Comparison of Young Seedling Growth and Sodium Distribution among *Sorghum* Plants under Salt Stress

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Abstract: Young seedlings of 22 *Sorghum* cultivars including sorghum, sudangrass and sorghum-sudangrass hybrids, were examined for their growth characteristics and sodium ion accumulation in different plant parts, under salt treatment. The salt treatment was started with 100 mM NaCl and increased to 150 mM during the experiment. The plant dry weight decreased under NaCl treatment in all cultivars, and especially the dry weight of leaf blade decreased markedly. The cultivar difference in the plant dry weight under salt stress was affected by that in relative growth rate which was mainly changed by net assimilation rate (NAR). Cultivars that maintained higher NAR under salt stress had a smaller specific leaf area and higher nitrogen content per unit leaf area. *Sorghum* plants under salt stress retained Na⁺ mainly in roots preventing the distribution of excess amount of Na⁺ to leaves, but the root dry weight was increased by salt stress. It was therefore considered that thicker leaf blades and apparent increases in root dry weight were the main contributors to the maintenance of dry matter yield and enhanced the growth of *Sorghum* cultivars under NaCl treatment.

Key words: Growth analysis, NaCl treatment, Net assimilation rate, Nutrient concentration, Salt resistance, Sodium accumulation.

Soil salinity is an important constraint to plant growth, and is a limiting factor to crop production in arid and semi-arid regions around the world (Munns, 2002). Globally, a total land area of 831 million hectares is salt-affected (Asfaw, 2011). The yield of essential food and forage crops is limited by soil salinity in many regions of the world’s land area, so genetic improvements to salt tolerance are essential to sustain global food production (Munns, 2010). Crop genotypes with increased salt tolerance are needed for stable cultivation, but the attempts to improve crop salt tolerance by conventional breeding programmes have been met with limited success. To achieve this goal by breeding and to select the desired traits in different genetic backgrounds, understanding of the complexities of the physiological and genetic mechanisms of salt tolerance is necessary (Munns et al., 2006).

Salt tolerance can be assessed in terms of yield, plant height, relative growth rate (RGR), and so on (Ashraf and Harris, 2004). It is usually assessed as the percentage of biomass production in saline versus control conditions (Munns, 2002). RGR has been considered to be a more suitable parameter for the comparison of growth among species or genotypes than absolute growth rate (Cramer et al., 1994) which was found in Gramineae plants in other studies such as wheat (El-Hendawy et al., 2005), maize (Azevedo Neto et al., 2004), and sorghum (Lacerda et al., 2005). Changes in RGR under salt stress could be attributed to enhanced or reduced salt effects on the net assimilation rate (NAR) (physiological response) and/or leaf area ratio (LAR) (morphological response) depending on the variation of plant genotypes (Ishikawa et al., 1991; Bayuelo-Jiménez et al., 2003). Therefore, it would be possible to select salt tolerant plants based on these growth parameters.

The effect of salinity on plant growth varies with the plant genotype, ion toxicity, and growth environment. Plant growth responds to soil salinity in two contrasting phases (Läuchli and Grattan, 2007; Munns and Tester, 2008): First, in the rapid growth phase, which responds to the osmotic effect of salt, and secondly, in the slower growth phase, which responds to salt toxicity in the leaves. However, among all the effects of salinity, accumulation of Na⁺ is the major cause of toxicity ion accumulation and damage in many cereal crops (Tester and Davenport, 2003).

*Sorghum* is a grain and fodder crop, that is moderately tolerant to salinity (Almodares and Sharif, 2007;
There are several types of *Sorghum* plants such as grain sorghum, forage or sweet sorghum, sudangrass, and sorghum-sudangrass hybrids (Iptas and Brohi, 2003), and they have been extensively used for forage production in salt-affected areas (Hedges et al., 1989; Begdullayeva et al., 2007; Khanum et al., 2010). The tolerance to high saline concentrations in *Sorghum* seems to vary with the genotype, and some studies revealed large genotypic differences in the tolerance to salinity of *Sorghum* (Maiti et al., 1994; Krishnamurthy et al., 2007). Several research studies have shown that salinity reduces the root and shoot growth of *Sorghum* seedlings (Lacerda et al., 2003; Netondo et al., 2004; Shariat Jafari et al., 2009). Salt tolerance of *Sorghum* plants have also been associated with Na\(^+\) concentrations in various plant tissues (Munns, 2002; Netondo et al., 2004).

