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Integration of crop rotation and arbuscular mycorrhiza (AM) inoculum application for enhancing AM activity to improve phosphorus nutrition and yield of upland rice (*Oryza sativa* L.)

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Abstract Upland rice (*Oryza sativa* L.) is a major crop of Eastern India grown during the wet season (June/July to September/October). Aerobic soils of the upland rice system, which are acidic and inherently phosphorus (P) limiting, support native arbuscular mycorrhizal (AM) activity. Attempts were made to improve P nutrition of upland rice by exploiting this natural situation through different crop rotations and application of AM fungal (AMF) inoculum. The effect of a 2-year crop rotation of maize (*Zea mays* L.) followed by horse gram (*Dolichos biflorus* L.) in the first year and upland rice in the second year on native AM activity was compared to three existing systems, with and without application of a soil–root-based inoculum. Integration of AM fungal inoculation with the maize–horse gram rotation had synergistic/additive effects in terms of AMF colonization (+22.7 to +42.7%), plant P acquisition (+11.2 to +23.7%), and grain yield of rice variety Vandana (+25.7 to +34.3%).

Keywords Arbuscular mycorrhiza · Inoculation · Rice (*Oryza sativa* L.) · Crop rotations · Phosphorus · Grain yield

Introduction

Rice (*Oryza sativa* L.) is the major crop of rainfed uplands in India and other rice-growing countries of the Asian continent. Upland rice is grown under aerobic soil conditions as a direct seeded crop. Unpredictable drought spells lead to inefficient nutrient acquisition, particularly of less mobile phosphorus (P) (Fageri et al. 1982). Arbuscular mycorrhizal fungi (AMF) are naturally active under upland ecology and upland rice has been reported to be partially dependent on native AMF for P acquisition (Saha et al. 2006), especially in cropping systems with semi-concurrent component crops that harbor AM and allow active presence of native AMF for extended periods in the soil system (Maiti et al. 2006). Higher native AMF soil populations during a fallow period and better mycorrhizal colonization of roots in upland rice–pulse (*Cajanus cajan* L. and *Arachis hypogea* L.) intercropping systems have previously been demonstrated (Rana et al. 2002). Such enhancement of native AMF activities, in terms of root colonization and growth promotion of succeeding crops, by pre-cropping with a mycorrhizal crop has been frequently reported (see for example, Johnson et al. 1992; Oliveira and Sanders 1999; Harinikumar and Bagyaraj 2005; Grant et al. 2009).

AMF inoculum developed from native sources is considered to be more efficient (Oliveira et al. 2005), cost effective, adapted to the target ecology, and to have less negative ecological consequences in terms of invasive species introduction as unintended contaminants (Schwartz et al. 2006). On-farm produced AMF inoculum has been used as an amendment to horticultural potting media for the production of vegetable seedlings (Douds et al. 2006). Application of soil–root-based native AMF inoculum has been reported to enhance P acquisition by upland rice, and *in situ* multiplication of AMF inoculum on *Sorghum* roots in partially sterilized micro-plots by soil solarization during summer has been standardized as a farmer-friendly method (Maiti et al. 2009). In the present investigation, an attempt was made to integrate inoculation of native AMF with different crop rotations with the aim of enhancing AMF activity, facilitating plant P acquisition, and increasing the yield of upland rice.

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Materials and methods

Field experimentation

An experiment was initiated in the wet season of 2006 and continued in 2007, 2008, and 2009 in field plots (plot size= 15 m^2) located at the research farm of Central Rainfed Upland Rice Research Station (CRURRS), Hazaribag in the Jharkhand state of India. The land situation of the experimental site was a 10–20% sloped upland with acidic (pH 5.8), red Alfisol soil. The soil was very poor in organic carbon (0.47%), moderate in available P (19.3 kg P_2O_5/ha), and adequate in K (176 kg K_2O/ha) content. Rice-based crop rotation (2 years) of maize (*Zea mays* L.), relay-cropped by horse gram (*Dolichos biflorus* L.) in the first year followed by upland rice in the second year (M-HG/R) was compared with three existing cropping systems *viz*.: (1) 2-year rotation of pigeon pea (*Cajanas cajan* L.) and rice in alternate years (R/PP), (2) rice+finger millet (*Eleusine coracana* Gaertn) intercropping (4:2 row ratio) (R+FM), and (3) rice sole-cropping. The first 2-year crop rotations were during the wet seasons of 2006–2007 and were repeated during the wet seasons of 2008–2009. The experiment was laid out in a split-plot design with four cropping systems in the main plot and two inoculation treatments (with and without AMF inoculum) in the sub-plots with four replications as follows.

