ISSN : 1812-5379 (Print)
ISSN : 1812-5417 (Online)
http://ansijournals.com/ja

JOURNAL OF AGRONOMY

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

OPEN ACCESS Journal of Agronomy

ISSN 1812-5379
DOI: 10.3923/ja.2017.65.75

Research Article

Effect of Witchweed (*Striga asiatica* L. Kuntze) Infestation and Moisture Stress on Selected Morpho-physiological Traits of Sorghum (*Sorghum bicolor* L. Moench) Genotypes in Zimbabwe

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Abstract

Background and Objective: Sorghum production is hampered by the parasite *Striga asiatica* and the recurring droughts due to climate change. However, the morphological and physiological effects of these two stresses are poorly understood. The aim of this study was to determine the effects of both abiotic and biotic factors occurring simultaneously on sorghum productivity. **Methodology:** Two pot experiments were set up to determine the effects of the two factors on the morpho-physiological traits of sorghum genotypes. A 2×2×5 factorial experiment laid down as a completely randomized design replicated 3 times was carried out twice at Bindura University of Science Education (BUSE) nursery. The first factor was water availability at two levels: 50 and 100% of Field Capacity (FC). *Striga asiatica* infestation was the second factor at two levels: Infested and uninfested and the third factor was sorghum genotypes at five levels. Sorghum chlorophyll content, Normalized Difference Vegetation Index (NDVI) and dry matter traits were analyzed using Genstat version 14 to compare treatments effects. **Results:** Watering at 100% FC gave the higher ($p<0.01$) NDVI across all the measured period. The results indicated that sorghum genotypes differed ($p<0.05$) sharply with respect to chlorophyll content and the NDVI with the genotype Mukadziusaende having the most chlorophyll and NDVI ($p<0.05$), whilst the least was wild sorghum. Generally, *Striga* infestation did not lower chlorophyll content when it co-occurred with drought stress. The chlorophyll content of genotypes Mukadziusaende, wild sorghum and Chiredhi was not significantly reduced by limited water availability. Mukadziusaende had the highest ($p<0.05$) head weight and head index. Infestation with *Striga* significantly reduced ($p<0.05$) head weight. **Conclusion:** Drought stress and *Striga* infestation had mutually exclusive effects on chlorophyll content and NDVI. However, both infestation and drought stress reduced head weight illustrating the two factors were synergistic on their effects on sorghum head weight.

Key words: Sorghum, moisture stress, *Striga asiatica*, field capacity, head weight

Received: September 27, 2016 Accepted: February 07, 2017 Published: March 15, 2017

Citation: Mandumbu Ronald, Mutengwa Charles, Mabasa Stanford and Mwenje Eddie, 2017. Effect of witchweed (*Striga asiatica* L. Kuntze) infestation and moisture stress on selected morpho-physiological traits of sorghum (*Sorghum bicolor* L. Moench) genotypes in Zimbabwe. J. Agron., 16: 65-75.

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Sorghum is an important cereal crop that feeds more than a third of the population in Southern Africa. One of the remarkable characteristics of sorghum is its drought tolerance and that has made it an important cereal grown for food and beverages in Sub Saharan Africa (SSA). Among the major constraints of sorghum production are drought and *Striga asiatica*. *Striga* is a parasitic weed that attaches itself to the roots of sorghum from where it draws its moisture and nutrient requirements thus inhibiting host plant growth, reducing yield and in severe cases, cause plant death. *Striga* affects the major crops that supply the bulk of the carbohydrate and protein needs of the poor who reside in SSA[1]. Scholes and Press[2] and Ejeta[3] reported that over 50 million hectares of arable farmland under cultivation with cereals and legumes are infested with one or more *Striga* spp., in SSA.

About a third of the world's agricultural land currently suffers from chronically inadequate water availability[4] and this situation is predicted to worsen[5]. Global warming, changes in rainfall abundance and frequency and severity of rainfall events may exert a significant pressure on agricultural water use, with several regions currently experiencing water deficits likely to face further shortages[6]. Infact, many of the world's poorest people farm in areas with inadequate and unreliable rainfall. Even in traditionally irrigated areas, water stress is becoming a serious threat to crop production due to water scarcity resulting from the growing and competing demands for water uses. Despite all this, agricultural productivity must be increased to provide food for the world's ever increasing population. Future food demand for the rapidly increasing population pressures is likely to further aggravate the effects of drought[7].

Under natural conditions, a combination of two or more stresses such as drought, salinity and heat are common to many agricultural areas around the world and impacts crop productivity[8]. Data on plant performance under a more complex environment where multiple stresses co-occur is fragmentary[9]. Cramer *et al.*[10], asserted that the major crops of the world are likely to be exposed to a wide range and a number of abiotic and biotic stress conditions as well as their combinations. Stress combinations represent one of the most critical challenges facing sorghum production today and improved theory and practice are needed for quantification of genotype responses. The molecular responses of plants to a combination of heat stress and drought is unique and cannot be directly extrapolated from the response of plants to stresses such as drought or heat when applied individually[11-14].

