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Predicting rice yield under salinity stress using K/Na ratio variable in plant tissue

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ABSTRACT

Estimation of yield reduction in crop caused by the salinity stress is mostly based on variations of soil electrical conductivity and the severity of water stress. Crop response curves to salinity were developed without considering ion toxicity and nutritional imbalance in the plant. The objective of this study was to explore the possibility of using the ratio of the concentration of potassium by sodium in rice leaf (leaf-K/Na) to predict yield under the salinity stress. The rice (*Oryza sativa* L.) yield under fresh and saline condition and the leaf-K/Na related database was created. Data were collected from consecutive three seasons of a field experiment in the Africa Rice Center experimental farm in Senegal (16° 11' N, 16° 15'W). We studied the relationship between the relative yield (Y_r), a ratio of yield under the salinity stress to the potential yield and the leaf-K/Na (x). Furthermore, we did regression analyses and F-test to determine the best fitting function. Results indicate that the exponential function [i.e. $Y_r = 100 \exp(-b x)$] was the best fitting model with the lowest root mean square error (9.683) and the highest R^2 value (0.90). Example applications on independent data from published papers showed relatively good predictions, suggesting that the model can be used to predict rice yield in saline soils.

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Model; nutritional imbalance; *Oryza sativa*; yield reduction

Introduction

Salinity is one of the most severe constraints limiting the productivity of crops. The growth and productivity of plants are reduced because of physiological disorders caused by saline stress. One mechanism of the plant growth reduction is an injury to cells caused by ion toxicity and nutritional imbalance (Hasan and Miyake 2017). For example, sodium (Na) or Chloride (Cl) ions accumulated in plant leaf tissue may cause necrotic tips or margins (Hniličková et al. 2019). Another mechanism for salt stress to inhibit plant growth is that salt in the soil solution reduces the ability of the plant to take up water and this causes water-deficit effects on the plant (Reddy et al. 2017). Some adaptive mechanisms to resist to salt stress are reported. Osmotic regulation can tolerate to the water-deficit effects of salinity stress on the plant growth and maintain leaf expansion and stomata conductance (Acosta-Motos et al. 2017). Another resistant mechanism classified as ion exclusion is to avoid the toxic effects of ions e.g. to minimize the amount of Na^+ accumulated in the cytosol with reducing Na

+ uptake by roots and/or excluding Na⁺ from newly expanding leaves (Hniličková et al. 2019). The last mechanism is to tolerate excess salts in the plants with compartmentalizing efficiently toxic ions in the vacuole or in particular cells where the damage to metabolism is minimized (Shabala and Munns 2012). Characterization of rice genotypes in relation to the types of resistance to salt stress is important for predicting their agronomic performance under salt stress. However, various other factors than salt concentration in soil such as meteorological factors related to evaporation demands, soil properties and plant conditions, damages by other abiotic and biotic stresses etc. may have interactive effects with the mechanisms of resistant to salt stress on the plant growth (Gupta and Huang 2014). Due to such complicated interactive effects, results obtained by field research themselves often cannot provide integrated information by which the best cropping management systems under a given saline condition can be designed. Modeling is a useful tool taking factors possessing interactions with each other into account to simulate yield under saline conditions for generating the appropriate cropping systems (Li et al. 2015). Since 1950s, a number of efforts have been paid to develop models to predict response of crops to soil salinity. Maas and Hoffman (1977) attempted to describe the relative yield, a ratio of actual yield under salt stress to the potential yield under favorable conditions (Y_r), by linear yield decrease with increased salinity beyond a certain salinity threshold beyond which no yield can be obtained:

$$Y_r = \begin{cases} 1 & 1C < C_t \\ 1 - b(C - C_t), & C_t < C < C_0 \\ 0, & C > C_0 \end{cases} \quad (1)$$

where b is the yield decrease per unit of salinity increase (absolute value of the declining slope), C_t is the maximum value of salinity without a yield reduction (threshold C).