T_1=Rice (R) every year without AMF inoculum: R

T_2=Rice every year (T_1)+mass-produced AMF inoculum (see below) (MI): R (+MI)

T_3=2-year rotation of maize, relay-cropped by horse gram (M-HG) in the first year and rice (R) in the second year (M-HG in 2006 and 2008, and rice in 2007 and 2009) without MI: M-HG/R

T_4=2-year rotation of maize, relay-cropped by horse gram (M-HG) in the first year and rice (R) in the second year (M-HG in 2006 and 2008, and rice in 2007 and 2009): M-HG/R (+MI)

T_5=2-year rotation of pigeon pea (PP) in the first year and rice (R) in the second year (PP in 2006 and 2008, and R in 2007 and 2009) without MI: PP/R

T_6=2-year rotation of pigeon pea (PP) in the first year and rice (R) in the second year (PP in 2006 and 2008, and R in 2007 and 2009): PP/R (+MI)

T_7=Rice+finger millet (FM) intercropping every year without MI: R+FM

T_8=Rice+finger millet (FM) intercropping every year+ MI: R+FM (+MI)

The crop varieties were: rice 'Vandana', pigeon pea 'Birsa Arhar 1', maize 'Swan', horse gram 'Birsa Kulthi 1', and finger millet 'A 404'. The crops were sown directly (dry seeding) in rows: rice, horse gram, and finger millet at 20 cm apart (with continuous seeding); maize at 60 cm apart (with 20 cm seed to seed); and pigeon pea at 75 cm apart (with 25 cm seed to seed), at the recommended seeding rate (R-100, PP-20, M-30, HG-30, FM-12 kg/ha). In the intercropping systems (R+FM), the seeding rates were adjusted to 4:2; R/FM row ratio. The crops were fertilized as follows:

(a) R and R+FM=60 (in three splits of 10+25+25):20:20 kg $N:P_2O_5:K_2O$ kg/ha
(b) PP=20:40:0; $N:P_2O_5:K_2O$ kg/ha
(c) M=120 (in three splits of 45+25+50):40:30; $N:P_2O_5:K_2O$ kg/ha
(d) HG=0:30:0; $N:P_2O_5:K_2O$ kg/ha

The $N:P_2O_5:K_2O$ fertilizers were applied in the forms of di-ammonium phosphate (DAP; basal dose of N and P_2O_5 as full dose of basal application), muriate of potash (K_2O as full dose of basal application), and urea (N as top dressing as per schedule). In the mass-produced inoculum treated plots, a soil–root-based inoculum, prepared by multiplying AMF inoculum following the protocol developed by Maiti et al. (2009) (see below), was applied at 1.5 t/ha.

The off-season (October/November to May/June next year) tillage schedule component (supporting optimum activities of native AMF) of separating two tillage operations by more than 13 weeks (Maiti et al. 2010) was practiced. Tillage operations were done separately in the field plots with the help of a bullock-drawn country plough. Final land preparation was done manually using spades prior to sowing.