There has been contrasting responses of different plants to different stress combinations. Demirevska *et al.*[15] found that tobacco showed the same physiological responses to drought and heat and their combinations. In barley, the effect of drought or heat stress reduced plant growth with a more severe effect coming from drought. The combination of drought and heat stress reduced plant growth to a much greater extent than drought or heat applied individually[8]. However, Iyer *et al.*[16] reported that the response of *Medicago truncatula* showed contrasting responses to a combination of ozone and drought stress. Ozone stress caused development of chlorotic and necrotic tissue and drought alone caused wilting and collapse of leaves but a combination of the two stresses cancelled the effects of both stresses. Drought leads to stomatal closure and reduce the uptake of pollutants via stomata thereby ameliorating the effect of gaseous pollutants like ozone[17,18]. Actually Suzuki *et al.*[8] posited that some stress combinations might have beneficial effects compared with the occurrence of separate stresses. Understanding the limits of stress tolerance and acclimation to stress is of great importance and practical value in predicting the potential and released limits of plant productivity[19].

Wahid and Rasul[20] found that the major effect of drought is reduction in photosynthetic machinery and pre-mature leaf senescence culminating in reduction of food production. Drought stress produces changes in photosynthetic pigments and components[21] and diminishes the activities of the Calvin cycle enzymes which reduce yields[22]. According to Cramer *et al.*[10] the hormones abscisic acid (ABA) and ethylene have been found to be important regulators of plant responses to both abiotic and biotic stresses. *Striga* has been shown to increase ABA in infested maize and sorghum plants[23,24]. The ABA induces stomatal closure which allows a reduction in water loss and as a consequence, the maintenance of beneficial water potential. Farooq *et al.*[9] reported that the stoma close gradually as the drought progresses followed by the parallel decline in net photosynthesis. Studies done on maize have shown that drought stress leads to morphological, physiological and biochemical changes, including reduced photosynthesis[25,26]. Drought stress frequently enhances allocation of dry matter to the roots which enhance water uptake[27].

Although the sorghum crop has evolved appropriate stress tolerance strategies, they are largely incompatible with the exploitative root parasitic strategy of *Striga* spp.[28]. Given that global change involves a series of environmental factors occurring concurrently and changes in the severity of different stress factors, knowledge on how plants acclimate to multiple stresses is of key importance in understanding the effects of

the future climate on crops[29]. An urgent need to generate crops with enhanced tolerance to stress combinations therefore exists[8]. It is necessary to select for sorghum genotypes with enhanced tolerance to *Striga asiatica*, drought and their combinations. To determine the response of sorghum to a combination of abiotic and biotic stresses applied simultaneously, the effects of *Striga asiatica* parasite and drought on chlorophyll content, internode length, dry matter traits and productivity of sorghum were studied. A combination of drought and *Striga* stress represent conditions encountered by many cereal crops growing in the semi-arid environments of the sub tropical regions of Africa. It becomes necessary to select for sorghum genotypes with enhanced tolerance to drought and *Striga asiatica* and their combinations to ensure food security for the poorly resourced farmers.

MATERIALS AND METHODS

Experimental site: The pot experiments were carried out at Bindura University of Science Education (BUSE) Astra Campus nursery, Bindura (17° 18′ 58″ South and 31° 19′ 23″ East). Bindura is located 89 km North of the city of Harare. The soil type used was sandy with 4.3% clay content and a pH of 4.4. The area receives an annual rainfall of about 700 mm annum^{-1}, with an average temperature of 25°C in the summer months.

Seed sources: *Striga asiatica* seeds were obtained from Henderson Research Station (Weed Research team) at Mazoe in Zimbabwe. The seeds were collected from Chiwundura communal lands in the Midlands province in Zimbabwe from farmers' fields in the 2009 summer season. Sorghum seed was obtained from the GenBank at the Department of Research and Specialist Services in Harare. Wild sorghum seeds were collected from Gwebi Agricultural College Fields, 27 km West of Harare.

Experimental design and treatments: The experiment was a 2×2×5 factorial experiment laid down as a randomized complete block design replicated 3 times. The first factor was sorghum genotype at five levels, the second factor was infestation at two levels, which are infested and uninfested. The third factor was irrigation at two levels 50 and 100% of field capacity. The moisture level of 50% was included to mimic the low rainfall areas in SSA where total rainfall is usually bellow 400 mm and that is where *Striga* has deleterious effects. Irrigation scheduling was done using the 100% field capacity application. The experiment was repeated twice over time and denoted as experiments I and II.

