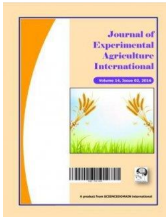

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Amaranth Response to Water Stress

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Authors' contributions

This work was carried out in collaboration among all authors. Authors JGS, AB and JPMA conducted the experiment. Authors JGS and AB wrote the first draft of the manuscript. Author AB was the mentor of the idea. Authors AB, FAL and MFM discussed the results, correct and improve the writing of the manuscript. Author PMCC wrote the final version of the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

Amaranth is a species that has rapid growth, tolerates drought and produces grains of high food value. In this work the potential for dry season cropping in the Brazilian savannah of two amaranth species (*Amaranthus caudatus* e *Amaranthus cruentus*) was studied, subjecting them to three different periods of water availability at the beginning of the crop. Weekly data were collected on height, dry matter mass of shoot, panicle and roots, and at the end of the cultivation, yield, harvest index, thousand-grain weight, water-productivity. It was also determined the falling plant estimation. In the dry matter production evaluation, it was observed that the water deficit caused the reduction of the shoot, but significant increase of the root. The *A. caudatus* Inca did not show a significant productivity difference between the treatments, with a mean of 1,591.0 kg ha^{-1} and reached harvest

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point at 63 days. The *A. cruentus* BRS Alegria had better productivity in the treatment without water restriction, average of 2,008.6 kg ha^{-1} and reached harvest point at 86 days. Both species have potential for dry season cropping in the Brazilian savannah.

Keywords: Amaranthus caudatus INCA; Amaranthus cruentus BRS Alegria; dry season cropping; water deficit; Brazilian Savannah.

1. INTRODUCTION

The use of new plant species is important for crop diversification, since only five species (rice, potato, maize, soy and wheat) form the basis of world food for human. In this context, *Amaranthus* sp. is an alternative, since it has a high protein value with balanced amino acid, close to the ideal for human nutrition [1], being rich in lysine, arginine and histidine [2,3].

Another appeal to the consumption of amaranth is in the gluten-free, and for this reason, amaranth flour has received, in recent years, considerable attention as an interesting source for the formulation of gluten-free products, due to its high nutritional value and free from prolamins, which lead to gluten intolerance, toxic to celiac [4].

From the agronomic point of view, amaranth stands out as an option to diversify grain cultivation in the Brazilian savannah. Although the region has experienced rapid growth in agriculture, it is based mainly on soya, cotton, maize and, to a lesser extent, on beans [5]. Experiments with amaranth demonstrated their potential for cultivation for both soil protection and grain production in the Brazilian savannah [6].

According to Achigan-Dako et al. [7] *Amaranthus* sp was found as a promising food crop, mainly due to its resistance to heat, droughts, diseases and pests, and the high nutritional value of its seeds and leaves. However, although this genus of plant is highly tolerant to adverse environmental conditions, including poor soils, lack of water and severe defoliation, field yields are generally lower than those produced by cereals [8]. Under rainfed conditions in the Uttarakhand hills of India, Shukla et al. [9] recorded yield of 1,117 kg ha^{-1} of *A. hypochondriacus* grains.

A. caudatus, of Andean origin, possess lower adaptability in regions of tropical climate under high temperatures [10], but has showed high grain yields in the Brazilian savannah of 1,892 kg ha^{-1} [11]. *A. cruentus* has been adapted to the crop in Brazil, especially to the Brazilian savannah, with favorable agronomic performance, both in biomass production and in grain production [12], with a yield of 1,886 kg ha^{-1} [11].

Faced with the scarcity of information on the effect of water stress on the development of amaranth crop, the objective of this work was to evaluate the effect of water restriction on the production of *A. caudatus* Inca and *A. cruentus* BRS Alegria under climatic conditions of the Cuiabana lowland of Mato Grosso state.

2. MATERIALS AND METHODS

The work was developed at the Experimental Farm of the Federal University of Mato Grosso, Brazil, (15°51' S, 56°04' W) at 140 masl. The climate of the region, according to the classification of Köppen [13], is Aw, with mean monthly temperature between 22.0°C to 27.2°C and average annual rainfall of 1,320 mm.

