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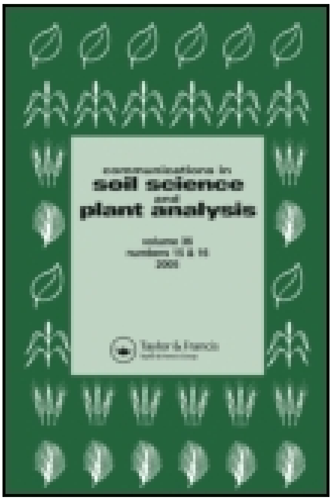

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The present investigation was carried out at Palampur, India, during 2009–11 to enhance plant water relations and productivity in pea through arbuscular mycorrhizal fungi (AMF) in a Himalayan acidic Alfisol. The field experiment was replicated three times in a randomized block design comprising 14 treatments involving AMF, inorganic phosphorus (P), irrigation regimes, generalized recommended nitrogen, phosphorus, and potassium (NPK) dose and irrigations, and farmers' practice in the region. The study revealed that treatments involving AMF inoculation along with inorganic P nutrition at varying irrigation regimes led to significantly greater relative leaf water content (2%), xylem water potential (12%), and water-use efficiency (10%), respectively, in comparison with non-AMF inoculated counterparts. Similarly, maximum increase in quality parameters such as total soluble solids (6%), ascorbic acid (6%), and crude protein content (3%) in pea was registered under AMF inoculation involving treatments. Further, AMF-inoculated treatments indicated an economy of about 25% in soil-test-based P dose without impairing crop productivity.

Keywords Acidic Alfisol, arbuscular mycorrhizal fungi, relative leaf water content, water-use efficiency, xylem water potential

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Introduction

Garden pea (*Pisum sativum* L.) is an important vegetable crop in wet, temperate north-western (NW) Himalayas because of the well-suited agroclimatic conditions, and it fetches premium prices for hill farmers (Anonymous 2012). Garden pea is very palatable, nutritious, and amenable to preservation and consumption in the off-season. However, most soils in NW Himalayas are acidic (Suri et al. 2011a). Phosphorus (P) availability to plants is a major constraint in acidic soils with average efficiency of merely 10–20% (Pattanayak, Sureshkumar, and Tarafdar 2009). In acidic Alfisols, soluble iron (Fe), aluminium (Al), and manganese (Mn) are usually present in greater concentrations (Sharma, Verma, and Bhumbla 1980), and P reacts with these ions and produces insoluble phosphatic compounds, rendering P unavailable to plants. With fixation of P by hydrous oxides of Fe and Al or by adsorption, P availability is decreased (Sharma, Verma, and Bhumbla 1980; Das 2011; Suri et al. 2011a). The soils of this region have low water retention due to silty–clay loam texture, causing less availability of water to plants (Suri and Choudhary 2012). Erratic and ill-distributed rainfall pattern and poor irrigation infrastructure in NW Himalayas are other constraints for vegetable production especially in *Rabi* season (dry season) in the region (Paul et al. 2011).

In this scenario, adoption of mycorrhizal fungi in crop production, which is an inexpensive and ecofriendly input, is capable of enhancing both P availability and water-use efficiency of crops (Harrier and Watson 2003). Being fungi, arbuscular mycorrhizal fungi (AMF) are well suited to acidic soils. Arbuscular mycorrhizal fungi symbiosis refers to a mutualistic, symbiotic relationship formed between fungi and living roots of higher plants (Harley and Smith 1983; Sieverding 1991). Mycorrhizal fungi carry out their functions by expanding the surface area of the plant root system 10- to 1000-fold into the soil through their ramifying hyphae, thereby increasing their exploratory area for harnessing P and water (Harrier and Watson 2003). Arbuscular mycorrhizal fungi also release organic acids (oxalic, mallic acids, etc.), which solubilize insoluble phosphates and other insoluble nutrients and make them available for plant use (Zou, Binkley, and Caldwell 1995; Nahas 1996). By secreting many enzymes (chitinase, peroxidase, cellulase, protease, phosphatase, etc.), AMF convert complex organic compounds into simple ones absorbed and used by fungi or host plants to meet their energy needs for growth and reproduction (Chen, Condron, and Xu 2007). Besides P, AMF also supply other plant nutrients such as nitrogen (N), potassium (K), calcium (Ca), copper (Cu), and zinc (Zn) to the plants, which are absorbed from soil (Barea and Jeffries 1995), leading to increased input economy (Suri et al. 2011b) as well as greater crop yields with better quality (George et al. 1992). Mycorrhizal hyphae penetrate the soil pores that are inaccessible to root hairs, thereby absorbing water that is unavailable to nonmycorrhizal plants (Auge 2001). Arbuscular mycorrhizal fungi develop an extensive extraradical hyphal network that grows away from the root, through the rhizosphere into the surrounding bulk soil matrix (Harrier and Watson 2003; Suri et al. 2011a). The network makes a significant contribution in improvement of soil structure and water relations (Tisdall and Oades 1982; Miller and Jastrow 1990; Tisdall 1991).

Currently, information on the role of AMF as seen through P and irrigation management in pea crop is lacking in general and Himalayan acidic Alfisol in particular, and needs to be generated urgently. Thus, the present investigation was conducted to quantify changes in crop productivity and enhancing water-use efficiency in pea, so that necessary recommendations could be made to the farmers in NW Himalayas.

