Original Research Article

The highmetal macronutrients selectivityover $Na^+$of *Puccinelliachinampoensis*Ohwiin the rhizosphere of sodicsoil

ABSTRACT

The uptake of metal macronutrients (K^+, Ca^{2+}, Mg^{2+}) and Na^+ of *Puccinelliachinampoensis*Ohwi (*P. chinampoensis*), asodictolerant plant, were investigated in both sodic and alkaline soil. In the first experiment, sodicsoil was collected from Songnen Plain in Jilin Province in northeast China.*P. chinampoensis*, *Festucaarundinacea*Schreb. (*F. arundinacea*) and *Dactylisglomerata* L.(*D. glomerata*) were grown in the sodicsoil in growth chamber under natural light, but the plants did not grow.Then, the plants were grown insodic 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 content than the other plants and maintained low Na content 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, andthe soil electrical conductivity (soil EC) and exchangeable sodium percentage (ESP) were lower than the original sodic soil.In the second experiment,*P. chinampoensis* and *Leymuschinensis*[Trin.] Tzvelev(*L. chinensis*)were grown on natural alkaline areain the Songnen Plain.There were no significant differences of the Na, K, Ca, and Mgcontent in the both plants. Especially, though the concentration of exchangeable $K^+$was more than double, K content 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 andexchangeable Na^+ were more harmful than high soil pH for plant growth on sodic soils.

*Key words:sodic soil; alkaline soil; Songnen Plain; northeast China; Puccinelliachinampoensis*Ohwi*;sodium; potassium; soil EC*

1. INTRODUCTION

Desertification areacaused by accumulated salts is gradually spreading in arid or semi-arid areas in the world[1]. In cultivated landsofthe world, about 23% are salineand 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 dosaline 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 $Mg^{2+}$is extremely low[12]. Thus, the plants grown insodic 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, theincrease of sodic soil areas has beenaserious problemsince 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 ofsodic soil areas, *Leymuschinensis*[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 sodificationwith 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 *Puccinelliachinampoensis*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 withthe project for the utilization of the *P.chinampoensis*torecovervegetation 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 aboutsodic tolerant plants such as *Puccinelliatenuiflora* or *Chlorisvirgate* [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 characteristicsof nutrient uptake.

Further study about the characteristics of nutrient uptake insodic tolerant plants such as *P.chinampoensis*and a demonstration of the usefulness of these plantscouldmake meaningful contributions to improvement of the revegetation of sodic soil. Therefore, the focus ofthis 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 innutrient uptaketo 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 assodic 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 uptakeof *P.chinampoensis* grown insodic soils and to show the usefulness of the plant for improving revegetationinsodicsoil.

2. MATERIAL AND METHODS

2.1 Cultivation of *P. chinampoensis* in sodic soil in growth chamber under control conditions

Sodicsurface soil of 10 kgwas 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 severalgrasses present, such as *P. chinampoensis* and *Chlorisvirgate*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 sunlightconditions with the adjusted temperature (12 h daytime at +25℃ and 12 h nightti me at +15℃) from December in 2009 to January in 2010. Each pot (200 ml) was prepared containing 200 g of the sodicsoil or 200 g of the sodic soilmixedwith vermiculite(v/v, 1: 1).Vermiculilte was purchased from MiyakoCalcine 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 methodsas 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*, *Festucaarundinacea*Schreb. (*F. arundinacea*; Tall fescue), or *Dactylisglomerata* L. (*D. glomerata*; Orchard grass) were sownin6 pots, three pots contained the collected sodic soil and the other 3 pots contained artificial soil. The same weight of each seed was sowninto 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 +80℃ 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 weremeasured by the flame atomic absorption spectrometry (AA-6200, Shimadzu, Kyoto).

2.2Cultivation of *P. chinampoensis*on alkaline soil in Songnen Plain

This experiment was conducted from middle June to middle August in 2012 on alkaline soil in the experimental field, which did not suffer from sodification, of Jilin Agricultural Universityin the Songnen Plain. The area isunder the continental monsoon climate, and seasonal temperatures vary from −34℃ to +37℃. From middle April to early June, th ere 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 sitewas prepared,and the surface soil samplein 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℃ to a constant weight. Three samples (f ive 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).

