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YIELD AND N ACCUMULATION RESPONSES OF LATE-SEASON DETERMINATE SOYBEAN TO IRRIGATION AND INOCULATION WITH VARIOUS STRAINS OF BRADYRHIZOBIUM JAPONICUM

Key Words: (Glycine max L.), drought, xylem water potential, cultivar, nodulation, N-fixation.

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ABSTRACT

Cobb and Coker 488, late-season (maturity group VIII) cultivars of soybean [Glycine max (L.) Merr], were grown under irrigated and non-irrigated conditions on a Norfolk loamy sand in a two-year field experiment. Each cultivar was inoculated with Bradyrhizobium japonicum strains [USDA 3I1b110; Brazil 587; NifTAL 184 and 102 (NifTAL cultures of Brazil 587 and USDA 110, respectively); and North Carolina 1001, 1004, 1005, 1010, and 1029]. Drought conditions were present both years, and irrigation significantly increased the overall yield (2.49 vs 1.92 Mg ha^{-1}). Coker 488 was significantly higher in seed yield than Cobb (2.55 vs 2.02 Mg ha^{-1}). Strain of B. japonicum also affected seed yields. NC1010-inoculated soybean was significantly higher in seed yield rank than all other soybean at the $P<0.01$ level, when compared by single degree of freedom contrast (sdfc). The

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yield ranking of soybean inoculated with NC1001 was significantly lower than soybean inoculated with all other strains, when compared by sdfc ($P<0.10$). Other strains differed in responses which ranged from good to poor inoculants under specific water management conditions. For instance, under nonirrigated conditions, soybean inoculated with strains of B. japonicum from North Carolina was significantly higher in seed yield than those inoculated with the cultures of USDA 110, B587, or the control, when compared by sdfc ($P>0.03$, 0.05, 0.06, respectively). Since soybean inoculated with either strain of USDA 110 was generally high in yield rank under irrigated conditions, their response to irrigation was large relative to soybean inoculated with the NC strain ($P<0.04$). Neither seed nitrogen nor xylem water potential was highly correlated to seed yield. Since seed yield and N content were not highly correlated, the amount of N accumulated in soybean dry mass and that removed in seed were not highly correlated. Thus, the amount of N returned to the soil would be affected by management combinations of late-season determinate soybean cultivar, B. japonicum strain, and irrigation.

INTRODUCTION

Water deficit is the most common yield-limiting factor for soybean in the Southeastern Coastal Plain of the United States. Additionally, water deficit stress causes reductions in nodulation and subsequent dinitrogen fixation (1,2,3). Irrigation can alleviate water deficits, but it has both economical and environmental costs (4). Thus, it is very important to obtain the combination of B. japonicum strain and soybean cultivar capable of producing good seed yield under both irrigated and nonirrigated conditions. Hunt et al. (1) reported that 'Lee' soybean inoculated with USDA strain 3Ilb110 (110) of B. japonicum produced higher yields than soybean infected with indigenous strains of B. japonicum under irrigated conditions, but the reverse was true under nonirrigated conditions. They also reported that strain-110-inoculated Lee soybean had lower xylem water potentials under irrigated conditions, and the reverse was true under drought conditions. The xylem water potential differences were not attributable to soybean dry matter differences.

Variation in the response of inoculated soybean to environmental condition other than water deficits also occur. For instance, strain B587 was reported to be less sensitive to temperature and drought than strain 110 by Munevar and Wollum (5,6,7) and Mahler and Wollum (8,9). Soybean inoculated with strain B587 has also been reported to be less affected by row orientation and irrigation than soybean inoculated with strain 110 (10). These studies were, however, conducted on full-season soybean. The objectives of this study were to determine if the strain of *B. japonicum* used in inoculation affected the N accumulation and seed yield of late-season soybean grown under irrigated or nonirrigated conditions and to determine if these effects were consistent between irrigated and nonirrigated conditions.