Materials and Methods

Study Area

Field studies were conducted on brinjal (*Solanum melongena* L.)–pea (*Pisum sativum*) cropping system during 2009–11 at Experimental Farm, CSK Himachal Pradesh Agricultural University, Palampur, India (32° 6′ N latitude and 76° 3′ E longitude, 1250 m above mean sea level). This article presents the results obtained on pea during the second year of the brinjal (*Solanum melongena* L.)–pea (*Pisum sativum*) cropping cycle. The climate of the experimental area is characterized as wet temperate with mild summers (March to June) and cold winters (December to March). The rainfall received during *Rabi* (dry season) 2010–11 was 362 mm. The initial properties of experimental soil were silty–clay loam texture with sand 28.9%, silt 47.2%, and clay 23.1%, pH 5.3, organic carbon 7.4 g kg^{-1}; and available nitrogen (N) 264 kg ha^{-1}, phosphorus pentoxide (P_2O_5) 43 kg ha^{-1}, and dipotassium oxide (K_2O) 134 kg ha^{-1}. The soil texture was determined by the international pipette method (Piper 1950), while soil reaction (1:2.5 soil/water suspension using glass electrode pH meter, Jackson 1967), organic carbon (rapid titration method, Walkley and Black 1934), available N (alkaline permanganate method, Subbiah and Asija 1956), available P [0.5 M sodium bicarbonate ($NaHCO_3$) extraction method at pH = 8.5, Olsen et al. 1954], and available K (neutral normal ammonium acetate extraction method, Black 1965) were estimated using standard procedures.

Experimental Details

The field experiment was replicated three times in a randomized block design comprising 14 treatments with 12 treatment combinations of two arbuscular mycorrhizal fungi (AMF) levels [0 and 12 kg ha^{-1}], three P levels [50, 75, and 100% of recommended soil-test-based P dose], and two irrigation regimes [$IW/CPE_{0.6}$ and $IW/CPE_{1.0}$] besides one treatment with "generalized recommended NPK dose with generalized recommended irrigations (GRD)" and one treatment based on farmers' practice of plant nutrition and irrigation management in the NW Himalayan region were imposed (Table 1). Nitrogen (N), P, and potassium (K) were supplied through urea (46% N), single superphosphate (16% P_2O_5), and muriate of potash (60% K_2O), respectively. The farmyard manure (FYM) and NPK fertilizers were applied as per treatment levels in different plots (Table 1). A nominal amount of FYM (1/4 recommended dose) was incorporated in all plots, except those having the generalized recommended dose (T_1). The recommended NPK dose for garden pea was applied at 50:60:60 kg ha^{-1}.

AMF Inoculation

The AMF used in the present experimentation belonged to *Glomus mosseae* (Source: Indian Agricultural Research Institute, New Delhi, India). Arbuscular mycorrhizal fungi spore count in this culture was 28–30 per 10 g culture as determined by the method suggested by Gaur and Adholeya (1994). The actual inoculation of pea seeds with AMF culture was performed by preparing a soil slurry of this culture and dipping the seeds into it for half an hour, followed by shade drying, making seed pallets, and sowing in the field (Suri et al. 2011a).

Table 1
Details of experimental treatments evaluated in garden pea in the current study

Treatment	Treatment details	Treatment code
T_1	No AMF + 100% NPK + irrigations as per need and soil moisture content (generalized nutrient recommended dose and generalized irrigations)	V_0NPK 100% + $FYM_{12.8t}$ I_{AR} (GRD)
T_2	No AMF + $N_{25\%}P_0K_0$ + irrigations now and then depending on water availability (farmers' practice)	$V_0N_{25\%}P_0K_0FYM_{3t}I_{WA}$ (FP)
T_3	No AMF + 30 kg P_2O_5 ha^{-1} + irrigation at $IW/CPE^*_{0.6}$	$V_0P_{50\%}$ $IW/CPE_{0.6}$
T_4	No AMF + 45 kg P_2O_5 ha^{-1} + irrigation at $IW/CPE_{0.6}$	$V_0P_{75\%}$ $IW/CPE_{0.6}$
T_5	No AMF + 60 kg P_2O_5 ha^{-1} + irrigation at $IW/CPE_{0.6}$	$V_0P_{100\%}$ $IW/CPE_{0.6}$
T_6	12 kg AMF ha $^{-1}$ + 30 kg P_2O_5 ha^{-1} + irrigation at $IW/CPE_{0.6}$	$V_{12}P_{50\%}$ $IW/CPE_{0.6}$
T_7	12 kg AMF ha $^{-1}$ + 45 kg P_2O_5 ha^{-1} + irrigation at $IW/CPE_{0.6}$	$V_{12}P_{75\%}$ $IW/CPE_{0.6}$
T_8	12 kg AMF ha $^{-1}$ + 60 kg P_2O_5 ha^{-1} + irrigation at $IW/CPE_{0.6}$	$V_{12}P_{100\%}$ $IW/CPE_{0.6}$
T_9	No AMF + 30 kg P_2O_5 ha^{-1} + irrigation at $IW/CPE_{1.0}$	$V_0P_{50\%}$ $IW/CPE_{1.0}$
T_{10}	No AMF + 45 kg P_2O_5 ha^{-1} + irrigation at $IW/CPE_{1.0}$	$V_0P_{75\%}$ $IW/CPE_{1.0}$
T_{11}	No AMF + 60 kg P_2O_5 ha^{-1} + irrigation at $IW/CPE_{1.0}$	$V_0P_{100\%}$ $IW/CPE_{1.0}$
T_{12}	12 kg AMF ha $^{-1}$ + 30 kg P_2O_5 ha^{-1} + irrigation at $IW/CPE_{1.0}$	$V_{12}P_{50\%}$ $IW/CPE_{1.0}$
T_{13}	12 kg AMF ha $^{-1}$ + 45 kg P_2O_5 ha^{-1} + irrigation at $IW/CPE_{1.0}$	$V_{12}P_{75\%}$ $IW/CPE_{1.0}$
T_{14}	12 kg AMF ha $^{-1}$ + 60 kg P_2O_5 ha^{-1} + irrigation at $IW/CPE_{1.0}$	$V_{12}P_{100\%}$ $IW/CPE_{1.0}$

Notes. IW, irrigation water (mm); CPE, cumulative pan evaporation (mm); AR, as per requirement; WA, as per water availability. FYM application at 3 t ha^{-1} on dry weight basis, i.e., 5 t ha^{-1} on fresh-weight basis was applied in 13 treatments (T_2–T_{14}), whereas in T_1 FYM was applied at 12.8 t ha^{-1} on a dry-weight basis or 20 t ha^{-1} on a fresh-weight basis. Recommended NPK dose for pea is 50:60:60 kg ha^{-1}. Rabi season starts in October and ends in April.