2.3Statistical 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 chamberunder control conditions

The soil pH of sodic soil or artificial soil washigher than 10 (Table 1). The soil EC and ESP of artificial soil containing vermiculitewas lower than those of sodic soil. The soil CEC of artificial soil was higher than that ofsodic 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 higherthan 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, boththe sodic soil obtained from Dàān, Jilin prov., China and the artificial soil were sodic soils (Table 1) [4].

In the pots containingsodic 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(Figure 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 Figures 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 levelamong 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.

The results of the cation levels ratio of the plants are shown in Figures 3a, 3b, and 3c.*P. chinampoensis*showed thelowest 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.

Table 1. **Chemical properties ofsodic and artificial soil**

EC: electrical conductivity, CEC: cation exchange capacity, ESP: exchangeable sodium percentage.

Data are shown as mean ±standard error (SE).

	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

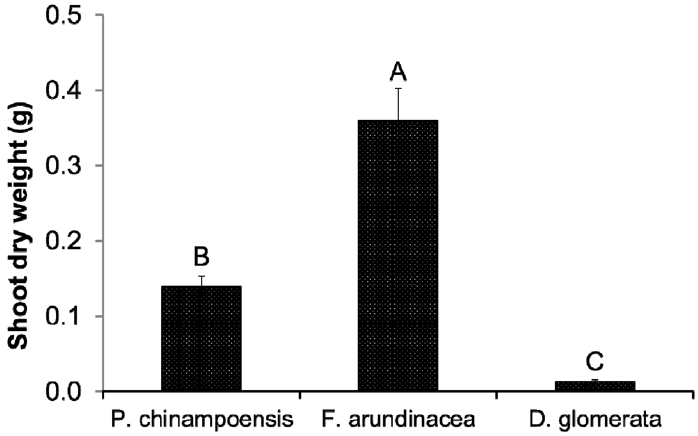

Fig. 1.Shoot dry weight of plants

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.

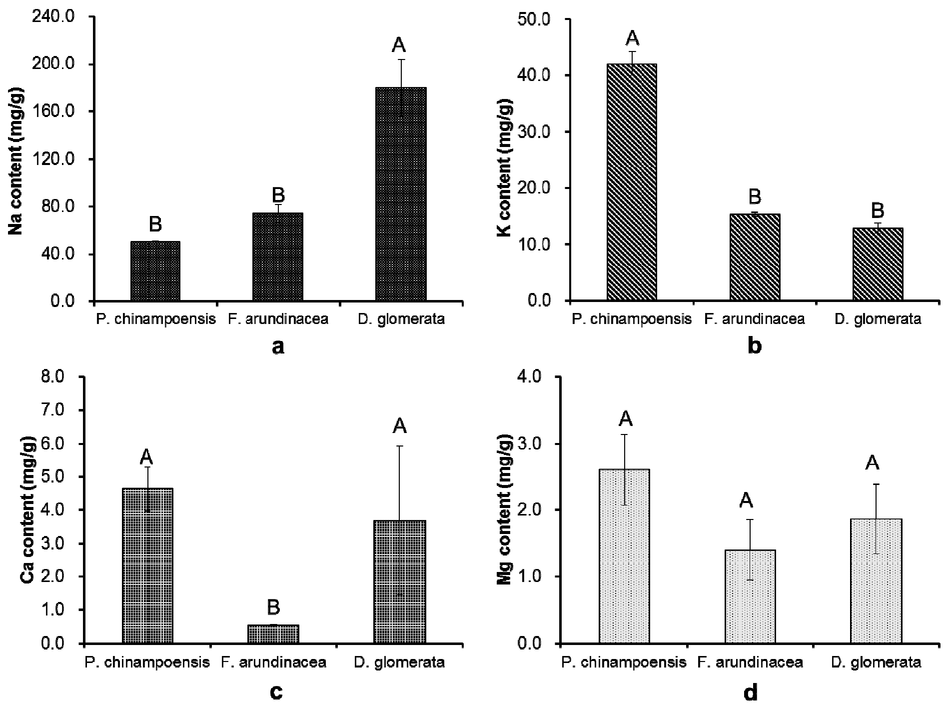

Fig.2.Cation contents of plants (a) Na content (mg/g), (b) K content (mg/g), (c)Ca content (mg/g), and (d) Mg content (mg/g)

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.

