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Yield Response of Spring Wheat Cultivars at Different Irrigation Rates*

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Abstract: We found in a previous study that Brazilian tall cultivars of spring wheat (*Triticum aestivum* L.) were more resistant to drought in respect of photosynthesis as compared to Mexican and Japanese semidwarf cultivars. In this study, a yield trial was performed with the same 20 cultivars to elucidate the yield and yield component responses to the soil water conditions in Cerrados, a semiarid region of Brazil.

Under dry conditions, the dry matter yield of the Brazilian cultivars was significantly higher than the yields of the Mexican and Japanese cultivars. The grain yield of the Brazilian cultivars was also 34-46% greater than those of the Mexican and Japanese cultivars. Under fully-irrigated conditions, however, the Mexican and Japanese cultivars showed higher harvest indices and 18-21% greater grain yield than the Brazilian cultivars, although no practical difference was found among the cultivar groups in terms of dry matter yield.

An analysis of yield components showed that the Brazilian cultivars had a larger 1000 kernel weight than the Mexican and Japanese cultivars under dry conditions, while the Mexican and Japanese cultivars had a higher kernel number than the Brazilian cultivars under fully-irrigated conditions. The reverse rotation of yield ranking among the cultivars under non-irrigated and fully-irrigated conditions is due to the fact that the Mexican and Japanese cultivars are more sensitive to soil moisture than the Brazilian cultivars.
Key words: Cultivar difference, Drought resistance, Irrigation, Semiarid region, Semidwarf cultivar, *Triticum aestivum* L., Wheat, Yield.

異なる灌漑条件下におけるコムギ品種の収量反応：和田道宏・Luiz J.C.B. CARVALHO**・Gustavo C. RODRIGUES***・石井龍一****（農業研究センター・**ブラジル植物遺伝資源研究所・***セラード農業研究センター・****東京大学大学院農学生命科学研究科）

要　旨：前報で春コムギ（*Triticum aestivum* L.）のブラジル長稈品種はメキシコあるいは日本の半矮性品種にくらべて，光合成の面での耐干性が高いことが示された．本試験では，ブラジルの半乾燥地帯であるセラードにおいて，異なる灌漑条件に対する収量および収量構成要素の反応を調べた．非灌漑下において，ブラジル品種はメキシコおよび日本品種に比べて全乾物収量が有意に高く，子実収量も34～46%高かった．しかし，十分な灌漑条件下では，メキシコおよび日本品種はブラジル品種とほぼ同じ全乾物収量を示したが，収穫指数が高く，子実収量も18～21%高かった．収量構成要素の解析によれば，非灌漑条件下ではブラジル品種の千粒重が重く，灌漑条件下ではメキシコおよび日本品種の粒数が多かった．非灌漑と灌漑下におけるコムギ品種の収量順位の逆転はメキシコおよび日本品種の土壌水分感受性がブラジル品種よりも高いことに起因していると考えられた．

キーワード：灌漑，コムギ，収量，耐干性，土壌水分欠乏，半乾燥地，半矮性，品種間差．

A determination of the mechanisms behind differences in the morphological and physiological response of spring wheat cultivars to soil water conditions would help establish breeding criteria for high-yielding cultivars, both in semiarid regions, such as Cerrados, Brazil, and in humid regions in the middle latitudes. Many studies on the yield performance of drought resistant cultivars have been conducted on wheat[8,11] and other grain crops[2,3,6,9]. Semidwarf cultivars of spring wheat bred in Mexico (CIMMYT) and the United States have recently been reported to have higher yields than local varieties, not only in ideal environments, but also in arid areas[7,8,13]. Few comparative studies have been made, however, on the tall Brazilian cultivars well adapted to cultivation in semiarid areas and the semidwarf Japanese cultivars bred in a relatively humid climate. Their productivity under various water conditions has not been elucidated.

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We reported in our previous paper[15] that, in a low-density population of wheat, traditional Brazilian tall cultivars showed higher leaf photosynthesis and grain yield than modern Mexican or Japanese semidwarf cultivars, under non-irrigated conditions. Moreover, no significant difference in leaf photosynthesis or grain yield among the cultivar groups was seen under irrigated conditions. This suggests that Brazilian cultivars are more drought resistant than Mexican or Japanese cultivars, and that potential yield of Brazilian cultivars is not necessarily low, even under well-watered conditions. Results under irrigated conditions, however, do not agree with other reports that modern semidwarf cultivars show higher yield than traditional tall cultivars.

