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CHARACTERIZATION OF MORPHOPHYSIOLOGICAL TRAITS OF RICE GENOTYPES WITH DIVERSE MANGANESE EFFICIENCY

SHALINI JHANJI*, N.K. SEKHON, U.S. SADANA AND T.P.S. GILL

Department of Soil Science, Punjab Agricultural University, Ludhiana-141004, Punjab

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SUMMARY

Manganese (Mn), one of the most important micronutrient, is a key regulator of photosynthesis that is the major determinant of growth and yield in plants. A rapid increase in Mn deficiency in Punjab soils has imposed a need to grow Mn-efficient rice genotypes exhibiting yield at low inputs that can sustain crop production. The present investigation was conducted to characterize the morphophysiological traits for Mn efficiency in 12 genotypes of rice categorized as Mn-efficient (PR116, PAU201, PR115 and PR120) moderately Mn-efficient (3108, PUSA44, 3139 and 3141) and Mn-inefficient (3133, 3142, 3056 and 3124). Rice genotypes were grown in Mn-deficit soil (2.2 ppm available Mn) at two Mn levels (0 & 50 ppm). Per cent decline in grain yield, grain weight/panicle, grain size and grain number/panicle under Mn deficiency was less in Mn-efficient genotypes indicating that these genotypes retain high yielding attributes under Mn deficit-conditions. Higher leaf area of Mn-efficient genotypes resulted in higher accumulation of dry matter in different plant parts at both Mn levels. The root length explained 94% variation in dry matter yield at flowering and 63% at tillering indicating that root length is one of the most important parameter contributing to yield. Mn-efficient genotypes maintained higher nitrate reductase activity (NRA) than inefficient genotypes under Mn deficiency. Grain yield was strongly related to grain weight/panicle (r = 0.951) and number of grains/panicle (r = 0.932) under Mn deficiency. Thus root length, dry weight and yield contributing parameters can be used as an index of Mn efficiency.

Keywords: **Manganese efficiency, morphophysiological traits, rice genotypes.**

INTRODUCTION

Manganese is an essential micronutrient for plants, involved in several metabolic processes, mainly in photosynthesis and as a cofactor for some antioxidant enzymes. The main role of Mn in photosynthesis is its involvement in the water splitting system of photosystem II (PS II), which provides electrons necessary for photosynthetic electron transport (Goussias *et al.* 2002). A group of four Mn atoms is considered as a catalyst for oxidation of water during photosynthesis (Zouni *et al.* 2001). Manganese also plays a role in ATP synthesis (Pfeffer *et al.* 1986), in RuBP carboxylase reactions i.e. CO_2 assimilation (Houtz *et al.* 1988) and nitrate assimilation (Ducic and Polle 2005). Mn is essential for the biosynthesis of chlorophyll and to maintain the integrity of double membrane structure of chloroplast. Severe Mn deficiency can cause chloroplast breakdown (Lidon *et al.* 2004). Thus, Mn deficiency poses a threat to crop growth and yield (Graham *et al.* 1983, Bansal and Nayyar 2000). In the last few decades, Mn deficiency in field crops is emerging as an upcoming nutritional problem worldwide that is adversely affecting the crop growth and yield particularly in calcareous soils with high pH (Chen *et al.* 2001 and Yang *et al.* 2007).

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*Corresponding author, shalini_jhanji@yahoo.com

Cultivation of high yielding wheat cultivars in rotation with rice on coarse-textured soils has resulted in Mn deficiency in Punjab (India) that has imposed a threat on yield (Nayyar *et al.* 1985). Alleviation of Mn deficiency with basal application of fertilizer Mn is difficult in high pH soils as Mn is rapidly converted into unavailable form i.e. oxidized form. Under such conditions, foliar application of 0.5-1% $MnSO_4$ is an immediate effective measure to combat Mn deficiency but requires three to four sprays for each crop and needs repeated sprays every year. Further, it was also reported that repeated foliar sprays were not able to fully alleviate the deficiency of Mn (Hebbern *et al.* 2005). High costs of fertilizers and its repeated application justifies the need for a long term solution to the problem. An alternative could be the selection of crop species that grow and yield well in Mn-deficient soils. Growing of such genotypes would not only be cost effective, as little or no fertilizer is required, but would also represent a more "environment-friendly" and sustainable approach (Chalmers *et al.* 1999). Mn efficiency of a genotype is its ability to cope with low plant available Mn soils and produce high yields (Ascher-Ellis *et al.* 2001). Identification of crops and their genotypes for Mn efficiency has been the focus of many researchers (Fang *et al.* 2000, Krahmer and Sattelmacher 2001, Chibba and Nayyar 2002, Sadana *et al.* 2003, Sayyari-Zahan *et al.* 2009). Most of the modern genotypes have been screened by the breeders from the germplasm under high inputs but the need of the day is to develop cultivars with high efficiency under deficit conditions i.e. high yield with low inputs. The new Mn efficient cultivars can be developed by studying the variation in tolerance to Mn depletion and understanding the mechanism for Mn efficiency in existing cultivars. In Punjab, where rice-wheat cropping system is predominant, studies have been done to screen wheat genotypes for Mn efficiency as well as to understand the mechanism to improve efficiency (Bansal and Nayyar 1998, Sadana *et al.* 2002; 2005) but such studies are lacking for rice. Manganese deficiency symptoms are not observed in flooded rice because reduced conditions on soil submergence increase Mn solubility, but large part of Mn leaches down to lower layers causing Mn deficiency in the succeeding winter crops (Nayyar 1999). Though increasing Mn deficiency in the soil may not be showing visual symptoms in rice but it might be imposing threat to crop growth, yield and grain nutritional status. Till date, very little information is available regarding genotypic variation in Mn efficiency in rice (Fageria *et al.* 2008) and there are virtually no reports of work to identify Mn efficient rice genotypes from diverse germplasm and reveal the underlying mechanism of superiority. In view of the importance of rice as a staple food crop, lack of screening of efficient rice genotypes and increasing Mn deficiency in soils, an experiment was conducted to characterize morphophysiological traits for Mn efficiency in diverse rice genotypes that can be used by breeders to develop Mn efficient cultivars.