AMF inoculum production

Inoculum was produced following an on-farm production method developed by Maiti et al. (2009). Surface sterilized (Chloramine T, 1 min) spores of a native AMF consortium, predominated by *Glomus* and *Acaulospora* (Maiti et al. 1995), were isolated following the wet sieving–decanting method (Gerdmann 1955) and multiplied on *Sorghum* (*Sorghum bicolor* L; variety SPV 1616) grown in a sterilized soil/sand/FYM mixture (1:1:1; v/v/v; SSF substrate). The top soil (Alfisol) used in the SSF substrate came from the CRURRS research farm (32% sand, 45% silt, 23% clay, 0.09% total N, 7.9% available P, 0.01% available K). Acid-washed coarse sand was used and FYM was from a compost peat of the same research farm (55% dry matter, 13.5% organic matter, 0.54% total N, 0.96% total P, 0.82% total K). Surface sterilized (0.01% aqueous $HgCl_2$, 1 min) *Sorghum* seeds were grown in SSF substrate inoculated with the native AMF spores (50–75/100 g SSF substrate), with regular watering in a glasshouse (day temperature maintained up to 35±5°C) for 30 days to prepare starter inoculum. Starter inoculum was further multiplied on *Sorghum*, grown in field micro-plots (4×

4 m^2) of partially sterilized by soil solarization (Katan et al. 1976) using transparent, thin (1–2 mm) low density polyethylene (LDPE) film as mulching for 30 days during peak summer months (April–May). The LDPE cover was removed after 30 days and furrows (10–15 cm depth) were opened manually at 10 cm apart. The starter inoculum was placed as a band in furrows (200 g/0.5 m^2) followed by dense sowing (20–24 kg/ha) of *Sorghum* and covered by the plot soil. The micro-plots were watered regularly until germination and the plants grown with life-saving irrigation for 30 days during May–June to ensure that the mass-produced inoculum was ready prior to sowing of upland rice (normally third to fourth week of June depending on the onset of monsoon). After 30 days' growth of *Sorghum* in the micro-plots, aerial plant parts were removed, soil and roots harvested down to 15 cm, roots cut into small pieces, mixed thoroughly, air dried under shade, and used as mass-produced inoculum. Mass-produced inoculum containing 60.8–80.7 IP/g was applied at a rate of 1.5 t/ha in furrows opened for sowing seeds and placed beneath the seeds.

Sampling and estimations

Plant samples (shoots and roots) were taken at 90 days after emergence (DAE) for estimation of P uptake and root colonization (%) by AMF. Tiller number, panicle number, panicle weight, and number of filled grain/panicle at maturity (rice only) and grain yield (all crops) were recorded following the methods described by Yoshida et al. (1976). Grain yields were expressed on a dry-weight basis by drying sub-samples at 70°C for 48 h. For crops other than rice, rice equivalent yields were calculated based on their minimum support prices announced by the Directorate of Economics and Statistics, Department of Agricultural Co-operation, Ministry of Agriculture, Government of India each year (http://dacnet.nic.in/eands/msp/MSP_4th-Sep-English.pdf) using the following formula:

$$\text{Rice equivalent yield of other crops} = \text{Yield of other crop}\left(\frac{\text{support price of other crop}}{\text{support price of rice}}\right).$$

Sampled roots were cut into pieces of about 1 cm in length and fixed in a formalin/acetic acid/70% alcohol (5:5:90 FAA) solution for 48 h. The fixed roots were cleared in 10% KOH and stained with trypan blue according to Kormanik et al. (1980). The stained roots were observed under stereo-zoom microscope and root length colonization (RLC %) was assessed using systematic gridline-intersect method (Giovennetti and Mosse 1980). Grain and shoot/straw samples were analyzed for P content by digesting ground samples in tri-acid mixture (Jackson 1962) and estimating P colorimetrically (Murphy and Riley 1662). Percent P in samples was converted to P uptake (mg P/g plant).

Soil samples (0–20 cm) were collected twice: prior to sowing of crops (June) in the wet season and just after harvesting of crops. Five sub-samples from each plot were pooled and final samples of 600 g were stored. Infective propagules (IP) AMF population was monitored in the soil samples by the most probable number (MPN) method (Powell 1980). The Mehlich 1 'P' content of soils (double acid extractable P using 0.05 N HCl and 0.025 N H_2SO_4) was estimated colorimetrically using the blue color ascorbic acid method.

Statistical analyses

The "Balanced ANOVA (BOAV)" procedure of the "CROPSTAT 7.2" statistical package developed by the International Rice Research Institute, Philippines, was used for statistical analysis of data.