Therefore, we conducted this experiment on the actual grain yield in a normal planting density population under four different levels of irrigation.

Materials and Methods

1. Cultivars

Twenty cultivars of spring wheat (*Triticum aestivum* L.) were used in our experiments : 12 Brazilian, 5 Mexican, and 3 Japanese cultivars (Table 1). Brazilian cultivars were bred from indigenous varieties in the region of Cerrados and the southern states of Brazil, and were recommended as early maturing under non-irrigated conditions in Cerrados. All Brazilian cultivars, except IAC24 and Candeias, were tall. Mexican cultivars were semidwarfs bred at the International Maize and Wheat Improvement Center (CIMMYT) in Mexico, including cultivars bred from CIMMYT cultivars in Brazil, which were recommended under irrigated conditions in Cerrados. Japanese cultivars were early maturing and semidwarfs, brought from Japan for our experiments. Wheat yield is affected by the length of the growth period, especially in dry regions[2,8]. For our experiments, we selected early maturing cultivars with similar heading dates.

2. Cultivation

Experiments were conducted at the Cerrados Agricultural Research Center (CPAC) in Brazil in 1985. Field soil was dark red latosol, whose acidity had been improved in the previous year with 3 t ha^{-1} of lime. Field was plowed with a disk plow, and then harrowed with rotary harrows. Fertilizer was preplanting-applied at rates of N, 40 kg ha^{-1} ; P_2O_5, 250 kg ha^{-1} ; and K_2O, 60 kg ha^{-1}. Top dressings were made twice for each 40 kg ha^{-1} of N on June 20 in the jointing stage, and on July 8 in the flag leaf emergence stage. Seeds were hill-sown at 32 cm×5 cm spacing on May 15 after the dry season started. Plant density was 125 plants m^{-2} with 2 plants per hill, corresponding to the density used by local farmers in this region. The cultivars were assigned randomly in each of four irrigation blocks, with no replication. The area of each cultivar plot in a block was 2.4 m^2. Anthesis occurred on around July 26.

3. Irrigation

Plants were preirrigated with 139 mm water, including 10 mm of rainfall from May 1, the beginning of the dry season, to June 22 in the

Table 1. List of wheat cultivars used in the experiment and their culm length

Cultivar		Culm length (cm)	Cultivar		Culm length (cm)
BR 8	(B)	102.2	Candeias	(B)	76.5
IAC 18	(B)	101.9	IAC 24	(B)	65.5
Santiago	(B)	100.6	Anahuac	(M)	76.5
Minuano 82	(B)	99.2	Nambu	(M)	75.6
BH 1146	(B)	99.1	BR 10	(M)	69.9
Butui	(B)	96.8	Alondra 4546	(M)	68.6
IAC 5	(B)	96.7	Buckbuck	(M)	62.8
IAC 21	(B)	96.1	Norin 61	(J)	81.9
BR 9	(B)	95.1	Asakaze komugi	(J)	76.3
Peladinho	(B)	91.5	Chikushi komugi	(J)	75.4

Culm length was determined at harvest time for the plants grown under fully-irrigated conditions.
(B), (M), and (J) stand for Brazilian, Mexican, and Japanese cultivars, respectively.

jointing stage. Plants, thereafter, were grown at four levels of irrigation, until harvest at the beginning of September, twice a week using hose spreading. The amount of water for non-, 1/3-, 2/3- and, fully-irrigated conditions corresponded to 0, 147, 283, and 441 mm, respectively. The amount of water for the fully-irrigated conditions was set based on the CPAC standard. Irrigation and evaporation, also both different since the beginning of the dry season, are shown in Table 2. The amount of evaporation was measured by an evaporation pan.

Table 2. Irrigation rates in each plot.

Irrigation plot	May 1-Jun. 22 Preirrigation (mm)	May 1-Jun. 22 Evaporation (mm)	Jun. 23-Sep. 2 Irrigation (mm)	Jun. 23-Sep. 2 Evaporation (mm)	May 1-Sep. 2 IED (mm)
Non-Irrigated	139	296	0	489	−646
1/3-Irrigated	139	296	147	489	−499
2/3-Irrigated	139	296	283	489	−363
Fully-Irrigated	139	296	441	489	−205

Dry season started on May 1 ; Harvesting date, Sep. 2.
Preirrigation in the period of May 1-Jun. 22 includes 10 mm of rainfall on May 3, and irrigation in the period of Jun. 23-Sep. 2 was no rainfall.
IED, Differential of irrigated and evaporated water (Irri.-Evapo.).