Yet, little is known about the differences in seedling growth characteristics with the *Sorghum* genotype under salinity. It is therefore necessary to investigate the salt tolerance of the seedlings of various *Sorghum* types, such as grain sorghum, sweet sorghum, sudangrass, and sorghum-sudangrass hybrids and also to investigate ion toxicity, mainly, Na\(^+\) accumulation in *Sorghum* plant tissues. In this study, we cultivated 22 *Sorghum* cultivars by hydroponics with and without NaCl salinity to determine the plant growth, relative growth rate, and dry matter production and also to clarify the Na\(^+\) distribution in different plant parts. The relationships among these responses were also examined for a more clear understanding.

**Materials and Methods**

1. **Plant materials and NaCl treatment**

Twenty-two cultivars of *Sorghum* plants were used: 15 cultivars of sorghum-sudangrass hybrids, three of sweet sorghum, two grain sorghum (*Sorghum bicolor* (L.) Moench), and two sudangrass (*Sorghum sudanense* Stapf) which are shown in Table 1. The experiment was conducted in a greenhouse under natural light conditions at the Graduate School of Bioresources, Mie University, Japan, in June and July of 2010. The mean day and night temperatures during the experiment were 31°C and 23°C, respectively. Seeds were germinated on the surface of tap water in the plastic pots. Six days after germination (6 DAG), the seedlings at the second leaf age were transplanted into a hole in a styrene board placed on a 220L plastic container filled with a 100% strength of Kimura A culture solution containing (µM) 182 (NH\(_4\))\(_2\)SO\(_4\), 283 K\(_2\)SO\(_4\), 365 MgSO\(_4\), 548 KNO\(_3\), 182

| Number | Name of cultivar | *Sorghum* type*\(^1\)* |
|--------|------------------|-------------------------|
| 1      | Fain sorugo      | Sorghum-sudangrass hybrid (HB1) |
| 2      | Sudakkusu futushu | Sorghum-sudangrass hybrid (HB2) |
| 3      | Sudakkusu 316    | Sorghum-sudangrass hybrid (HB3) |
| 4      | Sudakkusu ryokuhiyou | Sorghum-sudangrass hybrid (HB4) |
| 5      | Genki sorugo     | Sorghum-sudangrass hybrid (HB5) |
| 6      | Kumiai sorghum nyu 2 gou | Sorghum-sudangrass hybrid (HB6) |
| 7      | Brown tohumitsu  | Sorghum-sudangrass hybrid (HB7) |
| 8      | Lucky sorugo     | Sorghum-sudangrass hybrid (HB8) |
| 9      | Lucky sorugo 2   | Sorghum-sudangrass hybrid (HB9) |
| 10     | King sorugo      | Sorghum-sudangrass hybrid (HB10) |
| 11     | Ryokuhiyou sorugo | Sorghum-sudangrass hybrid (HB11) |
| 12     | Wind brake       | Sorghum-sudangrass hybrid (HB12) |
| 13     | BMR sweet (sito) | Sorghum-sudangrass hybrid (HB13) |
| 14     | Green sorugo     | Sorghum-sudangrass hybrid (HB14) |
| 15     | Tsuki tarou      | Sorghum-sudangrass hybrid (HB15) |
| 16     | Kannni sorghum   | Sweet sorghum (SS16) |
| 17     | Supersugar sorghum | Sweet sorghum (SS17) |
| 18     | Koutoubun sorghum | Sweet sorghum (SS18) |
| 19     | Haiguren sorghum | Grain sorghum (GS19) |
| 20     | Mini sorghum     | Grain sorghum (GS20) |
| 21     | Summer bale hosokuki | Sudangrass (SU21) |
| 22     | Oishii sudan     | Sudangrass (SU22) |

