

Original Research Article

Production of amaranth under water stress

ABSTRACT

Amaranth is a species that has rapid growth, tolerates dry 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 present a significant productivity difference between the treatments, with a mean of 1,591.0 kg ha⁻¹ and reached harvest 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 all world food. 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 rediscovered 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.

Amaranthus caudatus, of Andean origin, presents lower adaptability in regions of tropical climate under high temperatures [10], but has presented 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].

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

43 2. MATERIAL AND METHODS

44 The work was developed at the Experimental Farm of the Federal University of Mato Grosso,
 45 Brazil, (15° 51' S, 56° 04' W) at 140 m altitude. The climate of the region, according to the
 46 classification of Köppen [13], is Aw, with mean monthly temperature between 22,0 °C to 27,2 °C
 47 and average annual rainfall of 1,320 mm.

48 The experimental design was a randomized block design, in a 3 x 2 factorial scheme (three
 49 periods of irrigation x two species of amaranth), making a total of six treatments, with three
 50 replications. The plots were 36 m², with five rows of twelve meters long, spaced of 0.5 m [12],
 51 and 0.2 m between plants. The chemical analysis (0-20 cm depth) of the soil revealed the
 52 following results: pH in CaCl₂=4.9; P=9.2 mg dm⁻³; K=36.00 mg dm⁻³; Ca²⁺+Mg²⁺=2.5 cmol_cdm⁻³
 53 ³; Al=0.0 cmol_cdm⁻³; H+Al=3.5 cmol_cdm⁻³ and V = 42.9%.

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

63 The plants emerged five days after sowing and, weekly, were evaluated: plant height, dry mass of
 64 plants, panicles and roots, and stem diameter at 50 mm height. At the end of the cultivation, grain
 65 yield, water-productivity, thousand-grain weight [14] and harvest index were evaluated [16].
 66 Harvesting was manually, when the panicles were mature, in the two central lines of each plot,
 67 covering an area of 1.5 m².

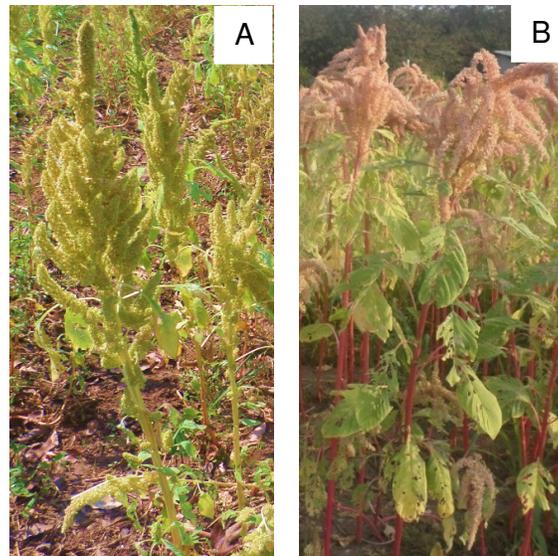
68 Characteristics such as thin and flexible stem facilitate the tipping of plants, especially in plants
 69 with longer cycles [17], mainly in environments with higher frequency and intensity winds. Thus,
 70 for the amaranth, a formula was developed to estimate the risk of plant falling, considering as
 71 flexion-promoting magnitudes the bending moment, defined by plant height (h) and panicle mass
 72 (PM) and, such as magnitudes of flexion-resistance, the stem diameter of the plant (d) and the
 73 shoot mass (SM), with values from 0 to 100, in which the closer to 100 the greater the possibility
 74 of falling and the near to zero the lowest chance of occurrence of falling, according to Expression
 75 1:

$$76 \quad FPE = \frac{h \cdot PM}{d \cdot SM} \quad (\text{Expression 1})$$

77 Where,

78 FPE = Falling Plant Estimation (dimensionless);
 79 h = plant height (mm);
 80 PM = panicle mass (g);
 81 d = stem diameter of the plant (mm); and
 82 SM = shoot mass without the panicle (g).