The experimental design was a randomized block design, in a 3 x 2 factorial scheme (three periods of irrigation x two species of amaranth), making a total of six treatments, with three replications. The 36.0 m^2 plots consisted of five rows of plants, twelve meters long, spaced 0.5 m [12], and 0.2 m between plants in the row. The chemical analysis (0-20 cm depth) of the soil revealed the following results: pH in $CaCl_2$=4.9; P=9.2 mg dm^{-3}; K=36.00 mg dm^{-3}; Ca^{2+}+Mg^{2+}=2.5 $cmol_c dm^{-3}$; Al=0.0 $cmol_c dm^{-3}$; H+Al=3.5 $cmol_c dm^{-3}$ and V = 42.9%.

Seeding was carried out with a manual seeder on June 26, 2014, using seeds of *A. cruentus* with BRS Alegria cultivar, developed by EMBRAPA [12] and *A. caudatus* with the Inca variety. These seeds were stored in a refrigerated chamber (17 ± 2°C) until sowing, with 94 and 98% germination, respectively, for *A. cruentus* and *A. caudatus* by Rules for Seed Analysis method [14]. The irrigations were in the morning by a conventional sprinkler irrigation system, using sector sprinklers, which allowed irrigation of the plots individually. The evaluation of water distribution uniformity was performed according to Christiansen [15]. Soil water was maintained close to field capacity and monitored by soil moisture determination equipment, with probes permanently installed at 150 mm and 300 mm depth in all plots.

The plants emerged five days after sowing and, weekly, were evaluated: plant height, dry mass of plants, panicles and roots, and stem diameter at 50 mm height. At the end of the cultivation, grain yield, water-productivity, thousand-grain weight [14] and harvest index were evaluated [16]. Harvesting was manually, when the panicles were mature, in the two central lines of each plot, covering an area of 1.5 m^2.

Characteristics such as thin and flexible stem facilitate the tipping of plants, especially in plants with longer cycles [17], mainly in environments with higher frequency and intensity winds. Thus, for the amaranth, a formula was developed to estimate the risk of plant falling, considering as flexion-promoting magnitudes the bending moment, defined by plant height (h) and panicle mass (PM) and, such as magnitudes of flexion-resistance, the stem diameter of the plant (d) and the shoot mass (SM), with values from 0 to 100, in which the closer to 100 the greater the possibility of falling and the near to zero the lowest chance of occurrence of falling, according to Expression 1:

$$FPE = \frac{h\,MP}{d\,SM} \qquad \text{(Expression 1)}$$

Where,

FPE = Falling Plant Estimation (dimensionless);

h = plant height (mm);

PM = panicle mass (g);

d = stem diameter of the plant (mm); and

SM = shoot mass without the panicle (g).

In addition, this formula was developed due to the conformation of plants with dominant panicles, located at the apex, with relatively large masses in relation to the rest of the plants (Fig. 1) and which may facilitate plant falling, an undesirable characteristic because it makes harvesting difficult and reduces crop yields.

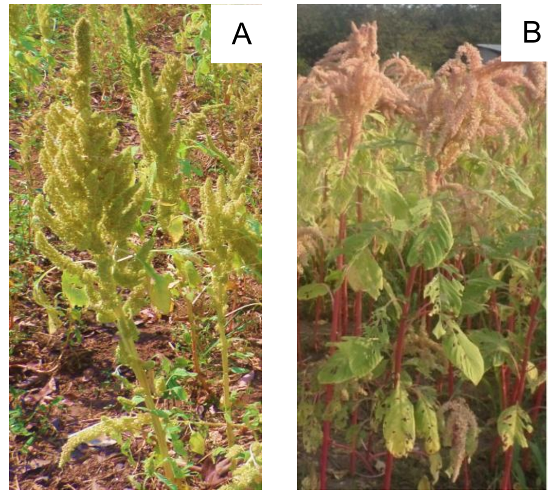


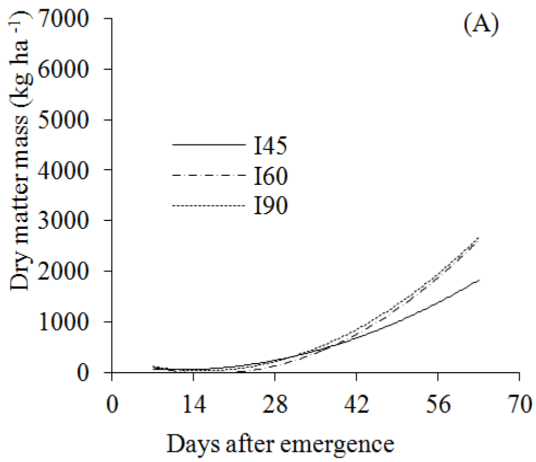
Fig. 1. *Amaranthus caudatus* Inca (A) and *Amaranthus cruentus* BRS Alegria (B) plants in the harvest point, evidencing the panicles