MATERIALS AND METHODS

A greenhouse experiment was conducted at Punjab Agricultural University, Ludhiana, India (30°56'N, 75°32'E and 247m above MSL) to screen Mn efficiency in twelve diverse rice genotypes including cultivars, advanced lines and introgression lines selected from 38 genotypes grown in field. These genotypes were categorised into Mn efficient (PR 116, PR115, PR120 and PAU 201), moderately Mn efficient (3133, 3142, 3056 and 3124) and Mn inefficient (3108, Pusa 44, 3139 and 3141) on the basis of grain yield and Mn uptake. Five healthy 30-day old seedlings of 12 rice genotypes were transplanted in plastic pots filled with 9 kg of Mn-deficient soil (DTPA- extractable Mn 2.2 mg kg^{-1} soil). The plants were grown at two levels of applied Mn - 0 and 50 mg Mn kg^{-1} soil. Treatments were replicated nine times and three replicates were used for taking observations at each developmental stage i.e. tillering, flowering and maturity. The height and number of tillers of five plants in a pot were recorded. SPAD index of 10 leaf samples per pot was recorded using SPAD 502. Maximum length and width of a leaf was recorded and leaf area calculated by multiplying leaf length and width with a constant (0.83) for rice leaf. Nitrate reductase activity (NRA, μ moles NO_2^- reduced g^{-1}fresh weight hr^{-1}) of fresh leaf segments was estimated by *in vivo* method of Jaworski (1971). At tillering stage, the plants into leaves and stems, while at anthesis into leaves, stem and panicles. Different plant parts were dried in an oven at 60°C upto a constant dry weight. The roots were washed free of adhering soil and root length was estimated by using WinRhizo Basic V. 2009c software with root scanner (EPSON PERFECTION V700 PHOTO). At maturity stage, the plants were harvested and separated into different parts *viz.*, leaves, stem, rachis, panicles and grain. Dry weight of individual parts were recorded. Grain yield and yield contributing traits *viz.* grain weight/panicle, grain number/panicle and 1000 grain weight were also recorded.

Data was subjected to statistical analysis to calculate critical difference by using analysis of variance for factorial randomised block design. Correlation coefficients between yield and morphophysiological parameters were worked out (Singh *et al.* 2001b).

RESULTS

Plant height: The data of plant height revealed that the efficient genotype PR 120 attained maximum height whereas 3141 attained the minimum (Table 1). Among efficient genotypes, the plant height of cultivars PR 115 and PR 120 were at par but differed significantly from cultivars PR 116 and PAU 201 which were also at par to each other. The plant height of moderately efficient genotypes, 3133 and 3124 differed significantly from 3142 and 3056. The inefficient genotype 3141 differed significantly from other genotypes *viz.* PUSA 44, 3139 and 3108. The plant height of genotypes, 3141 and PUSA 44 increased significantly with Mn application at tillering.

Number of tillers: There was a great variation in mean number of tillers ranging from 4 in PR120 to 7 in 3133 at tillering stage (Table 2). The genotypes PR 120, 3056, 3108 and 3139 had significantly lesser number of tillers than other genotypes. Although significant genotypic difference was observed but the number of tillers was not affected due to Mn application.

SPAD index: The value of SPAD index indicates the relative greenness of leaves which is an indirect indicator of chlorophyll content. The decline in SPAD value under low Mn level was only 5% (Table 3). The value of SPAD index was lowest for genotype 3139 and highest for PR 120 and 3124 at tillering, and 3133 at flowering.

Table 1. Effect of Mn application on plant height (cm) at different stages of growth.

Genotypes	Mn level, mg kg^{-1} soil					
	0	50	Mean	0	50	Mean
		Tillering			Flowering	
PR 116	77.3	74.1	75.7	95.5	93.3	94.4
PAU 201	78.6	80.0	79.3	105.4	100.7	103.1
PR 115	90.4	93.0	91.7	106.1	107.0	106.5
PR 120	92.1	95.1	93.6	112.7	116.4	114.5
3133	83.6	78.7	81.2	106.1	101.3	103.7
3142	89.1	95.5	92.3	108.1	105.3	106.7
3056	88.4	90.0	89.2	108.7	103.1	105.9
3124	80.6	79.9	80.2	98.8	96.1	97.5
3108	87.3	85.6	86.5	103.0	102.3	102.7
PUSA 44	79.3	86.9	83.1	100.8	97.3	99.0
3139	82.1	81.3	81.7	95.8	105.1	100.5
3141	67.8	76.8	72.3	79.8	89.3	84.5
MEAN	83.0	84.7		101.7	101.4	
LSD (0.05)						
Mn levels		NS			NS	
Genotypes(G)		4.08			5.42	
Mn × G		5.77			NS	

Table 2. Effect of Mn application on number of tillers at different stages of growth.

Genotypes	**Mn level, mg kg^{-1} soil**					
	0	**50**	**Mean**	**0**	**50**	**Mean**
		Tillering			**Flowering**	
PR 116	5.7	5.7	5.7	3.8	3.8	3.8
PAU 201	5.6	6.3	5.9	4.1	4.2	4.1
PR 115	5.4	5.2	5.3	3.7	3.9	3.8
PR 120	3.5	4.7	4.1	3.1	2.9	3.0
3133	6.2	6.8	6.5	5.5	5.6	5.5
3142	5.4	5.8	5.6	3.6	3.7	3.6
3056	4.2	4.7	4.5	3.9	4.1	4.0
3124	5.2	6.2	5.7	3.8	4.5	4.2
3108	4.6	4.6	4.6	4.9	3.7	4.3
PUSA 44	4.1	6.4	5.3	5.4	4.8	5.1
3139	4.4	4.9	4.6	4.4	4.2	4.3
3141	5.3	5.8	5.6	4.7	4.9	4.8
MEAN	4.9	5.6		4.2	4.2	
LSD (0.05)						
Mn levels		NS			NS	
Genotypes(G)		0.56			0.32	
Mn × G		NS			NS	

Table 3. Effect of Mn application on SPAD index at different stages of growth.

