

Drought Tolerance Characteristics of Brazilian Soybean Cultivars — Evaluation and characterization of drought tolerance of various Brazilian soybean cultivars in the field —

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Abstract : Drought is one of the major constraints for soybean production in Brazil. Seed yield of ten Brazilian soybean cultivars sheltered from rain (drought stress) for one month after the first flowering was examined over two growing seasons in the field in Londrina, Brazil. The drought tolerance on the basis of seed yield varied with the cultivar, and the yield ranking among cultivars was nearly the same across two years. In cultivars with higher drought tolerance, crop growth rate (CGR) during the drought stress period was higher than in other cultivars. They also maintained a larger leaf area during the stress period. Although reproductive development was retarded by the drought stress, it tended to be retarded less in drought-tolerant cultivars. The information obtained in this research may be useful for breeding drought-tolerant cultivars or selecting diverse germplasms of soybean cultivars.

Key words : Brazil, Crop growth rate, Cultivar difference, Drought tolerance, Harvest index, Rain shelter, Seed yield, Soybean.

The commercial production of soybean in Brazil started in the 1960s and exceeded 40 million tons in 2002. Brazil is now the second greatest producer of soybean in the world next to the United States of America (FAO STAT). Average yield of soybean in Brazil is slightly lower than 3 tons per hectare that can be considered highly productive and similar to that in other countries in North and South America (FAO STAT). Stable and high productivity of soybean in Brazil is needed not only for the Brazilian economy but also for the world economy (Kokubun and Fujisaki, 1997).

Although the total annual precipitation in Brazil is sufficient for soybean cultivation, water deficiency is caused by a dry spell of more than a few weeks without rainfalls in the middle of growth period in a particular location.

Soybean has been reported to have a wide variation in drought tolerance. In this study, drought tolerance was defined as high yield under water deficit. A cultivar is considered drought tolerant when the yield was significantly higher than the other cultivars in a drought environment but not in a non-drought environment and also when the yield difference among the cultivars is significant in both drought and non-drought environments and the yield level was ranked higher under drought environments (Sneller and Dombek, 1997). Brown et al. (1985) found a cultivar

that exhibited less reduction in yield component such as 100-seed weight and the number of seeds under water stress conditions than other cultivars among four American cultivars. A soybean genotype originally introduced from Japan, PI416937, also showed less yield reduction with slow wilting leaves under a drought condition (Sloane et al., 1990). Hida et al. (1995) found cultivar differences in drought tolerance based on yield in Japanese and American cultivars, and Neumaier et al. (1995; 1997) also found cultivar differences in drought tolerance in Brazilian cultivars. Although Sammons (1978) found cultivar differences in drought response at the seedling stage, those cultivars were unable to be consistently categorized by the several measured variables such as water potentials, leaf development, and leaf photosynthesis. Moreover, the differences in drought response in the seedling stage of the cultivars were not entirely consistent with the drought response of the cultivars based on yield data (Mederski and Jeffers, 1973). Therefore, some indices at a specific growth stage should be established to relate with drought tolerance on a yield basis.

Drought stress during the vegetative growth stage is compensated to some extent by the subsequent rainfall during the reproductive growth stage. However, stress during the reproductive growth stage tends to reduce yield directly (Doss et al., 1974; Sionit and Kramer, 1977; Hirasawa et al., 1994; Saitoh et al., 1999). The

Table 1. Genetic backgrounds and characteristics of the ten Brazilian soybean cultivars (Embrapa Soja, 2002).

Cultivar	Parents		Maturity*	Height (cm)	Seed protein content (%)	Seed oil content (%)	Lodging**
	♀	♂					
BR-16	D69-B10-M58	Davis	S	80	39.0	21.3	R
BR-37	União(2)	Lo76-1763	M	74	38.6	22.9	M
Embrapa 48	Davis x Paraná	IAS 4 x BR-5	E	80	39.1	21.4	M
Embrapa 59	FT-Abyara	BR83-147	S	80	38.6	20.5	R
BRS 132	BR80-20703	FT-12 (Nissei)	E	83	37.4	19.0	R
BRS 133	FT-Abyara	BR83-147	S	82	38.6	18.0	R
BRS 134	BR83-147	BR84-8309	M	82	37.8	18.8	M
BRS 183	Embrapa 1(3)	IAC-12	E	73	40.6	20.6	R
BRS 184	FT-Guaíra	IAC-13-C	S	83	39.0	24.2	R
BRS 185	FT-Abyara	IAC-13	S	84	39.8	22.5	R

Days from emergence to physiological maturity are -115 d in early (E), 116-125 d in semi-early (S), and 126-137 d in medium (M) cultivars. *Flowering dates of individuals in each cultivar with different maturities differed 3-4 days at most. **R : Resistant, M : Moderately susceptible.

drought stress at the pod filling stage seems to be most serious (Fukui, 1965; Doss et al., 1974; Sionit and Kramer, 1977; Saitoh et al., 1999).

It is difficult to predict exactly when the plant will encounter drought stress during its cultivation period. Preventive measures include the change of planting dates and/or adoption of the cultivars with different maturities, to avoid encountering a severe drought at the reproductive growth stage. However, once a drought occurs unexpectedly, soybean plants cannot escape from it. Therefore, cultivars with high drought tolerance are strongly desired.