*\(^1\)* HB: sorghum-sudangrass hybrid, SS: sweet sorghum, GS: grain sorghum, SU: sudangrass.
KH₂PO₄, 182 Ca(NO₃)₂, and 14 FeO₃ (Baba and Takahashi, 1958). At 13 DAG (fourth leaf age) salt treatment was started with 100 mM NaCl and at 21 DAG, the concentration of NaCl was increased to 150 mM, and the culture solution strength was adjusted to 150% nutrient strength that is suitable and beneficial for growth. Then the plants were grown there until the end of the experiment (29 DAG). For the control group, the nutrient solution without NaCl was used. During the experiment, an air pump was used to supply enough air into the culture solution in both the control group and the treated plots. The culture solution was adjusted daily to pH6.5, using 1N H₂SO₄ or 1N KOH, and renewed every 3 days.

2. Measurement of plant growth and growth analysis

The plants were sampled two times: at 13 (before treatment), and 29 DAG. In each sampling, ten replicated plants for each cultivar in both the control and treatment groups were taken and carefully rinsed with distilled water. The plant samples were divided into three parts: leaf blade, stem (including the leaf sheath), and root. The leaf area was measured by using an automatic area meter (Hayashi Denko AAM-9, Japan). Dry weight was obtained after drying at 70°C for 72hr. Growth analysis was conducted according to Kevet et al. (1971) to determine RGR, NAR, LAR, and specific leaf area (SLA) at 13 and 29 DAG.

3. Nitrogen and ion concentrations in different plant parts

The dried samples ground into a powder were reduced to ash in a furnace (Yamato FO300, Japan), and then extracted with 1N HNO₃. In this extract, Na⁺ concentration in each plant part was determined using ion chromatography with a conductivity detector (Shimadzu CDD-6A, IC-C3, Japan). The amount of total nitrogen (N) was also analyzed by the semi-micro Kjeldahl method.

4. Statistical analysis

A statistical analysis was performed using Student’s t-test: paired samples as means for all measurements. For the correlation among plant growth parameters, and Na⁺ concentration, the correlation coefficients were determined for all pairs.

Results

1. Plant growth

Fig. 1 shows the dry weight of *Sorghum* plants, both in control and treated groups at the end of the experiment (29 DAG). Salt stress significantly reduced the dry weight of plants in all cultivars (*P* < 0.01). Fig. 2 shows the relative value of the dry weight, which was calculated from the percentage of dry weight of the treated plants versus that of control; this is an indicator of salt tolerance. The relative value of the leaf dry weight was 67 – 26% showing a significant reduction (*P* < 0.01) under NaCl treatment. The stem dry weight was also reduced by NaCl treatment, but not as much as leaf dry weight (Fig. 2). The relative value of root dry weight exceeded 100% in 16 out of 22 cultivars, which shows that NaCl treatment increased the root dry weight in these cultivars. The relative value of the plant (whole plant) dry weight was lower than 100% in all cultivars showing weight reduction under salt stress. The relative value of the plant dry weight was less than 50% in HB5 and HB12, and the highest in HB11 (Fig. 2). HB11 was the most salt-tolerant cultivar.

2. Growth analysis

Table 2 shows the results of multiple regression analysis between the relative value of the dry weight increment during NaCl treatment (from 13 to 29 DAG) of plant (whole plant) (ΔW) and those of leaf blade (ΔLW), stem (ΔSW) and root (ΔRW). The partial regression coefficients, standard partial regression coefficients, and partial correlation coefficients of relationships between the relative values of ΔW and those of ΔLW, ΔSW and ΔRW are...
shown in this table. The standard partial regression coefficient was highest in \( \Delta LW \) (0.49), whereas, the partial regression coefficient was highest in \( \Delta SW \) (0.57). The partial correlation coefficient was significant in all plant parts.

Fig. 3 shows the relationship between the relative value of root dry weight and that of shoot (stem and leaf blade) dry weight at 29 DAG, which was positively significant \( (r = 0.64, P < 0.01) \). The relative value of \( \Delta W \) in each cultivar is shown in Fig. 4. The mean of the relative value of \( \Delta W \) was 70%. Assuming that the cultivars showing a relative value higher than 70% are salt tolerant, nine cultivars: HB3 (Sudakkusu 316), HB7 (Brown toumitsu), HB8 (Lucky sorugo), HB10 (King sorugo), HB11 (Ryokuhiyou sorugo), SS17 (Supersugar sorghum), GS19 (Haiguren sorghum), GS20 (Mini sorghum), and SU22 (Oishii sudan), are tolerant to salt stress.