Experimental procedures: Plastic pots with a height of 27 cm and diameters of 25 and 17.5 cm for the top and bottom, respectively were filled with 8 kg of soil. All pots had 6 drainage holes at the bottom. Half the pots were infested with 1 g of *Striga asiatica* seeds and mixed with the top 10 cm of the soil. Fertilizer was applied at a rate of 5 g maizefert (8 N: 14 P_2O_5: 7 K_2O) per pot. Top dressing was done at 4 weeks After Crop Emergence (WACE) by applying 2.5 g of ammonium nitrate (34.5% N). Ten sorghum seeds were planted and germinated after 6 days and were thinned to one plant per pot at 2 WACE. Weeds other than *Striga* were hand pulled as soon as they emerged.

Irrigation: The soil had its water holding capacity determined and half the pots were watered with water that gave the Field Capacity (FC) and the other by half that amount. To determine field capacity, five pots with the same oven dried soil with 6 drainage holes at the bottom were weighed and gradually filled with water until the addition of any extra water created a tiny flood layer. The pots were then left to drain freely for 48 h and weighed again. This method was according to Kabiri *et al.*[30]. The amount required to reach field capacity was 1.5 L pot^{-1}. The pots were irrigated to a moisture content of 100 and 50% field capacity according to Webster and Grey[31] and Chauhan and Johnson[32].

Data collection: Data collected during crop growth were:

- Normalized Difference Vegetation Index (NDVI), chlorophyll content and sorghum internode length. The NDVI was measured using a handheld greenseeker optical sensor unit (NTech industries, Inc., USA)
- Chlorophyll content was measured using a chlorophyll meter (SPAD 502, KONICA MINOLTA Incl)
- At the end of the experiment, head weight and total dry matter were determined using a sensitive scale. At crop maturity, the sorghum plants were harvested and partitioned into roots, leaves and stems. They were put in the drier at 104°C for 48 h for dry matter determination. A sensitive scale was used for mass determination
- Total dry matter constituted the total weights of roots, leaves, stems and head for each treatment
- Head, stem, leaf and root indices were computed as follows in Eq. 1:

$$HI = \frac{\text{Head weight}}{\text{Total dry mass}} \quad (1)$$

Statistical analysis: Data were analyzed using two-way analysis of variance followed by Genstat version 14. The values followed by the same letters were not significantly different and different letters within the treatments indicated significant differences at the 0.05 probability level.

RESULTS

Chlorophyll concentration and NDVI: Sorghum varieties differed sharply with respect to chlorophyll concentration ($p<0.01$). Across all the measured periods (6 and 10 WACE) in both experiments, the sorghum genotype Mukadziusaende gave the highest chlorophyll content and the least was recorded for wild sorghum (Table 1). At increased moisture availability, there were significantly higher ($p<0.005$) NDVI values compared to 50% FC across the measured periods in both experiments (Table 2).

At 10 WACE in experiment II, there was significant interaction of genotype and water availability on NDVI (Fig. 1a). For the genotype Chiredhi, higher NDVI were found at 100% FC compared to 50% FC. All the other genotypes had similar NDVI despite different moisture availabilities (Fig. 1a).

Chlorophyll content was not significantly affected by *Striga* infestation except at 6 WACE in experiment II (Table 3). Infestation did not affect chlorophyll content in experiment I and at 10 WACE in experiment II. At 6 WACE, uninfested sorghum had a significantly higher chlorophyll content compared to infested (Table 3).

The genotypes Mukadziusaende, wild sorghum and Chiredhi maintained the chlorophyll content despite variations in moisture availability. The chlorophyll concentration of genotypes Isifumbathe and SC Sila was significantly ($p<0.05$) lowered by reduced moisture availability (Fig. 1b).

Table 1: Sorghum genotypes effects on chlorophyll content at 6 and 10 WACE

	Chlorophyll concentration (mmol cm^{-2})			
	Experiment I		Experiment II	
Sorghum genotype	6 WACE	10 WACE	6 WACE	10 WACE
SC Sila	40.21±2.14^a	40.50±2.025^a	38.39±2.035^a	31.04±3.152^a
Mukadziusaende	43.00±2.14^a	47.23±2.025^b	42.33±2.035^b	33.55±3.152^a
Wild sorghum	34.90±2.14^b	36.30±2.025^c	32.39±2.035^c	29.78±3.152^a
Chiredhi	40.07±2.14^a	42.09±2.025^a	38.49±2.035^a	32.95±3.152^a
Isifumbathe	43.77±2.14^a	41.46±2.025^a	39.80±2.035^a	31.97±3.152^a