In this study, drought tolerance was evaluated by the yield in drought environments relative to that in non-drought environments (relative yield). The drought environment was simulated by sheltering the plants from rain in the field. The objectives of this study were to investigate whether there were differences in drought tolerance among soybean cultivars currently cultivated in Brazil and to examine the physiological characteristics causing the differences in drought tolerance in terms of yield and growth characteristics.

Materials and Methods

1. Location and cultivars

Experiments were conducted in two growing seasons of 1999/2000 and 2000/2001 at Soybean Research Center of Brazilian Agricultural Research Corporation (Embrapa Soja) (23°11'37"S, 51°11'03"W, elevation 630 m) in Londrina, Paraná, Brazil.

Ten determinate soybean cultivars bred by Embrapa Soja (BR-16, BR-37, Embrapa 48, Embrapa 59, BRS 132, BRS 133, BRS 134, BRS 183, BRS 184, BRS 185) were used as the materials (Table 1). They are all adapted to and recommended for the southern regions in Brazil, especially in Paraná State (Embrapa Soja, 2002). Among them, BR-16 is considered to be a cultivar with less drought tolerance according to the previous studies by Embrapa Soja (Nepomuceno et al., 1994; Farias et al., 1995; Neumaier et al., 1995; 1997).

2. Plant cultivation and drought treatments

Standard cultural practices in Brazil were employed including soil fertilization with N, P and K of 0-28-20 chemical fertilizer at 250 kg ha⁻¹ and inoculation of the seed with *Bradyrhizobium japonicum* at sowing. Herbicides and pesticides were used when necessary. The soil at this location is classified as kaolinitic, clayey (very fine) thermic typic Haplorthox.

The ten cultivars were sown on 11 and 22 November and harvested on 24 to 27 March and 21 March in the season of 1999/2000 and 2000/2001, respectively. There were four replicates of each cultivar that consisted of eight rows spaced 0.5 m apart and 4 m long (6 m × 4 m). There were approximately 20 plants m⁻¹ of row, giving a population of 40 plants m⁻².

The plants were irrigated (IR plots) manually when soil water potential, as measured with tensiometers, decreased to -0.05 MPa at a depth of 0.30 m. No water was applied to the non-irrigated (NI) rain-fed plots. A split-plot design was employed, where the irrigation regime was assigned to the main plot and cultivar to the sub-plot. There were also plots of 6 m × 3 m, where the plants were artificially drought stressed by sheltering them from rain (RS plots) with three replicates adjacent to the other two plot areas. The plants were kept from rain for one month after the first flowering (from R1 to R5 stage, according to Fehr et al., 1971). Soil moisture contents were determined by collecting soil samples from top soil layer (10-20 cm in 1999/2000, 0-20 cm in 2000/2001) in each plot. The soil samples were dried for the estimation of gravimetric water content. Data were averaged from four soil samples for the IR plot and five samples for the RS plot on each sampling day.

It can be considered that yield in the IR plot represents the potential yield, and the yield in the NI plot represents the yield under a rain-fed condition, and the yield in the RS plot represents the yield under drought stress during the early reproductive stage.