As shown in Fig. 5, the relative values of \( \Delta W \) significantly correlated with RGR \( (r = 0.98, P < 0.01) \). Fig. 6 shows the correlation of the relative value of RGR with that of NAR and LAR. The RGR significantly correlated with NAR \( (r = 0.69, P < 0.01) \), but not with LAR \( (r = -0.22, P > 0.01) \). There was a significant negative correlation between the relative value of NAR and that of specific leaf area (SLA) \( (r = -0.65, P < 0.01) \) as shown in Fig. 7A. In addition, there was a positive correlation between the relative value of NAR and that of nitrogen content per unit leaf area (NCLA) as shown in Fig. 7B \( (r = 0.40, P < 0.10) \).

### 3. \( \text{Na}^+ \) concentration in different plant parts

The \( \text{Na}^+ \) concentrations in different plant parts of

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**Table 2.** Partial regression coefficient, standard partial regression coefficient, and partial correlation coefficient of relationships between the relative values of increment from 13 to 29 DAG of plant dry weight (\( \Delta W \)) and that of the leaf blade (\( \Delta LW \)), stem (\( \Delta SW \)), and root (\( \Delta RW \)).

| Parameters | Partial regression coefficient \(^1\) | Standard partial regression coefficient | Partial correlation coefficient |
|------------|---------------------------------|--------------------------------------|-----------------------------|
| \( \Delta LW \) | 0.5729                          | 0.4388                               | 0.9755**                    |
| \( \Delta SW \) | 0.3365                          | 0.4910                               | 0.9754**                    |
| \( \Delta RW \) | 0.0749                          | 0.1432                               | 0.9056**                    |

\(^1\) \( Y = (0.5729) (\Delta LW) + (0.3365) (\Delta SW) + (0.0749) (\Delta RW) + 4.6194 \).  
\( ** \) indicates significant differences at the 0.01 probability level by multiple regression analysis.
Sorghum plants in the control and treated plants are shown in Table 3. A significant difference ($P < 0.01$) in Na$^+$ concentration (in whole plants) was observed between control and treated plants. The Na$^+$ concentration in almost all parts of the plant was higher in treated plants than in the control plants. The concentration was the highest in root followed by stem and leaf in both treated and control plants.

Fig. 8 shows the correlation of the relative values of dry weight of leaf, stem and root with the Na$^+$ concentration in leaf, stem and root, respectively, at the end of the treatment. The relative values of root dry weight was the highest followed by that of stem and leaf dry weight. Significant correlation with Na$^+$ content was not observed in all organs, even in root. Fig. 9 shows the correlation of the relative values of dry weight of leaf, stem and root with that of Na$^+$ concentrations in leaf, stem and root,
respectively, at the end of the treatment. There was no correlation between the relative value of Na\(^+\) concentration and dry weight of leaf and stem, but the relative value of the Na\(^+\) concentration in root was positively correlated with that of root dry weight \((r = 0.44, P < 0.05)\) (Fig. 9).

**Discussion**

The growth, growth rate and dry weight of *Sorghum* plants were obviously reduced under salt stress in the present experiment as in other studies (Lacerda et al., 2003; Shariat Jafari et al., 2009). In the present study using young seedlings of 22 cultivars of *Sorghum*, salt stress significantly inhibited plant growth in most of the cultivars (Fig. 1). The relative values of dry weight (% of dry weight under salt stress versus control condition, which represents salt tolerance) of whole plant, stem and leaf blade, especially leaf blade, were lower than 100%, but that of root dry weight was higher than 100% in more than half of the cultivars (Fig. 2). In other words, stem and leaf dry weights were decreased in all cultivars, but root dry weight of many cultivars was increased by salt stress (Fig. 2). This was in agreement with the report by Azevedo Neto et al. (2004) that the response of maize genotypes to salt stress was more substantial in the leaf than in the root. The pronounced effect of NaCl treatment on the leaf blade was also reported by Netondo et al. (2004), in which the treatment with NaCl induced 67% greater decrease in dry weight in the young leaf blade than in the oldest leaf blade in grain sorghum varieties. Some studies showed that salt stress not only reduced the leaf elongation rate but also reduced the final leaf length and enhanced leaf senescence and injury in forage sorghum genotypes (Lacerda et al., 2003), and that reduction in shoot growth accounted for a reduction in leaf area and stunted shoot (Läuchli and Grattan, 2007).