This threshold-slope model has been adopted to describe rice yield under the stress (Skaggs et al. 2006; van Genuchten and Gupta 1993). Furthermore, several models using a similar threshold approach with various types of a yield response curve to salinity increase (Skaggs et al. 2014; Steduto et al. 2012; van Straten et al. 2019) have been developed. In most models, the relative yield, a ratio of the yield under the stress to the potential yield (Y_r), was explained as a direct function of soil electrical conductivity (EC) or plant water uptake. Curves adopted in the equations in these approaches were determined a priori without considering nutritional aspects in the plants. One of the mechanisms of plant growth inhibition by salinity stress is an injury to cells caused by ion toxicity and nutritional imbalance. It is reported that excessive sodium (Na) uptake to the detriment of potassium (K) uptake may affect the growth and the survival of plants (Mel et al. 2018); therefore, we focused on the ratio of the concentration of K to the concentration Na in plant leaf (leaf-K/Na) and attempted to explain relative yield as a function of this parameter.

Materials and methods

Experimental site and plant materials

The rice yield response data collected from three season's field experiments in the Africa Rice Center (AfricaRice) experimental farm located in Ndiaye (16° 11' N, 16° 15' W) in Senegal was used. The AfricaRice farm covers an area of about 11 hectares which is surrounded by a protecting dike on the side of the river branch. The soil salinity mapping in this perimeter indicates a general heterogeneity of the salinity level which may be divided into three parts: the non-saline part (EC < 1 dS/m), composed of land portions regularly cultivated which represent approximately 45% of the total area, the moderately saline part (1 dS/m < EC < 4 dS/m) with a relatively low frequency of cultivation compared the non-saline part representing about 20% of the total area, and the saline part (EC > 4 dS/m) which is less cultivated or often abandoned representing about 35% of the total area. Two adjacent trials were implemented in a saline land portion (saline condition) and a non-saline land portion (fresh condition). The plant materials were composed of five advanced breeding lines, namely IR4630-22-2-5-1-3 (salt tolerant), IR72593-B-3-2-3-8 (salt tolerant),

IR 59,418-7B-21-3 (salt tolerant), IR 76,346-B-B-10-1-1-1 (tolerant) and IR31785-58-1-2-3-3 (salt susceptible), and one popular improved variety Sahel 108 (moderately susceptible). We used a factorial design in a split-plot arrangement with fertilizer treatments as the whole plot and rice cultivars as subplot treatments, in three replications. The size of the main plots for fertilizer treatment was 74 m² (13.6 m × 5.4 m), while the subplot size for the rice cultivars was 8 m² (4 m × 2 m). These six rice cultivars were evaluated under the fresh and saline conditions. The trial was consecutively repeated three times from March 2012 to August 2013 and managed equally in term of land preparation, fertilizer application, water and weed control.

Sampling, measurements and analyses

All cultivars did not have similar phenology thus at the panicle initiation stage of each cultivar, the three topmost fully expanded leaves per cultivar were sampled and the K and Na concentration of the sampled leaves were determined by flame photometry (Flame photometer Jenway – model PFP7, UK) after extraction by a normal solution of hydrochloric acid, following the procedure of Yoshida et al. (1976). In both saline and fresh condition, grain yields were measured and adjusted at 14% grain moisture content. The relative yield (Y_r) in the saline condition to that in the fresh condition was calculated using the following formula:

$$Y_r(\%) = \frac{(GY_{NS} - GY_S)}{GY_{NS}} \times 100 \quad (2)$$

where Y_r is the relative yield in percent, GY_{NS} is grain yield obtained in non-saline soil in tons per hectare and GY_S is grain yield obtained in saline soil in tons per hectare.

We assessed the relationship between the relative yield (Y_r) and the K/Na ratio in rice leaf (x) measured in the saline condition using Microsoft-Excel. In the aim to determine the best fitting function, the XLSTAT software 2015 version was used to perform regression analyses and F-test.