Table 3. Grain yield of wheat cultivars under different levels of irrigation.

Cultivar		Grain yield (g/m^2) Non irrigated	1/3 irrigated	2/3 irrigated	Fully irrigated
IAC 5	(B)	158(48)	238	289	327(100)
IAC 18	(B)	154(44)	239	305	348(100)
IAC 21	(B)	150(52)	236	271	289(100)
IAC 24	(B)	149(45)	200	248	329(100)
BR 9	(B)	142(43)	264	229	329(100)
BH 1146	(B)	142(55)	210	253	258(100)
BR 8	(B)	118(37)	260	243	320(100)
Peladinho	(B)	104(38)	164	168	275(100)
Norin 61	(J)	102(28)	163	270	370(100)
Nambu	(M)	100(26)	238	299	392(100)
Buckbuck	(M)	90(27)	187	240	331(100)
Santiago	(B)	89(33)	182	207	267(100)
Chikushi comugi	(J)	85(25)	221	272	346(100)
Candeias	(B)	84(31)	196	208	274(100)
Asakaze komugi	(J)	84(22)	174	241	383(100)
Butui	(B)	83(29)	206	198	283(100)
BR 10	(M)	83(24)	179	203	340(100)
Minuano 82	(B)	81(24)	183	282	342(100)
Anahuac	(M)	74(21)	177	265	345(100)
Alondra 4546	(M)	69(18)	172	217	380(100)
Mean		107(30)	204	245	326(100)
C.V.%		28.3	15.6	15.1	12.4

For irrigation levels, see Table 2.
The cultivar sequence is by the rank of grain yield under non-irrigated conditions.
Figures in parentheses in the "non-irrigated" column are the relative values to fully-irrigated plot.
(B), (M), and (J) stand for Brazilian, Mexican, and Japanese cultivars, respectively.

4. Grain yield and yield components

Plants from an area of 0.8 m^2 per plot were sampled at the beginning of September, which was the harvest time for all cultivars. The grain yield and yield components were examined according to the usual method.

Results

1. Cultivar differences in grain (GY) and dry matter yield (DY)

Mean GY for all cultivars increased with the increased irrigation level, reaching 326 g m^{-2} in the fully-irrigated plot, 2.5 times the ordinary farmer's yield level in this region (Table 3). The variation coefficient of GY in the non-irrigated plot was higher than in any other irrigated plot, indicating that the GY cultivar difference in the non-irrigated plot was large compared to those in irrigated plots. The sequence of cultivars in Table 3 follows the rank of GY in the non-irrigated plot. Brazilian cultivars are in the high rank, followed by Mexican and Japanese.

The covariance analysis of grain yield in cultivar groups in terms of the breeding country, is shown in Table 4. This table shows that the increase of yield with the increase of irrigation level is significant in the first and third elements of the linear model. An interactive reaction in the yield was also found between cultivar group and the first element of irrigation treatment. As shown in Figure 1, calculated mean GY values for each cultivar group also clearly showed that Brazilian cultivar GY was higher than Mexican and Japanese GY, only in the non-irrigated plot. This superiority disappeared, however, in the 1/3- and 2/3-irrigated plots, and mean Brazilian cultivar GY became significantly lower than those of Mexican and Japanese cultivars in the fully-irrigated plot.

The mean DY for Brazilian cultivars in the non- and 1/3- irrigated plots were also significantly higher than those of Mexican or Japanese cultivars, but no significant differences between cultivar groups were observed in the 2/3- and fully- irrigated plots (Fig. 1). This suggests that the high Brazilian cultivar GY in the dry plot is attributable to the high rate of dry matter production, and that the high GY of Mexican and Japanese cultivars in the irigated plot is attributable to the high allocation rate of dry matter to grain.

The relative GY and DY values in the non-irrigated plot compared to the fully-irrigated plot were smaller in Mexican and Japanese cultivars than in Brazilian cultivars (Table 3, parentheses; Fig. 1). This indicates that the sensitivity of Mexican and Japanese cultivars to soil water content is comparatively larger than that of the Brazilian cultivars.

