Original Research Paper

Soil moisture stress and nitrogen supply affect the growth characteristics and yield of upland rice cultivars

ABSTRACT

Aims: To assess the effect of soil moisture stress and nitrogen fertilizer application on the growth characteristics and yield of upland rice cultivars.

Study design: Completely randomized design in a factorial arrangement.

Place and duration of study: National Crops Resources Research Institute, Namulonge, Uganda between March and July 2015.

Methodology: The experiment comprised four nitrogen (N) application levels (0 as control, 40, 80 and 120 kg N/ha) as main plots and four soil moisture levels (25% as control, 15, 10 and 5%) as sub-plots.

Results: Plant heights for stressful moisture levels (15, 10 and 5%) at all N levels were lower ($P < .001$) than those of the control treatments at the respective N levels. Also, rice plants under stressful treatments at each N level took longer ($P < .001$) to mature when compared with the control treatments at the respective N levels. Subjecting rice plants that were supplied with 0 kg N/ha to moisture stress did not significantly ($P > .05$) affect the number of panicles produced when compared with the control. Under the 40 kg N/ha level, number of panicles produced by rice plants subjected to 15 and 10% moisture stress levels (3.56 and 4.00) were significantly lower than those of the control (6.00). For the 80 and 120 kg N/ha levels, number of panicles decreased significantly at all moisture stress levels when compared with the respective control treatments. Subjecting rice plants to moisture stress at the 40, 80 and 120 kg N/ha levels significantly ($P < .001$) reduced the grain yield when compared with the respective control treatments.

Conclusion: Namche-3 rice cultivar performed optimally when subjected to 15% moisture stress and 120 kg N/ha application rate. Thus, farmers growing Namche-3 rice in areas with limited soil moisture may apply N at 120 kg/ha if they are to realize better grain yields.

***Key words**: Namche-3 rice cultivar, nitrogen fertilizer, soil moisture stress, upland rice.*

1. INTRODUCTION

Rice production in Uganda has increased tremendously in the past decade due to many factors including the increased demand in urban areas, changing food habits, decline in the production of traditional food crops particularly finger millet, bananas and cassava, and the introduction and promotion of high yielding New Rice for Africa (NERICA) varieties [1, 2]. NERICA varieties were developed by the Africa Rice Center by crossing *Oryza sativa* (Asian rice) and *Oryza glaberrima* (African rice) to improve the yield of African rice varieties [3]. They are adapted to the rain-fed upland ecology, are high yielding, early maturing (75-100 days), and are tolerant to drought, Africa's major pests and diseases, soil acidity and iron toxicity. They were introduced in Uganda in 2002 [4, 5]. The rice germplasm was received by the National Crops Resources Research Institute (NaCRRI) Namulonge, and was used to develop upland varieties suited to Uganda's conditions. In 2013, varieties named Namche-1, Namche-2, Namche-3 and Namche-4 were released (J. Lamo, NaCCRI Namulonge, Uganda, personal communication). However, most of the increase in rice production in Uganda has been as a result of area expansion rather than an increase in yield. Cultivated area expanded from 72,000 hectares (ha) in 2000 to 140,000 ha in 2010, while in the same period rice production increased from 109,000 to 218,000 metric tonnes (MT) [6].

Namche-1 matures in 105-110 days after germination and yields 3.8 MT/ha. Milled grain is very white, and the panicle is long and compact. The flag leaf angle semi-erect, flag leaf is large but short, leaf blade colour is light green, and the grain husk is straw in colour. It is drought tolerant. Namche-2 matures in 128-132 days after germination and yield 4.3 MT/ha. Milled grain is glossy white, the panicle is long and scattered. The flag leaf angle is semi-erect, flag leaf is large and long, leaf blade colour is dark green, and the grain husk is straw in colour. This variety is resistant to rice yellow mottle virus disease and is adapted to both upland and rain-fed lowland areas. Namche-3 matures in 122-128 days after germination and yields 4.55 MT/ha. Milled grain is white, and the panicle is long and compact. The flag leaf angle is erect, flag leaf is large but short, leaf blade colour is dark green, and the grain husk is golden in colour. Namche-4 matures in 125-130 days after germination, and yields 4.5 MT/ha. Milled grain is white, and the panicle is long and compact. The flag leaf angle is erect, flag leaf is large but short, leaf blade colour is dark green, and the grain husk is golden in colour.