Genotypes	**Mn level, mg kg^{-1} soil**					
	0	**50**	**Mean**	**0**	**50**	**Mean**
		Tillering			**Flowering**	
PR 116	36.6	39.8	38.2	36.0	38.6	37.3
PAU 201	38.9	40.2	39.5	37.5	39.4	38.4
32PR 115	38.1	40.5	39.3	38.0	39.3	38.6
PR 120	39.5	39.7	39.6	35.3	37.6	36.4
3133	38.5	40.1	39.3	38.1	39.5	38.8
3142	36.6	38.0	37.3	35.8	37.6	36.7
3056	37.0	39.4	38.2	35.8	38.7	37.3
3124	38.7	40.4	39.6	34.8	38.0	36.4
3108	36.7	39.4	38.1	35.9	37.5	36.7
PUSA 44	36.5	38.1	37.3	37.8	37.1	37.5
3139	35.3	38.1	36.7	33.9	35.3	34.6
3141	36.1	37.6	36.9	35.7	36.3	36.0
MEAN	37.4	39.3		36.2	37.9	
LSD (0.05)						
Mn levels		0.54			1.29	
Genotypes(G)		1.45			1.49	
Mn × G		NS			NS	

Significant difference in value of SPAD index was observed between genotypes and Mn levels but the difference in SPAD index of different genotypes was independent of Mn application.

Leaf area per plant: Leaf area at tillering ranged from 740 to 920 cm^2 for efficient genotypes and, 610 to 790 cm^2 for inefficient genotypes (with Mn application). The leaf area declined for all genotypes under Mn deficiency but this decline was maximum for cv. PUSA 44 (38%) (Fig. 1). Although the cv. PR 120 had highest leaf area but the decline under low Mn was 18% in contrast to only 6% for other efficient genotype PAU 201.

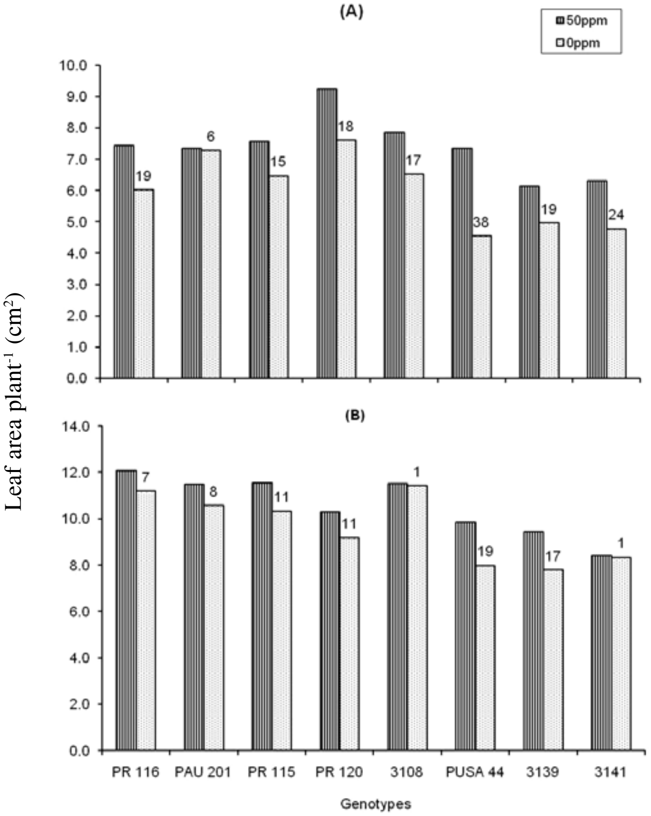


Fig. 1. Effect of Mn application on leaf area of different rice genotypes at tillering (A) and flowering (B). (Values on bars indicate per cent decline under Mn deficit conditions).

The leaf area for different genotypes at flowering ranged from 830 to 1120 cm^2 under Mn deficiency and from 840 to 1210 cm^2 under sufficient Mn conditions. There was decline in leaf area in Mn deficient soil for all genotypes that ranged between 7 to 11% for efficient genotypes and 1 to 19% for inefficient genotypes (Fig. 1).

Nitrate reductase activity (NRA): Nitrate redutase activity recorded at both stages revealed that NRA for inefficient genotypes was higher (Fig. 2) but the decline in NRA under low Mn was more for inefficient genotypes (63% for 3108 at tillering and 57% for 3139 at flowering) compared to efficient cultivars that recorded only 5% decline for PR116 at tillering and 12% for PAU 201 at flowering. The cv PR 115 retained maximum NRA under deficit conditions at tillering as well as flowering. The efficient genotypes on an average retained 96 and 83% of their maximum activity under deficit conditions at tillering and flowering, respectively in comparison to 77% and 59% by inefficient genotypes.

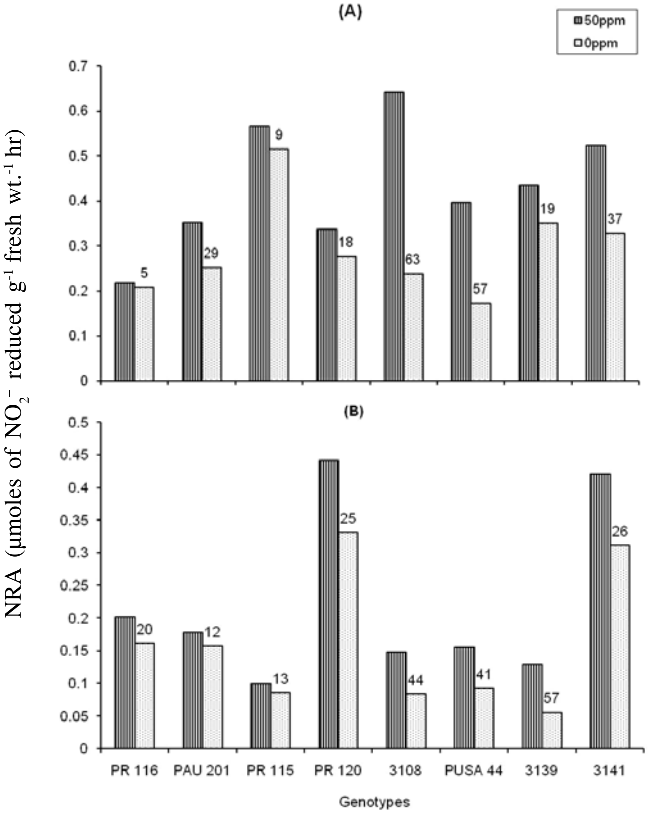


Fig. 2. Effect of Mn application on nitrate reductase activity in leaves of different rice genotypes at tillering (A) and flowering (B). (Values on bars indicate per cent decline under Mn deficit conditions).