3. RESULTS AND DISCUSSION

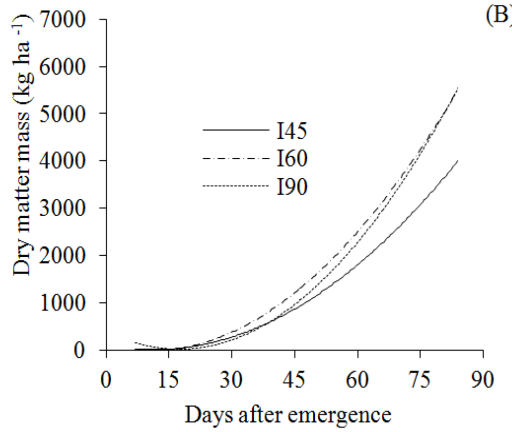
Because *A. caudatus* showed a smaller cycle among the species studied, 63 days did not show variation in most of the evaluated agronomic attributes. In contrast, the species *A. cruentus* presented a different behavior, being more demanding about the availability of water during the productive cycle.

The applied water stress caused reductions in the dry matter accumulation in both species studied, being the lowest for irrigated treatment up to 45 DAE (days after emergence) (Fig. 2). This is due to the fact that plants stressed due to lack of water tend to perform a lower rate of cell division, thus reducing leaf production, providing a lower accumulation of dry matter at the end of the cycle [18,19].

The dry matter accumulation for *A. cruentus* in irrigated treatments up to 60 DAE, about 5,492 kg ha^{-1}, was similar to the 6,120 kg ha^{-1} obtained by the plants that did not undergo water restriction (Fig. 2), which shows that 60 days of soil moisture are sufficient for the plant to accumulate enough dry matter to reach the maturity of the grains. However, for the treatments with suppression of irrigation at 45 days, it suffered a significant reduction in accumulated dry matter, with averages of 3,940 kg ha^{-1}. The value of biomass produced, of 6,120 kg ha^{-1}, can be, according Erasmo et al. [2], used in no-tillage system, in the region of Brazilian savannah, as dry season cropping, due to stability of grains and biomass production.



I45= 0,659**x^2 - 14,531**x + 126,99
R^2 = 0,95
I60=1,250**x^2 - 42,561*x + 338,17
R^2 = 0,98
I90=1,174**x^2 - 36,456x + 311,31
R^2 = 0,81



I45= 0,759**x^2 - 16,927**x + 100,94
R^2 = 0,99
I60=1,247**x^2 - 43,414*x + 391,57
R^2 = 0,97
I90=1,011**x^2 - 20,099**x + 68,357
R^2 = 0,98

Fig. 2. Shoot dry matter mass of the *Amaranthus caudatus* (A) e *Amaranthus cruentus* (B) plants subjected to irrigation up to 45 days (I45), up to 60 days (I60) and during the whole cycle (I90)

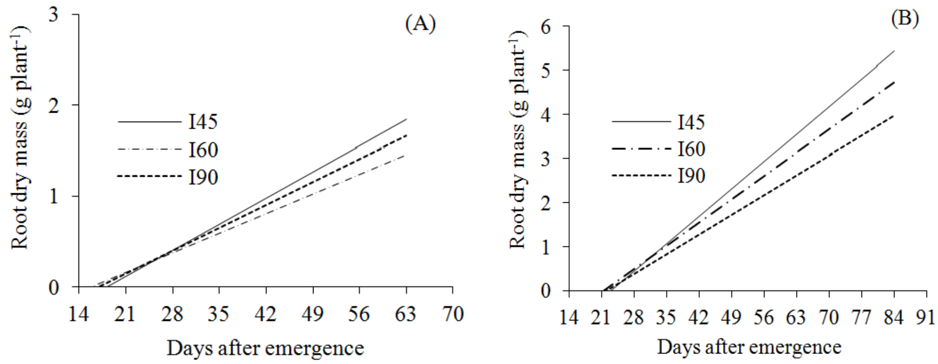
*** Significant at 1% probability, according to the analysis of variance and regression*