In spite of the release of these varieties, rice yields from Ugandan farmers' fields have remained low, around 1.5 MT/ha as opposed to 3.5 MT/ha under irrigated conditions [7]. These varieties have been introduced in areas receiving low rainfall hence there is insufficient water for growth. A large portion of smallholder farmers depend on rain-fed agriculture, where sufficient water supply is unpredictable. The occurrence of moisture stress affects many of the physiological processes such as photosynthesis and transpiration resulting in reduced growth and eventual yield loss [8]. The situation has been worsened by low soil fertility [9]. Nitrogen (N) is one of the macronutrients that are insufficient for growth of plants in many part of Uganda. Elsewhere, experiments showed that N fertilizer application significantly increased rice yields [10]. Because of its role in plant growth, N is one of the key inputs needed to achieve higher rice grain yields in Uganda. However, optimum quantities to apply under water deficit conditions have not yet been determined and could lead to adverse effects when the optimum level is exceeded [11]. Therefore, this study sought to determine the effect of moisture stress and N fertilizer application on the growth and yield of upland rice cultivars grown in Uganda under rain-fed conditions.

2. MATERIALS AND METHODS

2.1 Experimental design

The experiment was conducted in the greenhouse at the National Crops Resources Research Institute (NaCRRI), Namulonge, Uganda between March and July 2015. The experimental unit was a 30 cm diameter and 30 cm height plastic pot filled with 10 kg of soil (dry weight basis). Prior to the experiment, soil was analyzed for its physical (silt, sand and clay contents) and chemical (N, available P and K contents and pH) characteristics following methods described by Okalebo *et al.* [12] (Table 1). Analysis revealed that the soil used in the experiment was sandy loam with field capacity 20-25% moisture content. Based on the field capacity of soil, 25% moisture content was taken as a control. Layout of the experiment was a completely randomized design in a factorial arrangement with two factors, namely water stress and nitrogen fertilizer as treatments. Each treatment was applied at four levels and replicated three times. Nitrogen in form of urea (46% N) was applied at rates of zero (control), 40, 80 and 120 kg N/ha in two split applications. The first 50% of N for all the levels was applied two weeks after planting and the other 50% was applied at flowering as topdressing. Phosphorous and potassium fertilizers were applied at the rates of 50 kg P_2O_5/ha as triple super phosphate and 40 kg K_2O/ha as muriate of potash, respectively at the time of planting in all the experimental plots. Soil moisture levels comprised 25% as a control (normal field capacity) and 15, 10 and 5% as stressful moisture levels. During the first two weeks after planting, all treatments received the same amount of water as the control. Thereafter, irrigation treatments were carried out as planned until harvest.

Table 1: Characteristics of soil used in the greenhouse experiment (on DM basis)

pH	Organic matter	Nitrogen	Available phosphorus	Exchangeable potassium	Sand	Clay	Silt
	(g/kg)						
5.5	2.66	0.20	20.31	0.66	650	200	150

2.2 Data Collection

This commenced thirty days after planting and was done after every ten days till the end of the experiment. Data collected included soil moisture content, number of tillers, plant height (cm), days to maturity, number of panicles per hill, grain yield (g/m^2), biological yield (g/m^2) and harvest index.

2.3 Data analyses

All the data collected were summarized in Microsoft excel sheet and subjected to analysis of variance (ANOVA) using GenStat Statistical Software Version, Tenth-edition (VSN International Limited, 2011).

Treatment means for different parameters were separated using Fisher's least significance difference (LSD) at 5%.

3. RESULTS AND DISCUSSION

3.1 Effect of soil moisture stress and nitrogen fertilizer application on the growth characteristics of upland rice cultivars

3.1.1 Number of tillers and plant height

The number of tillers per hill were not significantly affected by the soil moisture levels, N fertilization and their interactions (Table 2). Soil moisture levels had significant effect (P < .001) on plant height but N levels and their interaction with moisture levels did not (Table 2). There were significant variations in plant heights within the soil moisture stress levels at each N fertilizer level. In the case of 0 kg N/ha level, plants height under 5, 10 and 15% moisture stress levels were not significantly different but were lower than the control (Table 2). At the 40 kg N/ha level, when Namche-3 was subjected to soil moisture stress, there were no significant differences in plant heights between the 5 and 15% moisture stress levels, but were lower than that of the control. The heights of plants subjected to the 10% moisture stress level were similar to those of the control. At 80 kg N/ha, plants that were subjected to 5 and 10% moisture levels had similar plant heights, and were higher than those of plants subjected to the 15% moisture level. However, the heights of plants subjected to the 15, 10 and 5% moisture were significantly lower than those of the control. In the case of 120 kg N/ha level, the height of plants subjected to 10 and 5% moisture stress levels were not significantly different from each other, but they were lower (P < .001) than those of the control. For the 15% moisture level, the plant heights were significantly lower than those of the other treatments as well as the control.