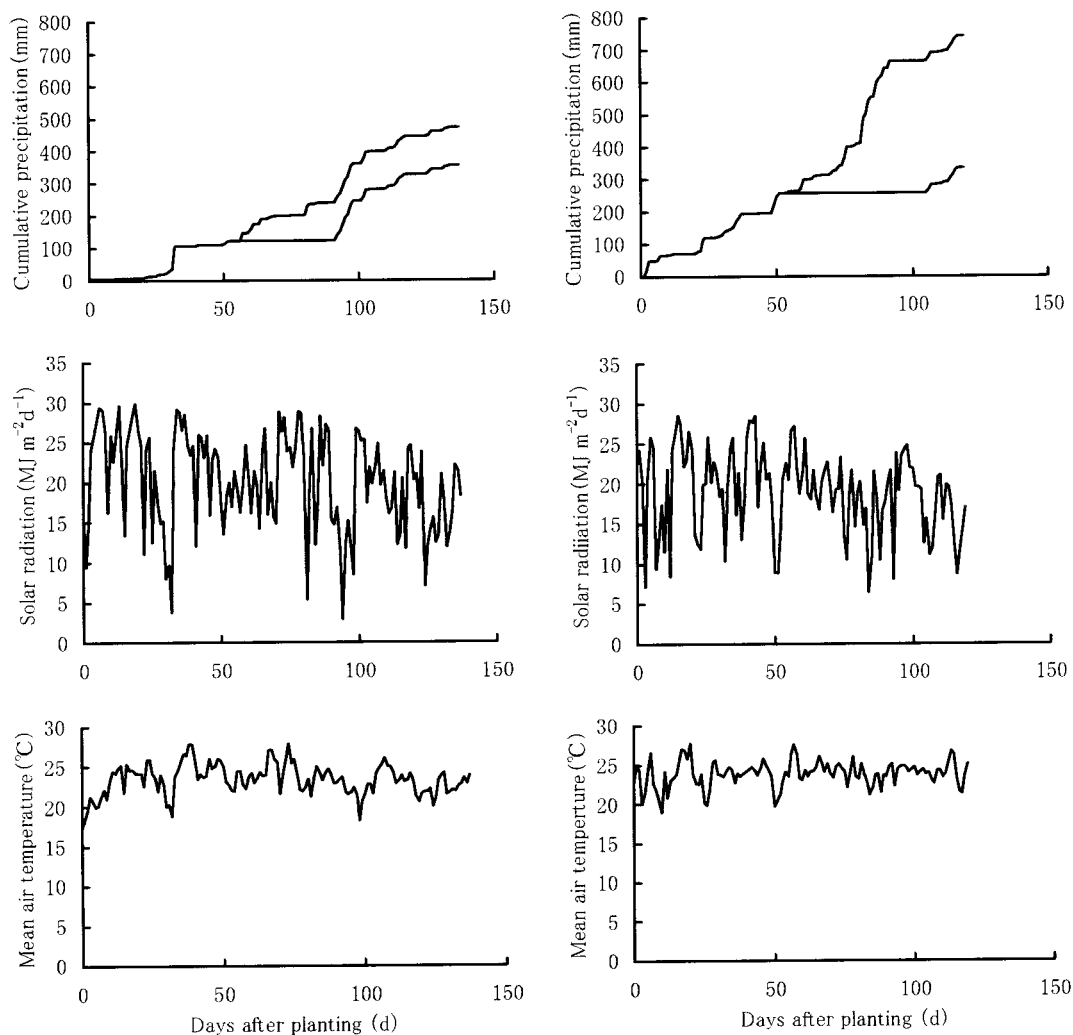


Fig. 1. Meteorological data during the experimental periods. In 1999/2000, soybean cultivars were planted on 11 Nov., flowered on 3 Jan., and were harvested on 24 to 27 Mar. In 2000/2001, they were planted on 22 Nov., flowered on 8 Jan., and were harvested on 21 Mar. Precipitation in NI and RS plots are shown by upper and lower lines, respectively.

3. Measurements

Five plants were periodically (every one or two weeks in 1999/2000, only four times during reproductive growth stage in 2000/2001) harvested from each replicate to determine the developmental stage, leaf area development, and plant dry weight. Leaves were detached and the leaf area was measured using a leaf area meter (LI-3100, Li-Cor, Lincoln, NE, USA). All plant materials were then dried at 60°C for at least 48 h for the estimation of plant dry weight per unit land area. Crop growth rates in RS plots were calculated as the slope of linear regression of dry mass during the period under the shelter from rain in 1999/2000. High regression coefficients (more than 0.75) were obtained except Embrapa 48 and Embrapa 59 (less than 0.50).

At maturity, all plants in a 1 m × 2 m section of each plot were harvested by hand and machine-threshed. The seed yield was expressed on the basis of 130g moisture kg⁻¹. Then yield analysis was carried out.

“Relative yield” was calculated by dividing mean yield of each cultivar in the RS plot by mean yield in the IR plot (potential yield). Similarly relative values for yield components were calculated.

Results

1. Meteorological data and soil water content

In each growing season, meteorological data were recorded daily adjacent to the experimental site. Fig. 1 shows precipitation, solar radiation and mean air temperature. Total amount of rainfall received by soybean plants in NI plots in 1999/2000 (471.0 mm) was almost a half of that in 2000/2001 (741.8 mm), but the plants in RS plots received almost the same amount of rainfall during the season in both years (354.3 and 335.0 mm in 1999/2000 and 2000/2001, respectively). Amount of rainfall before the flowering time also differed between 1999/2000 (121.7 mm) and 2000/2001 (256.8 mm).

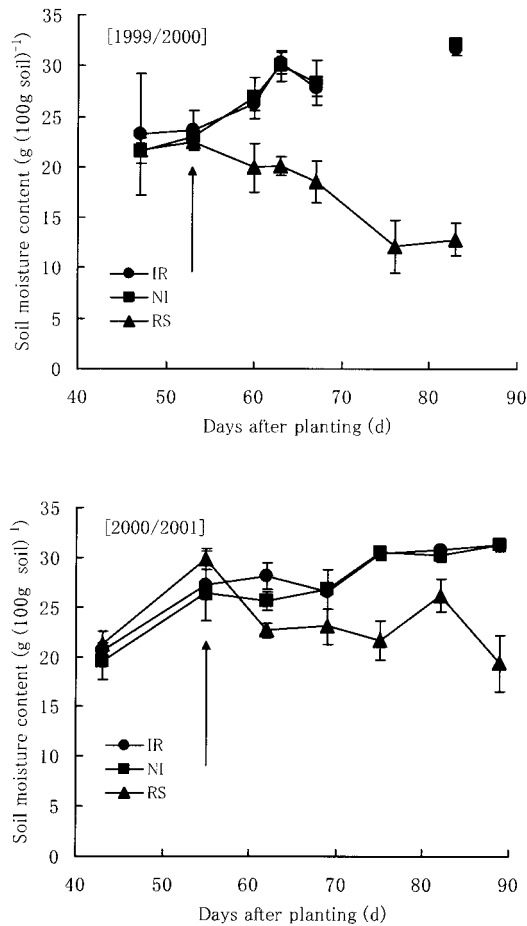


Fig. 2. Changes in soil moisture content in three experimental plots. Soil samples were collected from soil layer of 10-20 cm (1999/2000) or 0-20 cm (2000/2001). After drying them, soil moisture contents were calculated. RS plots were sheltered from rain from 53 and 55 days after planting (shown by arrows) in 1999/2000 and 2000/2001, respectively. Data are presented as means and SDs of four replicates.