WACE: Weeks after crop emergence

Table 2: Moisture stress effects on NDVI at 6 and 10 WACE

	Experiment I		Experiment II	
Water availability	6 WACE	10 WACE	6 WACE	10 WACE
100% FC	0.525±0.067^a	0.594±0.0242^a	0.590±0.0242^a	0.528±0.0267^a
50% FC	0.464±0.067^b	0.523±0.0242^b	0.523±0.0242^b	0.464±0.0267^b

Table 3: Effect of *Striga* infestation on chlorophyll content

	Chlorophyll content (mmol cm^{-2})			
	Experiment I		Experiment II	
Striga infestation	6 WACE	10 WACE	6 WACE	10 WACE
Infested	40.99±1.359^a	41.54±1.295^a	36.73±1.458^a	31.35±1.994^a
Uninfested	39.79±1.359^a	41.59±1.295^a	39.80±1.458^b	32.37±1.994^a

Table 4: Effect of *Striga* infestation and moisture availability on root weight and root index

	Experiment I		Experiment II	
Parameters	Root weight (g)	Root index	Root weight	Root index
Striga infested	39.6±4.53^a	0.489±0.029^a	34.0±3.99^a	0.479±0.028^a
Uninfested	29.4±4.53^b	0.429±0.029^b	28.8±3.99^a	0.426±0.028^a
100% FC	41.4±4.53^a	0.464±0.029^a	37.4±2.28^a	0.448±0.028^a
50% FC	27.6±4.53^b	0.453±0.029^a	25.4±2.28^b	0.457±0.028^a

Table 5: Effect of sorghum genotypes on head weight and head index

	Experiment I		Experiment II	
Sorghum genotype	Head weight (g)	Head index	Head weight (g)	Head index
SC Sila	4.04±1.304[a]	0.0560±0.0266[a]	5.52±1.228[a]	0.0659±0.0211[a]
Mukadziusaende	8.12±1.304[b]	0.1650±0.0266[b]	8.05±1.228[b]	0.1446±0.0211[b]
Wild sorghum	0.44±1.304[c]	0.0050±0.0266[a]	1.96±1.228[c]	0.0207±0.0211[c]
Chiredhi	3.22±1.304[a]	0.0544±0.0266[a]	3.40±1.228[c]	0.0486±0.0211[ac]
Isifumbathe	1.85±1.304[ac]	0.0339±0.0266[a]	1.94±1.228[c]	0.0268±0.0211[dc]

Table 6: Effect of *Striga* infestation on head weight and head index

	Experiment I		Experiment II	
Striga infestation	Head weight (g)	Head index	Head weight (g)	Head index
Infested	2.31±0.825[a]	0.0385±0.0168[a]	2.83±0.777[a]	0.0432±0.0134[a]
Uninfested	4.76±0.825[b]	0.0874±0.0168[b]	5.52±0.777[b]	0.0795±0.0134[b]

Table 7: Effect of water availability on head weight and head index across the two experiments

	Experiment I		Experiment II	
Striga infestation	Head weight (g)	Head index	Head weight (g)	Head index
FC 100%	4.93±0.825[a]	0.0755±0.034[a]	6.14±0.777[a]	0.777±0.0133[a]
FC 50%	2.14±0.825[b]	0.0504±0.034[a]	2.21±0.777[b]	0.045±0.0133[b]

Internode length: Sorghum internode length was significantly lowered by infestation ($p<0.01$). The uninfested sorghum genotypes gave a longer internode lengths compared to infested ones (Fig. 2).

A significant interaction of *Striga* infestation and drought ($p<0.01$) showed that under *Striga* infestation, internode length was the same both for 100 and 50% FC, whilst under non infested conditions, 100% FC increased sorghum internode compared to 50% FC (Fig. 3).

Dry matter traits: Head weight and head index were significantly affected by sorghum genotype across the two experiments (Table 4). Head weight was highest on the genotype Mukadziusaende with head index of 0.16 and 0.45 in experiment I and II, respectively. The least head weight and head index was recorded for wild sorghum in both experiments (Table 5).

The results revealed that infestation significantly reduced head weight and head index in both experiments. Non infestation led to increase in head weight and head index in both experiments (Table 6).

Increased water availability significantly increased head weight and head index in both experiments except head index in experiment I (Table 7). Increased moisture availability significantly increased ($p<0.05$) head weight for SC Sila and Mukadziusaende, whilst the rest of the sorghum genotypes did not respond to water availability (Fig. 4).

The yield of wild sorghum, Chiredhi and Isifumbathe was not affected by water availability. However, yields of SC Sila and Mukadziusaende were lowered by reduced moisture availability although they remained higher than the other genotypes (Fig. 5). The yield of Mukadziusaende at 50% water availability was still higher compared to wild sorghum at 100% FC (Fig. 5).