Similar findings on the number of tillers were reported by Akram *et al.* [13] who also observed a non-significant effect on the number of tillers per hill when three basmati rice (*Oryza sativa* L.) cultivars were subjected to moisture stress. The results on plant height are in agreement with those of Sikuku *et al.* [14]

who stated that water stress affects nearly all the plant growth processes. However, the stress response depends upon the intensity, rate and duration of exposure and the stage of crop growth. Plant growth involves both cell division, cell enlargement and differentiation and these activities are very sensitive to water stress due to their dependence on turgor pressure [15]. The inhibition of cell activity may have affected the heights of rice plants under stressful soil moisture levels. Under stressful conditions plants could not absorb sufficient nutrients from the soil due to lack of available soil moisture, consequently crop growth became stunted [16].

Table 2. Effect of soil moisture stress and nitrogen on the growth characteristics of Namche-3 rice cultivar

Nitrogen levels kg/ha	Soil moisture levels (%)	Number of tillers	Plant height (cm)	Days to maturity	Number of panicles
0	25	7.89^{b}	86.22^{bc}	100.33^{h}	4.44^{de}
	15	6.00^{bcd}	66.56^{g}	125.67^{cde}	5.00^{cd}
	10	5.89^{bcd}	72.11^{efg}	130.67^{c}	3.78^{ef}
	5	6.00^{bcd}	71.22^{fg}	123.0^{def}	4.11^{ef}
40	25	7.33^{bc}	88.33^{ab}	106.00^{gh}	6.00^{b}
	15	7.22^{bcd}	71.00^{fg}	120.33^{ef}	3.56^{fg}
	10	6.56^{bcd}	80.67^{bcde}	144.67^{a}	4.00^{ef}
	5	6.56^{bcd}	78.67^{cdef}	110.7^{g}	5.78^{bc}
80	25	5.44^{cd}	95.11^{a}	111.33^{g}	7.44^{a}
	15	10.78^{a}	56.67^{h}	127.33^{cd}	1.00^{i}

	10	4.89^{d}	77.56^{def}	144.33^{a}	2.56^{h}
	5	5.00^{cd}	82.00^{bcd}	137.67^{b}	2.78^{gh}
120	25	6.33^{bcd}	91.22^{a}	100.67^{h}	7.22^{a}
	15	5.89^{bcd}	70.11^{fg}	101.67^{h}	1.67^{i}
	10	5.44^{cd}	82.11^{bcd}	117.67^{f}	3.67^{ef}
	5	5.44^{cd}	86.11^{bcd}	110.67^{g}	4.00^{ef}
LSD$_{(0.05)}$					
Nitrogen levels		2.69ns	11.76ns	8.29	1.07
Stress levels		8.77ns	8.62	5.86	0.80
Nitrogen × Stress		6.45ns	17.79ns	12.25	2.65

^{abc}Means within the same column having different superscripts are significantly (*P* < .05) different, ns = Not significant (*P* > .05).

Under stressful conditions, the transport of cytokinins from roots where they are produced up the xylem to the shoot meristem where they induce growth [17], could have been affected due to the deficiency of soil moisture. Although it has been found out that an ATP-binding cassette transporter, AtABCG14, is essential for the root to shoot translocation of the root-synthesized cytokinins [18], presence of water in the xylem is necessary to facilitate the transport. This was similar to the observation of Siopongco *et al*. [19] who reported that soil moisture stress treatments led to production of shorter plants. Similarly, the supply of available N progressively increased the plant height irrespective of growth stages. Plant height is controlled by genetic factors but it also varies because of the management practices and input supply [20]. However, in order to express their full genetic potential, it is better to provide rice plants with necessary inputs such as water and N. These results are in conformity with those of Hussain *et al.* [21] who also observed variations in plant height due to soil moisture stress.