Irrigation Scheduling

For irrigation scheduling, a climatological approach was adopted that involved atmospheric evaporative demand for the given soil, crop, and climatic conditions that can be estimated by working out the ratio between irrigation water applied (mm) to cumulative pan evaporation (CPE) (mm). The present experiment involved two IW/CPE ratios of 1.0 and 0.6. An irrigation 5 cm deep was applied in respective plots by the pipe irrigation method when this ratio (IW/CPE) reached the predetermined levels. For this purpose, the evaporation data were collected regularly from the meteorological observatory of the university situated near to the experimental plots.

Plant Water Studies

Relative Leaf Water Content. Relative leaf water content (RLWC) indicates the moisture status of plants. For determining RLWC, five leaves were sampled from different plants in each plot, brought to laboratory in tightly closed polythene begs, and then fresh weights were recorded, followed by chopping the leaves into 0.5-cm pieces and saturation overnight in Petri plates. The saturated leaves were taken out the next day and nominally dried between the folds of a filter paper, followed by recording of their turgid weights. The leaves were then transferred to an oven for 72 h, after which their weight was taken. The RLWC was computed from the fresh weight, turgid weight, and oven-dry weight according to the method given by Weatherly (1950) as

$$\text{RLWC}\ (\%) = \frac{\text{Fresh weight} - \text{oven dry weight}}{\text{Fully turgid weight} - \text{oven dry weight}} \times 100$$

Xylem Water Potential. Xylem water potential (XWP) indicates energy status of plant water. Xylem water potential was determined in the field on standing pea crop using pressure bomb apparatus at 120 DAS (Waring and Cleary 1967). From each plot, a fully exposed leaf from middle of the plant along the petiole was selected. The leaf was then subjected to gradual pressure until the sap oozed out from the leaf petiole. The pressure at the point of oozing of sap was recorded. The observations were taken at 0700 hours (morning) and 1400 hours (afternoon). It is expressed as Kpa.

Water-Use Efficiency. The water-use efficiency (WUE) was computed by using following formula:

$$\text{WUE}\left(\text{kg ha}^{-1}\text{mm}^{-1}\right) = \frac{\text{Yield}\ \left(\text{kg ha}^{-1}\right)}{\text{Total amount of water used (ha mm)}}$$

Total water used was calculated by taking into consideration the total number of irrigations, depth of water applied, and effective rainfall received during crop duration.

Quality Indices

Total Soluble Solids (TSS). The total soluble solids (TSS) were determined using Zeiss Pocket refractrometer, 0 to 32.0 brix, by putting a drop of extracted juice of fresh pea seeds on the prism and recording the reading. Temperature corrections were duly applied when the readings were made at a temperature other than 20 °C (AOAC 1975).

Crude Protein Content. Crude protein in pea pods from different treatments was determined by estimating their total N content (Jackson 1967). Total N values thus obtained were multiplied with a factor of 6.25 to obtain crude protein content.

Ascorbic Acid Content. Ascorbic acid (vitamin C) content in fresh seeds of pea was estimated by 2-6-dichlorophenol indophenol visual titration method (Ranganna 1976) outlined as follows:

$$\text{Vitamin C}\left(\text{mg 100 g}^{-1}\right) = \frac{\text{Titre} \times \text{Dye factor} \times \text{volume made up}}{\text{Aliquot of extract taken for titration} \times \text{weight of sample taken for estimation}} \times 100$$

where Titre is the volume of dye used to titrate the aliquot of extract of a given sample.

Statistical Analysis

All the data obtained on various soil and plant parameters on pea crop were statistically analyzed using the F-test as per the procedure given by Gomez and Gomez (1984). Least significance difference (LSD) values at $P = 0.05$ were used to determine the significant differences between treatment means.

Results and Discussion

Plant Water Relations

Relative Leaf Water Content (RLWC). This parameter was estimated as an indicator of plant moisture level at two important stages of crop growth at 60 and 120 days after sowing (DAS) (Table 2). At 60 DAS, during morning hours (0700 h), the greatest magnitude of RLWC (1.5%) was registered under $V_{12}P_{100\%}$ IW/CPE$_{1.0}$ treatment as compared to 100% NPK + 12.8 t FYM ha^{-1} (GRD). Similarly, treatments $V_{12}P_{75\%}$ IW/CPE$_{0.6}$ and $V_{12}P_{75\%}$ IW/CPE$_{1.0}$ exhibited significant respective increases of 1.2 and 1.1% in these parameters over GRD. Further, AMF inoculation imbedded treatments $V_{12}P_{100\%}$IW/CPE$_{1.0,}$ $V_{12}P_{75\%}$IW/CPE$_{1.0,}$ and $V_{12}P_{50\%}$IW/CPE$_{1.0}$ exhibited respective significant increases of 1.6, 1.4, and 1.2% over their non-AMF counterparts involving the same P and irrigation regimes of $V_0P_{100\%}$IW/CPE$_{1.0,}$ $V_0P_{75\%}$IW/CPE$_{1.0,}$ and $V_0P_{50\%}$IW/CPE$_{1.0}$ (Table 2).