In experiment II, leaf index, stem weight and stem indices were significantly affected by sorghum genotypes (Table 8). However, SC Sila had a significantly ($p<0.01$) higher dry weight and the least was Mukadziusaende and the trend was repeated for experiment II (Table 8). Infestation did not affect leaf weight, leaf index, stem weight and stem index and total dry matter for both experiments (Table 9). However, irrigation at 100% field capacity gave a significantly higher leaf weight, leaf index, stem weight, stem index and total dry matter in both experiments (Table 10).

There was a significant effect of infection and drought on leaf index ($p<0.05$) (Fig. 6). Under infestation, 100% irrigation had a lower leaf index compared to 50% and under infestation there were no significant differences (Fig. 6). There was a significant interaction of variety and *Striga* infestation on stem dry matter ($p<0.05$). Stem weight of wild sorghum was reduced by *Striga* infestation ($p<0.05$) whilst it was vice versa for Chiredhi (Fig. 6).

Table 8: Effect of sorghum genotypes on leaf dry matter, leaf index, stem weight and index and total dry matter in both experiments

	Experiment I					Experiment II				
Sorghum genotype	Leaf index	Leaf dry matter (g)	Stem weight (g)	Stem index	Total dry matter (g)	Leaf weight (g)	Leaf index	Stem weight (g)	Stem index	Total dry matter (g)
SC Sila	0.1970±0.028[a]	14.54±1.754[a]	21.2±3.2[a]	0.284±0.032[a]	78.4±9.21[a]	14.92±1.684[a]	0.2055±0.024[a]	19.00±2.91[a]	0.262±0.034[a]	75.8±7.83[a]
Mukadziusaende	0.1888±0.028[a]	9.20±1.754[b]	15.9±3.2[a]	0.312±0.032[a]	49.7±9.21[b]	8.85±1.684[b]	0.1767±0.024[a]	14.84±2.91[a]	0.291±0.034[a]	49.8±7.83[b]
Wild sorghum	0.2028±0.028[a]	16.81±1.754[a]	18.4±3.2[a]	0.248±0.032[a]	76.3±9.21[a]	15.70±1.684[a]	0.2314±0.024[a]	17.12±2.91[a]	0.238±0.034[a]	71.5±7.83[a]
Chiredhi	0.1972±0.028[a]	14.62±1.754[a]	22.9±3.2[a]	0.293±0.032[a]	77.9±9.21[a]	13.32±1.684[a]	0.1954±0.024[a]	21.27±2.91[a]	0.303±0.034[a]	71.4±7.83[a]
Isifumbathe	0.2220±0.028[a]	15.94±1.754[a]	18.4±3.2[a]	0.248±0.032[a]	74.1±9.21[a]	12.91±1.684[a]	0.1925±0.024[a]	19.30±2.91[a]	0.292±0.034[a]	66.7±7.83[a]

Table 9: Effect of *Striga* infestation on leaf weight and index, stem weight and index and total dry matter in both experiments

	Experiment I					Experiment II				
Striga infestation	Leaf weight (g)	Leaf index	Stem weight (g)	Stem index	Total dry matter (g)	Leaf weight (g)	Leaf index	Stem weight (g)	Stem index	Total dry matter (g)
Infested	14.63	0.205±0.018[a]	19.4±2.03[a]	0.267±0.014[a]	75.9±5.82[a]	13.48±1.06[a]	0.2028±0.015[a]	17.99±1.84[a]	0.269±0.02[a]	68.3±4.95[a]
Uninfested	13.82	0.197±0.018[a]	19.3±2.03[a]	0.287±0.014[a]	66.7±5.82[a]	12.80±1.06[a]	0.1978±0.015[a]	18.62±1.84[a]	0.285±0.02[a]	65.7±4.95[a]

Table 10: Effects of water availability on leaf weight and index, stem weight and index and total dry matter

	Experiment I					Experiment II				
Water availability	Leaf weight (g)	Leaf index	Stem weight (g)	Stem index	Total dry matter (g)	Leaf weight (g)	Leaf index	Stem weight (g)	Stem index	Total dry matter (g)
FC 100%	15.81±1.109[a]	0.1947±0.0176[a]	22.1±2.03[a]	0.266±0.302[a]	84.2±5.82[a]	15.08±1.065[a]	0.1943±0.015[a]	21.30±1.842[a]	0.269±0.02[a]	79.9±4.95[a]
FC 50%	12.64±1.109[b]	0.1922±0.0176[a]	16.6±2.03[b]	0.287±0.302[b]	58.4±5.82[b]	11.20±1.065[b]	0.2063±0.015[a]	15.32±1.842[b]	0.285±0.02[a]	54.1±4.95[b]