Results

Native AMF population dynamics

Initial (June 2006) native AMF populations (IP) in the soils of the experimental plots were fairly uniform ranging between 4.9 and 5.8 IP/g soil (Pr>F=0.098) (Table 1). All the crop rotations, including rice alone, increased native AMF populations by the end of the crop season (wet season; June to October) followed by a decline during the fallow (November to June next year). Over the years, the highest increment during the cropping season and lowest decline during fallow (Pr>F=0.000) was under the maize–horse gram/rice (M-HG/R) rotation irrespective of AMF inoculum application (Table 1). This was followed by the rice+finger millet intercropping system and the pigeon pea/rice crop rotation. The least increment in native AMF populations during wet season and the highest decline during off-season were under rice cultivation alone. In the absence of AMF inoculation, the pigeon pea/rice crop rotation and the rice+finger millet intercropping system caused an initial (June) elevation in indigenous AMF populations in the first 2 years (June 2006 to June 2007) with no further increase during the subsequent years (2008 and 2009), while the maize–horse gram/rice rotation induced a significantly steady increase (Pr>F=0.000) of populations over the years. Rice alone, grown every year, maintained populations with an off-season crash and a wet-season rise without significant changes over the years. Introduction of an AMF inoculum containing 60.8–80.7 MPN infective propagules/g, on the other hand, concomitantly increased AMF populations leading to a

Table 1 Interactive effect of upland rice-based cropping rotations/systems and native AMF inoculation on AMF population dynamics in soil as a function of time

Cropping system/monitoring stage	AMF population (MPN/g soil)								
	June 2006	Oct. 2006	June 2007	Oct. 2007	June 2008	Oct. 2008	June 2009	Oct. 2009	Mean
Rice sole	5.20	12.38	4.60	10.25	6.45	29.58	7.60	31.90	13.49
Rice sole+MI	5.13	33.83	9.23	53.60	15.73	78.35	29.23	94.68	39.97
Maize–horse gram/rice	4.90	54.93	29.13	84.18	35.65	109.20	49.18	98.90	58.26
Maize–horse gram/rice+MI	4.98	119.20	53.08	151.08	63.08	229.45	85.68	149.83	107.04
Pigeon pea/rice	5.17	26.23	17.70	59.26	12.63	77.26	18.20	58.63	34.38
Pigeon pea/rice+MI	4.61	56.03	30.88	92.48	28.23	127.48	37.38	118.85	61.99
Rice+finger millet	5.75	39.25	16.93	51.68	16.93	99.18	12.23	67.23	38.65
Rice+finger millet+MI	5.50	93.83	36.30	108.83	28.58	161.25	37.78	146.33	77.30
Mean	5.15	54.46	24.73	76.41	25.91	113.96	34.66	95.79	
5% LSD (monitoring stage wise treatment means of observations)	0.73	4.95	4.04	7.18	4.47	9.39	4.21	19.09	
5% LSD (treatment means)									4.29
5% LSD (monitoring stages means)									4.29
5% LSD treatment×stage								12.14	

Data are the mean of four observations

MI mass-produced inoculum (soil–*Sorghum* root based) of native AMF

significantly gradual increase (Pr>F=0.000) in soil populations over the years in all the cropping rotations/systems, including rice alone. A significant additive effect was highest in the maize–horse gram/rice rotation.

Native AMF colonization and P uptake in rice

Effects of integration of upland rice-based cropping rotations/systems with application of AMF inoculum on (1) mycorrhizal root colonization and (2) P uptake in rice were monitored at crop maturity (90 days after emergence) during the second years (2007 and 2009) of the 2-year rotations (2006–2007 and 2008–2009) when rice was grown following the first-year crops.

All the three cropping rotations of maize–horse gram/rice, pigeon pea/rice and rice+finger millet intercropping resulted in higher native AMF root colonization in rice compared to rice alone every year, corroborating earlier observations (Rana et al. 2002), with consistent and statistically significant (2006–2007 and 2008–2009) increases in the maize–horse gram/rice rotation (Fig. 1). When the mass-produced inoculum containing a native AMF population of 60.8–80.7 propagules/g was applied, mycorrhizal colonization in rice increased significantly (Pr>F=0.000) in all the cropping rotations/systems with highest additive effects in maize–horse gram/rice rotation in both seasons (2007 and 2009).