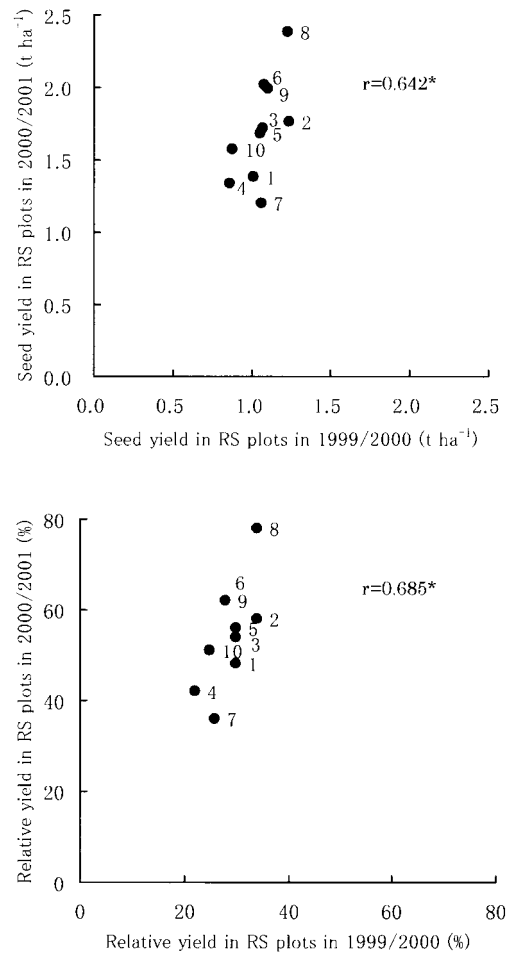


Fig. 3. Seed yield in RS plots and relative seed yield (seed yield in RS plots relative to that in IR plots) in the ten Brazilian soybean cultivars in two growing seasons. 1 : BR-16; 2 : BR-37; 3 : Embrapa 48; 4 : Embrapa 59; 5 : BRS 132; 6 : BRS 133; 7 : BRS 134; 8 : BRS 183; 9 : BRS 184; 10 : BRS 185. *Significant at 0.05 level.

Table 2. Seed yield of the ten Brazilian soybean cultivars under three different water availabilities.

Cultivar	Seed yield (t ha ⁻¹)					
	1999/2000			2000/2001		
	IR	NI	RS	IR	NI	RS
BR - 16	3.33	3.12 (94)	1.01 (30)	2.86	2.78 (97)	1.38 (48)
BR - 37	3.62	3.63 (100)	1.24 (34)	3.02	2.92 (97)	1.76 (58)
Embrapa 48	3.57	3.24 (91)	1.07 (30)	3.18	3.00 (94)	1.72 (54)
Embrapa 59	3.87	3.84 (99)	0.86 (22)	3.16	3.01 (95)	1.34 (42)
BRS 132	3.54	3.57 (101)	1.05 (30)	2.98	2.82 (95)	1.68 (56)
BRS 133	3.87	3.87 (100)	1.08 (28)	3.27	3.27 (100)	2.02 (62)
BRS 134	4.15	4.23 (102)	1.06 (26)	3.35	3.16 (94)	1.20 (36)
BRS 183	3.67	3.13 (85)	1.23 (34)	3.06	2.86 (93)	2.38 (78)
BRS 184	3.98	3.85 (97)	1.10 (28)	3.23	3.43 (106)	1.99 (62)
BRS 185	3.56	3.27 (92)	0.88 (25)	3.08	3.11 (101)	1.57 (51)
LSD (0.05)	0.72	0.81	0.70	0.51	0.44	0.84

IR : Irrigated plot, NI : Non-irrigated plot, RS : Plot sheltered from rain (drought stress) during one month after the first flowering. Values in parentheses in NI and RS plots are relative yield (%) to IR plots.

Table 3. Harvest index of the ten Brazilian soybean cultivars in IR and RS plots.

Cultivar	Harvest index			
	1999/2000		2000/2001	
	IR	RS	IR	RS
BR - 16	0.52±0.10	0.30±0.04	0.39±0.02	0.45±0.01
BR - 37	0.33±0.10	0.35±0.19	0.39±0.09	0.51±0.02
Embrapa 48	0.47±0.07	0.30±0.00	0.31±0.07	0.42±0.01
Embrapa 59	0.39±0.02	0.25±0.08	0.52±0.13	0.42±0.04
BRS 132	0.34±0.02	0.31±0.02	0.41±0.08	0.43±0.03
BRS 133	0.36±0.04	0.21±0.06	0.52±0.02	0.42±0.06
BRS 134	0.28±0.03	0.22±0.01	0.62±0.11	0.41±0.03
BRS 183	0.45±0.06	0.29±0.08	0.52±0.11	0.46±0.02
BRS 184	0.49±0.02	0.29±0.00	0.43±0.07	0.46±0.03
BRS 185	0.43±0.15	0.25±0.14	0.54±0.10	0.48±0.03

Mean ± SE of three replicates.