MATERIALS AND METHODS

A 2-year field study was conducted in 1981 and 1983 on Norfolk loamy sandy (fine-loamy, siliceous, thermic, Typic Paleudult) at Florence, SC. The previous crop had been soybean. The experimental design was a completely randomized block with determinate soybean cultivar (Cobb vs. Coker 488) and water treatment (irrigation vs. no irrigation) as main plot treatments with *Bradyrhizobium japonicum* strains used as the split plot treatments. Ten and four replications were used in 1981 and 1983, respectively. Fertilization consisted of 1257 kg ha^{-1} of dolomitic lime and 25, 46, and 8 kg ha^{-1} of P, K, and S, respectively. 'Treflan' (trifluralinα,α,α-Trifluro-2,6-dinitro-N,N-dipropyl-p-toluidine) was applied prior to planting at the rate of 1.2 L ha^{-1}.

Soybean was planted on July 13 and 15 in 1981 and 1983, respectively. *Bradyrhizobium japonicum* strains [Brazil B587 (587); NIFTAL 102 and 184 (T102 and T184, which are NifTAL cultures of USDA110 and B587, respectively), NC 1001, 1004, 1005, 1010 and 1029 (1001, 1004, 1005, 1010 and 1029) and USDA 3I1b110 (110)] were applied in an aqueous form directly to the furrow and seed at a rate of 10^{8} cells cm^{-1} of row. Experimental units for each inoculation treatment were 1- and 2-m row segments with 0.75-m row spacings in 1981 and 1983, respectively. The control was inoculated with an aqueous supernate of a 1:10 soil to water suspension. Soil for this suspension was from the plot area. Irrigation water was applied with trickle tubing, when soil water tensions as measured by tensiometers exceeded 25 kPa at the 30-cm depth.

Plant tops and roots were sampled 52 and 85 days after planting (DAP) in 1981. Thirty-cm samples were taken from four replicates. Plant top samples were dried at 70C, weighed, ground to pass a 0.4 mm screen, digested with 3 ml of 30% H_2O_2 and 7 ml H_2SO_4, and analyzed for total Kjeldahl N on a Technicon* Auto Analyzer using Industrial Method 334-74 W/B (11).

Root samples extracted to a 30-cm depth were assayed for N-fixation by the acetylene-reduction method (12). Nodules were then removed from the roots, counted, and weighed. Leaf water potential was measured 56, 64, 86, and 94 DAP in 1981 with a pressure chamber (13). Nodule occupancy was measured by the ELISA technique on 20 nodules per experimental unit (14). Seed yields were taken from 0.75 m of row in 1981 and from 1.5 m of row in 1983. Only seed yield data were taken in 1983.

Data were analyzed by analysis of variance, single degree of freedom contrast (sdfc), and least significant difference (LSD) as outlined by Steel and Torrie (15).

RESULTS AND DISCUSSION

An extended drought (120 mm of rainfall in 76 days) occurred during the soybean reproductive growth stage in 1981, and occasional drought conditions occurred throughout the 1983 growing season (Table 1). Rainfall totals were 295 and 355 mm, and total irrigation water applied was 200 and 180 mm in 1981 and 1983, respectively. Soybean seed yields for 1981 and 1983 were 2.45 and 2.16 Mg ha^{-1}, respectively (Table 2). Mean yields during the two-year period for irrigated and nonirrigated treatments were 2.49 and 1.92 Mg ha^{-1}, respectively.

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* Mention of trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the USDA or the North Carolina Agric. Res. Serv. and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

TABLE 1

Distribution of Rainfall Received by Soybean in 1981 and 1983.

Days after planting	Rainfall 1981	Rainfall 1983
	Vegetative stage	
	-----mm------	
2	0	27
12	0	18
17	48	0
19	8	0
20	5	45
21	14	0
24	6	0
27	11	0
30	53	9
35	5	0
36	0	2
37	14	0
38	8	2
41	3	2
Total	175	103
	Reproductive stage	
58	0	24
60	0	13
61	0	30
67	0	13
71	0	4
83	0	4
89	8	0
90	0	27
100	0	44
106	20	0
107	15	0
108	62	0
110	0	0
114	0	25
119	0	2
120	0	19
125	0	7
129	0	20
130	0	5
134	15	6
Total	120	252

TABLE 2

Seed Yield and Seed Yield Rank for Soybean Inoculated with Different *B. japonicum* Strain and Growth Under Irrigated and Nonirrigated Conditions in 1981 and 1983.