The increase in AMF colonization with inoculation of the rice-based cropping rotations/systems and integration of cropping rotations/systems was accompanied by concomitant enhancement of P uptake in rice (Fig. 2) in both years (Pr>F=0.004 in 2007 and 0.001 in 2009). Additive effects were consistently highest in case of the maize–horse gram/rice rotation integrated with AMF inoculation, followed by that of the rice–finger millet intercropping system. No significant differences (Pr>F=0.302 and 0.280, respectively) following crop rotation treatments were observed in the initial available soil P status prior to sowing in June (15.5–20.2 kg P_2O_5/ha in 2007 and 12.7–17.9 in 2009).

Plant growth, panicle character, and grain yield of rice

The plant growth parameters of total aerial dry matter production, tiller and panicle density (number/m^2) of rice were generally higher across treatments (Table 2) in the second year (2007) of the first rotation which received higher rainfall (+21.6%) than average compared to the second rotation which had a rainfall of 8.9% below average (Fig. 3). Tiller and panicle densities were significantly (Pr>F=0.0000) higher in 2007 with only a nominal increase of aerial dry matter production. The panicle characteristics (panicle weight and grain filling), on the other hand, showed the opposite trend (Table 3). In both 2007 and 2009, however, the maize–horse gram/rice followed by pigeon pea/rice rotation produced significantly highest (Pr>F=0.0000) tiller and panicle density (number/m^2), panicle weight, and grain filling compared

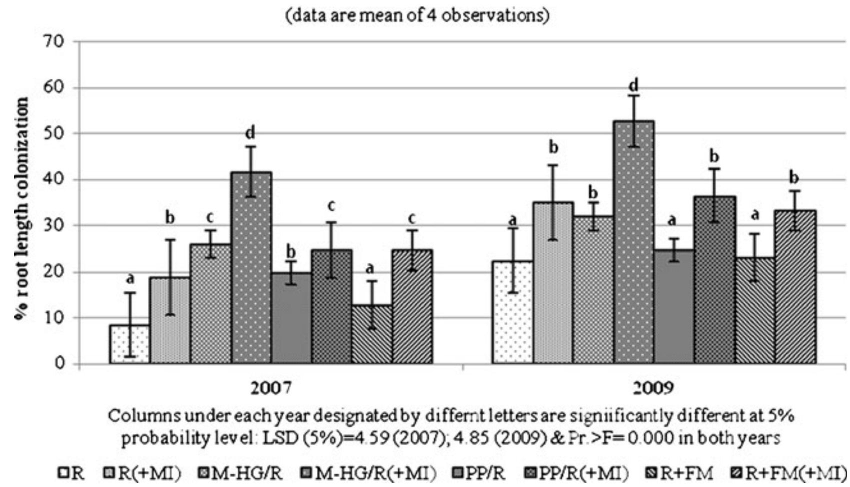

Fig. 1 Interactive effects of upland rice based cropping rotations/systems and AMF inoculation on colonization by AMF in upland rice cv. Vandana at crop maturity (90 days after emergence)

to the other cropping rotation/systems. Addition of the mass-produced inoculum of native AMF resulted in additive effects with statistically significant increases in tiller and panicle density in the year with less rainfall (2009), and of panicle characters (panicle density and grain filling) in both years (2007 and 2009).

Rice yield was, in general, low in the year of low rainfall (2009) compared to that of the year with above average rainfall (2007) (Table 4). With the improvement in rice growth parameters and panicle characters, concomitant increases in grain yield were evident in both years with significantly highest yields following maize–horse gram/rice and pigeon pea/rice rotations. Inoculation of native AMF resulted in concomitantly additive effects on rice yield in all the four cropping rotations/systems in both the test years, but these were only consistently significant (Pr>F=0.0000) for the maize–horse gram/rice rotation in both years (2007 and 2009).