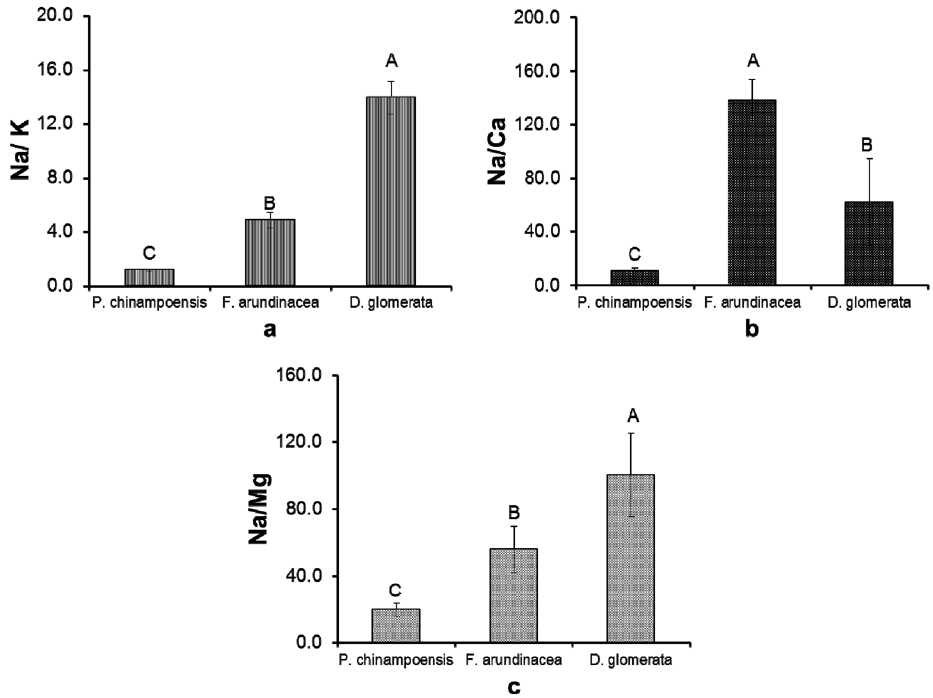

Fig.3.Cation content ratio of plants (a) Naand K ratio, (b) Na and Ca ratio, and (c)Na and Mg ratio

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.

3.2Cultivation 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 valuewas 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 wasmore than ten times higher thanthat of sodic soil. The amount of exchangeable $Na^{+}$was muchlower than that of the sodic soil. The exchangeableK^{+} and Mg^{2+} were more than double than those of the sodic soil. Thus, it seemed that this soil was rich in Ca andhad the characteristics offertile soil such as chernozem(Table 2) [28].

The results of the shoot dry weight of plants can be seen in Figure 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 Figures 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.*

The results of the cation levels ratio of plants are shown in Figures 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).

Table 2. **Chemical properties of the soil in experiment field**

EC: electrical conductivity, CEC: cation exchange capacity, ESP: exchangeable sodium percentage.

Data are shown as mean ± standard error (SE).

	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

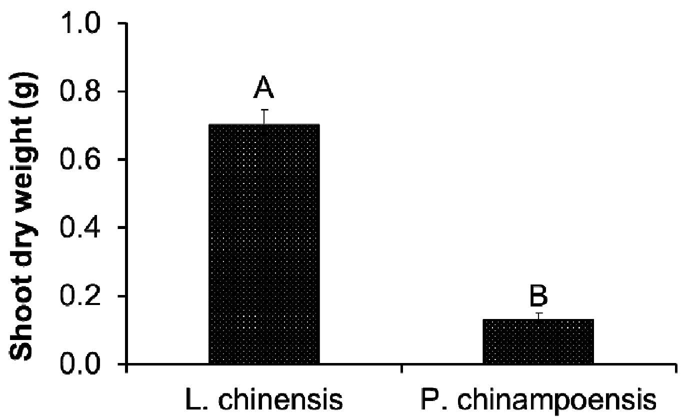

Fig. 4.Shoot dry weight of plants

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.

