ levels and the EC value for recovering vegetation of the sodic soil. In addition, exchangeable Ca^{2+} and Mg^{2+} levels in the artificial soil were also elevated as compared with those of the sodic soil. Therefore, the increase of exchangeable Ca^{2+} and Mg^{2+} in the sodic soil may be also effective in improving plant growth (Table 1 and Fig. 1).

P. chinampoensis showed the lowest Na level and highest K, Ca, and Mg levels in the shoot as compared with the other plants (Figs. 2a, 2b, 2c, and 2d). This result showed that *P. chinampoensis* had high selectivity of K^+, Ca^{2+}, Mg^{2+} over Na^+ in rhizosphere of sodic soils. Thus, this activity would be advantageous for *P. chinampoensis*to survive in sodic conditions. *P. chinampoensis* is widespread and forms communities in sodic soils in the Songnen Plain in spite the unlikeliness of *L. chinensis* to grow. Furthermore, *P. chinampoensis* showed the lowest values of cation levels ratio of Na/K, Na/Ca, and Na/Mg as compared with the other plants (Figs. 3a, 3b and 3c). These lower cation level ratios also indicated the high cations selectivity of *P. chinampoensis*. *F. arundinacea* also showed low Na level similar to *P. chinampoensis* (Fig. 2a), and this may be one of the reasons *F. arundinacea* had high shoot dry weight (Fig. 1) when grown in the artificial soil. However, *F. arundinacea* showed the lower uptake of K^+ and Ca^{2+}, which was a different tendency of those of *P. chinampoensis* (Figs. 2b and 2c). It is reported that *F. arundinacea* grows on calcareous soils in the area of Rocky mountains of North America [34], which contain a high amount of Ca and high pH values up to 8.5. This plant has tolerance to survive there [34], thus, the plant may have ability to repress the Ca^{2+} uptake. The plant was also reported to have high tolerance to environmental damage [34]. Therefore, *F. arundinacea* may have some functions to repress the Na^+ uptake but may not have similar selectivity of K^+ over Na^+ compared to *P. chinampoensis* (Figs. 2a, 2b and 3a).*D. glomerata*, one of the glycophytes, showed the lowest shoot dry weight (Fig. 1), therefore, *D. glomerata* did not have tolerance to sodic conditions. In fact, *D. glomerata* showed the highest Na level and lowest K level among the plants (Figs. 2a and 2b), and may not have similar selectivity of K^+ over Na^+ compared to *P. chinampoensis*. The highest Ca level of *D. glomerata* shoots may have resulted from the high amount of exchangeable Ca^{2+} in the soil (Table 1). There were no significant differences of Mg levels among the plants (Fig. 2d). *P. chinampoensis*, however, showed the lowest value of Na/Mg (Fig. 3c). Therefore, *P. chinampoensis* also had selectivity of Mg^{2+} over Na^+ similarly to those of K^+ and Ca^{2+}.

Growth of *L. chinensis* was faster than that of *P. chinampoensis*. The faster growth of *L. chinensis* would be advantageous to its survival in alkaline conditions. Presumably, this is one of the reasons why the dominant plant in the alkaline area was not *P. chinampoensis* but *L. chinensis* in the Songnen Plain [16,17,18].In the experimental field, the alkaline soil contained higher amounts of exchangeable Ca^{2+} and K^+ than those in the sodic soil (Table 2). The concentration of exchangeable K^+ in the alkaline soil was twice of that in the artificial soil. However, K level of shoots of *P. chinampoensis* grown in the alkaline soil was one-tenth of that grown on the artificial soil (Figs. 2b and 5b).It seemed that the K^+ selectivity over Na^+ in *P. chinampoensis* was not shown in the growth in the alkaline soil. The K^+ selectivity over Na^+ of the plant was shown specifically in the sodic soil. Additionally, the Na/K ratio of *P. chinampoensis* grown on the alkaline soil was 0.6 compared with that grown on the artificial soil, 1.2 (Figs. 3a and 6a). The Na/K ratio was less affected by the soil types than the other cation level ratios (Figs 3b, 3c, 6b, and 6c). Considering the large differences in Na levels of the plant depending on the soil types, the Na/K ratio was fairly constant. The Na/K ratio might be controlled to avoid the effect of the characteristics of soils. There may be some physiological mechanisms to maintain the Na/K ratios. Thus, it was indicated that *P. chinampoensis* was well adapted to the conditions of sodic soils, and *P. chinampoensis* can be the dominant plant only in sodic soils. Additionally, *L. chinensis* showed the significantly higher value of Na/Mg than that of *P. chinampoensis* in the alkaline soil (Fig. 6c). *L. chinensis* may have a little higher cation selectivity of Mg^{2+} over Na^+ than *P. chinampoensis* under alkaline conditions, and *L. chinensis* would be more suitable to the condition of pH 8.5 and a Ca rich environment. However,it was reported the plant cannot survive in pH 10 and Na rich conditions, the so-called sodic condition [16,17,18,19,20,21,22,23]. Therefore, metal macronutrients selectivity of *L. chinensis* may not function in sodic soils.