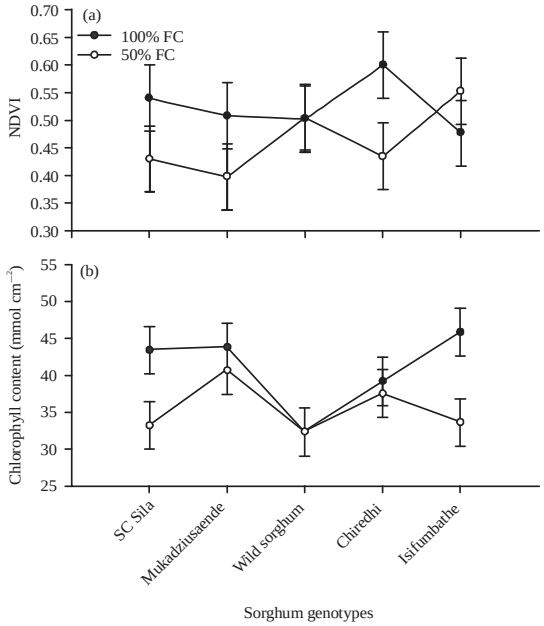

Fig. 1(a-b): Interaction effects of sorghum genotype and moisture availability on (a) NDVI at 10 WACE and (b) Chlorophyll concentration at 6 WACE in experiment II

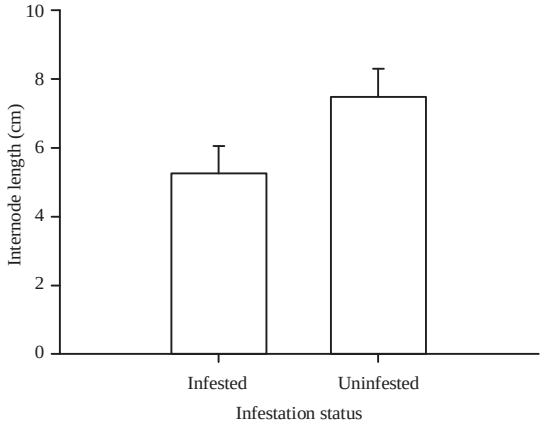

Fig. 2: Effect of *Striga* infestation on internode length

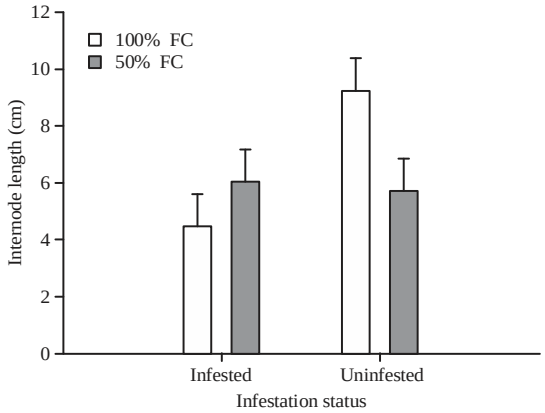

Fig. 3: Interaction effects of *Striga* infestation and water availability on sorghum internode length

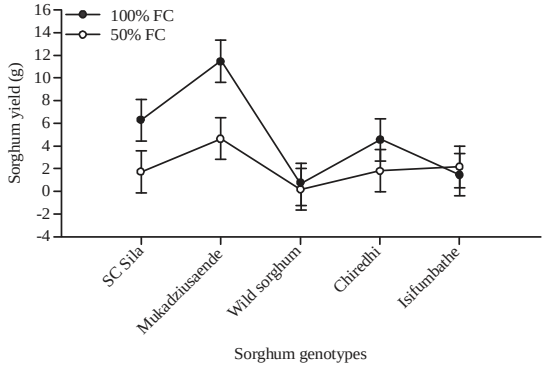

Fig. 4: Response of sorghum genotypes yield to moisture availability

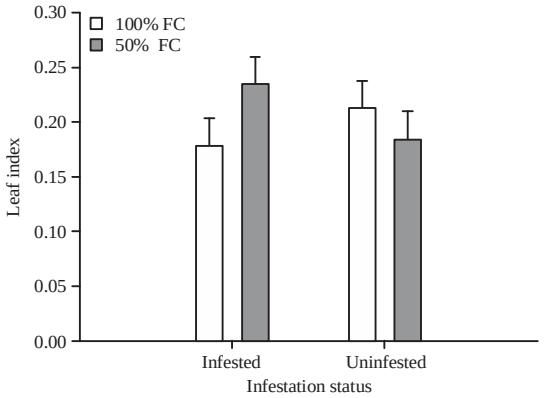

Fig. 5: Interaction effects of water availability and *Striga* infestation on leaf index in experiment I

DISCUSSION

The objective of the study was to determine the effects of both abiotic and biotic factors occurring simultaneously on sorghum productivity. The sorghum genotype Mukadziusaende had the highest chlorophyll concentration of 47.33 mmol cm^{-2} and the least was recorded for wild sorghum with 29.78 mmol cm^{-2}. This trend for chlorophyll concentration was the same for both experiments. These values are in the range commensurate with Gurney *et al.*[33] findings, where a maximum of 47.44 and a minimum of 32.33 mmol cm^{-2} were reported.