Fig. 2 shows the changes in the soil moisture content in three experimental plots. Soil moisture content in RS plots declined already on seven days after the start of sheltering from rain in both years as compared with the other two plots. No difference in soil moisture content existed between IR and NI plots.

2. Seed yield

Irrigation had no significant effects on seed yields in either year between IR and NI plots (Table 2). However, seed yield in RS plots were only 22-34% and 36-78% of potential yield (IR plots) in 1999/2000 and 2000/2001, respectively. In RS plots, BRS 183 showed significantly higher seed yield compared with BR-16, Embrapa 59, and BRS 134 in 2000/2001, although a significant difference was not found in 1999/2000. In IR plots, BRS 134 showed significantly higher seed

yield compared with BR-16 in 1999/2000, although a significant difference was not found in 2000/2001. On the basis of the yield, BRS 183 was considered to have higher drought tolerance than BR-16, Embrapa 59 and BRS 134.

The yield ranking among cultivars in RS plots was stable in the two years (Fig. 3). The coefficient of correlation between the yields of individual cultivars in 1999/2000 and 2000/2001 was 0.64 in RS plots and that between the relative yield (yield in RS plots relative to that in IR plots) in the two years was 0.69 (both significant at 5% levels). Cultivars with high potential yields (yield in IR plots) like BRS 134 and Embrapa 59 had low relative yields (26% and 36% for BRS 134, and 22% and 42% for Embrapa 59, in 1999/2000 and 2000/2001, respectively) (Table 2). On the contrary, cultivar with higher relative yield like BRS 183 (34% and 78% in 1999/2000 and 2000/2001, respectively) had not so high potential yield, but had high yields in RS plots. Low yield of BR-16 in RS plots was due to low potential yield rather than low relative yield (30% and 48% in 1999/2000 and 2000/2001, respectively). From the viewpoint of relative yield also, BRS 183 was considered to have high drought tolerance and Embrapa 59 and BRS 134 were considered to have low drought tolerance. Among the cultivars BRS 183, BRS 134, and Embrapa 59, difference in potential yield, relative yield, and RS yield were obvious, however, a negative association observed among these cultivars was not found in all cultivars.

Drought stress reduced harvest index (HI) in most

Table 4. Yield components of the ten Brazilian soybean cultivars in IR and RS plots.

Cultivar	1999/2000			2000/2001		
	Number of pods m ⁻²	Seeds/pod pod ⁻¹	Seed size g (100 seeds) ⁻¹	Number of pods m ⁻²	Seeds/pod pod ⁻¹	Seed size g (100 seeds) ¹
<i>IR plot</i>						
BR-16	792	2.45	17.2	1315	1.57	13.8
BR-37	1405	2.17	11.9	1611	1.69	11.1
Embrapa 48	1226	2.00	14.6	2493	1.19	10.7
Embrapa 59	1072	2.17	16.6	1153	2.20	12.5
BRS 132	1289	2.05	13.4	1514	1.65	11.9
BRS 133	1305	2.13	13.9	1343	1.96	12.4
BRS 134	1310	2.10	15.1	1203	2.38	11.7
BRS 183	1088	2.18	15.5	1070	2.05	13.9
BRS 184	1031	2.21	17.5	1536	1.42	14.8
BRS 185	986	2.16	16.7	1220	1.94	13.0
LSD (0.05)	564	0.19	2.3	815	0.82	2.0
<i>RS plot</i>						
BR-16	306 (39)	1.72 (70)	19.2 (112)	656 (50)	1.75 (111)	12.0 (87)
BR-37	500 (36)	1.70 (78)	14.6 (123)	783 (49)	2.21 (131)	10.2 (92)
Embrapa 48	493 (40)	1.66 (83)	13.1 (90)	1066 (43)	1.64 (137)	9.9 (92)
Embrapa 59	323 (30)	1.50 (69)	17.7 (107)	682 (59)	1.92 (87)	10.2 (82)
BRS 132	370 (29)	1.68 (82)	16.9 (126)	874 (58)	1.83 (111)	10.5 (88)
BRS 133	429 (33)	1.59 (75)	15.8 (114)	1060 (79)	1.84 (94)	10.4 (84)
BRS 134	486 (37)	1.54 (73)	14.2 (94)	729 (61)	1.73 (73)	9.5 (81)
BRS 183	371 (34)	1.75 (80)	19.0 (122)	969 (91)	1.87 (91)	13.1 (94)
BRS 184	418 (41)	1.56 (71)	16.9 (97)	969 (63)	1.73 (121)	11.9 (81)
BRS 185	361 (37)	1.43 (66)	17.1 (102)	674 (55)	1.94 (100)	12.0 (92)
LSD (0.05)	299	0.47	2.4	402	0.24	1.3

Values in RS plots relative to that in IR plots (%) are presented in the parentheses.

Table 5. Reproductive development of the ten Brazilian soybean cultivars in IR and RS plots (1999/2000).