During afternoon hours (1400 h), magnitudes of increase in RLWC were 1.5, 1.4, and 1.2%, respectively, under $V_{12}P_{100\%}$ IW/CPE$_{1.0}$, $V_{12}P_{75\%}$ IW/CPE$_{0.6,}$ and $V_{12}P_{50\%}$ IW/CPE$_{0.6}$ treatments in comparison to GRD (Table 2). Further, AMF imbedded treatments, $V_{12}P_{100\%}$IW/CPE$_{1.0,}$ $V_{12}P_{75\%}$IW/CPE$_{1.0}$, and $V_{12}P_{50\%}$IW/CPE$_{1.0}$ exhibited significant increases of 1.3, 1.4, and 1.4%, respectively, over their non-AMF counterparts, $V_0P_{100\%}$IW/CPE$_{1.0,}$ $V_0P_{75\%}$IW/CPE$_{1.0,}$ and $V_0P_{50\%}$IW/CPE$_{1.0}$. There was adequate, well-distributed rainfall during the cropping season. As such, irrespective of various AMF and P levels, effects of two irrigation regimes (IW/CPE: 0.6 and 1.0) on various RLWC were found to be nonsignificant. At 120 DAS, RLWC trend in pea was similar to that observed at 60 DAS stage covering both morning and afternoon hours (Table 2).

The probable reason for high plant water status in AMF imbedded treatments may be attributed to the fact that mycorrhizal plants maintain greater tissue water content, which imparts a greater drought resistance to plants (Auge 2001). Overall, mycorrhizal plants in afternoon (1400 h) maintained a moisture level near to morning hours (0700 h), indicating the ability of mycorrhizal plants to retain more moisture than nonmycorrhizal ones at moisture stress, which helps to maintain plants' vigor even on bright sunny days or in drought conditions, implying resistance to drought in mycorrhizal plants in the case of

Table 2
Effects of integrated use of AM fungi, inorganic phosphorus, and irrigation regimes on plant water relations and water-use efficiency in garden pea

Treatment		Relative leaf water content (%)				Xylem water potential (k Pa)		Water-use efficiency
		60 DAS		120 DAS		120 DAS		
		Morning	Afternoon	Morning	Afternoon	Morning	Afternoon	(kg ha^{-1}mm^{-1})
T_1	$V_0$100% NPK + $FYM_{12.8t}$ I_{AR} (GRD)	85.1	83.0	85.2	83.2	−620	−760	22.7
T_2	$V_0N_{25\%}P_0FYM_{3t}$ I_{WA} (FP)	84.2	82.2	83.1	81.1	−700	−820	14.1
T_3	$V_0P_{50\ \%}$ $IW/CPE_{0.6}$	84.9	82.9	83.8	81.9	−640	−780	21.4
T_4	$V_0P_{75\%}$ $IW/CPE_{0.6}$	85.0	83.0	85.0	80.1	−640	−760	22.9
T_5	$V_0P_{100\%}$ $IW/CPE_{0.6}$	85.0	83.2	85.1	82.1	−620	−760	23.0
T_6	$V_{12}P_{50\%}$ $IW/CPE_{0.6}$	86.1	84.0	86.3	83.8	−600	−730	21.5
T_7	$V_{12}P_{75\%}$ $IW/CPE_{0.6}$	86.2	84.2	86.5	84.6	−580	−710	23.7
T_8	$V_{12}P_{100\%}$ $IW/CPE_{0.6}$	86.2	84.3	86.2	84.9	−580	−700	25.1
T_9	$V_0P_{50\%}$ $IW/CPE_{1.0}$	84.9	82.7	84.8	81.9	−630	−790	20.1
T_{10}	$V_0P_{75\%}$ $IW/CPE_{1.0}$	84.9	83.0	85.5	83.0	−630	−780	21.2
T_{11}	$V_0P_{100\%}$ $IW/CPE_{1.0}$	85.1	83.2	85.1	83.2	−620	−770	22.6
T_{12}	$V_{12}P_{50\%}$ $IW/CPE_{1.0}$	86.0	83.9	85.9	83.7	−570	−690	20.6
T_{13}	$V_{12}P_{75\%}$ $IW/CPE_{1.0}$	86.1	84.2	86.4	84.7	−570	−700	22.1
T_{14}	$V_{12}P_{100\%}$ $IW/CPE_{1.0}$	86.5	84.3	87.2	84.9	−560	−690	23.1
LSD ($P = 0.05$)		0.67	0.12	0.57	0.23	17	32	1.65

moisture stress due to improved plant water relations (Hamblin 1985; Tisdall 1991), as well as improved growth of mycorrhizal plants (Auge 2001). Water-stressed plants have been found to accumulate organic osmolytes such as sugars and amino acids (proline) that are known to contribute to host plant tolerance under water-deficit conditions (Aziz, Boosalis, and Furbank 2000).

The treatments imposed with irrigation either at IW/CPE: 0.6 and 1.0 at varying P levels with or without AMF inoculation registered similar values in these parameters. Crops did not suffer from moisture stress at important physiological stages, flowering and fruit/pod formation. Total rainfall throughout the crop season was adequate and well distributed. Hence, effects due to irrigation regimes were nonsignificant. The farmers' practice was the trailing treatment with respect to the parameter. It is attributable to the fact that farmers of wet temperate NW Himalayas apply only one-fourth the recommended N dose and FYM (Paul et al. 2011). Moreover, use of phosphatic and potassic fertilizers is almost negligible (Choudhary 2011; Suri et al. 2011a, 2011b). Besides these facts, very few farmers use biofertilizers, which reflects a greater technology gap in this region (Paul et al. 2011).