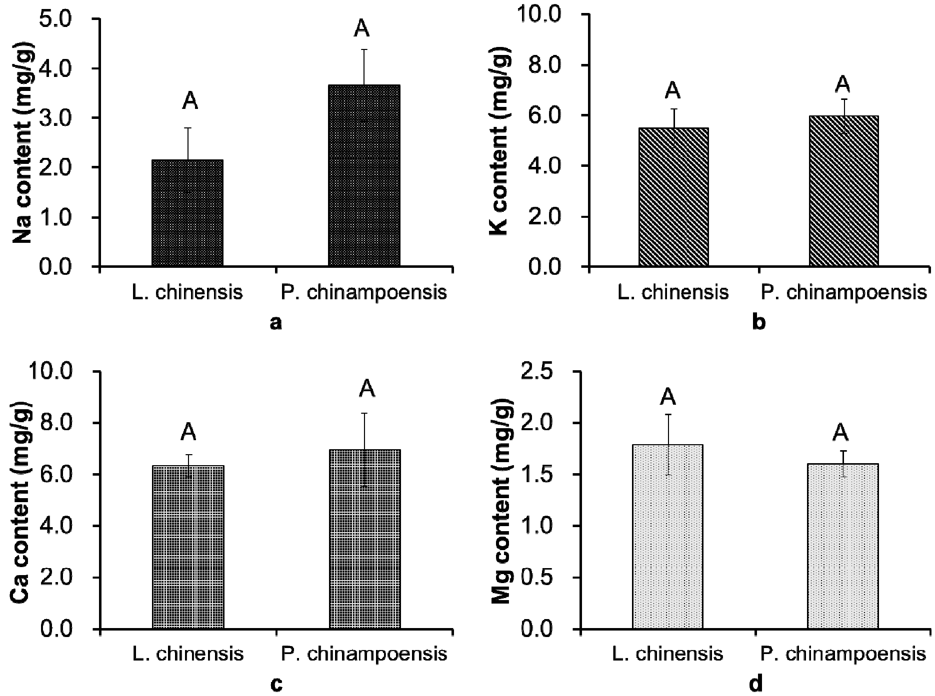

Fig.5.Cation contents of plants (a) Na content (mg/g), (b) K content (mg/g), (c)Ca content (mg/g), and (d) Mg content (mg/g)

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.

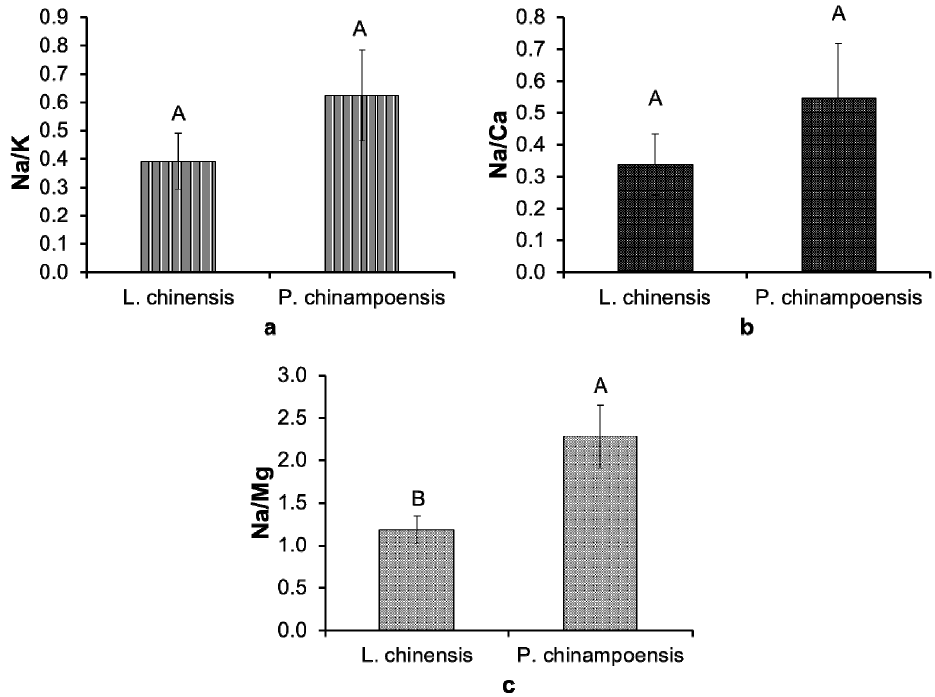

Fig.6.Cation content ratio of plants (a) Naand K ratio, (b) Na and Ca ratio, and (c)Na and Mg ratio

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.

4. DISCUSSIONS

In the experiment withsodic 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 germinationabilityof several plantsin salt or sodic conditions [8, 29, 30], and *P. chinampoensis*may also have superiorgermination ability undersodic conditions which may be advantageous to its survival.Further investigation is needed to reach a conclusion.