Cultivar	Days after planting (d)							
	53	62	69	76	85	106	119	127
<i>IR plot</i>								
BR-16	R2	R2	R3.5	R5	R6	R6	R6.5	R8
BR-37	R1	R2.5	R3	R4.5	R5.5	R6	R6	R7.5
Embrapa 48	R2	R2.5	R2.5	R4.5	R5	R6	R6	R7.5
Embrapa 59	R2	R2.5	R4	R5.5	R6	R6	R6	R7.5
BRS 132	R2	R2	R4	R5	R5.5	R6	R6.5	R8
BRS 133		R1.5	R2	R2.5	R5	R6	R6	R7
BRS 134		R2	R2.5	R3	R5	R6	R6	R7
BRS 183	R1.5	R2	R3	R4.5	R5.5	R6	R7	R8
BRS 184	R1	R2	R3	R5	R6	R6	R7	R8
BRS 185	R2	R2.5	R4	R5	R6	R6	R6.5	R8
<i>RS plot</i>								
BR-16	R1.5	R2	R3	R3	R4	R6	R6	R6.5
BR-37		R2	R2.5	R3	R4	R5.5	R6	R6
Embrapa 48	R1.5	R2	R2	R2.5	R2.5	R5.5	R6	R6
Embrapa 59		R2	R2	R2.5	R3	R5.5	R6	R6.5
BRS 132		R2	R3	R3.5	R5	R6	R6	R6.5
BRS 133		R2	R2	R2	R2.5	R5	R6	R6
BRS 134		R1.5	R2	R2	R2.5	R5	R6	R6
BRS 183	R1	R1.5	R2.5	R3.5	R5	R6	R6	R7
BRS 184	R1.5	R2	R3	R3.5	R4.5	R6	R6	R7
BRS 185	R1	R2	R3	R4	R5	R6	R6	R7

Reproductive development stages (R1-R8) are shown as means of two replicates for each cultivar.

of the cultivars in 1999/2000, but not in 2000/2001 (Table 3). HI in RS plots was lower than 0.30 in 1999/2000 in all cultivars, but was higher than 0.40 in all cultivars even in RS plots in 2000/2001. No cultivar-specific responses were found.

3. Yield components

Averaged relative values (values in RS plots relative to that in IR plots) of each yield component in the ten cultivars were, 36 and 61% (number of pods per unit land area), 75 and 106% (seed number per pod), 109 and 87% (seed size) in 1999/2000 and 2000/2001,

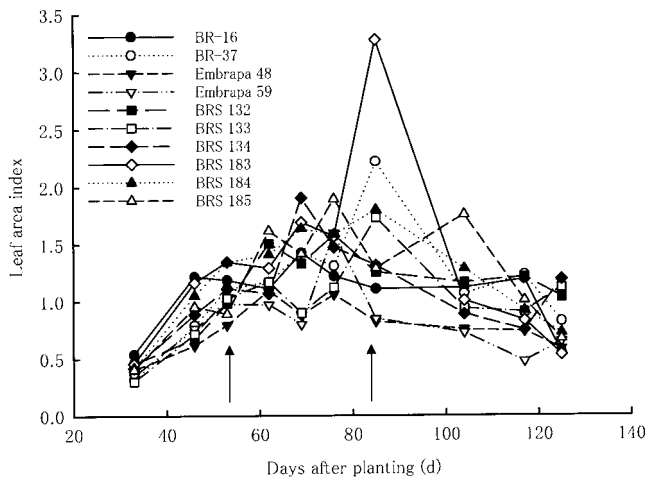


Fig. 5. Leaf area development of the ten Brazilian soybean cultivars in RS plots in 1999/2000. At each sampling, five plants were harvested for each plot, and the data are presented as the means of three replicates.

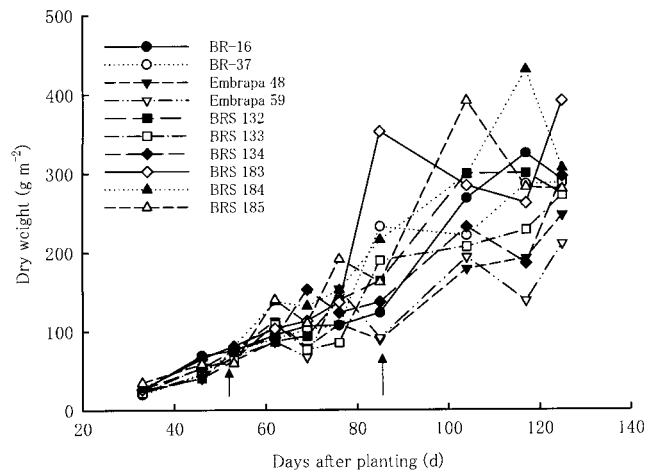


Fig. 4. Dry matter accumulation of the ten Brazilian soybean cultivars in RS plots in 1999/2000. At each sampling, five plants were harvested for each plot, and the data are presented as the means of three replicates.

respectively (Table 4). Drought stress in RS plots reduced the yield mainly through the reduction of pod number per unit land area. It reduced the seed number per pod in 1999/2000 and the seed size in 2000/2001, but increased the seed size in 1999/2000 and did not affect the seed number per pod in 2000/2001.