3.1.2 Number of days to maturity

There were significant differences in the days to maturity (P < .001) among the treatments of N application and moisture stress levels. There was also significant interaction between N application and moisture levels (P = .007) on days to maturity of Namche-3 rice cultivar. Generally, subjecting rice plants to moisture stress significantly (P < *.001*) increased the number of days to maturity at all N application levels when compared with the respective control treatments (Table 2). At 0 kg N/ha level, the rice plants subjected to 15 and 5% moisture stress levels took similar number of days to reach maturity, but those subjected to 10% moisture level took significantly (P < .001) higher number of days to maturity than those at the 5% moisture level. For all the stressful treatments, their growth periods were longer (P < .001) than those of the control.

At the 40 kg N/ha application rate, rice plants subjected to the 10% moisture stress level took longer (P < .001) to reach maturity, followed by plants that were subjected to 15% moisture stress level. Rice plants that were subjected to 5% moisture level took the shortest number of days to mature and were similar to those of the control (Table 2). In the case of 80 kg N/ha level, the number of days to maturity for the 10% moisture level were significantly higher than those of the 5% moisture level, which were in turn higher (P < .001) than those of the 15% moisture level. At 120 kg N/ha level, rice plants that were subjected to the 15% moisture level and the control took similar number of days to reach maturity, while those 10% level took the highest (P < .001) number of days to reach maturity, and were followed by those at the 5% moisture level.

The intensity and occurrence of soil moisture stress have been associated with the delay of maturity or flowering. The delay in flowering and maturity under soil moisture stress in rice is deleterious and indicates poor adaptation to moisture stress [22]. Rice exposed to soil moisture stress can advance flowering or maturity by up to one week or more with corresponding decreases in the number of spikelets, total number of grains per panicle and reduced 1000-grain weight [13]. Ontogenic characteristics especially appropriate flowering time play an important role in moisture stress avoidance of rain-fed rice [23].

3.1.3 Number of panicles

When stress was imposed on rice plants that were supplied with 0 kg N/ha, the number panicles for all the moisture levels including the control were similar (Table 2). At the 40 kg N/ha level, number of panicles for the 15 and 10% stressful treatments were similar, but they were significantly lower than that of the control and the 5% moisture level (Table 2). When rice plants were exposed to moisture stress treatments (15, 10 and 5%) and N at 80 kg N/ha, number of panicles for all the stress treatments significantly (P < .001) decreased when compared with that of the control. The same trend in the reduction of number of panicles was observed when the same soil moisture treatments were applied to rice plants supplied with N at the rate of 120 kg N/ha (Table 2).

The current results are consistent with those reported by Rahman *et al*. [24] who observed a reduction in the number of panicles when rice plants were subjected to soil moisture stress. The panicle reduction under soil moisture stress might be due to the slowdown of cell division that, which in turn led to reduced numbers of individual cells formed [25]. The damaging effect of moisture stress on spikelet development as reported by Purushothaman *et al.* [23] resulted in high chaff percentage. Soil moisture stress during tillering stage resulted in significant reduction in the number of panicles while stress during grain development and ripening reduced the percentage of filled grains of rice [26]. Bakul *et al*. [25] and Suresh *et al.* [27] reported that increased absorption of nutrients at panicle initiation stage favored increased production of grains per panicle. Roy *et al.* [28] reported that N stimulated the buildup and translocation of carbohydrates and grain development which increased the number of filled grains and number of panicles.

3.1.4 Grain yield

Soil moisture stress levels significantly ($P < .001$) affected the grain yield but N application levels were not significant ($P = .98$) (Table 3). The interaction between N application levels and moisture stress levels was also significant ($P = .002$). When rice plants were subjected to moisture stress, the 25% soil moisture level (control) had significantly ($P < .001$) higher grain yield at all the N application levels, except that of 0 kg N/ha level which had very low grain yield as compared to the other N application levels. At the 0 kg N/ha level, grain yield obtained at the 5% moisture stress level was significantly higher than that of the control as well as those obtained at the 15 and 10% moisture stress levels (Table 3).