The *A. caudatus*, due to its smaller size, reached lower dry mass values than the other species studied, but the behavior was similar, with production of biomass about 2,284.51 kg ha^{-1} and 2,350.35 kg ha^{-1} for 60 and 90 days of water supply, which differentiated from the 1,947.15 kg ha^{-1} of dry matter produced with only 45 days of irrigation. It was noticed for this species (*A. caudatus*), after the fruiting, a tendency of the plants to drop, by senescence, the lower leaves when submitted to the water stress. This may also explain the fact that treatment with suppression of irrigation at 45 days showed a reduction in accumulated mass at 63 days, a fact that did not occur when irrigation was maintained beyond this date.

Root growth with water restriction was altered for both *A. caudatus* and *A. cruentus* (Fig. 3). Under these circumstances, the tendency of the plant roots were grow to lower, more moist soil layers until the water supply is exhausted in the environment [18]. If water has been available, as in the treatment with full irrigation, the plants would concentrate their roots in the superficial layers, where the growth is easier, with the expenditure of less energy.

Increasing the amount of root during drought helps the plant to obtain water at deeper levels in the soil profile, as well as helping to avoid water deficits in the more superficial layers of the soil [20]. When in an adverse situation of water deficiency, the plants prioritize greater allocation of photoassimilates to the roots, favoring the search for moisture and less water loss due to transpiration, if it were invested in the increase of aerial part.

The possibility of tipping the amaranth increased with the development of the plant because the mass of its panicle grew at the same time as the plant continued to grow, as shown in Fig. 4. The *A. caudatus* and *A. cruentus*, respectively, got emergence of panicles at 28 and 42 DAE, reaching 44.18% and 36.95% of the shoot matter mass of the plant at the time of harvest. In this sense, because the panicle is in the apex of the plant, the higher the plant and the heavier the panicle were, the greater was the falling plant estimation.



I45= 0,041**x - 0,7411 R^2 = 0,63
I60= 0,031**x - 0,485 R^2 = 0,78
I90= 0,036**x - 0,609 R^2 = 0,69

I45= 0,089**x - 2,031 R^2 = 0,72
I60= 0,0751**x - 1,588 R^2 = 0,87
I90= 0,064**x - 1,384 R^2 = 0,83

Fig. 3. Root dry mass per plant of the *Amaranthus caudatus* (A) e *Amaranthus cruentus* (B) subjected to irrigation up to 45 days (I45), up to 60 days (I60) and during the whole cycle (I90)
*** Significant at 1% probability, according to the analysis of variance and regression*

The Falling plant estimation (FPE), proposed in this work, seemed to be sensitive to the variables used, due to its increasing and quadratic behavior (Fig. 4), consistent with what was observed during the development of the studied plants. In the presence of winds, a bending moment appears that is a direct function of the plant height and the panicle mass. The plant height had quadratic response, as a function of time, and the panicle mass had linear response, thus, the bending moment had quadratic behavior as well.

It is observed that in this work that the FPE for *A. caudatus* was larger than *A. cruentus* and perceptible values appeared earlier, because it had an earlier develope cycle, developed proportionally larger panicles, and reached maturation earlier. However, the FPE depends on other factors than the species and water availability, such as fertilization, density and time of sowing, as well as occurrence of winds.

The thousand-grain weight was not affected by the water stress, but there was a significant difference between the studied species (Tukey test ($p < 0.05$)). The *A. caudatus* seeds had a mean of 863 mg, higher than that found for *A. cruentus*, which presented a mean of 780 mg. These data lead us to infer that the species *A. caudatus* has grains of greater diameter and thickness when compared to *A. cruentus*.