The performance of the equation obtained by the best fitting model i.e. lowest root mean square error (RMSE) and the higher R^2 value was evaluated on independent data (e.g. data published by other researchers

Results

Parameters estimation in the model

It was observed that the Y_r decreased with the increase of the leaf-K/Na until a threshold leaf-K/Na (leaf-K/Na = 4) (Figure 1). From regression analyses and F-test, the exponential function was the best applicable fitting model with the smallest RMSE (9.68) and highest adjusted R^2 (0.90). In the exponential function [$Y_r = a \exp(-b x)$], the constant a represents the maximum attainable percentage of relative yield reduction. Although $a = 107.07$ in our analyses (Figure 1), this value should be 100 (i.e. the maximum yield reduction). The model equation recalculated with $a = 100$ is as follows:

$$Y_r = 100 \exp(-bx) \quad (7)$$

where b is corresponding to the slope of the regression curve. Therefore, this parameter may change depending on the resistance level of the tested cultivars.

The value of b in the exponential function was 0.414 for IR31785, 0.532 for Sahel 108, 0.614 for IR59418, 0.690 for IR76346, 0.717 for IR72593, and 0.775 for IR4630 (Table 1). The four tolerant cultivars clearly showed higher values of b than the two susceptible cultivars. Based on our result, minimum values of the parameter b in the model application could be 0.4 for salt susceptible cultivar, 0.5 for moderately tolerant cultivar and 0.6 for tolerant cultivar (Table 1); the intermediate value of

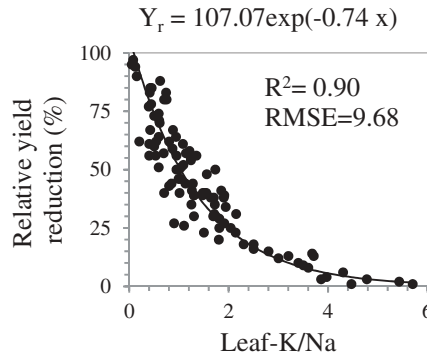


Figure 1. Regression curve of the relative yield reduction (%) in function of leaf-K/Na from the database of combined six cultivar cultivars (IR31785, Sahel 108, IR4630, IR76346, IR59418 and IR72593). The regression equation, R^2 value, and RMSE value are indicated in the chart.

Table 1. Estimated parameter b in the exponential function $Y_r = 100 \exp(-b x)$ for each tested cultivar.

Cultivar	Resistance level	Value of b	R^2
IR31785	S	0.414	0.586
Sahel 108	MS	0.532	0.942
IR59418	T	0.614	0.870
IR76346	T	0.690	0.966
IR72593	T	0.717	0.961
IR4630	T	0.775	0.841

S: Salt susceptible, MS: Moderate salt susceptible, T: Salt tolerant

b can be chosen in function of the tolerance ranking of cultivars. In the fresh condition (without stress) the default value of b could be 1.