At the 40 kg N/ha level, grain yields dropped significantly at all the moisture stress levels but the reduction was most pronounced at the 15% moisture stress level as compared to the control. However, the grain yields at the 5 and 10% moisture stress levels were similar. At the 80 kg N/ha level, grain yield obtained from the 5 and 15% moisture stress levels were similar but significantly lower than that of the control. For the 10% moisture stress level grain yield was significantly lower than that of the 5% level. In the case of 120 kg N/ha level, soil moisture stress caused significant drop in grain yields when compared with the control. Grain yield obtained for the 15% moisture stress level was significantly higher than that for the 10% while the one for the 5% soil moisture level was the lowest.

Table 3. Effect of nitrogen and soil moisture levels on the yield of Namche-3 rice cultivar

Nitrogen levels kg/ha	Soil moisture levels (%)	Grain yield (g/m^2)	Biological yield (g/m^2)	Harvest index (%)
0	25	5.19^{ghi}	130.00^{g}	2.69^{cde}
	15	7.41^{e}	131.11^{g}	1.84^{de}
	10	2.59^{fgh}	175.53^{f}	3.42^{c}
	5	8.89^{d}	303.33^{c}	1.93^{de}
40	25	20.00^{b}	291.14^{c}	7.61^{ab}
	15	4.07^{ij}	335.56^{ab}	2.51^{cde}
	10	6.30^{efg}	327.40^{b}	1.89^{de}
	5	7.04^{ef}	224.44^{e}	2.88^{cd}
80	25	22.96^{a}	273.33^{cd}	7.96^{a}
	15	4.07^{ij}	207.40^{e}	1.92^{de}
	10	3.33^{jk}	141.84^{g}	2.33^{cde}
	5	4.81^{hi}	346.67^{a}	1.36^{e}
120	25	24.07^{a}	353.33^{a}	6.35^{b}
	15	13.33^{c}	353.33^{a}	6.35^{b}
	10	5.93^{ij}	131.33^{g}	6.99^{ab}
	5	4.44^{k}	55.53^{h}	2.62^{cde}

$LSD_{(0.05)}$			
Nitrogen levels	4.66ns	25.70	1.60
Stress levels	4.04	19.10	1.46
Nitrogen × Stress	7.94	40.50	2.83

[abc]Means within the same column having different superscripts are significantly ($P < .05$) different, ns = Not significant ($P > .05$).

Nitrogen is an essential macronutrient required in large amounts for grain formation. Application of N increases photosynthetic capacity of leaves by increasing stromal and thylakoid proteins in leaves [29]. Bouman and Toung [30] reported that irrigated rice grain yield declined as soon as the field water content dropped below saturation, and the magnitude of grain reduction depended mostly on the severity of the water stress and crop growth stage. Reduced grain yield under lower soil moisture levels might be due to inhibition of photosynthesis and less translocation of assimilates towards grain leading to spikelet sterility [31]. Moisture stress adversely affects grain development due to scarcity of water which impairs nutrient uptake. During soil moisture stress conditions, the topsoil layers where most of the nutrients are found become desiccated. This makes it difficult for these nutrients to be absorbed by plants, because in dry soils very little transportation of nutrients to the plant roots takes place.

3.1.5 Biological yield

The analysis of variance for biological yield indicated highly significant differences between soil moisture and N application treatments and their interaction ($P < .001$). The biological yields at 0 kg N/ha for the 10 and 5% moisture stress levels were significantly higher than that of the control. (Table 3). At the 40 kg N/ha level, the biological yields for the 10 and 15% moisture stress levels were similar but significantly ($P < .001$) higher than that of the control as well as that of the 5% moisture stress level. At the 80 kg N/ha level, the highest biological yield was obtained at the 5% moisture stress level and was higher than that of the control, while those obtained at the 15 and 10% moisture stress levels were lower than that of the control. When moisture stress was imposed on rice plants that were supplied with the biological yield obtained at the 15% moisture stress level was similar to that of the control, and was higher than the yields obtained at the 10 and 5% moisture stress levels.

Biological yield is the total aboveground biomass produced by a crop per unit area. It is the combined contribution of yield components such as number of tillers per unit land area, plant height and the number of grains per spike. Any change in these components will be reflected in the biological yield of a crop. These results are in conformity with those of Kalamian *et al*. [32].