Chlorophyll concentration was lowered by moisture deficit when irrigated at 50% FC compared to 100% FC (Table 2) but was not affected by infestation (Table 4). This

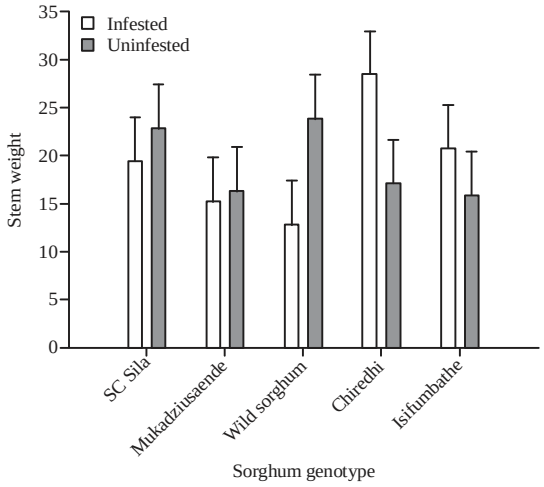

Fig. 6: Interaction effects of sorghum genotypes and *Striga asiatica* infestation on stem weight

contrasts with the findings of Gurney *et al.*[33], where *Striga asiatica* infestation alone reduced chlorophyll concentration. Similar results were also found by Wahid and Rasul[20] and Fu and Huang[22] who reported that drought impairs the photosynthetic machinery of the plant which eventually reduces food production. Likewise, Anjum *et al.*[21] also reported changes in photosynthetic pigments and their components as a result of drought. According to Niinemets[29] measurements of chlorophyll provides an important tool to gaining insight into modifications of foliage physiological activity. The sensitivity of photosynthesis to both biotic and abiotic stress varies with plant genotype tolerance. This study revealed that sorghum genotypes vary greatly with respect to chlorophyll concentration when exposed to the same environmental limitations. Palta *et al.*[34] and Zhang *et al.*[35] reported that water deficits result in early senescence which results in reduced chlorophyll concentrations. The results of this study suggested that drought stress takes precedence over *Striga asiatica* stress when they co-occur in sorghum. This may be attributed to the fact that water has to be available prior to *Striga asiatica* infestation in sorghum. The results may also suggest that the two are mutually exclusive on their effects on chlorophyll concentration in sorghum.

The responses of sorghum genotypes to chlorophyll content under 50 and 100% FC tended to differ (Fig. 1a). The genotypes Mukadziusaende, wild sorghum and Chiredhi had similar chlorophyll content at both irrigation regimes but lowered in SC Sila and Isifumbathe genotypes by reduced water availability. Similar results were found by Gurney *et al.*[33] who reported a maize variety, 'Staha', whose foliar chlorophyll concentration was unaffected by the parasite. In the current study, it was hypothesized that the genotypes Mukadziusaende, wild sorghum and Chiredhi showed resilience to both stresses hence photosynthesis can be maintained in these genotypes despite the presence of both stresses which may help maintain sorghum productivity. This may be due to the relative sensitivity of the genotypes towards drought. According to Cameron *et al.*[36], it is known that the responses of the genotypes to reduced water availability might be high osmotic adjustments that help maintain leaf water potential. Bloom *et al.*[37] reported that even in limited supply of resources, plants have to maintain a balanced investment such that all functions and organs are limited to the same degree. Across all the two experiments, NDVI was higher at 100% FC compared to 50% FC. The NDVI is a measurement of amalgamated plant growth that reflects various plants growth factors and is highly correlated with plant available soil moisture[38]. For the genotypes SC Sila, Mukadziusaende, wild sorghum and Isifumbathe, NDVI was lowered by drought treatments. Bjorkman and Powles[39] reported that the effect of *S. asiatica* on both photosynthetic performance and photo-inhibition of maize plants under light conditions is similar to the effects observed when abiotic factors such as water shortage are imposed. For the genotype Chiredhi, NDVI was higher at 100% moisture compared to 50%, whilst the rest of the genotypes were not affected. Irrigation at 50% of field capacity could have limited nitrogen assimilation and consequently lowered chlorophyll concentration in the affected genotypes.

Under infested conditions, moisture availability did not affect internode length but 100% FC under uninfested conditions increased internode length (Fig. 3). The fact that drought reduces internode length in sorghum is in tandem with Deligoz and Gur[40] findings who reported that drought stress causes physiological and metabolic changes which negatively affects growth and development of plants. Actually, Farooq *et al.*[9] reported that growth is accomplished by cell division, enlargement and differentiation. Nonami[41] posited that under water deficient conditions, cell elongation can be inhibited by interruption of water flow from xylem vessels to surrounding cells. This study revealed that in relation to internode length, the effect of reduced water availability is equal to the effect of *Striga*. Under 50% FC, non infested sorghum could not grow and it only grew when water was made available at 100% FC.