Xylem Water Potential (XWP). Xylem water potential was estimated as an indicator of plant moisture level. During morning hours (0700 h), the greatest XWP was registered under $V_{12}P_{100\%}IW/CPE_{1.0}$ treatment followed by $V_{12}P_{75}$ $IW/CPE_{1.0}$, $V_{12}P_{50}$ $IW/CPE_{1.0}$, $V_{12}P_{75}$ $IW/CPE_{0.6}$, and $V_{12}P_{100}$ $IW/CPE_{1.0}$, all of which gave a greater xylem water potential over treatment general recommended dose (GRD), 100% NPK + 12.8 t FYM ha^{-1} (Table 2). The probable reason for high plant water status in AMF imbedded treatments may be attributed to the fact that mycorrhizal plants maintain greater tissue water content, which imparts a greater drought resistance power to plants (Auge 2001).

During afternoon hours (1400 h), maximum XWP was registered under the treatments $V_{12}P_{100\%}IW/CPE_{1.0}$ and $V_{12}P_{50\%}$ $IW/CPE_{1.0}$, followed by $V_{12}P_{75\%}IW/CPE_{1.0}$ and $V_{12}P_{75\%}IW/CPE_{0.6}$. All of these treatments registered greater XWP over GRD. However, $V_{12}P_{100\%}IW/CPE_{1.0}$, $V_{12}P_{75\%}IW/CPE_{1.0}$, and $V_{12}P_{50\%}IW/CPE_{1.0}$ exhibited greater XWP over $V_0P_{100\%}IW/CPE_{1.0}$, $V_0P_{75\%}IW/CPE_{1.0}$, and $V_0P_{50\%}IW/CPE_{1.0}$ both in morning and afternoon hours. Lowest XWP was observed with $V_0N_{25\%}P_0FYM_{3t}$ (farmers' practice).

Treatments imposed with irrigation at $IW/CPE_{0.6}$ at different P and AMF levels ($V_{12}P_{50\%}$ $IW/CPE_{0.6}$, $V_{12}P_{75\%}$ $IW/CPE_{0.6}$, and $V_{12}P_{100\%}$ $IW/CPE_{0.6}$) exhibited similar XWP values compared to plots irrigated at $IW/CPE_{1.0}$ at different P and AMF levels ($V_{12}P_{50\%}IW/CPE_{1.0}$, $V_{12}P_{75\%}IW/CPE_{1.0}$, and $V_{12}P_{100\%}IW/CPE_{1.0}$). It is evident that two irrigation regimes did not influence XWP significantly (Table 2). Total rainfall throughout the crop season was adequate and well distributed. Hence, effects due to irrigation regimes were nonsignificant.

Water-Use Efficiency (WUE). The greatest WUE was registered in $V_{12}P_{100\%}IW/CPE_{0.6}$, which exhibited a significant increase of 10% over GRD (Table 2). However, differences among $V_{12}P_{75\%}IW/CPE_{0.6}$, $V_{12}P_{100\%}IW/CPE_{1.0}$, and GRD were nonsignificant. Arbuscular mycorrhizal fungi imbedded treatments $V_{12}P_{100\%}IW/CPE_{1.0}$, $V_{12}P_{75\%}IW/CPE_{1.0}$, and $V_{12}P_{50\%}IW/CPE_{1.0}$ were found nominally superior by 2, 4, and 2%, respectively, over non-AMF counterparts ($V_0P_{100\%}IW/CPE_{1.0}$, $V_0P_{75\%}IW/CPE_{1.0}$, and $V_0P_{50\%}IW/CPE_{1.0}$), though they were statistically at par. A similar trend was followed in treatment imposed with irrigation at $IW/CPE_{0.6}$ at varying P levels and/or without AMF inoculation. Plots irrigated at $IW/CPE_{0.6}$ or $IW/CPE_{1.0}$ at varying P and AMF levels did not differ significantly with respect to WUE. As such, irrigation regime effects were not reflected in WUE. Farmers' practice ($V_0N_{25\%}P_0FYM_{3t}$) was the trailing treatment with respect to WUE (Table 2).

Greater WUE in mycorrhizal plants might be due to ability of roots to absorb soil moisture, thereby maintaining stomata in open condition (Hardie and Leyton 1981). Further, high dry-matter production resulting from AMF use in crops might partially explain why mycorrhizal plants exhibited greater WUE than nonmycorrhizal ones (Duan et al. 1996; Al-Karaki and Al-Raddad 1997). Another reason for greater WUE in mycorrhizal plants may be due to development of more roots as well as requirement of more water to sustain high plant growth rate, which might have influenced greater water use by mycorrhizal plants (Nagarathna et al. 2007). Further, mycorrhizal hyphe penetrate soil pores that are inaccessible to root hairs, and as such, they absorb water that is not available to nonmycorrhizal plants (Farahani et al. 2008). Similar findings were also reported by Kothari, Marschner, and George (1990) and Al-Karaki (1998) in maize and wheat crops. Thus, it is concluded that AMF improved the plant water relations through drought resistance mechanisms in pea crop under water-stressed situations.