Discussion

In all the four cropping rotations tested, the three off-seasons (November to June) of 2006–2007, 2007–2008, and 2008–2009 resulted in a population crash in the native AMF probably due to what is called “fallow disorder” (Thompson 1987; Kabir et al. 1999; Oliveira and Sanders 1999). This decline was, however, significantly and consistently least after the maize–horse gram rotation, followed by that of pigeon pea and the rice+finger millet intercropping system. Maize being highly colonized by native AMF, it supported maximum AMF activities in soil (Oliveira and Sanders 1999; Maiti et al. 2006). These were further sustained by the post-maize–horse gram culture which provided a favorable soil environment until the third week of November, as compared to that of post-rice fallow, in case of rice alone, and the rice+finger millet intercropping system after harvest of rice and finger millet in mid-

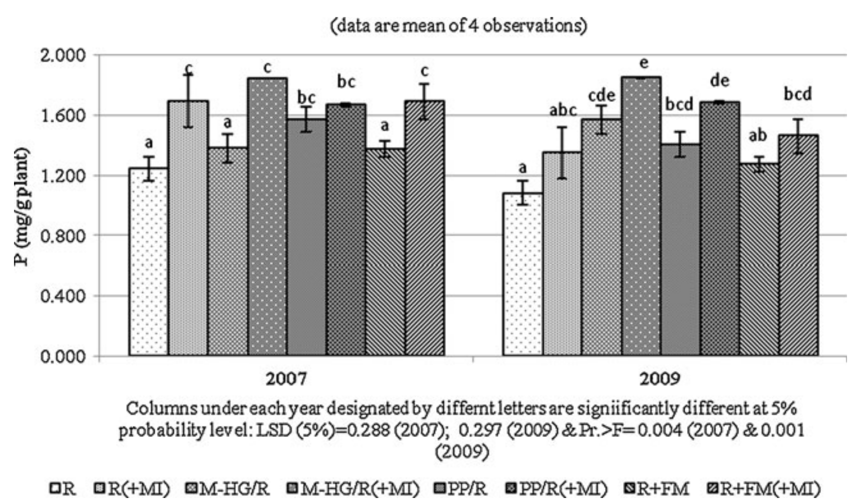

Fig. 2 Interactive effects of upland rice based cropping rotations/systems and AMF inoculation on P uptake by upland rice cv. Vandana at crop maturity (90 days after emergence)

Table 2 Interactive effects of upland rice based cropping rotations/systems and native AMF inoculation on plant growth parameters of upland rice (cv. Vandana)

Treatments	Tiller #/m^2			Panicle #/m^2			Aerial dry matter production (kg/ha)		
	2007	2009	Mean	2007	2009	Mean	2007	2009	Mean
Rice sole	200.3	52.4	126.3	179.4	29.1	104.2	3,950.0	3,449.8	3,699.9
Rice sole+MI	203.8	63.9	133.8	181.3	43.7	112.5	4,208.8	4,171.7	4,190.2
Maize–horse gram/rice	231.9	104.1	168.0	218.8	77.6	148.2	5,674.0	5,842.9	5,758.5
Maize–horse gram/rice+MI	247.2	119.1	183.1	230.9	96.8	163.9	6,152.3	6,234.0	6,193.1
Pigeon pea/rice	194.7	89.2	142.0	173.8	53.8	113.8	5,168.3	4,821.4	4,994.8
Pigeon pea/rice+MI	221.3	73.3	147.3	203.1	65.0	134.1	6,389.0	4,876.5	5,632.7
Rice+finger millet	104.1	58.8	81.4	99.7	43.9	71.8	3,375.3	4,376.8	3,871.5
Rice+finger millet+MI	113.4	76.7	95.1	101.3	57.7	79.5	3,733.3	5,286.9	4,510.1
Mean	189.6	79.7		173.5	58.5		4,831.4	4,881.4	
5% LSD (year wise treatment means of observations)	42.3	12.5		45.6	7.6		1,203.2	782.2	
Pr>F	0.0000	0.0000		0.0000	0.0000		0.0001	0.0000	
5% LSD (treatment means)			21.2			21.9			825.9
Pr>F			0.0000			0.0000			0.0000
5% LSD (year means)		10.6			10.9			NS	
Pr>F		0.000			0.000				
5% LSD (treatment×year means)		30.0			31.0				1,168.0
Pr>F		0.0000			0.0000				0.0252