The rate of reduction in pod number per unit land area by drought stress varied with the cultivar in both years, but no significant difference among cultivars was found in reduction rate. Only BRS 183, a cultivar with high drought tolerance, showed relatively low reduction rate in pod number in 2000/2001.

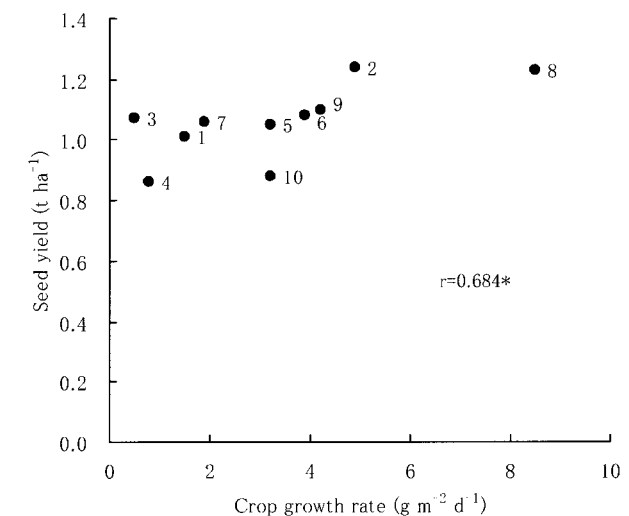


Fig. 6. The relationship between crop growth rate during the period sheltered from rain (drought stress) and seed yield in the ten Brazilian soybean cultivars in RS plots in 1999/2000. 1 : BR-16; 2 : BR-37; 3 : Embrapa 48; 4 : Embrapa 59; 5 : BRS 132; 6 : BRS 133; 7 : BRS 134; 8 : BRS 183; 9 : BRS 184; 10 : BRS 185. *Significant at 0.05 level.

Relative seed size (values in the RS plot relative to that in IR plot) in 1999/2000 was 90, 94, and 97% (less than 100%) in Embrapa 48, BRS 134, and BRS 184, respectively, but was 126, 123, and 122% (higher than 120%) in BRS 132, BR 37, and BRS 183, respectively (Table 4). Relative values in these two groups were significantly different. In 2000/2001, no significant difference in the relative seed size among cultivars was observed.

Relative seed number per pod was 73 and 87% in BRS 134 and Embrapa 59, respectively, and one in Embrapa 48 was 137% in 2000/2001 (Table 4). Relative values in these two groups were significantly different. In 1999/2000, no significant difference in the relative values among cultivars was observed.

High drought tolerance of BRS 183 resulted from small reduction in pod number and seed size under drought condition. On the other hand, low drought tolerance of Embrapa 59 resulted from a large reduction in seed size, and that of BRS 134 from a large reduction in seed number per pod and seed size.

4. Growth and development

Reproductive development of soybean plants was retarded in RS plots, but the developmental stage at the end of the drought-stress period varied with the cultivar from R2.5 to R5 (Table 5). The retardation of development somewhat reduced seed yield (compare Table 5 with Fig. 3).

BRS 183 accumulated more dry matter by the end of the drought-stress period (85 d after planting), compared with the other cultivars (Fig. 4). Dry weight at the end of the drought-stress period was low in BR-16, Embrapa 59, and BRS 134. The dry weight of Embrapa 59 was kept low till the end of the experiment.

The leaf area of BRS 183 was larger than that of other cultivars at the end of the drought-stress period (85 d), and that of Embrapa 59 was smaller throughout the experimental period (Fig. 5). Maximum leaf area was achieved on 85 d in BRS 183, but on 69 d in BR-16 and BRS 134, which might have lowered their dry weight at the end of the drought-stress period (85 d).

Significant correlations were observed between crop growth rates (CGRs) during the drought stress period (early reproductive growth period) and seed yields in 1999/2000 (Fig. 6), suggesting the importance of this period for yield determination.

Discussion

In this study, yield ranking of the ten soybean cultivars was fairly stable in IR and RS plots across two years ($r=0.90$ and 0.64 in IR and RS plots, respectively). Sneller and Dombek (1997) reported that the rank correlation of yield between the sets of two years was not significant under conditions without irrigation but significant under irrigated conditions. Thus, they

emphasized the usefulness of the yield-basis selection for drought tolerance under irrigated conditions. In this study, the nearly same yield ranking in the RS plots in the two years suggested that the effect of drought for one month after the first flowering was large enough to be detected by the yield-basis analysis. For breeding and analysis of the physiological mechanisms of drought tolerance, relative yield (yield in RS plots relative to that in IR plots) may be a more important index. High correlation coefficients between yield in RS plots and relative yield were observed in both two years ($r=0.89$ and 0.98 in 1999/2000 and 2000/2001, respectively), whereas only low correlation coefficients between yield in RS plots and yield in IR plots were observed ($r=0.02$ and -0.01 in 1999/2000 and 2000/2001, respectively). This indicated that the yield in RS plots related more to relative yield than to potential yield in this experiment.