Root length: Moderately Mn efficient genotypes had longer roots (62 m/plant) at tillering as compared to other genotypes. The root length of inefficient genotypes was poor in Mn sufficient soil (range 19-35 m/plant) that further declined by 23% in Mn deficit soil. This decline in root length was 9% for efficient genotypes and 11% for moderately efficient genotypes (Fig. 3).

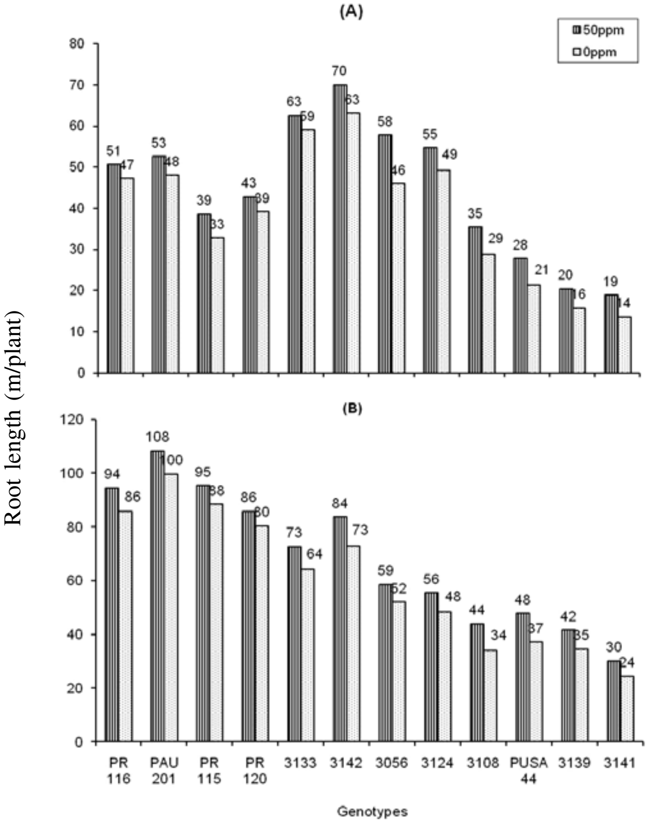


Fig. 3. Effect of Mn application on root length of different rice genotypes at tillering (A) and flowering (B). (Values on bars indicate root length).

The efficient genotypes had longest roots under both Mn levels at flowering (Fig. 3). The efficient genotype PAU 201 had root length of 108 m whereas 3141 had root length of 30 m. The decline in root length under low Mn was 19% for inefficient genotypes whereas it was 8% for efficient genotypes.

Dry matter accumulation: A significant increase in dry matter accumulation was observed when genotypes were grown under sufficient Mn supply.The efficient genotypes accumulated more dry matter at all stages as compared to inefficient genotypes (Table 4). On an average the dry matter accumulated at different growth stages was significantly reduced when grown under Mn deficiency. Under Mn deficit conditions, the efficient, moderately efficient and inefficient genotypes accumulated 94, 90 and 83% respectively, of their dry matter accumulated under Mn sufficient conditions. The cv PR 116 accumulated maximum dry matter i.e.16.82 g/plant that declined by 5% under low Mn whereas genotype 3139 accumulated 9.26 g/plant that declined by 20% under Mn deficit conditions. Dry matter accumulated by inefficient genotypes declined by 23% at maturity and 17% each at flowering and tillering under Mn deficit conditions in comparison to only 6% decline by efficient genotypes at all stages and 6, 8 and 10% at maturity, flowering, and tillering, respectively in moderately efficient genotypes (Fig. 4).

Yield and yield components: Results demonstrated that efficient genotypes had higher yield than moderately efficient and inefficient genotypes. There was significant reduction in grain yield of all genotypes under Mn deficient conditions. The grain yield of efficient genotype PR 116 was maximum (5.95 g/plant) under sufficient Mn and declined by only 4% under Mn deficiency. However, inefficient genotype 3141 recorded grain yield of 2.68 g/plant under sufficient Mn that declined by 27% under Mn deficiency (Table 5). On average, the efficient genotypes retained 92% grain yield under Mn deficiency compared to sufficient Mn whereas moderately efficient and inefficient genotypes retained 88 and 83%, respectively (Fig. 4).

The mean 1000-grain weight was significantly reduced by Mn deficiency. On an average, 1000-seed weight was 24.50 g for efficient, 21.10 g for moderately Mn efficient and 19.30 g for inefficient genotypes. The maximum decline in 1000-seed weight under low Mn supply was 12% for 3141 whereas PR 120 retained the same weight (Table 5). The 1000-seed weight showed significant difference between Mn levels and genotypes but the interaction between genotypes and Mn levels was not significant.

Table 4. Effect of Mn application on dry weight (g/plant) at different stages of growth.

Genotypes	**Mn level, mg kg^{-1} soil**								
	0	**50**	**Mean**	**0**	**50**	**Mean**	**0**	**50**	**Mean**
		Tillering			**Flowering**			**Maturity**	
PR 116	3.59	3.37	3.48	11.70	12.19	11.95	16.00	16.82	16.41
PAU 201	4.46	4.25	4.35	11.67	12.69	12.18	14.62	15.48	15.05
PR 115	4.05	3.79	3.92	12.82	13.58	13.20	14.35	15.61	14.98
PR 120	3.64	3.44	3.54	11.50	12.13	11.82	13.74	14.59	14.16
3133	3.60	3.54	3.57	10.36	11.33	10.85	13.96	15.59	14.78
3142	4.39	4.16	4.27	10.32	11.18	10.75	12.01	13.14	12.57
3056	3.57	3.31	3.44	10.25	10.86	10.56	11.62	12.78	12.20
3124	3.53	3.31	3.42	9.46	10.43	9.94	11.84	13.13	12.48
3108	3.50	2.98	3.24	7.07	8.30	7.69	7.93	9.51	8.72
PUSA 44	3.31	2.28	2.80	6.76	8.60	7.68	8.00	9.75	8.87
3139	3.19	2.72	2.95	6.24	7.54	6.89	7.39	9.26	8.32
3141	2.74	1.91	2.32	5.54	6.61	6.08	8.45	9.87	9.16
Mean	3.63	3.25		9.47	10.45		11.66	12.96	
LSD (0.05)									
Mn levels		0.242			0.333			0.612	
Genotypes(G)		0.359			0.584			0.403	
Mn × G		NS			NS			NS	

Table 5. Effect of Mn application on grain yield and 1000-grain weight at different stages of growth.