Photosynthesis is generally decreased in plants facing water shortage. Lower photosynthetic rate coupled with reduced translocation of metabolites from the plant organs to the head and seeds resulted in low biological yield [33]. Water stress limits photosynthesis through stomatal closure and metabolic impairment [34]. However, chloroplast capacity to fix carbon dioxide may affect photosynthesis more than by increased diffusive resistance due to stomatal closure [35]. Reduction in chlorophyll contents due to dehydration under water stress situation especially in older leaves could be another reason for reduced photosynthesis under water stress situations [36]. Variations in photosynthetic capacity of rice genotypes under disturbed water supply have been reported [37]. A common adverse effect of moisture stress on rice plants is the reduction on biological yield, which was observed by Tahir *et al.* [38]. Reduced biomass production sometimes has a little effect on ultimate yield because the period of reduced growth may trigger some physiological processes that actually increase yield under stress condition [39].

3.1.6 Harvest index

The harvest index was significantly affected by N fertilizer application (P = .016) and soil moisture levels (P < .001) as well as the interaction effect of soil moisture and N fertilizer application (P = .011). All the harvest indices for the moisture stress levels at 0 kg N/ha level were similar to that of the control (Table 3). At the 40 kg N/ha level, the harvest indices recorded for all the moisture stress levels (15, 10 and 5%) were similar, but were significantly lower than that of the control. A similar trend was observed at the 80 kg N/ha level. Subjecting rice plants to moisture stress and N application rate of 120 kg/ha resulted in harvest indices that were similar to that of the control, with the exception of the harvest index for the 5% moisture stress level which was significantly lower than the rest (Table 3).

The physiological efficiency of rice plants to convert dry matter into the grain is measured in terms of harvest index. The more the harvest index value, the more will be the physiological efficiency of rice to convert dry matter into grain. Ghafoor *et al*. [40] reported that high harvest index is very important for increasing yield potential in crops. However, they stated that it was a complex parameter in cereals, largely due to high sensitivity to environmental variations. A severe moisture deficit stress at flowering stage greatly decreased seed numbers and harvest index. Farooq *et al.* [41] reported that when rice plants were exposed to a prolonged period of moisture stress, grain yield was severely reduced by decreasing the reproductive organs, number of fertile tillers per plant and the number of grains per spike.

4. CONCLUSIONS

In this study, a combination of different doses of N fertilizer and soil moisture regimes significantly influenced the number of days to maturity, number of panicles and grain yield of Namche-3 rice cultivar. Soil moisture stress significantly increased the number of days to maturity, but reduced the number of panicles and grain yield when compared with the control. The average number of days to maturity were generally shorter (108 days) at the 120 kg N/ha application rate when compared with the control (120 days) and other stressful treatments (120 and 130 days for the 40 and 80 kg N/ha rates, respectively). Grain yield for the 120 kg N/ha rate (11.94 g/m^2) was significantly higher than that of the control (6.02 g/m^2), but was not different from those of the 40 and 80 kg N/ha rates. Nitrogen fertilizer can thus alleviate soil moisture stress and in turn improve the growth and yield of upland rice varieties. Based on these results, it was concluded that the combination of 15% moisture stress level and 120 kg N/ha level was the best for optimal production of Namche-3 rice cultivar. Thus, farmers growing upland rice in areas with limited soil moisture (rainfall) should apply N fertilizer if they are to realize better grain yields. But more studies on the response of upland rice cultivars to moisture stress at higher levels of N fertilizer application, together with an economic analysis to determine the optimum water and N fertilizer application rates for maximum economic benefit are recommended.

REFERENCES

1. Miyamoto K, Maruyama A, Matsumoto S, Haneishi Y, Tsuboi T, Asea G, Okello SE, Takagaki M, Kikuchi M. NERICA cultivation and its yield determinants: The case of upland rice farmers in Namulonge, Central Uganda. Journal of Agricultural Science. 2012;4(6):120^{-1}35.

2. Fujiie H, Maruyama A, Fujiie M, Kurauchi N, Takagaki M, Kikuchi M. Potential of NERICA Production in Uganda: Based on the Simulation Results of Cropland Optimization. Tropical Agriculture and Development. 2010;54(2): 44-50.

3. Somado EA, Guei RG, Keya SO, editors. Africa Rice Center (WARDA)/FAO/SAA. NERICA: the New Rice for Africa – a Compendium. Cotonou, Benin: Africa Rice Center (WARDA); Rome, Italy: FAO; Tokyo, Japan: Sasakawa Africa Association; 2008.

4. Kijima Y, Otsuka K, Sserunkuuma D. An Inquiry into Constraints on a Green Revolution in Sub-Saharan Africa: The Case of NERICA Rice in Uganda. World Development. 2011;39(1):77–86. doi:10.1016/j.worlddev.2010.06.010.