Data are the mean of four observations

MI mass-produced inoculum (soil–*Sorghum* root based) of native AMF

October. Such improvement of native AMF infectivity in crops pre-cropped with other crops, even with non-mycorrhizal crops, as compared to fallow, has also been reported by Harinikumar and Bagyaraj (2005); Grant et al. (2009) and Ocampo and Hayman (1981) in various crop combinations. The maize–horse gram rotation in addition reduced the fallow period prior to rice by about 6–7 weeks in the subsequent wet season, as compared to rice alone or the rice+finger millet intercropping system, and maintained significantly higher AMF populations leading to higher colonization of rice. Despite a longer presence of the crop in the field, pigeon pea (harvested first to second week of December) did not result in any further enhancement of AMF activities owing to the lower mycorrhizal colonization (pigeon pea) as compared to maize and horse gram (Maiti et al. 2006). With the longest fallow (November to June next year) in the rice+finger millet intercropping system, maintenance of AMF populations was low but significantly higher than with rice alone, possibly because of greater AMF propagation supported by higher density of the fibrous root systems under the intercropping system (Harinikumar and Bagyaraj 1988).

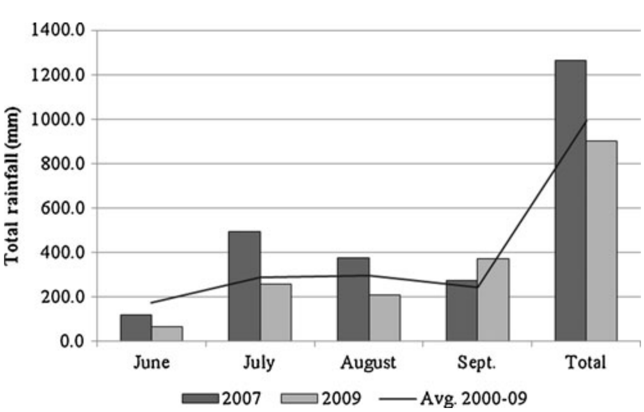

Fig. 3 Monthly total rainfall during wet seasons of 2007 and 2009

Integration of native AMF inoculation led to additive effects in all cropping rotations with highest additive effect in the maize–horse gram/rice rotation. The AMF population of the ecosystem under study was predominantly comprised of the genera *Glomus* and *Acaulospora* (Maiti et al. 1995). Higher AMF activities in terms of growth promotion of various crops by inoculation with an AMF inoculum of native origin are well documented (Mohammad et al. 2004; Douds et al. 2005; Oliveria et al. 2005). The continuous cultivation of the maximum “AMF-supportive” crop rotation (maize–horse gram/rice) integrated with the introduction of mass-produced AMF inoculum for two consecutive rotations (2006–2007 and 2008–2009) resulted in the highest steady increase in the native AMF population.

Table 3 Interactive effects of upland rice-based cropping rotations/systems and native AMF inoculation on panicle characters of upland rice (cv. Vandana)

Treatments	Panicle wt. (g/panicle)			Filled grain #/panicle		
	2007	2009	Mean	2007	2009	Mean
Rice sole	1.22	1.84	1.53	50.4	57.1	53.7
Rice sole+MI	1.51	2.12	1.82	55.1	71.7	63.4
Maize–horse gram/rice	1.66	2.05	1.85	58.3	78.7	68.5
Maize–horse gram/rice+MI	1.98	2.49	2.23	66.4	88.8	77.6
Pigeon pea/rice	1.72	2.10	1.91	64.4	71.6	68.0
Pigeon pea/rice+MI	1.99	2.37	2.18	63.7	81.1	72.4
Rice+finger millet	1.42	1.75	1.58	47.5	68.0	57.8
Rice+finger millet+MI	1.53	2.20	1.87	55.7	79.3	67.5
Mean	1.62	2.11		57.7	74.5	
5% LSD (year wise treatment means of observations)	0.27	0.20		12.3	5.5	
Pr>F	0.0000	0.0000		0.0390	0.0000	
5% LSD (treatment means)			0.17			6.69
Pr>F			0.0000			0.0000
5% LSD (year means)		0.84				3.34
Pr>F		0.0000				0.0000
5% LSD (treatment×year means)		0.24				9.46
Pr>F		0.3092				0.0843