Crop Productivity

The greatest garden pea pod yield was registered under joint application of $V_{12}P_{100\%}IW/CPE_{1.0}$ followed by $V_{12}P_{100\%}$ $IW/CPE_{0.6}$ and GRD, all of which were statistically at par with one another, indicating a net saving of 25% in applied fertilizer P (Table 3). However, $V_{12}P_{100\%}IW/CPE_{1.0,}$ $V_{12}P_{75\%}IW/CPE_{1.0,}$ and

Table 3
Effects of integrated use of AM fungi, inorganic phosphorus, and irrigation regimes on productivity and quality parameters of garden pea

Treatment		Green pod yield (q ha^{-1})	TSS (%)	Ascorbic acid (mg per 100g)	Crude protein (%)
T_1	$V_0$100% NPK + $FYM_{12.8t}$ I_{AR} (GRD)	97.1	16.5	25.7	19.6
T_2	$V_0N_{25\%}P_0FYM_{3t}$ I_{WA} (FP)	53.5	14.0	24.0	17.4
T_3	$V_0P_{50\%}$ $IW/CPE_{0.6}$	80.9	16.0	25.3	19.3
T_4	$V_0P_{75\%}$ $IW/CPE_{0.6}$	86.6	16.0	26.5	19.4
T_5	$V_0P_{100\%}$ $IW/CPE_{0.6}$	93.2	15.8	26.1	19.6
T_6	$V_{12}P_{50\%}$ $IW/CPE_{0.6}$	84.5	17.3	27.0	20.6
T_7	$V_{12}P_{75\%}$ $IW/CPE_{0.6}$	92.9	17.2	27.4	20.3
T_8	$V_{12}P_{100\%}$ $IW/CPE_{0.6}$	98.6	17.1	27.5	20.2
T_9	$V_0P_{50\%}$ $IW/CPE_{1.0}$	82.7	16.2	25.5	19.5
T_{10}	$V_0P_{75\%}$ $IW/CPE_{1.0}$	87.4	16.1	26.0	19.6
T_{11}	$V_0P_{100\%}$ $IW/CPE_{1.0}$	92.9	16.2	26.0	19.6
T_{12}	$V_{12}P_{50\%}$ $IW/CPE_{1.0}$	88.2	17.4	26.7	20.2
T_{13}	$V_{12}P_{75\%}$ $IW/CPE_{1.0}$	94.5	17.2	28.0	20.1
T_{14}	$V_{12}P_{100\%}$ $IW/CPE_{1.0}$	98.7	17.0	27.6	20.2
LSD ($P = 0.05$)		5.87	0.74	0.93	0.35

$V_{12}P_{50\%}IW/CPE_{1.0}$ exhibited significantly greater pod yield than non-AMF counterparts of $V_0P_{100\%}IW/CPE_{1.0,}$ $V_0P_{75\%}IW/CPE_{1.0,}$ and $V_0P_{50\%}$ $IW/CPE_{1.0}$ by 6.3, 8.1, and 7%, respectively. A similar trend was followed under treatments irrigated at $IW/CPE_{0.6}$ with or without AMF inoculation. Lowest pod yield was registered in $V_0N_{25\%}P_0FYM_{3\,t}$ (FP).

It is observed that AMF application along with varying P levels, on average, registered 7.1% greater pod yield compared to treatments supplied with varying P levels alone (Table 3). However, treatments supplied with 100 and 75% soil-test-based P dose coupled with AMF inoculation at two irrigation regimes, $IW/CPE_{1.0}$ and $IW/CPE_{0.6}$, exhibited statistically at par values of pod yield, thereby saving about 25% applied fertilizer P. Different treatments at the same levels of AMF and soil-test-based P dose at both irrigation regimes, $IW/CPE_{0.6}$ and $IW/CPE_{1.0}$, behaved statistically similar because of rains at regular intervals. Further, treatments supplied with 100 and 75% soil-test-based P dose alongwith AMF inoculation at two irrigation regimes, on average, increased the pod yield by 11.3% over treatments supplied with 50% soil-test-based P dose alone at the same levels of AMF and irrigation regimes (Table 3). Thus, it can be inferred that AMF can economize soil-test-based fertilizer–P dose by about 25%.

The AMF application enhanced the pea yield attributes (pod length, pod girth, and average pod weight), which consequently resulted in greater pod yield. Soluble Fe, Al, and Mn are usually present in greater concentrations in acidic Alfisol (Sharma, Verma, and Bhumbla 1980); thus, P reacts with these ions and produces insoluble phosphatic compounds, rendering P unavailable to plants. So, AMF have the ability to utilize greater amount of P as a result of efficient solubilization and mobilization by releasing various enzymes and acids (Nahas 1996; Kumar 2010; Suri et al. 2011a; Suri and Choudhary 2012). Thus, AMF application enhanced the pea pod yield in a Himalayan acidic Alfisol.

Quality Indices

Total Soluble Solids (TSS). Total soluble solids are an important indicator of crop quality estimated at pea pod filling stage. Maximum increase in TSS was registered under $V_{12}P_{50\%}IW/CPE_{1.0}$ followed by $V_{12}P_{50\%}IW/CPE_{0.6}$ and $V_{12}P_{75\%}IW/CPE_{1.0}$ and $IW/CPE_{0.6}$, respectively; all of which were significantly superior over GRD by 5.4, 4.8, and 4.2%, respectively (Table 3). Moreover, significant respective increases of 4.9, 6.8, and 7.4% was registered under AMF imbedded treatments $V_{12}P_{100\%}IW/CPE_{1.0,}$ $V_{12}P_{75\%}IW/CPE_{1.0,}$ and $V_{12}P_{50\%}IW/CPE_{1.0}$ compared to their non-AMF counterparts at the same P and irrigation regimes ($V_0P_{100\%}IW/CPE_{1.0,}$ $V_0P_{75\%}IW/CPE_{1.0,}$ and $V_0P_{50\%}IW/CPE_{1.0}$). Lowest TSS values were observed in treatment $V_0N_{25\%}P_0FYM_{3t}$ (Table 3). Mycorrhizal plants ensure continuous supply of various nutrients (N, K, Ca, Cu, Zn, etc.), which help in promoting assimilation of carbohydrates and in turn the synthesis of ascorbic acid (Barea and Jeffries 1995). Further, fruits are often major sinks for P and about 65% of P absorbed by mature plants is transferred to the sink (Chakraborty, Maiti, and Chattopadhyay 1990). Accordingly, mycorrhizal plants could possibly have translocated considerable amounts of monocalcium phosphate to the fruits. Utkhede (2006) and Guru, Panchaksharam, and Kurusangu (2011) also registered significantly greater ascorbic acid and total soluble sugars in tomato following dual inoculation with AMF and *Azospirillum*.