Assessment of the model performance

Data from previously published experiments in Hakim et al. (2014) and Kumar and Khare (2016) were used to evaluate the performance of the best model obtained in our experiment, i.e. [$Y_r = 100 \exp(-b x)$]. Hakim et al. (2014) assessed the responses of the growth, nutrient accumulation and yield to different salinity conditions (four salinity levels 0, 4, 8 and 12 dS/m) using eight rice cultivars. The eight rice varieties were composed of five Malaysian cultivars (i.e. MR33, MR52, MR211, MR232 and MR219), two Philippines cultivars (i.e. Pokkali and IR20) and the last one cultivar (BRRI dhan 29) was from Bangladesh. Pokkali is an international reference cultivar and known as salt tolerant, while BRRI dhan 29 and IR20 were salt sensitive. Results from the work of Hakim et al. (2014) are summarized in Table 2. It was reported that MR211 and MR232 were relatively tolerant to salt than Pokkali, followed by MR52, MR19 and MR33. MR19 and MR33 cultivars were moderately tolerant, while BRRI dhan 29 and IR20 cultivars were very much affected by salinity (Hakim et al. 2014). Therefore in the model application, $b = 0.6$ for Pokkali cultivar, 0.5 for MR19 and MR33, 0.4 for IR20 and BRRI dhan 29 cultivars. Assuming the tolerance ranking of these studies cultivars (e.g. MR211 ~ MR232 > Pokkali > MR52 > MR19 ~ MR33 > BRRI dhan 29 ~ IR20), the intermediate values of b were chosen to simulate the response of MR211, MR232 (e.g. $b = 0.7$) and MR52 (e.g. $b = 0.55$). The simulation responses are shown in Figure 2. Among the eight cultivars tested, simulations were almost accurate with few differences between the measured Y_r and the simulated Y_r for five cultivars (MR232, MR52, MR219, IR20 and BRRI dhan 29).

For MR232, the measured Y_r was 0, 16.08, 50.32 and 87.42% while the simulated Y_r was 0.35, 12.58, 56.9 and 81.9 %, respectively, at the salinity level of 0, 4, 8 and 12 dS/m (Figure 2b). For MR52, the measured Y_r

Table 2. Interaction effects of variety and salinity levels on yield, relative yield reduction, and shoot-K/Na of eight rice cultivars. Data were summarized from Hakim et al. (2014).

Cultivar	Salinity level	Yield* (g/hill)	Y _r ** (%)	Shoot-K/Na
MR219	0 dS/m	14.90	0	4.53
	4 dS/m	8.69	41.68	1.69
	8 dS/m	2.37	84.09	0.45
	12 dS/m	0.00	100.0	0.14
MR211	0 dS/m	14.37	0	5.98
	4 dS/m	12.35	14.06	4.37
	8 dS/m	7.00	51.29	1.65
	12 dS/m	1.50	89.56	0.40
MR232	0 dS/m	13.99	0	5.67
	4 dS/m	11.74	16.08	2.96
	8 dS/m	6.95	50.32	0.81
	12 dS/m	1.76	87.42	0.29
Pokkali	0 dS/m	12.62	0	7.33
	4 dS/m	10.76	14.74	4.45
	8 dS/m	4.90	61.17	1.80
	12 dS/m	1.28	89.86	0.38
MR52	0 dS/m	16.97	0	5.67
	4 dS/m	12.44	16.08	2.96
	8 dS/m	3.31	50.32	0.81
	12 dS/m	0.00	100	0.29
MR33	0 dS/m	14.45	0	2.61
	4 dS/m	8.42	41.73	1.11
	8 dS/m	3.58	75.22	0.29
	12 dS/m	0.00	100.0	0.08
BRRI dhan29	0 dS/m	15.12	0	4.84
	4 dS/m	6.73	55.49	1.58
	8 dS/m	0.00	100.0	0.33
	12 dS/m	0.00	100.0	0.15
IR20	0 dS/m	13.24	0	3.65
	4 dS/m	5.48	58.61	1.01
	8 dS/m	0.00	100.0	0.20
	12 dS/m	0.00	100.0	0.04

*Significant difference in yields between genotypes and salinity levels were observed