Data are the mean of four observations

MI mass-produced inoculum (soil–*Sorghum* root based) of native AMF

Table 4 Interactive effects of upland rice-based cropping rotation/system and native AMF inoculation on grain yield of upland rice (cv. Vandana) and cropping system productivity

Treatments/monitoring stage	Grain yield (rice and/or rice equivalent yield)[a]			
	Grain yield of rice (t/ha)		Total productivity of cropping rotations/systems (rice/rice+rice equivalent yield in t/ha)	
	2007	2009	2006 and 2007	2008 and 2009
Rice sole	1.12	0.51	3.11	3.29
Rice sole+MI	1.68	0.80	4.65	4.39
Maize–horse gram/rice	2.15	0.88	6.21	4.88
Maize–horse gram/rice+MI	2.58	1.50	7.58	4.86
Pigeon pea/rice	1.97	0.75	4.37	3.27
Pigeon pea/rice+MI	2.46	1.24	6.55	5.41
Rice+finger millet	0.34	0.82	4.68	4.12
Rice+finger millet+MI	0.46	1.15	5.42	4.64
5% LSD	0.15	0.63	0.89	1.07
Pr>F	0.000	0.000	0.000	0.004

Data are the mean of four observations. The support prices were obtained from announcement by the Directorate of Economics and Statistics, Department of Agricultural Co-operation, Ministry of Agriculture, Government of India each year (http://dacnet.nic.in/eands/msp/MSP_4th-Sep-English.pdf)

MI mass inoculum (soil–*Sorghum* root based) of native AMF (consortium)

[a] Rice equivalent yield of other crop $= \text{Yield of other crop}\left(\frac{\text{support price of other crop}}{\text{support price of rice}}\right)$.

Maintenance of a higher initial soil population in the month of June every year for rice (2007 and 2009) concomitantly enhanced AMF colonization of rice. The other two cropping systems/rotations of rice+finger millet and pigeon pea–rice resulted in comparatively lower increases in root colonization levels. This could be due to the fact that only the maize–horse gram/rice system maintained initial (June) AMF populations over the threshold level for producing significant increases in colonization of rice.

The increase in mycorrhizal colonization induced by the "AMF supportive" cropping rotations/systems was associated with a concomitant significant increase in P uptake by rice plants with a maximum increase under the maize–horse gram/rice rotation. The higher level of P fertilizer added to maize in 2006 and 2008, on the other hand, was depleted by the crop, bringing soil P to an almost uniform level with that of the other cropping systems in subsequent seasons (June 2007 and 2009). With introduction of the AMF inoculum, all the cropping rotations/systems showed significantly additive effects in terms of AMF colonization and P uptake in both seasons (2007 and 2009), with highest additive effects in the maize–horse gram/rice system. Such efficacy of AMF inoculum of native origin has also been demonstrated in other plant production systems (Douds et al. 2005).

The plant growth parameters tiller and panicle density of rice were significantly higher in the above average rainfall year (2007) as compared to the below average rainfall year (2009). Lower panicle density led to higher panicle weight and significantly higher grain filling in the year experiencing moisture stress. However, lower panicle weight and poor grain filling in the above average rainfall year (2007) was compensated by much higher panicle density which resulted in higher grain yield. The most "AMF-supportive" crop rotation of maize–horse gram/rice resulted in significantly highest grain yield and total productivity in terms of rice equivalent through a higher AMF activity and enhanced P acquisition, corroborating earlier observations on upland rice (Maiti et al. 2006). Significantly additive effects were obtained for growth parameters and rice yield when the same crop rotation was integrated with the application of AMF inoculum.

In conclusion, the present study clearly demonstrates the possibility of increasing the yield of upland rice through enhancement of AMF activity in facilitating plant P acquisition. An integrated approach for maximizing upland rice production in drought prone, rainfed uplands can be recommended which is based on an "AMF-supportive" 2-year maize–horse gram/rice crop rotation, coupled with the introduction of a native AMF-based inoculum produced in situ in solarized micro-plots.

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