2. Yield components

All yield components for all means of irigation showed significant differences among cultivar groups (Table 5, right column). In yield components for different irrigation levels, the kernel number per m^2 showed a {Japanese > Mexican > Brazilian} sequence in the fully-irrigated plot, but little difference in dry plots. The increase of kernel number in

Table 4. Covariance analysis by linear model of cultivar group (Group) and irrigation (Irr.) for wheat yield.

Source	DF	Sum of squares	Mean squares	F value	
Group	2	394.37	197.19	0.20	NS
Irr.	3				
Irr. 1st element	1	489609.38	489609.38	490.79	**
Irr. 2nd element	1	2141.69	2141.69	2.15	NS
Irr. 3rd element	1	6692.65	6692.65	6.71	*
Group × Irr.	6				
Group × Irr. 1st element	2	23762.22	11881.11	11.91	**
Group × Irr. 2nd element	2	1604.77	802.38	0.80	NS
Group × Irr. 3rd element	2	464.97	232.48	0.23	NS
Error	68	67836.23	997.59		
Total	79	592506.26			

*, ** are significant at 5% and 1% probability levels respectively. NS is not significant.

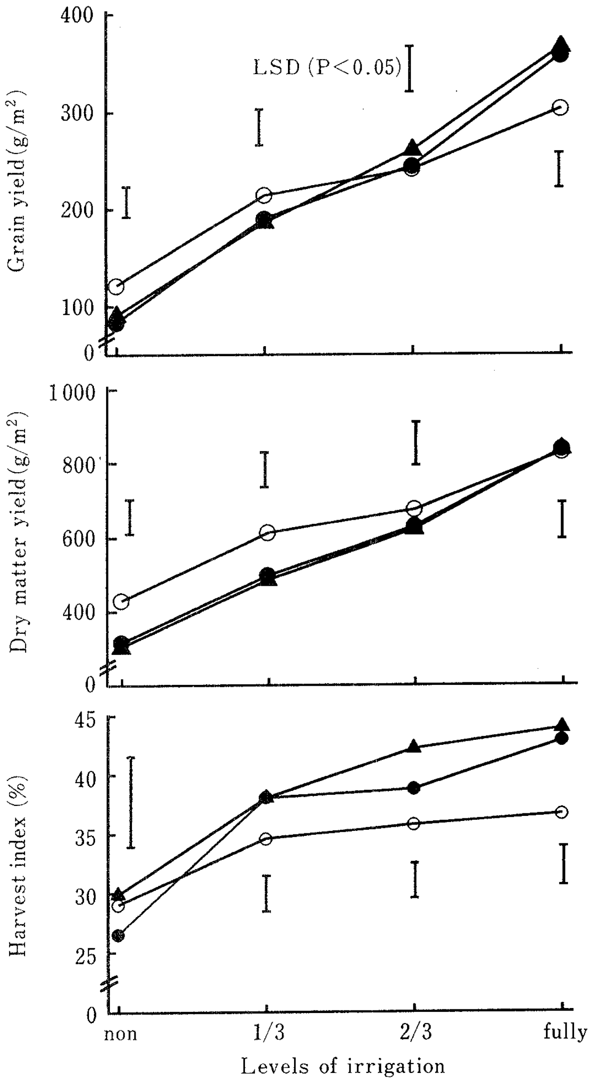

Fig. 1. Grain yield, dry matter yield and harvest index of each cultivar group under different levels of irrigation.
For irrigation levels, see Table 2.
Vertical bars represent LSD ($P<0.05$) among cultivar groups for a level of irrigation.
○, Brazilian cultivars ; ●, Mexican cultivars ; ▲, Japanese cultivars.

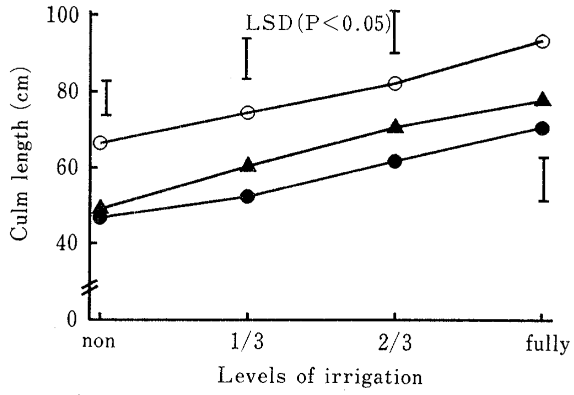

Fig. 2. Culm length of each cultivar group under different levels of irrigation.
For irrigation levels, see Table 2.
Vertical bars represent LSD ($P<0.05$) among cultivar groups for a level of irrigation.
○, Brazilian cultivars ; ●, Mexican cultivars ; ▲, Japanese cultivars.