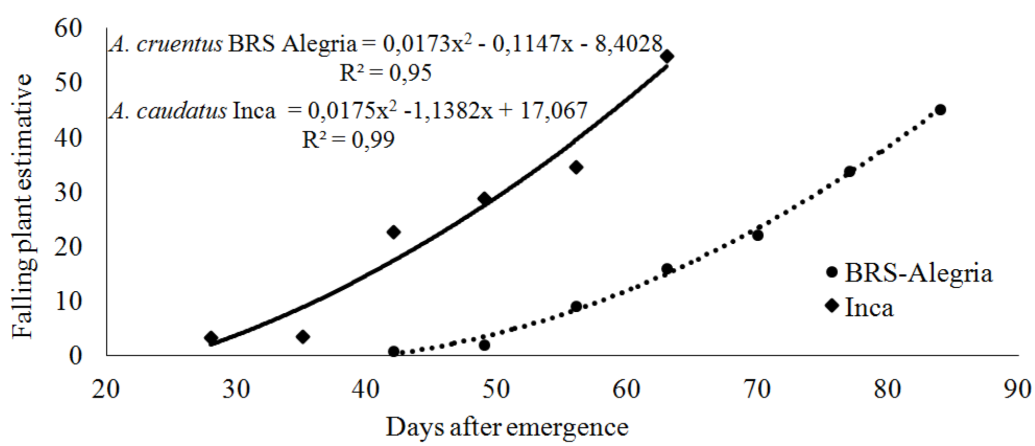


Fig. 4. Falling plant estimation (dimensionless) of the *Amaranthus caudatus* Inca and *Amaranthus cruentus* BRS Alegria, regardless of the water availability time

These values were near to the obtained for other researchers for *A. cruenthus* BRS Alegria. Spehar et al. [12] found, under Brazilian savannah conditions of cultivation, a mass of 680 mg. In Croatia, Pospisil et al. [21] obtained, in three consecutive years, mean values varying from 702 to 757 mg. In another field study, by Gimplinger et al. [3], in the extreme west of Austria, a mass of 670 mg was obtained. These data show little variation in the thousand-grain weight for this species and allow to infer that this characteristic for this species should be close to 700 mg. No data was found for *A. caudatus* Inca.

Productivity presented at least one cause of significant variation and the unfolding of the interaction between water regime and species for productivity is shown in Table 1. Comparing the species within the water regime, it was observed that in the suspension of irrigation at 45 days, *A. caudatus* was superior to *A. cruentus*, with higher productivity. The productivity of the two amaranth species did not differ when water was available up to 60 DAE. However, water supply up to 90 days favored *A. cruentus* in yield, which was 25% higher than that of *A. caudatus*.

A. caudatus was able to express its productive potential with only 45 days of water supply, showing that this species is tolerant to end-of-cycle water stress because it did not suffer a significant drop in grain production, in relation to other water regimes, even though it presented lower total mass accumulation than the other stress regimes (Fig. 2).

Another important factor is that the plant can save water for use in later periods, for example to achieve seed production [22]. Thus, the effects on grain production were attenuated, and there was no significant difference between treatments of water stress in *A. caudatus*. Another important factor is the stage of development that the water stress occurred, at 45 DAE, and *A. caudatus* was already in full anthesis, which prevented the productivity decrease [23]. Considering these results, it may be recommended to use *A. caudatus* for late cultures during the dry season cropping.

When the water was supplied for 60 and 90 DAE there was no difference in the yield of this species, in relation to the water supply only in the first 45 DAE. In this case it is necessary to consider that the plants reached the harvest point with 63 DAE and all the water applied after this time was unnecessary.

The yield of *A. cruentus* was affected by the available water and the highest yields were obtained when the water was available for longer crop period. This species has been shown to be more productive than *A. caudatus*, but is dependent on water available to achieve high yields.

Water stress had a significant effect on grain yield for this species, so severe water restriction (I45) reduced grain yield by 65%. The productivity found in the treatments I45 and I60 compared to the treatment I90, are related to the fact that in the first two treatments the water deficit occurred in the critical period, that is, from the preflowering to the beginning of the grain filling, so the recovery of the productive capacity of the culture did not occur satisfactorily, since reproductive events are faster than those observed during vegetative growth stage [24].