Ascorbic Acid. $V_{12}P_{75\%}IW/CPE_{1.0}$ exhibited a maximum and significant increase of 9% in ascorbic acid content compared to GRD (Table 3). Similarly, increase in ascorbic acid was to the tune of 7 and 6.6% under $V_{12}P_{100\%}IW/CPE_{0.6}$ and $V_{12}P_{75\%}IW/CPE_{0.6}$, respectively, compared to GRD. Moreover, significant respective increases of 6.1, 7.6, and 4.7% were registered in ascorbic acid content in AMF imbedded treatments, viz. $V_{12}P_{100\%}IW/CPE_{1.0,}$ $V_{12}P_{75\%}IW/CPE_{1.0,}$ and $V_{12}P_{50\%}IW/CPE_{1.0}$, compared to non-AMF counterparts, viz. $V_0P_{100\%}IW/CPE_{1.0,}$ $V_0P_{75\%}IW/CPE_{1.0,}$ and $V_0P_{50\%}IW/CPE_{1.0}$. Again, the lowest ascorbic acid was recorded under treatment $V_0N_{25\%}P_0FYM_{3t}$ (Table 3).

Further, treatments imposed with irrigation at $IW/CPE_{0.6}$ at varying levels of applied P and AMF, $V_{12}P_{50\%}IW/CPE_{0.6,}$ $V_{12}P_{75\%}IW/CPE_{0.6}$, and $V_{12}P_{100\%}$ $IW/CPE_{0.6}$) registered similar values of ascorbic acid in comparison to treatments supplied with same AMF and P levels at varying irrigation regimes $V_{12}P_{50\%}IW/CPE_{1.0}$, $V_{12}P_{75\%}IW/CPE_{1.0}$, and $V_{12}P_{100\%}$ $IW/CPE_{1.0}$ (Table 3). Utkhede et al. (2006) and Guru, Panchaksharam, and Kurusangu (2011) also registered significantly greater ascorbic acid in tomato following dual inoculation with AMF and *Azospirillum*. As mycorrhizal plants ensure continuous supply of plant nutrients that promote assimilation of carbohydrates and in turn ascorbic acid synthesis (Barea and Jeffries 1995).

Crude Protein. The greatest crude protein in pea seeds was registered under $V_{12}P_{50\%}IW/CPE_{0.6}$ over GRD (Table 3). Similarly, $V_{12}P_{50\%}IW/CPE_{1.0}$ and $V_{12}P_{75\%}IW/CPE_{1.0}$ exhibited significant increases of 3.4 and 2.9%, respectively, in crude protein over GRD. The increase in crude protein was 2.6, 2.5, and 3.8% under $V_{12}P_{100\%}IW/CPE_{1.0,}$ $V_{12}P_{75\%}IW/CPE_{1.0}$, and $V_{12}P_{50\%}IW/CPE_{1.0}$ treatments over non-AMF counterparts at same P levels and irrigation regimes $V_0P_{100\%}IW/CPE_{1.0,}$ $V_0P_{75\%}IW/CPE_{1.0,}$ and $V_0P_{50\%}IW/CPE_{1.0}$. The lowest crude protein was found in $V_0N_{25\%}P_0FYM_{3t}$ (FP). The treatments imposed with irrigation either at $IW/CPE_{0.6}$ or $IW/CPE_{1.0}$ at varying levels of AMF and P behaved statistically similarly. As such, influence of irrigation regimes on crude protein was found to be nonsignificant (Table 3).

Because of high rainfall, acidic Alfisols are highly susceptible to N leaching. As such, AMF is capable of mobilizing it from lower layers (Harrier and Watson 2003). As crude protein depends upon N concentration in plants, thus, AMF and P application improved plant N concentration, resulting in enhanced protein content in pea pods. Present results are in conformity with the findings of Prasad and Prasad (1998), who have also reported a considerable increase in crude protein in garden pea seeds with application of 90 kg P_2O_5 ha^{-1} under warn and humid conditions.

Conclusions

Integrated use of AMF and P nutrition in pea crop at varying irrigation regimes led to significantly greater relative leaf water content (2%), xylem water potential (12%), and water-use efficiency (10%), respectively, over non-AMF counterparts. Similarly, the greatest increase in quality parameters in pea seeds such as total soluble solids (6%), ascorbic acid (6%), and crude protein (3%) was registered under AMF imbedded treatments. Further, application of "AMF + 75% soil-test-based P dose at either of two irrigation regimes" remained statistically at par with "generalized recommended NPK dose" and "AMF + 100% soil-test-based P dose" with respect to crop productivity, which indicates a fertilizer economy by about 25% of soil-test-based P dose through AMF application. Further, mycorrhizal plants are able to maintain greater tissue water content, imparting greater drought resistance. Overall, AMF use in Himalayan production systems is of paramount importance in enhancing quality of vegetables and field crops and equally a low-cost farm input for resource-poor Himalayan farmers who ill afford expensive external inputs.

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References

Al-Karaki, G. N. 1998. Benefit, cost, and water-use efficiency of arbuscular mycorrhizal durum wheat grown under drought stress. *Mycorrhiza* 8:41–45.