Out of all the plants thatgrew 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*hadsodictolerance and *F. arundinacea* may also be useful for revegetation of sodic soils. Further studyis 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 loweredthoughhigh 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 thatplants grown in sodic soils sufferfromboth 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 ofexchangeable $Na^+$and EC value could bean essentialprocedure for therevegetation ofsodicsoil.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, *Puccinelliatenuiflora* (*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 was also elevated as compared with those of the sodic soil.Therefore, the increase of exchangeable Ca^{2+} and Mg^{2+} in the sodicsoil may be also effective in improving plant growth (Table 1 and Figure 1).

P. chinampoensis showed the lowest Na level and highest K, Ca, and Mg levelsin 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 insodic conditions. *P. chinampoensis* is widespread and forms communities in sodic soilsin 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 withthe other plants (Figs 3a, 3b and 3c). These lower cationlevel ratios also indicated the high cations selectivity of *P. chinampoensis*.*F. arundinacea*also showed low Na levelsimilar 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 wasa different tendency of those of *P. chinampoensis* (Figs 2b and 2c). It is reportedthat*F. arundinacea* grows on calcareous soils in the area of Rockymountains of North America [34], which contain a high amount of Ca and high pH values up to 8.5.This plant has tolerance to survivethere [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* mayhave somefunctions 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*didnot have tolerance tosodic 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 levelof *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*. Thefaster growth of *L. chinensis*would be advantageousto its survivalin alkaline conditions. Presumably, this is one of the reasonswhy the dominantplant in the alkaline area was not *P. chinampoensis* but *L. chinensis* in the Songnen Plain [16, 17, 18].In the experimental field, thealkalinesoil contained higher amounts of exchangeable Ca^{2+} andK^+ 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 soilwas 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 anda 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 10condition. *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 onsodic soils. Besides, it is considered that *P. chinampoensis*would be useful for improving revegetation of sodic soils.

At present, there are severalphysiological and molecular studies about sodictolerant mechanisms of sodic tolerant grasses. For example, it is known that *P. tenuiflora*and *Chlorisvirgata*, which aresodictolerant plants, can absorb K^+preferentially to Na^+[27, 35, 36]. It was also shown that *P.tenuiflora*hada 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 alsohave 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 adaptationtosodicconditions.

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^{-1}[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 uptakemechanisms not only metal macronutrients but also metal micronutrients and organic nutrients of sodic tolerant plantsis needed in the future.

5 CONCLUSIONS

The uptake of metal macronutrients (K^+, Ca^{2+}, Mg^{2+}) and Na^+ of *Puccinelliachinampoensis*Ohwi, one of the sodic tolerant plants,were examinedin the rhizosphere of sodic soil. *Puccinelliachinampoensis*Ohwishowed higher shoot levels of K, Ca, Mg and lower Na than those of*Festucaarundinacea*Schreb.and*Dactylisglomerata* L.when grown on the sodic soil mixed with vermiculite. Thus, data indicated that*Puccinelliachinampoensis*Ohwihad 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.*Puccinelliachinampoensis*Ohwi, however,did not show superiorcationsuptake ability in alkaline soil in the Songnen Plain in northeast China as compared with *Leymuschinensis.*The K level of *P. chinampoensis* grown in the alkaline soil was one-tenth of that of the sodic soil mixed with vermiculite, thoughthe amount of exchangeable $K^+$of alkaline soil was higher than that of the sodic soil mixedwith 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, *Puccinelliachinampoensis*Ohwiand 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 sodicsoil. However, the soil CEC increased, and the soil EC and ESP decreased. Thus, it seemed that high soil EC and high exchangeable Na^+weremore 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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Authors' Contributions

This work was carried out in collaboration among the all authors. Author T. Yoshida and S. Kawai designed the study, wrote the protocol, performed the statistical analysis and wrote the first draft of the manuscript. Author L. Zhao and H.B. Wang actively involved when the field experiment was conducted inChina and managed the literature searches. Author A. Sato, A.K. Xu, M.Q. Zhao, B.L. Xi and X.M. Guo gave the seeds of *Puccinelliachinampoensis*Ohwiand much essential information about the sodic soil in Songnen Plain in northeast China. All authors read and approved the final manuscript.