Genotypes	**Mn level, mg kg^{-1} soil**					
	0	**50**	**Mean**	**0**	**50**	**Mean**
		Grain yield, g/pot			**1000-seed wt, g**	
PR 116	28.70	29.75	29.23	22.90	23.50	23.20
PAU 201	25.95	27.60	26.78	25.80	26.70	26.30
PR 115	26.40	28.90	27.65	25.70	26.50	26.10
PR 120	25.00	27.50	26.25	22.40	22.40	22.40
3133	24.75	27.05	25.90	20.40	21.60	21.00
3142	18.95	23.30	21.13	20.60	22.40	21.50
3056	15.45	20.95	18.20	20.60	21.20	20.90
3124	17.40	20.75	19.08	19.50	22.30	20.90
3108	10.80	14.30	12.55	18.50	19.50	19.00
PUSA 44	11.55	14.85	13.20	19.20	21.20	20.20
3139	10.15	13.30	11.73	17.80	18.90	18.40
3141	9.80	13.40	11.60	19.30	19.70	19.50
MEAN	18.74	21.80		21.10	22.20	
LSD (0.05)						
Mn levels		0.221			0.064	
Genotypes(G)		0.293			0.085	
Mn × G		NS			NS	

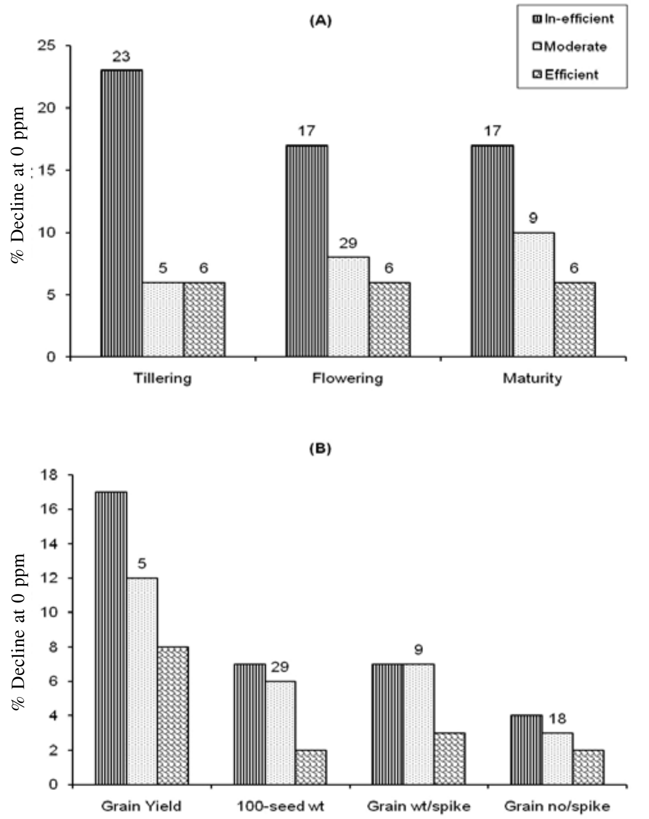


Fig. 4. Per cent deline in dry matter accumulated (A) and grain yield and its components (B) in different rice genotypes under Mn deficit conditions.

The grain weight/panicle in efficient genotypes ranged between 1.83 to 1.69 g/panicle whereas 1.03 to 1.37 g/panicle and 0.81 to 0.72 g/panicle respectively, for moderately efficient and inefficient genotypes under Mn deficiency (Table 6). The relative grain weight per panicle (grain weight under low Mn/grain weight under high Mn ×100) of efficient genotypes (97%) was higher than moderately efficient (87%) and inefficient (85%) genotypes.

The number of grains in a panicle showed no significant difference with Mn application, but differed significantly for genotypes. Cultivar PR 120 had 82 grains/panicle, whereas, 3108 had 38 grains/panicle under Mn deficit conditions (Table 6). The per cent decline in yield and yield contributing traits was more for inefficient genotypes as compared to efficient genotypes under Mn deficiency (Fig. 8).

Correlation analysis: Correlation analysis was done to find the relation of yield with various morphophysiological traits at different stages of growth (Table 7, Fig. 5). The values of correlation coefficients were higher for all traits under low Mn supply as compared to those under Mn sufficient conditions. The total dry matter ($R^2 = 0.745$) at tillering influenced the yield under low Mn supply only. The total dry matter at flowering explained 95% variation in grain yield under low Mn supply and 93% when Mn was sufficient. The results further revealed that root length is a major determinant of yield as it explains 94% variation in yield at flowering and 63% at tillering. Grain yield was strongly related to 100-seed weight ($R^2 = 0.928$) under Mn sufficient conditions and grain weight/ panicle ($R^2 = 0.951$) and number of grains/panicle ($R^2 = 0.932$) at low Mn supply. Thus root length, dry weight and yield contributing parameters can be used as an index of Mn efficiency.

DISCUSSION

Manganese deficiency severely hampered the plant growth of rice genotypes. The reduction in growth of other crop plants by Mn deficiency has also been reported (Behera and Behera 1993, Singh *et al.* 2001a, Husted *et al.* 2009).The suppression in plant growth is due to requirement of Mn in metabolic processes of plant growth and development and the limitation of synthesis of secondary plant products, whose decreased activity results in reduced growth (Millaleo *et al.* 2010).The inefficient genotypes were most sensitive to Mn deficiency in comparison to efficient and moderately efficient genotypes as revealed by their highest per cent decline in growth parameters viz. plant height and number of tillers under Mn deficit conditions (Table 1&2, Fig. 6). Manganese efficiency can be related to maintenance of better growth under deficit conditions. Several studies have also reported higher sensitivity in terms of growth of inefficient genotypes to Mn deficiency as compared to efficient genotypes (Chibba and Nayyar, 2002, Sadana *et al.* 2002, 2005).