Since the relative value of \(\Delta W\) relied on that of \(\Delta LW\), \(\Delta SW\) and \(\Delta RW\), we analyzed the standard partial regression coefficients between relative values of \(\Delta W\) and that of each parameter. As shown in Table 2, the standard partial regression coefficient of relationship between the relative value of \(\Delta W\) and that of \(\Delta SW\) (0.49) was the highest followed by that of \(\Delta LW\) and \(\Delta RW\) \((r = 0.44\) and 0.14, respectively). This implies that the effect of salt stress on \(\Delta SW\) was larger than that on \(\Delta LW\) and \(\Delta RW\). Dry weight of *Sorghum* plants consists of the dry weight of stem (47%), leaf blade (31%) and root (21%), and was increased by cell division and enlargement at the growing point (McCue and Hanson, 1990). However, the partial regression coefficient of relationships between the relative value of \(\Delta W\) and those of \(\Delta LW\), \(\Delta SW\) and \(\Delta RW\) were the highest in \(\Delta LW\) (0.57) followed by \(\Delta SW\) (0.34) and \(\Delta RW\) (0.07). In other words, the dry weight of *Sorghum* plants decreased mainly due to the reduction in dry weight of leaf blade under the NaCl treatment. However, there was a strong relationship between \(\Delta LW\) and \(\Delta SW\) (data not shown), and the decrease in leaf dry weight may be attributed to that in stem dry weight.

The effect of NaCl treatment on the relationship between root dry weight and shoot dry weight may be important to elucidate the effect of salt stress on plant growth. In Fig. 3, the relative value of root dry weight positively correlated with that of shoot (stem and leaf) dry weight, and it was higher than 100% in 16 out of 22 *Sorghum* cultivars investigated. Therefore, the increase in root dry weight under salt stress can be considered due to the increase in shoot dry weight under NaCl treatment. This is inconsistent with the report by Läuchli and Epstein (1990) that salinity often reduces shoot growth more than...
root growth. On the other hand, NaCl stress reduced plant growth by a decrease in dry weight of both shoot and root in all maize genotypes although one cultivar was not affected by salinity (Azevedo Neto et al., 2004). Our results showed the same trend as that reported by Shariat Jafari et al. (2009), who concluded that the root/shoot ratio of *Sorghum* increased substantially under high salinity stress (at 240 mM NaCl), suggesting that most plants partition more assimilates to the roots rather than to the shoot under salt stress. Thus, we assume that the increase in root dry weight is one of the mechanisms for salt resistance among *Sorghum* plants.

The biomass reduction rate has been used as an index for salt tolerance (Shah et al., 1987) and the rate of biomass production normally correlates with yield (Munns, 2002). In addition, during the developmental stages of annual crops, the salt tolerance was usually based on relative growth reductions (Läuchli and Grattan, 2007). Thus, RGR was used to account for the change in total dry weight in the current experiment. In our experiment, the relative of ΔW was positively correlated with that of RGR, meaning that the reduction in total dry weight is affected by the reduction of RGR in all *Sorghum* cultivars (Fig. 5).

In *Sorghum* plants, the relative value of RGR correlated with that of NAR, but not with that of LAR. It was therefore considered that RGR under salt stress of *Sorghum* plants is mainly correlated with NAR that is increased by the reduction of SLA (Figs. 6 and 7). According to Azevedo Neto and Tabosa (2000), RGR was one of the best parameters to express the salt stress effect on maize plants and also NAR and LAR were the best parameters to express the difference between cultivars in salt tolerance or