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



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

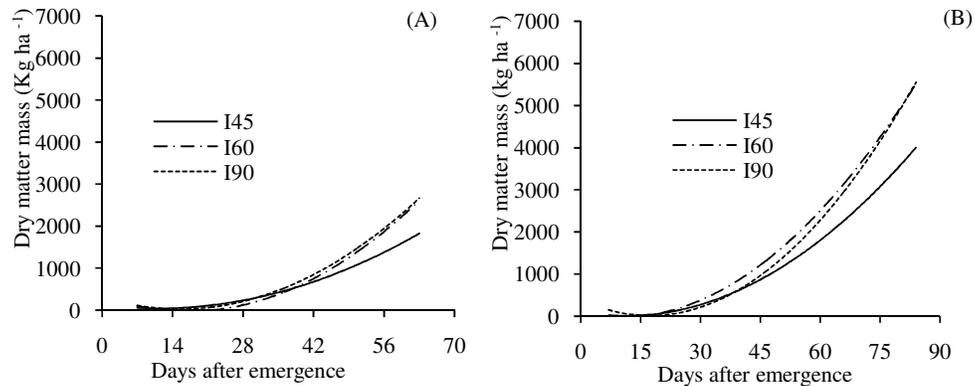
89 3. RESULTS AND DISCUSSION

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

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

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

107 The *A. caudatus*, due to its smaller size, reached lower dry mass values than the other species
 108 studied, but the behavior was similar, with production of biomass about 2,284.51 Kg ha^{-1} and
 109 2,350.35 Kg ha^{-1} for 60 and 90 days of water supply, which differentiated from the 1,947.15 Kg
 110 ha^{-1} of dry matter produced with only 45 days of irrigation. It was noticed for this species (*A.*
 111 *caudatus*), after the fruiting, a tendency of the plants to drop, by senescence, the lower leaves
 112 when submitted to the water stress. This may also explain the fact that treatment with suppression
 113 of irrigation at 45 days showed a reduction in accumulated mass at 63 days, a fact that did not
 114 occur when irrigation was maintained beyond this date.



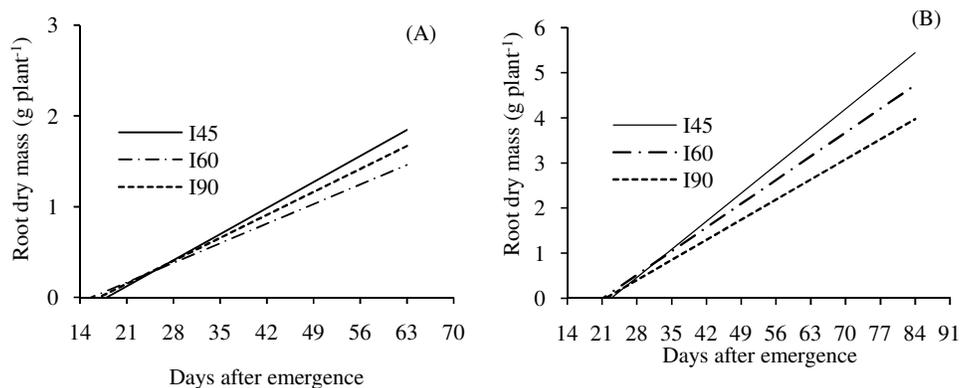
I45= 0,659**x ² - 14,531**x + 126,99	R ² = 0,95	I45= 0,759**x ² - 16,927**x + 100,94	R ² = 0,99
I60=1,250**x ² - 42,561*x + 338,17	R ² = 0,98	I60=1,247**x ² - 43,414*x + 391,57	R ² = 0,97
I90=1,174**x ² - 36,456x + 311,31	R ² = 0,81	I90=1,011**x ² - 20,099**x + 68,357	R ² = 0,98

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

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

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

120 Increasing the amount of root during drought helps the plant to obtain water at deeper levels in
 121 the soil profile, as well as helping to avoid water deficits in the more superficial layers of the soil
 122 [20]. When in an adverse situation of water deficiency, the plants prioritize greater allocation of
 123 photoassimilates to the roots, favoring the search for moisture and less water loss due to
 124 transpiration, if it were invested in the increase of aerial part.



I45= 0,041**x - 0,7411	R ² = 0,63	I45= 0,089**x - 2,031	R ² = 0,72
I60= 0,031**x - 0,485	R ² = 0,78	I60= 0,0751**x - 1,588	R ² = 0,87
I90= 0,036**x - 0,609	R ² = 0,69	I90= 0,064**x - 1,384	R ² = 0,83