REFERENCES

1. Dregne HE. Desertification of arid lands. London: Harwood Academic Publishers; 1983. ISBN 3-7186-0168-0.
2. Tanji KK. Salinity in the soil environment. In:Läuchli A, Lüttge U, editors. Salinity: environment-plants-molecules.Dordrecht: Kluwer Academic Publishers; 2002. ISBN: 978-1-4020-0492-6.
3. Yang CW, Jianaer A, Li CY, Shi DC, Wang DL. Comparison of the effects of salt-stress and alkali-stress on photosynthesis and energy storage of an alkali-resistant halophyte *Chlorisvirgate*. Photosynthetica. 2008;46(2):273-278.
4. Bear FE. Chemistry of the soil. 2nd ed. New York: Reinhold Publishing Corporation; 1964. ISSN 0065-7751.
5. Marschner H. Mineral nutrition of higher plants. 2nd ed. London: Academic Press; 1995. ISBN-13: 978-0-12-473543-9.
6. Peng YL, Gao ZW, Gao Y, Liu GF, Sheng LX, Wang DL. Eco-physiological characteristics of alfalfa seedlings in response to various mixed salt-alkaline stresses. J Integr Plant Biol. 2008;50(1):29-39.
7. Yang CW, Xu HH, Wang LL, Liu J, Shi DC, Wang DL. Comparative effects of salt-stress and alkali-stress on the growth photosynthesis, solute accumulation, and ion balance of barley plants. Photosynthetica. 2009;47(1):79-86.
8. Liu J, Guo WQ, Shi DC. Seed germination, seedling survival, and physiological response of sunflowers under saline and alkaline conditions. Photosynthetica. 2010;48(2):278-286.
9. Flowers TJ, Troke PF, Yeo AR. The mechanism of salt tolerance in halophytes. Plant Physiol. 1977;28:89-121.
10. Orcutt DM, Nilsen ET. Physiology of plants under stress. New York: John Wiley and Sons; 2000. ISBN 0-471-03152-6.
11. Tuna AL, Kaya C, Ashraf M, Altunlu H, Yokas I, Yagmur B. The effects of calcium sulphate on growth, membrane stability and nutrient uptake of tomato plants grown under salt stress. Environ Exp Bot. 2007;59:173-178.
12. Yamamoto T. Soil degradation and its rehabilitation in arid region. Tokyo: Kokonshoin; 2008. ISBN 978-4-7722-3107-7 C3040. Japanese.
13. Bian J, Tang J, Lin N. Relationship between saline-alkali soil formation and neotectonic movement in Songnen Plain, China. Environ Geol. 2008;55:1421-1429.
14. Liu SH, Kang YH, Wan SQ, Jiang SF, Zhang TB. Effect of different cultivation methods on germination and growth of *Puccinelliatenuiflora.*Int J Plant Prod. 2012;6(3):353-366.
15. Wang L, Seki K, Miyazawa T. The causes of soil alkalinization in Songnen Plain of Northeast China. Paddy Water Environ. 2009;7:259-270.
16. Wang R, Ripley EA. Effects of grazing on a *Leymuschinensis* grassland on the Songnen Plain of north-east China. J Arid Environ. 1997;36:307-318.
17. Wang R, Rispley EA, Zu Y, Nie S. Demography of reproductive and biomass allocation of grassland and dune *Leymuschinensis* on the Songnen Plain, north-east China. J Arid Environ. 2001;49:289-299.
18. Wang R, Gao Q, Chen Q. Effects of climatic change on biomass and biomass allocation in*Leymuschinensis* (*Poaceae*) along the North-east China Transect (NECT). J Arid Environ. 2003;54:653-665.
19. Kawanabe S, Zhu TC. Degeneration and conservational trial of *Aneurolepideumchinense* grassland in Northern China. J Japan Grassl Sci. 1991;37(1):91-99.
20. Ni J. Plant functional types and climate along a precipitation gradient in temperate grasslands, north-east China and south-east Mongolia. J Arid Environ. 2003;53:501-516.
21. Jiang SC, He NP, Wu L, Zhou DW. Vegetation restoration of secondary bare saline-alkali patches in the Songnen Plain, China. Appl Veg Sci. 2010;13:47-55.