Cult	Irr	1001	1004	1005	1010	1029	110	587	Nat	T102	T184
		$Mg\ ha^{-1}$									
Cobb	-	1.08	1.50	.89	1.17	1.28	.98	.85	.93	.83	1.03
	+	1.68	1.40	1.74	1.97	1.96	1.50	1.72	1.75	2.01	1.80
Coker 448	-	1.19	1.47	1.89	1.97	1.75	1.60	1.46	1.17	1.12	1.28
	+	2.32	2.94	2.38	3.03	2.07	2.92	2.53	2.59	2.52	2.37
LSD(0.05)=0.59											
LSD(0.01)=0.77											
		rank									
Cobb	-	101	143	78	110	111	92	78	85	77	97
	+	146	129	162	179	178	137	153	156	172	165
Coker 448	-	109	132	163	171	158	139	122	98	92	113
	+	186	258	204	270	184	253	235	225	212	192
LSD(0.05)=57											
LSD(0.01)=75											

Cultivars also caused a significant difference in yield, 2.55 and 2.02 $Mg\ ha^{-1}$, respectively, for 'Coker 488' and 'Cobb'. However, small plots tend to overestimate the dry matter production (16), and yield values from these small plots can be best compared on a relative basis. Yields will be discussed in terms of rank analysis for the remainder of the manuscript (Table 2).

The nodule occupancy for strain 110, 587, and T102 in 1981 were from 20 to 30% and 15 to 26% for Cobb and for Coker 488, respectively, under either irrigated or nonirrigated conditions. These percentages are within the range of nodule occupancies previously reported for inoculation treatment of soybean planted in Coastal Plain soils with indigenous populations. We did not make quantitative measurements of occupancy for the other strains because specific antiserum were not available. Treatments were not significantly different for nodule number or mass.

Soybean inoculated with strain NC1010 had the highest seed yield rank for both cultivars under irrigated conditions. Under non-irrigated conditions, they had the highest yield rank for Coker 448 and third highest for Cobb. Soybean inoculated with N.C. strain 1010 were significantly higher in seed yield rank than the other strains ($P<0.01$) by single degree of freedom contrast (SDFC). It appears to be a good strain for inoculation of these late-season soybean cultivars. Conversely, soybean inoculated with NC1001 were significantly lower for seed yield rank than soybean inoculated with all other strains, when compared by SDF ($P<0.10$), and it appears to be a poor inoculant for these cultivars.

Other strains differed in responses which ranged from good to poor under specific water management conditions. For instance, under nonirrigated conditions, soybean inoculated with strains of B. japonicum isolated from North Carolina were significantly higher in seed yield than those inoculated with USDA110, B587, or the control, when compared by sdfc; $P>0.03, 0.05, 0.06$; respectively. Cobb and Coker 488 soybean inoculated with NC1010 or NC1029 had seed yields that ranked among the top three nonirrigated yields. On the other hand, soybean inoculated with either USDA110 or T102 were generally low for seed yield rank under nonirrigated conditions, and T102 (T102 is a NifTAL culture of USDA110) had seed yields that ranked lowest for both cultivars under nonirrigated conditions.

Since soybean inoculated with either culture of USDA110 were generally high in yield rank under irrigated conditions, the response to irrigation was large relative to soybean inoculated with the North Carolina strain (Table 3). Consequently, those soybean inoculated with USDA110 were greater in yield response to irrigation than those inoculated with the North Carolina strains, when compared by sdfc ($P<0.04$). The interactive effects of B. japonicum strain and irrigation on seed yield responses were consistent with previously reported results by Hunt et al. (1,10,17). Strain 1029-inoculated soybean, which had a low response to irrigation, also had the least xylem water

TABLE 3

Rank of Inoculant Treatment on the Response of Inoculated Soybean Seed Yields to Irrigation (Irrigated Seed Yield Minus Nonirrigated Seed Yield).