Mexican and Japanese cultivars in irrigated plots were brought about by the increase in kernel number per ear. The 1000 kernel weight, however, showed a {Brazilian>Mexican>Japanese} sequence in dry plots, but little difference in irrigated plots (Table 5). This means that Mexican and Japanese cultivars have a high potential for sink capacity under irrigated conditions, but that the sink capacities of these two group are largely suppressed by soil water deficiency, resulting in a small sink capacity under dry conditions.

The relative values of yield components in the non-irrigated plot compared to the fully-irrigated plot were smaller in Mexican and Japanese cultivars than in the Brazilian cultivars (Table 5, parentheses).

It appears that these smaller values —greater sensitivity to soil water content— in Mexican and Japanese cultivars are one of the causes for the grain yield sequence of cultivars to be reversed by the irrigation level.

3. Harvest index

In the average harvest index for each cultivar group, although no significant difference was observed between cultivar groups in the non-irrigated plot, Mexican and Japanese cultivars showed significantly higher harvest indices than Brazilian cultivars in the 1/3-, 2/3-, and fully- irrigated plot (Fig. 1). This appears to reflect the fact that the sensitivity of GY and of yield components to soil water content is higher in Mexican and Japanese cultivars than in Brazilian cultivars.

4. Culm length

The culm length showed a {Brazilian>Japanese>Mexican} sequence, except for Brazilian cultivar IAC24 and Candeias, at different irrigation levels (Table 1, Fig. 2). The correlation between GY and culm length for all cultivars was high in each irrigated plot. It showed a positive $r=0.60^{**}$ in the non-irrigated plot and $r=0.52^{**}$ in the 1/3-irrigated plot, and a negative $r=-0.49^{**}$ in the fully-irrigated plot (Table 6). This means that long culm Brazilian cultivars could provide a higher grain yield under water deficit

Table 5. Yield components in each cultivar group under different levels of irrigation.

	Cultivar group	Non irrigated	1/3 irrigated	2/3 irrigated	Fully irrigated	Total mean
	F value	NS	NS	NS	* *	*
Kernel number m^{-2}	Brazilian	3744 (49)	6132	6456	7459 a (100)	5923 a
	Mexican	2867 (33)	5476	5893	8643 a (100)	5720 a
	Japanese	4558 (44)	7504	7902	10517 b (100)	7620 b
	F value	NS	NS	NS	*	*
Kernel number ear^{-1}	Brazilian	18.7 (64)	27.4	30.0	29.2 a (100)	26.3 a
	Mexican	22.2 (57)	29.0	31.0	39.1 b (100)	30.3 ab
	Japanese	23.3 (65)	34.7	34.6	37.4 b (100)	32.5 b
	F value	NS	NS	+	NS	* *
Ear number m^{-2}	Brazilian	208 (83)	227	211 ab	259 (100)	226 a
	Mexican	130 (59)	191	190 b	229 (100)	185 b
	Japanese	207 (74)	215	228 a	284 (100)	234 a
	F value	*	* *	NS	NS	* *
1000 kernel weight g	Brazilian	34.6 a (83)	35.7 a	38.9	41.1 (100)	37.6 a
	Mexican	29.4 a (71)	34.8 a	41.8	41.6 (100)	36.9 a
	Japanese	20.4 b (58)	25.2 b	33.0	35.0 (100)	28.4 b

For irrigation levels, see Table 2.
**, * and + are significant at the 1%, 5%, and 10% probability levels, respectively.
NS is not significant.
Values in the same column followed by different alphabetical letters are significantly different at the 5% probability level by LSD.
Figures in parentheses in the "non-irrigated" column are relative values to the fully-irrigated plot.

Table 6. Correlation coefficients of grain yield with dry matter yield, yield components, harvest index, and culm length in wheat cultivars.