** Y_r: Relative yield reduction by salinity

was 0, 26.69, 80.49 and 100% while the simulated Y_r was 1.19, 32.03, 64.37 and 89.09%, respectively, at the salinity level of 0, 4, 8 and 12 dS/m (Figure 2d). For MR219, the measured Y_r was 0, 41.68, 84.09 and 100% while the simulated Y_r was 1.08, 42.96, 79.79 and 93.35%, respectively, at the salinity level of 0, 4, 8 and 12 dS/m (Figure 2e). For IR20, the measured Y_r was 0, 58.61, 100 and 100% while the simulated Y_r was 2.60, 66.76, 92.31 and 98.41%, respectively, at the salinity level of 0, 4, 8 and 12 dS/m (Figure 2g). For BRRI dhan 29, the measured Y_r was 0, 55.49, 100 and 100% while the simulated Y_r was 0.79, 53.13, 87.70 and 94.34, respectively, at the salinity level of 0, 4, 8 and 12 dS/m (Figure 2h). Overall the difference between the measured Y_r and the simulated Y_r for these five cultivars varied between 0.35% and 16.12%. However, the exactness of the prediction was relatively weak for the other three cultivars (MR211, Pokkali and MR33), particularly at the salinity levels of 8 and 12 dS/m for MR211 and Pokkali; and at the salinity levels of 4 dS/m for MR33. For MR211, the measured Y_r was 0, 14.06, 51.29 and 89.56% while the simulated Y_r was 0.25, 4.69, 31.51 and 75.74%, respectively, at the salinity level of 0, 4, 8 and 12 dS/m (Figure 2a). For Pokkali, the measured Y_r was 0, 14.74, 61.17 and 89.86% while the simulated Y_r was 0.07, 6.91, 34.02 and 79.46%, respectively, at the salinity level of 0, 4, 8 and 12 dS/m (Figure 2c). For MR33, the measured Y_r was 0, 41.73,

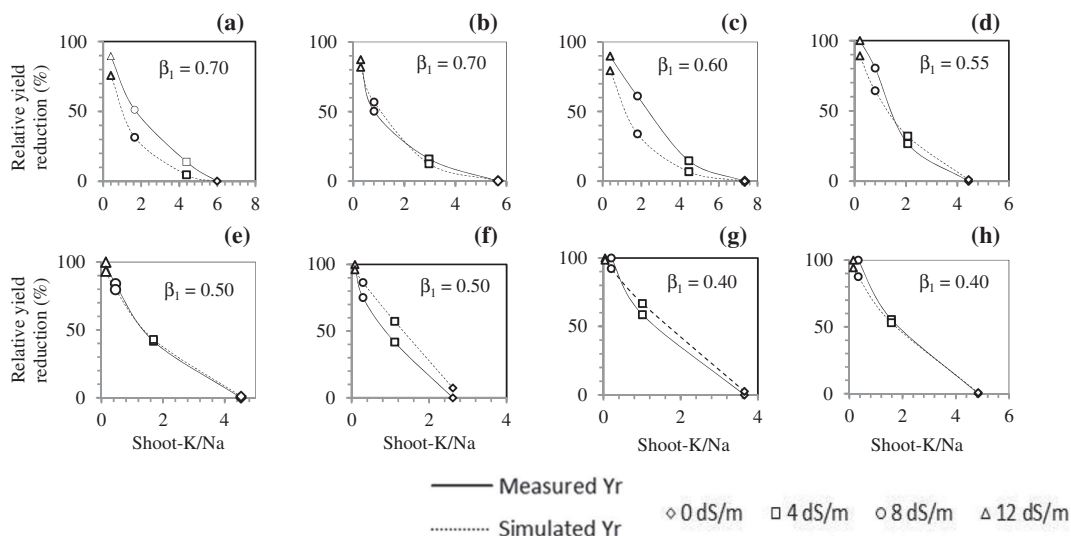


Figure 2. Comparison of measured and simulated relative yield (Y_r) at different value of shoot-K/Na during the experiments of Hakim et al. (2014) for the rice cultivars MR211(a), MR232 (b), Pokkali (c), MR52 (d), MR219 (e), MR33 (f), IR20 (g) and BRRI dhan 29 (h) under four soil salinity levels (0 dS m⁻¹, 4 dS m⁻¹, 8 dS m⁻¹ and 12 dS m⁻¹). Values of the adjustable coefficient β_1 are mentioned in the chart.