In order to survive on the sodic soil, tolerance for both salt and alkaline stress is essential [7,8,27,30,31]. It is indispensable to have the cations selectivity under a pH greater than 10 condition. *P. chinampoensis* did not show the superior cation selectivity in the alkaline soil of pH 8.5. The plant, however, showed the noticeable cation selectivity in the sodic soil pH was around 10. This result was surprising and provided meaningful information for revealing characteristics of plants grown in sodic soils. Besides, it is considered that *P. chinampoensis* would be useful for improving revegetation of sodic soils.

At present, there are several physiological and molecular studies about sodic tolerant mechanisms of sodic tolerant grasses. For example, it is known that *P. tenuiflora* and *Chlori svirgata*, which are sodic tolerant plants, can absorb K^+ preferentially to Na^+ [27,35,36]. It was also shown that *P. tenuiflora* had a plasma membrane localized Na^+/K^+ antiporter

(*PtSOS1*) which could function in preferential absorption of K^+ and exclusion of Na^+ (*PutHKT2;1*) [37,38]. *P. tenuiflora* was suggested the casparian bands of the endodermis as an apoplastic barrier and this barrier leads to higher levels of K^+ in the shoot and a large Na^+ gradient between the root and the shoot [39]. Furthermore, *P. tenuiflora* has some specific genes triggered in sodic conditions and the genes related to H^+ transport and citric acid synthesis [40]. *P. chinampoensis* may also have some physiological and molecular features similarly to *P. tenuiflora*. It was investigated, however, that there were some different physiological characteristics between *P. chinampoensis* and *P. tenuiflora* [23]. Thus, further work is required for revealing the mechanisms of *P. chinampoensis* for adaptation to sodic conditions.

Under the high alkaline condition with pH around 10, metal micronutrients such as Fe, Cu, Mn, Zn and other cations are precipitated. Therefore, absorption of the metals by plants may be repressed. Especially, Fe is precipitated as $Fe(OH)_3$ in alkaline soils, and the total concentration of inorganic Fe species in the soil solution is around 10^{-10} mol/L [5]. Therefore, Fe deficiency is one of the inhibitory factors in plant growth on alkaline soils [41]. Therefore, Fe acquisition ability is also important in the rhizosphere of sodic soils. There are possibilities that sodic tolerant plants such as *P. chinampoensis* have superior mechanisms to acquire metal micronutrients. Further researches about the comprehensive nutrient uptake mechanisms not only metal macronutrients but also metal micronutrients and organic nutrients of sodic tolerant plants is needed in the future.

5. CONCLUSION

The uptake of metal macronutrients (K^+, Ca^{2+}, Mg^{2+}) and Na^+ of *P. chinampoensis*, one of the sodic tolerant plants, were examined in the rhizosphere of sodic soil. *P. chinampoensis* showed higher shoot levels of K, Ca, Mg and lower Na than those of *F. arundinacea* and *D. glomerata* when grown on the sodic soil mixed with vermiculite. Thus, data indicated that *P. Chinampoensis* had high selectivity of K^+, Ca^{2+} and Mg^{2+} over Na^+ in the rhizosphere of sodic soil. This ability would be advantageous to survive on the sodic soil. *P. chinampoensis,* however, did not show superior cations uptake ability in alkaline soil in the Songnen Plain in northeast China as compared with *L. chinensis.* The K level of *P. chinampoensis* grown in the alkaline soil was one-tenth of that of the sodic soil mixed with vermiculite, though the amount of exchangeable K^+ of alkaline soil was higher than that of the sodic soil mixed with vermiculite. Thus, the superior cation uptake ability of *P. chinampoensis* may be shown only in sodic soils and the plant is well adapted to survive on there.

In the growth on the sodic soil mixed with vermiculite, *P. chinampoensis* and the other plants showed better growth than those in the original sodic soil. By the mixing vermiculite to sodic soil, soil pH was higher than 10, similar to sodic soil. However, the soil CEC increased, and the soil EC and ESP decreased. Thus, it seemed that high soil EC and high exchangeable Na^+ were more harmful than high soil pH around 10 for the growth of the plants in sodic soils.

Preventing land from degradation by soil sodification is an important global issue for food production in the 21st century. Therefore, clarification of the properties of plants growing in sodic soils and utilization of the plants to recover vegetation of soils is essential. Thus, further work is required to investigate the mechanism of the sodic tolerant plants such as *P. chinampoensis* in the future.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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