Striga infestation increased dry matter allocated to the roots in experiment I but had no effect on experiment II. This agrees with Poorter *et al.*[42], reported that plants allocate more dry matter to the roots as the limiting factor is bellow the ground. Similar results were also found by Farooq *et al.*[9] and Liu *et al.*[43]. The results indicated that root dry mass decreased

under drought were also found by Luttschwager *et al.*[44], found decreased root mass under drought in *Populus tremula*.

Head weight and head index were lowered by infestation and drought (Table 7, 8). The results are in tandem with the findings of Barker *et al.*[45] and Vasey *et al.*[46] in which infestation reduced dry matter allocated to the head. Similar results were found by Pandey *et al.*[47], found that the harvest index was lowered by increased water stress. Groene[48] concurs with the assertions and reported that drought has an effect on pollen viability, pollen tube germination and increases in ovule abortion rates as a result of reduction in assimilate supplies which are required for grain development. According to Ober *et al.*[49], water stress resulted in diminished grain set and kernel growth in wheat and decreased rate of endosperm cell division. *Striga asiatica* causes increases in abscisic acid[23,24]. Also, increases in ABA concentration as a result of drought has been previously documented by Aldesuquy and Ibrahim[50] and Gniazdowska *et al.*[51]. Cramer *et al.*[10], asserted that ABA is an important regulator of plant responses to both abiotic and biotic stresses. Both drought and *Striga* infestation have been reported to lead to an increase ABA production and consequently cause stomatal closure reducing carbon dioxide entrance into the leaf hence reduced productivity.

Leaf and stem indices were not affected by sorghum genotypes (Table 9) and infestation (Table 10) whereas they were both reduced by irrigation at 50% of field capacity. The results of this study were in disagreement with the findings of Aflakpui *et al.*[52], found that *Striga* infestation reduced leaf and stem indices. However, their study on maize was subjected to *Striga* only, whereas in this study, drought was also a factor that was added to *S. asiatica* infestation. Taken together, these results indicated that the response of sorghum to *S. asiatica* and drought is complex and cannot be extrapolated from the results of each stress applied singly. This confirms the assertion by Mittler[14] that two or more stresses may require a unique response on the hosts and that the responses may have synergistic or antagonistic effects on each other. From these results, drought effects got preference when they co-existed with *Striga* infestation. The simultaneous occurrence of different biotic and abiotic stresses was shown to result in a high degree of complexity in plant responses as the responses to these combined stresses are largely controlled by different signaling pathways that may interact or inhibit one another[53,54].

Consequently, the fact that drought only had a significant influence on leaf and stem biomass indicated that its influence was greater than that of *S. asiatica* or the response pathways to drought suppresses the effects of *S. asiatica*. The effects of *S. asiatica* are inhibited when it co-exists with drought in sorghum. Our results confirmed the findings of Urwin[55] that plants respond in a specific manner when they have to face more than one stress simultaneously and the response cannot be predicted based on the plant's response to the individual stresses.

Leaf index was higher under infested conditions at 50% irrigation compared to uninfested (Fig. 3). This demonstrated that the two stresses resulted in more dry matter being channeled to the leaves. These results confirmed the assertion by Suzuki *et al.*[8] that stress combinations might have beneficial effects on plants compared to each stress applied separately.

Stem weight was not significantly affected by infections for all varieties except for wild sorghum where infection lowered stem weight but increased stem weight for Chiredhi. Reduced allocation of dry matter to the stems combined with increased allocation to the roots was reported by Frost *et al.*[23] and Graves *et al.*[56]. It is now known that the parasite acts as a sink for carbon, inorganic solutes and water and also because of the reduced carbon gain in infested hosts as reported by Smith *et al.*[57] and Cechin and Press[58]. Under infestation, reduced water availability increased leaf index and this is likely an issue of overcompensation.

CONCLUSION

The results of this study showed the impact of both *Striga asiatica* and moisture stress on sorghum physiological and morphological traits. Sorghum is a very important crop in Zimbabwe's small holder sector and in the semi- arid climates. In these experiments we could notice the effects of both infestations and moisture stress on both NDVI and chlorophyll concentration. At the end of the experiment we noticed that the sorghum variety Mukadziusaende still yielded despite being subjected to both stresses. The most vulnerable was wild sorghum and hence it means it can not be used as a source of resistant traits during breeding for the studied traits. The results also show the commercial cultivar SC Sila was highly susceptible to both stresses. The implications of this study to sub Saharan Africa is to increase water availability through irrigation systems as that can reduce the effects of the parasite.

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