	Non irrigated	1/3 irrigated	2/3 irrigated	Fully irrigated
Dry matter yield	0.730**	0.877**	0.842**	0.545**
Kernel number m^{-2}	0.639**	0.456*	0.644**	0.764**
Kernel number ear^{-1}	0.408	0.239	0.394	0.495*
Ear number m^{-2}	0.260	0.310	0.682**	0.122
1000 kernel weight	0.038	0.300	0.034	−0.202
Harvest index	0.366	0.148	0.428	0.672**
Culm length	0.604**	0.517**	0.240	−0.487*

For irrigation levels, see Table 2.
** and * are significant at the 1% and 5% probability levels, respectively.

conditions, and short culm Mexican and Japanese cultivars could provide a highter grain yield uner well-watered conditions.

Discussion

The groups of wheat cultivars bred by national or international institutes have certain physiological and ecological tendencies influenced by the environments of their breeding places and policies. This study determined several physiological chracteristics in cultivars that grouped them by breeding place.

In the previous experiment[15] with low density population, Brazilian cultivars showed higher yields than Mexican and Japanese cultivars under non-irrigated condition, along with equal or slightly higher yields under irrigated conditions. In this study, with a normal planting density population, under arid conditions, yields of Brazilian cultivars exceeded those of Mexican and Japanese cultivars, whereas under fully-irrigated conditions, Mexican and Japanese cultivars had higher yields than Brazilian cultivars, which was a reverse trend to the previous paper[15]. Presumably this was caused by the fact that Mexican or Japanese semidwarf cultivars are much more adapted to high density populations than Brazilian tall cultivars.

In Brazil, early maturing wheat cultivars are usually grown in rainfed conditons in the season from January to April. Since dry season begins from mid-April in Brazil, wheat plants meet comparatively wet soil conditions in the former growing period, any dry soil conditions in the latter period. It was considered, therefore, that Brazilian wheat cultivars were developed through the selection to adapt for such seasonal climate change. In this paper, such soil water conditons were reproduced, and hence the drought resistance of Brazilian cultivars might have been demonstrated. On the other hand, it can be supposed that Mexican semidwarf cultivars are adapted to irrigated conditions, and Japanese cultivars are adapted to temperate, wet climatic conditions. Such difference in the adaptability to soil water conditions between these three cultivar groups seems to be reflected in the data obtained in this paper.

Relative yield values in the non-irrigated plot compared to the fully-irrigated plot have often been used to evaluate cultivar drought resistance to eliminate influence of potential cultivar yield. The relative values in this paper were larger in Brazilian cultivars, which are less sensitive to drought, and were smaller in Mexican and Japanese cultivars, which are highly sensitive to drought.

It is conceivable that, given the physiological background of different sensitivity in cultivars, Mexican and Japanese cultivars showed a lower photosynthesis capacity and water-use efficiency than Brazilian cultivars under dry conditions[15]. Under fully-irrigated conditions, however, the fact that semidwarf Mexican and Japanese cultivars showed a high yield is consistent with reports that modern semidwarf cultivars are highly sensitive to environmental factors, such as soil water and soil nitrogen, resulting in high yields under favorable conditions[1,4,8,12,14].

Japanese semidwarf cultivars used in this study have either the *Rht1* or *Rht2* dwarf gene[17]. Compared to the Norin 10 type Mexican semidwarf, Japanese cultivars show obvious morphological differences, such as thinner culm, greater numbers of ears and kernels, and low ear weight and 1000 kernel weight. Despite these differences, it was found that both semidwarf cultivars have characteristics in common in terms of photosynthetic ability and moisture sensitivity, and that they also have similar yields. Brazilian cultivars are well adapted to arid conditions, but sink as kernel number per ear must be increased and the harvest index improved[5] to increase their yield potential. Japanese and Mexican cultivars, in contrast, will need higher adaptability to a poor environment to maintain their yield potential. These cultivars may be able to contribute mutually in this respect.

It was shown in the present paper that Brazilian tall cultivars were more resistant to drought than semidwarf cultivars in respect of grain yield. Brazilian tall cultivars are also drought tolerant for photosynthesis, as shown in a previous paper. In this way, tall cultivars are more drought tolerant not only in physiological characteristics such as photosynthesis, but also in agronomic character, such as grain yield.

However, the mechanism for this relationship is still obscure, although there can be a speculative idea that tall cultivars might have root systems of strong suction force[10,16]. A precise examination of the relationship between culm length and drought resistance should be made in the future.

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