Cultivar	1001	1004	1005	1010	1029	110	587	Nat	T102	T184
	g plant^{-1}									
Cobb	55	35	87	69	62	67	64	57	79	67
Coker	56	99	57	72	50	92	101	94	92	74

LSD(.05)=33
LSD(0.01)=37

potential difference between the irrigated and nonirrigated treatments, 9.4 and 11.6 kPa, respectively. An interaction between xylem water potential and yield of 'Lee' soybean with B. japonicum strain was reported earlier by Hunt et al. (1). However, the relationship between xylem water potential and seed yield for particular B. japonicum treatments was not consistent in the current experiments.

Even though N-fixation normally supplies greater than 50% of the N for soybean grown in the Southeastern U.S., dry matter accumulations were significantly affected by water or B. japonicum treatments in only 1004-inoculated soybean. The 1004-inoculated plants accumulated the highest dry matter weights under irrigated conditions and the lowest under nonirrigated conditions, 49.4 and 26.5 g plant^{-1}, respectively. Total N accumulations in 1004-inoculated soybean were 1.23 and 0.68 g plant^{-1}, respectively, for irrigated and nonirrigated conditions (Table 4). However, these differences were not proportional to the seed yields. Neither the total N nor the acetylene-reduction levels of the other treatment was correlated to seed yield. The poor correlation (R^2=0.50) between total N accumulation and seed yield was similar to that previously reported by Morris and Weaver (18), Williams and Phillips (19), Karlen and Hunt (20), and Hunt et al. (10). As a result of the poor correlation

TABLE 4

Nitrogen Content of Soybean Shoots as Affected by Irrigation and *B. japonicum* Strain

Cultivar	Irr	1001	1004	1005	1010	1029	1110	587	Nat	T102	T184
		g plant^{-1}									
Coker 488	-	0.828	0.609	0.628	0.904	0.966	0.708	0.853	0.863	0.677	0.730
	+	0.850	1.147	1.045	0.867	0.978	0.552	0.927	0.729	1.045	0.752
Cobb	-	0.674	0.757	0.780	0.883	0.593	0.851	1.014	0.931	0.784	0.869
	+	1.159	1.306	1.075	0.745	0.548	1.438	0.843	0.863	1.857	0.775

LSD(.10)=0.379

between total N and seed yield, the net N returned to the soil (N obtained from dinitrogen fixation minus the N removed in the seed) could be dramatically affected by the combination of inoculant, cultivar, and water management. For instance, 1004-inoculated Cobb would likely have negative and positive annual balances of N under nonirrigated and irrigated conditions, respectively. The reverse is likely to be true for 1004-inoculated Coker 448.

CONCLUSIONS

The high seed yield produced by 1010-inoculated soybean under both irrigated and nonirrigated conditions is unusual, and this strain may have the genetic base to allow its use in many environments. Conversely, poor yields of soybean inoculated with 1001 indicate that it may have limited value in most environments. Consistently low yields produced by soybean inoculated with T102 under nonirrigated conditions indicate that this strain functions poorly under drought stress. Since T102 is a NifTAL culture of USDA110, it is possible that this culture contains a more drought-sensitive genetic base than the culture maintained in our laboratory. Cultures of *B. japonicum* strain 110 grown in different laboratories have been reported to have variations in their genetic composition that are expressed in their ability to grow on mannitol media (21,22). Dr. J. N. Mathis has determined that our culture of T102 has fewer nonmannitol utilizers than our culture of 110 (Personal communication, J. N. Mathis, School of Applied Biology, Georgia Institute of Technology, Atlanta, GA 30332). Variations in environmental tolerance could similarly exist among strains and cultures of the same strain, and this variation could be expressed if B. japonicum is involved in the whole plant physiology and/or rhizoplane microbial ecology in such a way as to affect seed yield. Such variation would dramatically affect the seed yield response to irrigation. These possibilities need to be more clearly defined and understood for improved water use efficiency, seed yield, and N management from B. japonicum and late-season, as well as full-season, soybean.

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