Table 3. Effect of Cl⁻, Na⁺ and NaCl stress on yield and relative yield reduction of the cultivars Panvel-3 and Sahyadri-3 in function of root-K/Na. Data were summarized from Kumar and Khare (2016).

Cultivar	Salinity level	Yield* (g/plant)	Y_r ** (%)	Root-K/Na
Panvel-3	Control	11.73	0	4.76
	Cl ⁻	9.94	15.26	4.00
	Na ⁺	9.83	16.20	2.50
	NaCl	6.15	47.57	1.01
Sahyadri-3	Control	13.39	0	4.54
	Cl ⁻	9.08	32.19	4.17
	Na ⁺	9.06	32.34	2.04
	NaCl	5.76	56.98	0.48

**Significant difference in yields between genotypes and salinity levels were observed

** Y_r : Relative yield reduction by salinity

75.22 and 100% while the simulated Y_r was 7.35, 57.41, 86.5 and 96.08%, respectively, at the salinity level of 0, 4, 8 and 12 dS/m (Figure 2f). For these three cultivars the minimum difference between the measured Y_r and the simulated Y_r was 0.07%, while the maximum difference was 27.15%.

In Kumar and Khare (2016), pot experiments were conducted to investigate the individual and additive effects of Na and Cl ions on two rice cultivars Panvel-3 and Sahyadri-3 from India. Results obtained are summarized in Table 3. The Panvel-3 cultivar was tolerant than Sahyadri-3. The model prediction was relatively accurate except at the Cl⁻ stress condition in which the simulated Y_r was 4.07% and the measured Y_r was 15.26% for Panvel-3 cultivar, and the simulated Y_r was 8.21% and the measured Y_r was 32.19% for Sahyadri-3 cultivar (Figure 3).

Discussion

Salt tolerance in plants is generally associated with low uptake and accumulation of Na⁺ ions, compared to the K⁺ ions in plant tissue. A significant correlation between yield reduction by salinity and the K/Na ratio in plant tissue has been reported by several authors (Chunthaburee et al. 2016; Reddy et al. 2017; Wakeel 2013). This could be because of the cell injury by ion toxicity and

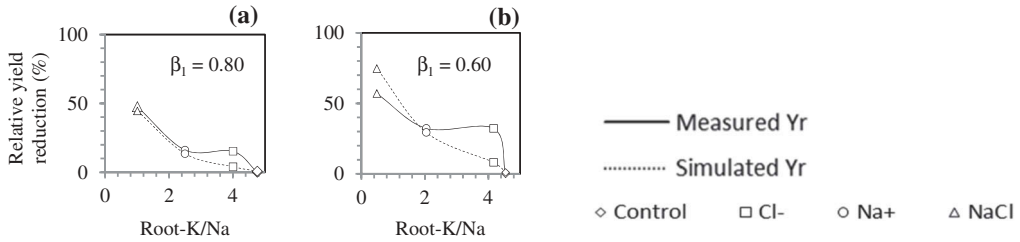


Figure 3. Comparison of measured and simulated relative yield (Y_r) at different value of root-K/Na during the experiments of Kumar and Khare (2016) for Panvel-3 (a) and Sahyadri-3 (b) rice cultivars subjected to Cl^- , Na^+ , and NaCl stress. Values of the adjustable coefficient β_1 are mentioned in the chart.

nutritional imbalance which are the dominant factors for salinity to reduce rice yield. Furthermore, Chunthaburee et al. (2016) showed that the K/Na ratio in rice shoot was negatively correlated to the standard salinity evaluation score and rice yield is expected to decrease with the increase of salinity evaluation score. The results obtained by Chunthaburee et al. (2016) were in agreement with our work hypothesis. We tried to assess the relationship between leaf-K/Na and yield (relative yield reduction by salinity) and develop an empirical model to predict rice yield under the salinity stress. The function is given by $[Y_r = 100 \exp(-b x)]$. The threshold leaf-K/Na without a yield reduction was 4, suggesting that the concentration of potassium in rice leave should be at least four times higher than the concentration of sodium in leave to achieve zero yield reduction by salinity. This threshold leaf-K/Na could serve as a reference in the screening of cultivars for salinity tolerance and in development of agronomic technologies for mitigating the effects of salinity stress.