The amaranth cycle can vary between 100 and 170 days, depending on the region, being smaller in hot climate regions [25]. *A. cruentus* BRS Alegria reached the harvest point at 86 DAE, being earlier than the crop done in Austria,

Table 1. Yield (kg ha^{-1}), water-productivity (kg ha^{-1} mm) and harvest index (%), to unfold the interaction in *Amaranthus caudatus* Inca and *Amaranthus cruentus* BRS Alegria in different water regimes

Water regimes (Irrigation)	Yield(kg ha^{-1})		Water-productivity (kg ha^{-1} mm)		Harvest index (%)	
	A. caudatus	***A. cruentus***	***A. caudatus***	***A. cruentus***	***A. caudatus***	***A. cruentus***
Up 45 days	1,285.7 Aa	702.1 Cb	5.80 Aa	3.18 Bb	0.60 Aa	0.21 Bb
Up 60 days	1,591.0 Aa	1,544.9 Ba	6.34 Aa	6.20 Aa	0.27 Bb	0.53 Aa
Up 90 days	1,510.5 Ab	2,008.6 Aa	4.15 Bb	6.40 Aa	0.49 Aa	0.32 Bb
CV (%)	12.22		14.13		8.13	

Means followed by the same letter, uppercase in the columns and lowercase in the lines, for the same variable, do not differ among themselves by the Tukey test at 5% probability. CV: Coefficient of variation where they obtained harvest at 119 days [3]. In the case of *A. caudatus*, the productive cycle obtained in this work was only 63 DAE and no reference was found about the productive cycle for the Inca variety. Considering that the average crop cycles of cultivated grains, such as soybean, maize and sorghum are over 90 days [26], it can be considered that the Inca variety has a very short crop cycle similar to that of beans [27].

The amaranth is a promising plant for the Brazilian savannah and researchers can raise the yield of *A. cruentus* beyond the values obtained here, as reported by other authors, in different environments. The yield obtained in studies conducted for two consecutive years in southern Germany reached 3,495 kg ha^{-1} for additions of 100 kg ha^{-1} of nitrogen, with harvest index of 0.32 [28]. In experiments in the extreme west of Austria, in Chernozem soil, obtained grain yields of up to 2,950 kg ha^{-1} for *A. hypochondriacus* and 3,000 kg ha^{-1} for *A. cruentus*.

Table 1 also shows the water-productivity in the species and the interaction with the water regimes. For *A. caudatus*, water regime of treatment I90 obtained the lowest value, being statistically different from treatment I45 and I60. In *A. cruentus*, treatment I45 obtained the lowest water-productivity, that is, increase in water availability promoted an increase in yield in this species. The highest values of water productivity were in the treatment I60 for *A. caudatus* and in the treatment I90 for *A. cruentus*, of 6,34 and 6,40 kg ha^{-1} mm respectively. Values between 5.7 kg ha^{-1} mm [27] and 7.3 kg ha^{-1} mm [29] were obtained when studying the efficiency use of water-productivity in bean, being similar to the amaranth study.

It was possible to verify the effect of the water deficit and the interaction between water regimes and species on the harvest index. It was observed that the most efficient species in the conversion of dry matter mass to grains, in treatment I45, was *A. caudatus* (Table 1). Thus, the greater capacity of dry matter conversion in economic product (grain yield), at a time when the environmental conditions no longer favor the crop, becomes a good indicator of resistance to drought. The harvest index is an efficiency measure to evaluate this conversion, which is used in many studies [30].

The highest harvest index found in *A. caudatus* is due to the fact that it has a relatively large panicle and a small plant size, thus the proportion of grains in relation to the total dry matter of the plant is higher, increasing the harvest index. In this sense, experimental results have shown that smaller plants, adapted for stress conditions, result in higher harvest index in relation to larger plants [30].

4. CONCLUSION

I. The *Amaranthus caudatus* Inca expressed its grain yield with only 45 days of water supply, being indicated for crops in the Brazilian savannah, at the end of the rainy season, when the cultivation period is smaller (dry season), approximately 45 days.

II. The *Amaranthus cruentus* BRS Alegria can be cultivated at the end of the rainy season, when the water availability is at least 60 days, because this species showed sensitivity to water stress, with decreases in yield and lower harvest index.

III. The water stress caused in the amaranth plants an increase in the roots dry matter mass and a reduction in the shoots dry matter mass and these variables are indicated for the study of water stress in amaranth.

IV. The formula developed "Falling Plant Estimation" presented satisfactory data, being feasible to be used to evaluate the possibility of losses in the harvesting of amaranth by falling plants, when subject to the water stress.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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