| Table 3. Na+ concentration in different plant parts of *Sorghum* in the control and treated plants. |
|-----------------------------------------------|
| No  | Control | Treatment |
|     | Leaf    | Stem     | Root    | Whole  | Leaf    | Stem     | Root    | Whole  |
| HB 1 | 10.3    | 20.6     | 26.6    | 16.1   | 190     | 537      | 798     | 467    |
| HB 2 | 15.0    | 16.9     | 21.4    | 16.5   | 184     | 419      | 1003    | 462    |
| HB 3 | 6.2     | 11.5     | 19.8    | 9.7    | 160     | 467      | 1165    | 500    |
| HB 4 | 6.3     | 13.2     | 19.2    | 10.3   | 224     | 406      | 1166    | 517    |
| HB 5 | 6.4     | 16.6     | 19.5    | 11.6   | 187     | 581      | 1031    | 561    |
| HB 6 | 5.2     | 17.3     | 18.6    | 11.2   | 158     | 536      | 1021    | 537    |
| HB 7 | 8.0     | 14.5     | 20.0    | 11.6   | 282     | 651      | 1047    | 615    |
| HB 8 | 9.3     | 12.9     | 20.4    | 11.8   | 217     | 666      | 911     | 574    |
| HB 9 | 8.8     | 13.9     | 19.1    | 11.8   | 286     | 611      | 863     | 568    |
| HB 10| 7.7     | 22.3     | 24.2    | 14.6   | 248     | 614      | 1017    | 569    |
| HB 11| 7.4     | 9.1      | 17.9    | 9.7    | 236     | 585      | 1092    | 571    |
| HB 12| 5.0     | 8.8      | 21.7    | 8.8    | 198     | 289      | 981     | 418    |
| HB 13| 9.0     | 9.5      | 22.9    | 10.9   | 294     | 677      | 789     | 578    |
| HB 14| 6.6     | 10.4     | 19.1    | 9.5    | 215     | 506      | 1108    | 544    |
| HB 15| 4.8     | 9.5      | 11.8    | 7.3    | 319     | 606      | 948     | 594    |
| SS 16| 11.1    | 14.0     | 15.7    | 12.6   | 234     | 493      | 1164    | 565    |
| SS 17| 5.8     | 9.0      | 17.8    | 8.3    | 207     | 489      | 1123    | 552    |
| SS 18| 6.2     | 10.9     | 21.3    | 9.7    | 232     | 484      | 1014    | 521    |
| GS 19| 6.3     | 12.5     | 17.0    | 9.5    | 248     | 455      | 1182    | 554    |
| GS 20| 5.6     | 9.7      | 15.0    | 7.9    | 211     | 482      | 808     | 446    |
| SU 21| 8.8     | 20.6     | 17.9    | 14.2   | 401     | 594      | 940     | 615    |
| SU 22| 5.7     | 17.5     | 22.5    | 12.2   | 296     | 656      | 945     | 579    |
| Average | 7.5     | 13.7     | 19.5    | 11.2   | 238     | 536      | 1005    | 541    |
| Maximum | 15.0    | 22.3     | 26.6    | 16.5   | 401     | 677      | 1182    | 615    |
| Minimum | 4.8     | 8.8      | 11.8    | 7.3    | 158     | 289      | 789     | 418    |

Significance ** ** ** **

1) HB: sorghum-sudangrass hybrid, SS: sweet sorghum, GS: grain sorghum, SU: sudangrass.

** indicates significant differences in the values between the control and treated plants at 0.01 probability level by Student’s *t*-test.
salt sensitivity, suggesting that the NAR is a good physiological characteristic of salt tolerance in maize.

In the present experiment, there was a negative relationship between the relative values of NAR and SLA (Fig. 7A), that is, the leaf blade was thicker or had a lower SLA under the NaCl treatment. Cultivars that maintained comparatively higher NAR under salt stress had smaller SLA and was suggested to be salt-tolerant cultivars. Several studies showed that an increase in leaf thickness is associated with an increase in the ratio of mesophyll area available for the absorption of CO₂ to leaf area. In other words, the reduction in leaf area implies less assimilate production, and hence, the reduced plant growth (Burslem et al., 1996; Omami et al., 2006). Our results were consistent with those reported by Azevedo Neto et al. (2004) which showed that NAR of salt-tolerant maize was...
slightly higher than that of the sensitive genotype. Similarly, El-Hendawy et al. (2005) found that NaCl treatment reduced RGR and NAR, but did not affect LAR in wheat, and concluded that NAR was a more important factor than LAR in determining the salt tolerance of moderately tolerant and salt-sensitive genotypes. Some studies showed that NAR of rice was affected by leaf morphogenesis such as thinning of the leaf blade when nutrients were supplied sufficiently (Ehara et al., 1990; Ehara, 1993). According to Ehara (1993), two reactions in the photosynthesis occur when SLA affects NAR. First, the CO₂ diffusion resistance through the stomata is affected by the structural change in the leaf blade, that is the increase in SLA leads to an increase in stomatal resistance and a decrease in CO₂ conductance. Similar results on the relationship between changes in SLA and stomatal resistance were reported in wheat under NaCl treatment (Watanabe et al., 1992).