Considering grain yield as a measure of Mn efficiency, Mn efficient genotypes yielded 40% higher than inefficient genotypes under low Mn supply (Table 5). The reduction in grain yield at low Mn supply has

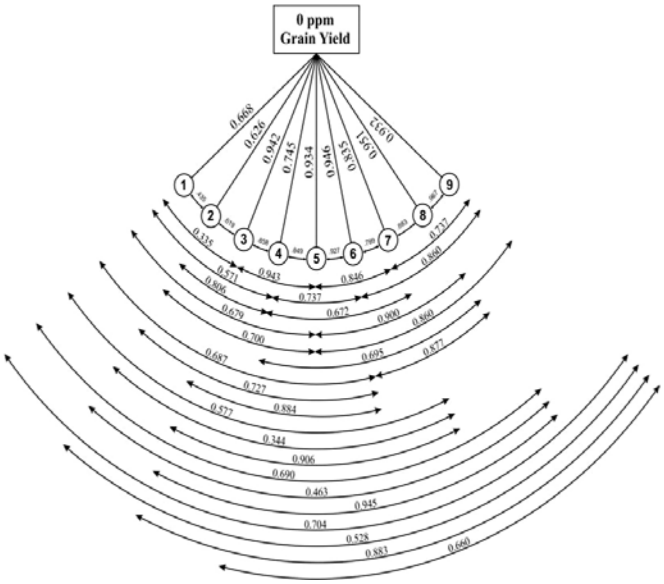
Table 6. Effect of Mn application on grain weight/panicle (g) and grain no. /panicle at different stages of growth

Genotypes	Mn level, mg kg^{-1} soil					
	0	50	Mean	0	50	Mean
		Grain yield, g/plant			Grain no./panicle	
PR 116	1.69	1.71	1.70	73.83	72.68	73.25
PAU 201	1.69	1.73	1.71	65.57	64.74	65.16
PR 115	1.76	1.84	1.80	68.43	69.29	68.86
PR 120	1.83	1.92	1.88	81.90	86.06	83.98
3133	1.27	1.29	1.28	62.10	59.67	60.88
3142	1.22	1.51	1.37	59.34	67.27	63.31
3056	0.90	1.16	1.03	43.67	54.63	49.15
3124	1.11	1.21	1.16	56.93	54.23	55.58
3108	0.72	0.88	0.80	38.92	45.21	42.06
PUSA 44	0.81	0.96	0.88	41.95	45.19	43.57
3139	0.74	0.81	0.77	41.29	42.75	42.02
3141	0.78	0.94	0.86	40.24	47.68	43.96
MEAN	1.21	1.33		56.18	59.12	
LSD (0.05)						
Mn levels		0.021			NS	
Genotypes(G)		0.150			7.812	
Mn × G		NS			NS	

Table 7. Effect of Mn application on values of correlation coefficient (r) between yield and morphophysiological parameters at various stages of growth of different rice genotypes.

Parameters	Mn level, mg kg^{-1} soil					
	0	50	0	50	0	50
	Tillering		Flowering		Maturity	
Plant Height	0.278	0.125	0.465	0.316		
No. of Tillers/plant	0.375	0.336	-0.451	-0.255		
SPAD	0.668*	0.716**	0.426	0.807**		
Leaf area	0.159	-0.028	0.091	-0.003		
NRA	0.041	-0.318	0.108	-0.095		
Root length	0.640*	0.655*	0.938**	0.933**		
Total dry weight	0.745**	0.673*	0.934**	0.958**		
1000-grain weight					0.835**	0.810**
Grain wt/panicle					0.951**	0.928**
Grain no./panicle					0.932**	0.876**

Critical value of R^2 at 0.05= 0.576 and 0.01= 0.708



1. SPAD (T); 2. Root Length (T); 3. Root Length (F); 4. Dry Matter (T); 5. Dry Matter (F); 6. Dry Matter (M); 7. 1000-grain Weight; 8. Grain weight/panicle; 9. Grain number/panicle

Fig. 5. Path diagram showing effect of different morphophysiological traits on grain yield and phenotypic association between various traits of different rice genotypes under manganese deficit conditions.
(Values on the arrows indicate the correlation coefficient.)
(T: tillering; F: flowering; M: maturity)

also been reported earlier in rice (Dube *et al.* 2002) and wheat (Soni *et al.* 1996). The various morphophysiological traits interacted and influenced one another in different ways and to different extents to boost the yield under Mn deficiency (Fig. 5). Grain yield is product of various yield contributing characters viz. 1000-seed weight, grain weight/panicle and grain number/panicle. The Mn efficient genotypes had higher relative 1000-seed weight, grain weight/panicle and grain number/panicle as compared to inefficient genotypes that ultimately led to their high yield under low Mn supply (Table 5&6). The enhancement in yield and yield contributing traits might be due to appropriate partitioning of nutrients and photosynthates between vegetative and reproductive parts in efficient genotypes (Joshi *et al.* 2000).

Strong positive association between grain yield and dry matter accumulation (r = 0.94) supports our findings that efficient genotypes with higher yield had accumulated more dry matter also. Dry matter production of efficient genotypes was higher than inefficient genotypes under Mn deficit conditions during all stages of growth (Table 4). Dry matter production is intimately linked with photosynthetic efficiency of plants (Singal *et al.* 1992). Mn deficiency retards photosynthesis due to impairment of photosynthetic oxygen evolution or disruption of structure of chloroplast or interference in biosynthesis of chlorophyll (Lidon *et al.* 2004, Jiang *et al.* 2006). The higher relative dry matter yield of efficient genotypes in our studies might be due to higher photochemical efficiency or lower Mn requirement of efficient genotypes. Higher NRA in leaves of efficient genotypes (Fig 3&4) indicates their higher photochemical efficiency because the reduction of nitrate requires reducing power i.e. NADPH generated by the photochemical reactions as well as the activity of nitrate reductase enzyme. Higher NRA means higher supply of NADPH.