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

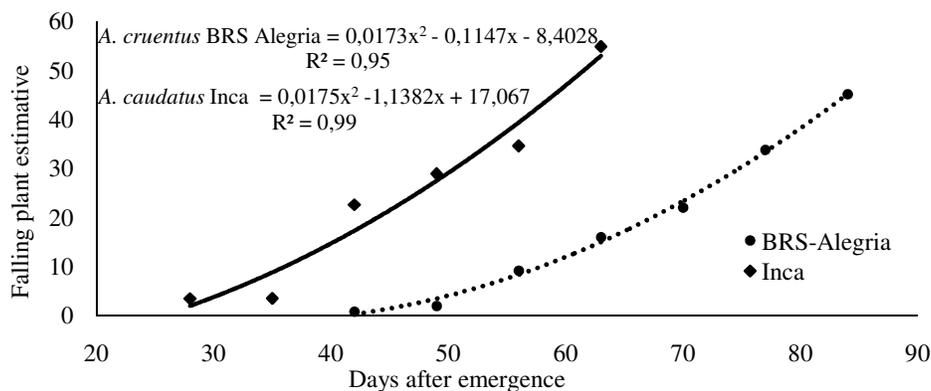
Figure 3. Root dry mass per plant of the *A. caudatus* (A) e *A. cruentus* (B) submitted to irrigation up to 45 days (I45), up to 60 days (I60) and during the whole cycle (I90)

125 The possibility of tipping the amaranth increased with the development of the plant because the
 126 mass of its panicle grew at the same time as the plant continued to grow, as shown in Figures 4.
 127 The *A. caudatus* and *A. cruentus*, respectively, emitted panicles at 28 and 42 DAE, reaching

128 44.18% and 36.95% of the shoot matter mass of the plant at the time of harvest. In this sense,
 129 because the panicle is in the apex of the plant, the higher the plant and the heavier the panicle
 130 were, the greater was the falling plant estimation.

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

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



142
 143 **Figure 4. Falling plant estimation (dimensionless) of the *A. caudatus* Inca and *A. cruentus***
 144 **BRS Alegria, regardl thousand-grain weight thousand-grain weight ess of the water availability**
 145 **time.**

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

151 These values were near to the obtained for other researchers for *A. cruentus* BRS Alegria.
 152 Spehar et al. [12] found, under Brazilian savannah conditions of cultivation, a mass of 680 mg. In
 153 Croatia, Pospisil et al. [21] obtained, in three consecutive years, mean values varying from 702 to
 154 757 mg. In another field study, by Gimplinger et al. [3], in the extreme west of Austria, a mass of
 155 670 mg was obtained. These data show little variation in the thousand-grain weight for this
 156 species and allow to infer that this characteristic for this species should be close to 700 mg. No
 157 data was found for *A. caudatus* Inca.

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

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

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

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

179 **Table 1. Yield (Kg ha⁻¹), water-productivity (kg ha⁻¹ mm) and harvest index (%), to unfold**
 180 **the interaction in *A. caudatus* Inca and *A. cruentus* BRS Alegria in different water regimes.**

Water regimes (Irrigation)	Yield (Kg ha ⁻¹)		Water-productivity (Kg ha ⁻¹ mm)		Harvest index (%)	
	<i>A. caudatus</i>	<i>A. cruentus</i>	<i>A. caudatus</i>	<i>A. cruentus</i>	<i>A. caudatus</i>	<i>A. cruentus</i>
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	

181 *Means followed by the same letter, uppercase in the columns and lowercase in the lines, for the same*
 182 *variable, do not differ among themselves by the Tukey test at 5% probability. CV: Coefficient of variation.*

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

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

192 The amaranth cycle can vary between 100 and 170 days, depending on the region, being smaller
 193 in hot climate regions [25]. *A. cruentus* BRS Alegria reached the harvest point at 86 DAE, being
 194 earlier than the crop done in Austria, where they obtained harvest at 119 days [3]. In the case of
 195 *A. caudatus*, the productive cycle obtained in this work was only 63 DAE and no reference was
 196 found about the productive cycle for the Inca variety. Considering that the average crop cycles of
 197 cultivated grains, such as soybean, maize and sorghum are over 90 days [26], it can be considered
 198 that the Inca variety presented a very short crop cycle similar to that of beans [27].

199 The amaranth is a promising plant for the Brazilian savannah and researches can raise the yield of
 200 *A. cruentus* beyond the values obtained here, as reported by other authors, in different
 201 environments. The yield obtained in studies conducted for two consecutive years in southern
 202 Germany reached 3,495 Kg ha⁻¹ for additions of 100 Kg ha⁻¹ of nitrogen, with harvest index of
 203 0.32 [28]. In experiments in the extreme west of Austria, in Chernozem soil, obtained grain yields
 204 of up to 2,950 Kg ha⁻¹ for *A. hypochondriacus* and 3,000 Kg ha⁻¹ for *A. cruentus*.

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

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

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

225 4. CONCLUSION

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

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

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

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

238 COMPETING INTERESTS

239 We declare that no competing interests exist.
 240
 241

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