Secondly, NAR is increased by the thickening of leaf blade through an increase in the nitrogen content per unit leaf area (NCLA). Based on these results in the present study, the difference in NAR under NaCl treatment would be attributed to that in SLA and NCLA as demonstrated by the nitrogen content of the leaf dry matter (Ehara et al., 1997).

In the present study, *Sorghum* plants under salt stress maintained a high Na⁺ concentration in the roots and a lower Na⁺ concentration in the stem and leaf blade (Table 3, Figs. 8 and 9). *Sorghum* plants under NaCl treatment might maintain a low Na⁺ concentration in the leaf blade by retaining a higher concentration of Na⁺ in the root and some in the stem. In the present experiment, the Na⁺ concentration in the roots was high suggesting no correlation with an increase in root dry weight, under NaCl treatment (Fig. 8C). The relative value of shoot (leaf + stem) dry weight also was not correlated with the Na⁺ concentration in the shoot (Fig. 8A, B). These results are in agreement with those reported by Netondo et al. (2004), which showed that *Sorghum* has the ability to maintain a high level of Na⁺ in the roots and stem but allocates Na⁺ to the leaf sheath for salt tolerance.

As shown in Fig. 2, root dry weight of *Sorghum* cultivars increased under NaCl treatment (relative value of dry weight was higher than 100%). Although the Na⁺ concentration under NaCl treatment was higher in root (Table 3), the effect of NaCl stress on dry weight was most pronounced in leaf blade (Fig. 2). Cultivars that showed a larger increase in root dry weight under salinity had higher Na⁺ concentration in root but lower Na⁺ concentration in stem and leaf blade (Fig. 9). Our result is in agreement with that of Rahnama et al. (2011) who concluded that the root of a bread wheat genotype showed a positive response to moderate salinity (at 100 mM NaCl), but some genotypes decreased root biomass under higher level of NaCl treatment (200 mM NaCl); indicating that an increase in root biomass might be a main index of improvement of salt tolerance. Asfaw (2011) also reported that root dry weight of some *Sorghum* cultivars was increased under low levels of salinity. Studies on root branching under salt stress are limited but some authors indicated that the length and weight of primary root might be enhanced by moderate salinity (Kurth et al., 1986).

In the present experiment, NaCl treatment reduced leaf dry weight in all the cultivars and increased root dry weight in 16 out of 22 *Sorghum* cultivars used, as well as in the other major crops of Poaceae. Nonetheless, in the present experiment, we did not investigate the physiological traits in relation to salt tolerance. It is considered that salt tolerant cultivars could deposit excess Na⁺ in the root. We assume that one of the mechanism of salt tolerance of *Sorghum* plants is the tolerance of root to high internal Na⁺ concentration.

In conclusion, *Sorghum* cultivars under NaCl treatment displayed reduced plant growth as demonstrated by decrease in dry weight, especially in leaf blade. Under salt stress, cultivars having high dry matter yield were recognized as tolerant to NaCl treatment although RGR was mostly decreased. RGR was correlated with NAR but not with LAR, which may be attributed to smaller SLA and thicker leaf blade under salt stress. *Sorghum* plants can retain Na⁺ mainly in the roots, thereby, preventing the distribution of Na⁺ to the leaf blade. A preferable leaf morphogenesis producing a thicker leaf blade and an apparent increase in root dry weight are main factors in the maintenance of dry matter yield and growth of *Sorghum* cultivars under NaCl treatment.

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