Photochemical efficiency also depends upon the area of the photosynthetic tissue, mainly leaves. Efficient genotypes had higher leaf area under low Mn supply that results in production of higher amount of photosynthates and hence support the enhanced dry matter accumulation in efficient genotypes (Fig. 1&2). The leaf area was more with sufficient Mn indicating the role of Mn in leaf development. Manganese sulphate treatment has been reported to increase leaf area index in soybean (Sanjana and Koti 2006) and mungbean (Roy and Bera 2000).

Correlation analysis revealed significant positive association of SPAD index with dry matter (r = 0.687) and grain yield (0.668) under low Mn supply that strengthens our results that genotypes with lower SPAD index had lower dry matter and grain yield. In our studies, we found difference in SPAD index with Mn level but the genotypes did not differ from each other (Table 3). As SPAD index is the measure of relative chlorophyll content, this indicates that genotypes did not differ in chlorophyll concentration when grown in Mn deficient soil, depicting no major role of chlorophyll concentration in conferring Mn efficiency in these genotypes. Thus, high photochemical efficiency of efficient genotypes might be due to reduction in number of chloroplasts depending upon the availablility of Mn, thus available Mn becomes sufficient for fewer chloroplasts and assure their full competence (Henriques 2003).

The plant growth and yield are dependent upon the root growth (Sadana *et al.* 2005). In the present investigation also yield was associated to root length ($R^2 = 0.630$). Efficient and moderately efficient genotypes had longer roots than inefficient genotypes under Mn deficiency and higher relative root length (root length under Mn deficit /root length under Mn sufficient conditions × 100). Therefore, Mn efficiency of these genotypes can be related to root growth under Mn deficiency. Sadana *et al.* (2002) also reported that root growth inhibition was stronger in Mn inefficient genotypes of wheat. The role of Mn in root growth was also observed by Nable and Laneragan (1984) as root growth was 50% less when Mn was not supplied. The function of Mn in root growth is due to its role in hormone activation (auxins particularly indole acetic acid, IAA) through IAA oxidases (Burnell 1988) and number of reactions leading to synthesis of phenols and lignins as Mn deficiency resulted in lower concentration of these compounds in wheat roots (Brown *et al.* 1984). Auxin is required for cell elongation and thus root growth.

Higher root length, leaf area, NRA and SPAD index increased the photosynthesis that resulted in more production of photosynthates and ultimately higher dry matter and grain yield. Breeding of these morphophysiological traits can be helpful to develop cultivars for high efficacy under Mn deficit conditions.

REFERENCES

Ascher-Ellis, J.S., Graham, R.D., Hollamby, G.J., Paul, J., Davies, P., Huang, C., Pallotta, M.A., Howe N., Khabez-Saberi H., Jefferies, S.P. and Moussavi-Nik, M. (2001). Micronutrients. In: Application of physiology in wheat breeding. M.P. Reynolds, J.I. Ortiz-Monasterio and A.M. Nab (eds.). CIMMYT, Mexico.

Bansal, R.L. and Nayyar, V.K. (2000). Differential tolerance of durum (*Triticum durum*) and bread wheat (*Triticum aestivum*) varieties to manganese in a manganese deficient field. *Indian J. Agri. Sci.***70:** 507-511.

Bansal, R.L. and Nayyar, V.K. (1998). Screening of wheat (*Triticum aestivum*) varieties tolerant to manganese deficiency stress. *Indian J. Agric. Sci.* **68:** 66–69.

Behera, B.C. and Behera, P.K. (1993). Manganese tolerance of *Amaranthus* species during seedling growth. *Ann. Plant Physiol.* **7:** 153-159.

Brown, P.H., Graham, R.D. and Nicholas, D.J.D. (1984). The effects of manganese and nitrate supply on the levels of phenolics and lignin in young wheat plants. *Plant Soil* **81:** 437-440.

Burnell, J. (1988). The biochemistry of manganese in plants. In: R.D. Graham, R.J. Hannam, N.J. Uren. (eds), Manganese in Soil and Plants, pp. 125–137. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Chalmers, A.G., Sinclair, A.H. and Carver, M. (1999). Nutrients other than nitrogen, phosphorus and potassium (NPK) for Cereals. HGCA Research Review No. 41. London: HGCA.

Chen, Z.S., Chiu, W.T.F. and Bay-Petersen J. (2001). Micronutrient deficiency of crops in Asia. In: Chen, Z.S. Z.S., Chiu, W.T.F. & Bay-Petersen, J. (eds.), food and fertilizer technology for the Asian and Pacific region, pp. 36–53. FFTC, Taipei, Taiwan.

Chhibba, I.M. and Nayyar, V.K. (2002). Response of raya (*Brassica juncea*) to manganese in a manganese-deficient ustochrept. *J. Res. Punjab Agric. Univ.* **39:** 177-180.

Dube, B.K., Kurana, N. and Chatterjee, C. (2002). Yield, physiology and productivity of rice under manganese stress *Indian J. Plant Physiol.* **7:** 392-395.

Ducic, T. and Polle, A. (2005). Transport and detoxification of manganese and copper in plants. *Braz. J. Plant Physiol.* **17:** 103-112.

Fageria, N.K., Barbosa, M.P., Filho, A. and Moreira (2008). Screening Upland Rice Genotypes for Manganese-use Efficiency. *Comm. Soil Sci. Plant Anal.* **39:** 2873 – 2882.

Fang, Z., Lu, S.H. and Zhang, F. (2000). A study of the difference of wheat and oilseed rape in tolerance to Mn deficiency in the field. *J. Hebei Agric. Univ.* **23:** 1–4.

Goussias, C., Boussac, A. and Rutherford, W. (2002). Photosystem II and photosynthetic oxidation of water: an overview. *Phil. Trans. R. Soc.* **357:** 1369-1381.

Graham, R., Davies, W., Sparrow, D. and Ascher, J. (1983). Tolerance of barley and other cereals to manganese-deficient calcareous soils of South Australia. In: BC

Loughman (ed), Genetic aspects of plant nutrition, pp. 339–334. Martinus Nijhoff, The Hague, The Netherlands.