5. Africa Rice Center (WARDA) (2006). The growing NERICA boom in Uganda. Brochure. <http://www.warda.org/publications/brochure/uganda.pdf>.

6. MAAIF (Ministry of Agriculture, Animal Industry and Fisheries). Statistical Abstract. Ministry of Agriculture, Animal Industry and Fisheries, Entebbe, Uganda. 2011.

7. Haneishi Y, Maruyama A, Asea G, Okello SE, Tsuboi T, Takagaki M, Kikuchi M. Exploration of rainfed rice farming in Uganda based on a nationwide survey: Regionality, varieties and yield. African Journal of Agricultural Research. 2013;8(29):4038-4048. doi:10.5897/AJAR12.121

8. Adejare FB, Unebesse CE. Water Stress Induces Cultivar Dependent Changes in Stomatal Complex, Yield and Osmotic Adjustments in *Glycine max* L. International Journal of Agricultural Research. 2008;3:287-295.

9. Briggs J, Twomlow SJ. Organic material flows within a smallholder highland farming system of Southwest Uganda. Agriculture, Eco-systems and Environment. 2002;89:191-212.

10. Haefele SM, Jabbar SMA, Siopongco JDLC, Tirol-Padre A, Amarante ST, Sta Cruz PC, Cosico WC. Nitrogen use efficiency in selected rice (*Oryza sativa* L.) genotypes under different water regimes and nitrogen levels. Field Crops Research. 2008;107:137-146. http://dx.doi.org/10.1016/j.fcr.2008.01.007

11. Wang D, Xu Z, Yu ZW, Zhang YL. Nitrogen accumulation and translocation for winter wheat under different irrigation regimes. Journal of Agronomy and Crop Science. 2012;191:439-449.

12. Okalebo JR, Gathua KW, Woomer PL. Laboratory methods of soil and plant analysis. A work manual published by the soil society of Easter Africa. 2002.

13. Akram HM, Ali A. Sattar A. Rehman HSU, Bibi A. Impact of water deficit stress on various physiological and agronomic traits of three basmati rice (*Oryza sativa* L.) cultivars. The Journal of Animal & Plant Sciences. 2013;23(5):1415-1423.

14. Sikuku PA, Netondo GW, Onyango JC, Musyimi DM. Effects of water deficit on physiology and morphology of three varieties of rainfed rice (*Oryza sativa* L.). Journal of Agricultural and Biological Science. 2010;5(1):23-28.

15. Street HE and Helgi O. The Physiology of Flowering plants: Their Growth and Development. 3rd Ed. Edward Arnold. 1984; 114-117.

16. Werner T, Nehnevajova E, Köllmer I, Novák O, Strnad M, Krämer U, Schmülling T. Root-specific reduction of cytokinin causes enhanced root growth, drought tolerance, and leaf mineral enrichment in Arabidopsis and tobacco. The Plant Cell. 2010;22:3905–3920, http://dx.doi.org/10.1105/tpc.109.072694

17. Campbell NA, Reece JB, Urry LA, Cain ML, Wasserman SA, Minorsky PV, Bradley JR. Biology. 8th ed. San Francisco: Pearson, Benjamin Cummings. 2008;827–830.

18. Matsumoto-Kitano M, Kusumoto T, Tarkowski P,Kinoshita-Tsujimura K, Václavíková K, Miyawaki K, Kakimoto T. Cytokinins are central regulators of cambial activity. Proceedings of the National Academy of Sciences of the USA. 2008;105:20027–20031, doi:10.1073/pnas.0805619105.

19. Siopongco JDLC, Sekiya K, Yamauchi A, Egdane J, Ismail AM, Wade LJ. Stomatal responses in rainfed lowland rice to partial soil drying: comparison of two lines. Plant Production Science. 2009;12: 17-28.

20. BRRI (Bangladesh Rice Research Institute). Master Plan of Five Year Research Programme of Bangladesh (2000-2005). Rice Research Institute, Gazipur. 2003.

21. Hussain I, Khan MA, Khan EA. Bread wheat varieties as influenced by different nitrogen levels. Journal Zhej University Science Biology. 2006;7(1):70-78.