BRS 183 was considered to be drought-tolerant because relative yield was higher than the other cultivars. On the other hand, BR-16, Embrapa 59, and BRS 134 were considered to be drought-sensitive because the relative yield was lower than other cultivars. Moreover, BR 134 was considered to be less tolerant than BR-16 because its yield in IR plot was significantly higher than that of BR-16. This is consistent with the comparatively higher relative yield of BR-16 than that of BRS 134.

The seed yield significantly correlated with CGRs during the early reproductive growth stage (Table 4). This is presumably because soybean has a certain period during which vegetative and reproductive growth progress simultaneously. During this period the leaf area becomes maximum and dry matter production is most active. Progress of the developmental stage during this period was retarded by drought stress in RS plots (Table 5). Spaeth et al. (1984) reported that harvest index (HI) in a cultivar was stable unless plants received drought stress in the late reproductive growth stage. In 1999/2000 little precipitation with large yield reduction from potential yield, HI was decreased in most cultivars. However, HI did not decrease in most cultivars in 2000/2001. Thus, the cultivar that maintained its dry matter production higher during the drought-stress period exhibited higher seed yield in this study. Maintenance of a high CGR during drought-stress period seems to be a key for high seed yield under drought conditions, that is, high tolerance to drought. Since there was a significant correlation ($r=0.63$, significant at 0.05 level) between dry matter accumulation before flowering and seed yield in RS plot in 1999/2000, the amount of vegetative growth is considered to affect the subsequent growth during the drought-stress period presumably through development of root systems. Comparing two years' results, cumulative precipitation in 1999/2000 was half of that in 2000/2001 (Fig. 1). The shortage

of soil moisture might restrict the dry matter production of soybean before the flowering period in 1999/2000, causing stronger effect of drought stress after flowering. Severe stress might have masked the difference in drought tolerance among cultivars.

PI416937 has been known as a drought-tolerant genotype. Its characteristics related to drought tolerance are high capability of osmotic adjustment and development of abundant fine adventitious roots in a shallow soil layer (Sloane et al., 1990; Hudak and Patterson, 1996). However, a more important characteristic may be its vigorous growth at the vegetative stage (Hudak and Patterson, 1995). Hirasawa et al. (1994) showed that the soybean plants which experienced drought before flowering had higher seed yields under a drought condition after flowering because they had already developed a larger root system before flowering. These reports clearly indicate that growth analysis of the aboveground of plants alone may be insufficient to explain drought tolerance. To adapt to short day length at low latitudes, many Brazilian cultivars have a long-juvenile characteristic that prevents soybeans from too early flowering without sufficient vegetative growth (Hatwig and Kiihl, 1979). Although this characteristic is considered favorable for drought tolerance, the relationship is still unclear.

The effects of drought stress on yield components may vary with the growth stage at the time of exposure to the stress (Fukui, 1965; Saitoh et al., 1999; Desclaux et al., 2000). Drought stress reduces the number of pods and seed size when applied from flower initiation till flowering period, the number of pods when applied in flowering period, the number of seeds per pod when applied from late flowering till early pod filling period, and the seed size when applied in the late pod filling period. Hida et al. (1995) formulated three sets of soybean cultivars, each of which had a pair of cultivars with similar phenology but different response to drought. Cultivar differences in response to drought were found in seed size but not in pod number in all cases. The cultivars with little reduction in yield in response to drought stress before flowering showed little reduction in seed size. Also in this study, even though pod number was greatly reduced, cultivar differences in response to drought stress were larger in the other yield components. The reduction in the number of pods and seed size by the drought stress from flower initiation till flowering period appears through the reduction of dry matter production (Fukui, 1965). Therefore, drought tolerance based on yield may reflect dry matter production under drought and the response of seed size to drought. In this study, BRS 183 showed smaller reduction in yield as well as dry matter production during the sheltered (drought-stress) period with less reduction in seed size compared to the other cultivars.

Soybean has a characteristic to remobilize carbon and nitrogen from leaves and stems to seeds. Westgate et al. (1989) observed that steady seed growth was maintained even when photosynthetic rate was decreased by drought stress. Leaves, stems and pericarps reduced their carbohydrate content during the stressed period, suggesting that the remobilization of carbon would support the seed growth. The reduction in seed size may be inescapable when drought continues longer. However, the cultivar with less reduction in seed size can be considered superior in remobilization capacity. Thus, it is speculated that both the vigor in vegetative growth and remobilization capacity may be important physiological characteristics for drought tolerance in soybean.

We found a wide variation in drought tolerance in ten released-cultivars in Brazil across two years. At least higher growth rate under a drought condition during early reproductive stage was associated with higher yield, that is, higher drought tolerance in soybean. The present information may be useful for breeding drought-tolerant cultivars or selecting diverse germplasms of soybean cultivars. It should be noted that for effective selection, it would be necessary to find any characteristics exhibited also in the earlier growth stage in soybean plants.

Acknowledgements

The authors wish to thank Nelson Delattre, Roseli Dagmar Rossi Cardoso, Dirceu Antonio de Oliveira, Everaldo Correia do Carmo, Mário Luiz Maxwell Zapparoli, Glaucia Maxwell Zapparoli, Júlio Cesar Pedroso, Alexandre Carvalho, Rafael, Scalloni, Jean, Marcio, and Marcos for their assistance in the field experiments and measurements of the plant materials.

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