Hebbern, C.A., Pedas, P., Schjoerring, J.K., Knudsen L. and Husted, S. (2005). Genotypic differences in manganese efficiency: a field trial with winter barley *Hordeum vulgare* L. *Plant Soil.* **272:** 233–244.

Henriques, F.S. (2003). Gas exchange, chlorophyll a ûuorescence kinetics and lipid peroxidation of pecan leaves with varying manganese concentrations. *Plant Sci.* **165:** 239–244.

Houtz, R.L., Nable, R.O. and Cheniae, G.M. (1988). Evidence for effects on the in vivo activity of ribulose-biphosphate carboxylase/oxygenase during development of Mn toxicity in tobacco. *Plant Physiol.* **86:** 1143-1149.

Husted, S., Kristian H.L., Christopher, A.H., Sidsel, B.S., Pai, P., Anna, H. and Poul, E.J. (2009). Manganese Deficiency Leads to Genotype-Specific Changes in Fluorescence Induction Kinetics and State Transitions. *Plant Physiol.* **150:** 825-833.

Jaworski, E.G. (1971). Nitrate reductase assay in intact plant tissues. *Biochem. Biophys. Res. Commun.* **43:** 1274-1279.

Jiang, W.Z. (2006). Mn use efficiency in different wheat cultivars. *Environ. Exp. Bot.* **57:** 41-50.

Joshi, O.P., Hillore, S.D. and Ramesh, A. (2000). Integrated micronutrient management in soybean. *J. Oilseeds Res.* **17:** 370-372.

Krahmer, R. and Sattelmacher, B. (2001). Determination of Cu and Mn efficiency of crop plants in pot experiments. In: Horst,W.J. (ed), Plant Nutrition: Food Security and Sustainability of Agro-Ecosystem Through Basic and Applied Research, pp 118–119. Kluwer Academic Publishers, The Netherlands.

Lidon, F.C., Barreiro, M. and Ramalho, J. (2004). Manganese accumulation in rice: implications for photosynthetic functioning. *J. Plant Physiol.* **161:** 1235-1244.

Millaleo, R., Reyes-Díaz, M., Ivanov A.G., Mora M. L., and Alberdi M. (2010). Manganese as essential and toxic element for plants: transport, accumulation and resistance mechanisms. *J. Soil Sci. Plant Nutr.* **10:** 476 – 494.

Nable, R.O. and Loneragan, J.F. (1984). Translocation of manganese in subterranean clover (*Trifolium subterraneum* L. cv. Seaton Park) II. Effects of leaf senescence and of restricting supply to part of a split root system. *Aust. J. Plant Physiol.* **11:** 113-118.

Nayyar, V.K. (1999). Micronutrient management for sustainable intensive agriculture. *J. Ind. Soc. Soil Sci.* **47:** 666-680.

Nayyar, V.K., Sadana, U.S. and Takkar, P.N. (1985). Methods and rates of application of Mn and its critical levels for wheat following rice on coarse textured soils. *Fertil. Res.* **8**: 173-178.

Pfeffer, P.E., Tu, S., Gerasimowicz, W.V. and Cavanaugh, J.R. (1986). *In vivo* 31P NMR studies of corn root tissue and its uptake of toxic metals. *Plant Physiol.* **80:** 77-84.

Roy, S.B. and Bera, A.K. (2000). Effect of mercury and manganese on leaf area, stomatal frequency, stomatal index and chlorophyll content of six-day old mungbean seedling. *Environ. Ecol.* **18:** 835-838.

Sadana, U.S., Lata, K. and Claassen, N. (2002). Manganese efficiency of wheat cultivars as related to root growth and internal Mn requirement. *J. Plant Nutr.* **25:** 2677-2688.

Sadana, U.S., Samal D. and Claassen, N. (2003). Differences in manganese efficiency of wheat (*Triticum aestivum* L.) and raya (*Brassica juncea* L.) as related to root-shoot relations and manganese influx. *J. Plant Nutr Soil Sci.* **166:** 385-389.

Sadana, U.S., Sharma, P., Castañeda, O.N., Samal, D. and Claassen, N. (2005). Manganese uptake and Mn efficiency of wheat cultivars are related to Mn-uptake kinetics and root growth. *J. Plant Nutr.* **168:** 581-589.

Sanjana, K. and Koti, R.V. **(**2006). Effect of manganese and boron on growth parameters and yield in rust infected soybean *Karnataka J. Agric. Sci.* **19:** 118-120.

Sayyari-Zahan, M.H., Sadana, U.S., Steingrobe, B. and Claassen, N. (2009). Manganese efficiency and Mn-uptake kinetics of raya (*Brassica juncea* L.), wheat (*Triticum aestivum* L.) and oat (*Avena sativa* L.) grown in nutrient solution and soil. *J. Plant Nutr. Soil Sci.* **172**: 425-434.

Singal, H.R., Sheoran, J.S. and Singh, R. (1992). Photosynthetic contribution of pods towards seed yield in *Brassica. Proc. Indian Nat. Sci. Acad.* **58**: 365-370.

Singh, P., Misra, A. and Srivastava N.K. (2001a). Inûuence of Mn deûciency on growth, chlorophyll content, physiology, and essential monoterpene oil(s) in genotypes of spearmint (Mentha spicata). *Photosynthetica.* **39:** 473–746.

Singh, S., Bansal, M.L., Singh, T.P. and Kumar, R. (2001b). Statistical methods for research workers, Kalyani Publishers, New Delhi.

Soni, M.L., Swarup, A. and Singh, M. (1996). Influence of rates and methods of manganese application on yield and nutrition of wheat in a reclaimed sodic soil. *J. Agric. Sci.* **127:** 433-439.

Yang, X.E., Chen, W.R. and Feng, Y. (2007). Improving human micronutrient nutrition through biofortification in the soil-plant system: China as a case study. *Environ. Geochem. Health.* **29:** 413-428.

Zouni, A., Witt, H., Kern, J., Fromme, P., Kraub, N., Saenger, W. and Orth, P. (2001). Crystal structure of photosystem II from *Synechococcus elongatus* at 3.8 Å resolution. *Nature* **409:** 739-743.