22. Wang Y, Wang Z, Han Z, Liang Z, Yang F, An F. Enzyme activities of saline-sodic soils under different vegetation types in the Songnen Plain, Northeast China. J Food Agr Environ;2013:11(3&4):1982-1985.
23. Wang RZ, Yuan YQ. Photosynthesis, transpiration, and water use efficiency of two *Puccinellia* species on the Songnen grassland, northeastern China. Photosynthetica;2001:39(2):283-287.
24. Zhao MQ, Lin QB, Chen GG, Kai XA, Chun ZY. Effect of different stage of Nitrogen application on seed and herbage yield of*Puccinelliachinampoensis*Ohwi. Agr Tech;2007:27(3):59-61.Chinese with english summary.
25. Yang CW, Zhang ML, Liu J, Shi DC, Wang DL. Effects of buffer capacity on growth, photosynthesis, and solute accumulation of glycophyte (wheat) and a halophyte (*Chlorisvirgate*). Photosynthetica. 2009;47(1):55-60.
26. Kamewada K. Soil exchange capacity (semi-micro schollenberger method). In: Editorial committee of methods of analysis, editor. Methods of soil environmental analysis. Tokyo: Hakuyusha; 1997. ISBN: 4-8268-0168-8. Japanese.
27. SAS Institute 2011. SAS/STAT 9.3 User's Guide. North Carolina:Cary; 2011.
28. Food and Agriculture Organization of the United Nations. World reference base for soil resources 2014 international soil classification system for naming soils and creating legands for soil maps. Rome: Food and agriculture organization of the United Nations; 2014. ISBN 978-92-5-108369-7.
29. Shen YY, Li Y, Yan SG. Effects of salinity on germination of six salt-tolerant forage species and their recovery from saline conditions.New Zeal J Agr Res. 2003;46:263-269.
30. Guo R, Shi L, Yang Y. Germination, growth, osmotic adjustment and ion balance of wheat in response to saline and alkaline stresses. SoilSciPlantNutr. 2009;55:667-679.
31. Yu J, Chen S, Wang T, Sun G, Dai S. Comparative proteomic analysis of *Puccinelliatenuiflora* leaves under Na_2CO_3 stress. Int. J. Mol. Sci. 2013;14:1740-1762.
32. Liu S, Kang Y, Wan S, Wang Z, Liang Z, Sun X. Water and salt regulation and its effect on *Leymuschinensis* growth under drip irrigation in saline-sodic soils of the Songnen Plain. Agr. Water Manag. 2011;98: 1469-1476.
33. Liu S, Kang Y, Wang Z, Liang Z, Jiang S, Wang R. Germination and growth of *Puccinelliatenuiflora* in saline-sodic soil under drip irrigation. 2012;109: 127-134.
34. Barnes RF, Miller DA, Nelson CJ. Forage volume 1 an introduction to grassland agriculture. 5th ed. Iowa: Iowa state university press; 1995. ISBN 1-800-862-6657.
35. Wang S, Zhao G, Gao Y, Tang Z, Zhang C. *Puccinelliatenuiflora* exhibits stronger selectivity for K^+ over Na^+ than wheat. J Plant Nutr. 2004;27(10):1841-1857.
36. Wang CM, Zhang JL, Liu XS, Li Z, Wu GQ, Cai JY, Flowers TJ, Wang SM. *Puccinelliatenuiflora* maintains a low Na^+ influx resulting in a high selectivity for K^+ over Na^+. Plant Cell Environ. 2009;32:486-496.
37. Guo Q, Wang P, Zhang JL, Bao AK, Wang SM. Selective transport capacity for K^+ over Na^+ is linked to the expression levels of *PtSOS1* in halophyte *Puccinelliatenuiflora*. Funct Plant Biol. 2012;39:1047-1057.
38. Ardie SW, Xie L, Takahashi R, Liu S, Takano T. Cloning of a high-affinity K^+ transporter gene *PutHKT2;1* from *Puccinelliatenuiflora* and its functional comparison with *OsHKT2;1* from rice in yeast and *Arabidopsis*. J. Exp. Bot. 2009;60(12):3491-3502.
39. Peng YH, Zhu YF, Mao YQ, Wang SM, Su WA, Tang ZC. Alkali grass resists salt stress through high [K^+] and an endodermis barrier to Na^+. J. Exp. Bot. 2004;55(398):939-949.
40. Zhang X, Wei L, Wang Z, Wang T. Physiological and molecular features of *Puccinelliatenuiflora* tolerating salt and alkaline-salt stress. J.Integr. Plant Biol. 2013;55(3): 262-276.
41. Abadía J, Vázquez S, Rellán-Álvarez R, El-Jendoubi H, Abadía A, Álverez-Fernández A, López-Millán AF. Towards a knowledge-based correction of iron chlorosis. Plant Physiol. Biochem. 2011;49:471-482.