22. McKersie BD, Ya'acov, YL. Stress and stress coping in cultivated plants. Kluwer Academic press, USA. 1994:148-177.

23. Purushothaman R, Krishnamurthy L, Upadhyaya V, Vadez HD, Varshney RK. Shoot traits and their relevance in terminal drought tolerance of chickpea (*Cicer arietinum* L.). Field Crops Research. 2016;197:10-27.

24. Rahman MT, Islam MT, Islam MO. Effect of water stress at different growth stages on yield and yield contributing characters of transplanted Aman rice. Pakistan Journal of Biological Science. 2002;5(2):169-172.

25. Bakul MRA, Akter MS, Islam MN, Chowdhury MA, Amin MHA. Water stress effect on morphological characters and yield attributes in some mutants T-Aman rice lines. Bangladesh Research Publication Journal. 2009;*3*(2):934-944.

26. Thomas U C, Varughese K, Thomas A. Response of upland rice to differential levels of irrigation, nutrients and seed priming. Journal of Aquatic Biology and Fisheries. 2013;2:775-779

27. Suresh K, Reddy N, Hemalatha S, Raju S, Madhulety T Y. Integrated nutrient management in rice: a critical review. International Journal of Plant production. 2013;2:34-39.

28. Roy BC, Leihner DE, Hilger TH, Steinmueller N. Tillering pattern of local and modern T. Aman varieties as influenced by nitrogen rate and management practices. Journal of Subtropical Agriculture Research and Development. 2004;2(2):6-14.

29. Bungard RA, McNeil D, Morton JD. Effects of nitrogen on the photosynthetic apparatus of *Clematis vitalba* grown at several irradiances. Australian Journal of Plant Physiology. 1997;24:205-214.

30. Bouman BAM, Toung TP. Field water management to save water and increase its productivity in irrigated lowland rice. Agricultural Water Management. 2001;49:11-30.

31. Mannan MA, Bhuiya MSU, Akhand MIM, Zaman MM. Growth and yield of Basmati and traditional aromatic rice as influenced by water stress and nitrogen level. Journal Science Foundation. 2012;10(2):52-62. http://dx.doi.org/10.3329/jsf.v10i2.17958

32. Kalamian S, Modares SAM, Sepehri A. Effect on of water deficit at vegetative and reproductive growth stages in leafy and commercial hybrids of maize. Agricultural Research Winter. 2006;5(3):38-53.

33. Hall AE, Schulze ED. Stomatal responses and possible interrelation between stomata: Effects on transpiration and carbon dioxide assimilation. Plant Cell Environment. 2004;3:467-474.

34. Lawson T, Oxborough K, Morison JIL, Baker NR. The responses of guard and mesophyll cell photosynthesis to CO_2, O_2, light, and water stress in a range of species are similar. Journal Experimental Botany; 2003;54:1743-52.

35. Yordanov I, Tsonev T, Velikova V, Georgieva K, Ivanov P, Petrova T. Changes in CO_2 assimilation, transpiration and stomatal resistance of different wheat cultivars experiencing drought under field conditions. Bulgalia Journal of Plant Physiology. 2001;27(3-4):20-33.

36. Waraich EA, Ahmed Z, Ahmad R, Shahbaz M. Physiological and biochemical attributes of *Camelina sativa* (L.) Crantz under water stress conditions Proceedings of the 17th ASA Conference, 20-24 September 2015.

37. Germ M, Kreft I, Stibilj V, Urbanc-Bericic O. Combined effects of selenium and drought on photosynthesis and mitochondrial respiration in potato. Plant Physiology and Biochemistry. 2007;45:162-167.

38. Tahir MHN, Imran M, Hussain MK. Evaluation of sunflower (*Helianthus annus* L.) inbred lines for drought tolerance. International Journal Agriculture and Biology. 2002;3:398-400.

39. Smith SE, Facelli E, Pope S, Smith FA. Plant performance in stressful environments: interpreting new and established knowledge of the roles of arbuscular mycorrhizal. Plant and Soil. 2010; 2010326:3-20.

40. Ghafoor A, Zahid MA, Ahmad A, Afzal M, Zubair M. Selecting superior mung bean lines on the basis of genetic diversity and harvest index. Pakistan Journal of Biological Science. 2008;3:1270-1273.

41. Farooq M, Wahid A, Kobayashi N, Fujita D, Basra SMA. Plant drought stress: Effects, mechanisms and management. Agronomy for Sustainable Development. 2009;29(1):185-212.