Furthermore the parameters of this function seem to well represent biochemical characteristics of the salinity response; because the maximum attainable percentage of yield reduction under the salinity stress is 100% and may decrease with the increase of the concentration of K/Na in shoot, root or leaves of rice plant. Experimental evidence shows that the value of the parameter b was relatively lower in the sensitive cultivar and higher in the tolerant cultivar. The predictions of the model were generally accurate except in some cases where there is an underestimation (up to 27.15%) or overestimation (up to 15.7%) of the Y_r . This shift may be due to the relative higher value of b in reference to the underestimation or the lower value of b in reference to the overestimation. In Kumar and Khare (2016), the model underestimated the Y_r under Cl^- stress and that is not surprising because some reports established that high soil Cl^- increased the yield reduction than Na^+ (Zhang et al. 2011). The model has been tested on rice crop; however, it could be tested also on other crop species. An example application on wheat crop (c.v. Goumria-19 and Line 103) from data published in Hamam and Negim (2014) is presented in Figure 4. The prediction of the model for these two wheat cultivars was relatively good (Figure 4).

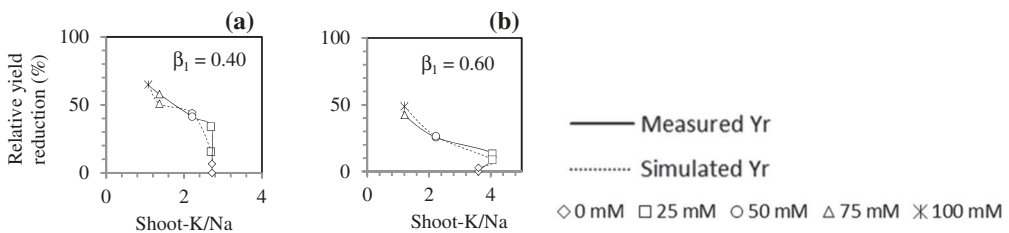


Figure 4. Comparison of measured and simulated relative yield (Y_r) at different value of shoot-K/Na during the experiments of Hamam and Negim (2014) for Goumria-19 and Line 103 (b) wheat cultivars under five salinity levels (0 mM, 25 mM, 50 mM, 75 mM and 100 mM NaCl). Values of the adjustable coefficient β_1 are mentioned in the chart.

However, we faced some difficulties finding the right value of the parameter b . We tried to run the model on the basis of results obtained in our experiment however this was not sufficient for sweeping overall responses, perhaps others factors like salinity tolerance score at the seedling and reproductive stage, the K-Na selectivity, etc. could help finding the coefficient b with low error and make the simulation more accurate. Finally further information through additional experiment is needed to estimate parameters of this model and make it very useful.

Conclusion

In saline soils, excess Na^+ in soil solution alters the nutritional balance of plants resulting in low K^+/Na^+ , $\text{Ca}^{2+}/\text{Na}^+$, etc., which may cause a reduction in yield. Some evidence from literature supports the assumption that increasing the ratio of the concentration of potassium by sodium (K/Na) in plant tissue can lead to decrease yield reduction caused by salinity. In this paper, we tried to develop a general empirical model to predict rice yield under the salinity stress in function of K/Na ratio in leaf. The response function was given by $Y_r = 100 \exp(-b \cdot x)$. Despite a relatively good prediction of the model, it was challenging to determine more accurately the slope parameter (b) of the function. Therefore, additional field experiment is needed, particularly with regard to the linkage between the parameter b and the tolerance level of tested cultivars.

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