Al-Karaki, G. N., and A. Al-Raddad. 1997. Effects of arbuscular mycorrhizal fungi and drought stress on growth and nutrient uptake of two wheat genotypes differing in drought resistance. *Mycorrhiza* 7:83–88.

Anonymous. 2012. *Complete package and practices for cultivation of vegetable crops in Himachal Pradesh*. Palampur, India: Directorate of Extension Education Publication, CSK Himachal Pradesh Agricultural University.

AOAC. 1975. *Official methods of analysis of the Association of Official Analytical Chemists*, 11th ed. Washington, D.C.: Benjamin Franklin Station.

Auge, R. M. 2001. Water relations, drought, and VA mycorrhizal symbiosis. *Mycorrhiza* 11:3–42.

Aziz, M. F., M. G. Boosalis, and R. T. Furbank. 2000. Effects of two species of vesicular arbuscular mycorrhizal fungi on drought tolerance of winter wheat. *New Phytologist* 14:507–511.

Barea, J. M., and P. Jeffries. 1995. Arbuscular mycorrhizas in sustainable soil–plant systems. In *Mycorrhiza: Structure, function, molecular biology, and biotechnology*, ed. A. Verma and B. Hock, 521–561. New York: Springer.

Black, C. A. 1965. *Methods of soil analysis*, 2nd ed. Madison, Wisc.: American Society of Agronomy.

Chakraborty, A. K., P. K. Maiti, and N. C. Chattopadhyay. 1990. Varietal difference in growth, uptake of nitrogen, and yield of tomato under low level of fertilizer application. *Indian Journal of Horticulture* 47:89–92.

Chen, C. R., L. M. Condron, and Z. Xu. 2007. Impacts of grassland afforestation with coniferous trees on soil phosphorus dynamics and associated microbial processes: A review. *Forest Ecology and Management* 255:396–409.

Choudhary, A. K. 2011. Resource conservation technologies under changing climate in NW Himalayas. In *Summer school on climate variability and its impact on crop production: Physiological perspective towards mitigation strategies*, held during August 23 to September 12, 2011 at Assam Agricultural University, Jorhat, India. *AAU Summer School Compendium*, 199–206. Jorhat, India: Assam Agricultural University.

Das, D. K. 2011. *Introductory soil science*. Delhi, India: Kalyani.

Duan, X., D. S. Neuman, J. M. Reiber, C. D. Green, A. M. Saxton, and R. M. Auge. 1996. Mycorrhizal influence on hydraulic and hormonal factors implicated in the control of stomatal conductance during drought. *Journal of Experimental Botany* 47:1541–1550.

Farahani, A., H. Lebaschi, M. Hussein, S. A. Hussein, V. A. Reza, and D. Jahanfar. 2008. Effects of arbuscular mycorrhizal fungi, different levels of phosphorus and drought stress on water-use efficiency, relative water content, and proline accumulation rate in coriander (*Coriandrum sativum* L.). *Journal of Medicinal Plants and Research* 2:125–131.

Gaur, A., and A. Adholeya. 1994. Estimation of VAM spore in the soil: A modified method. *Mycorrhiza News* 6:10–11.

George, E., K. V. Haussfer, D. Vetterlien, E. Gorgus, and H. Marschner.1992. Water and nutrient translocations by hyphae of *Glomus mosseae. Canadian Journal of Botany* 70:2130–2137.

Gomez, K. A., and A. A. Gomez. 1984. *Statistical procedures for agricultural research*, 2nd Ed. Hoboken, N.J.: John Wiley and Sons.

Guru, V., T. Panchaksharam, and V. Kurusangu. 2011. Influence of arbuscular mycorrhizal fungi and *Azospirillum* co-inoculation on the growth characteristics, nutritional content, and yield of tomato crops grown in south India. *Indian Journal of Fundamental and Applied Life Sciences* 1:84–92.

Hamblin, A. P. 1985. The influence of soil structure on water movement, crop root growth, and water uptake. *Advances in Agronomy* 38:95–158.

Hardie, K., and L. Leyton. 1981. The influence of vesicular arbuscular mycorrhizae on growth and water relation of red clover in phosphate deficient soil. *New Phytologist* 89:599–608.

Harley, J., and S. E. Smith. 1983. *Mycorrhizal symbiosis*. London: Academic Press.

Harrier, L. A., and C. A. Watson. 2003. The role of arbuscular mycorrhizal fungi in sustainable cropping systems. *Advances in Agronomy* 42:185–225.

Jackson, M. L. 1967. *Soil chemical analysis*. New Delhi, India: Prentice Hall of India.

Kothari, S. K., H. Marschner, and E. George. 1990. Effect of VA mycorrhizal fungi and rhizosphere microorganisms on root and shoot morphology, growth, and water relations in maize. *New Phytologist* 116:303–311.

Kumar, S. 2010. *Studies on vesicular arbuscular mycorrhizae in meeting P needs of okra–wheat sequence in Typic Hapludalf* (PhD thesis, Department of Soil Science, CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur, India).

Miller, R. M., and J. D. Jastrow. 1990. Hierarchy of root and mycorrhizal fungal interactions with soil aggragation. *Soil Biology and Biochemistry* 22:579–584.

Nagarathna, T. K., T. G. Prasad, D. J. Bagyaraj, and Y. G. Shadakshari. 2007. Effect of arbuscular mycorrhiza and phosphorus levels on growth and water use efficiency in sunflower at different soil moisture status. *Journal of Agricultural Technology* 3:221–229.

Nahas, E. 1996. Factors determining rock phosphate solobilization by microorganism isolated from soil world. *Journal Microbiology Biotechnology* 12:18–23.

Olsen, S. R., C. V. Cole, F. S. Watanabe, and L. A. Dean. 1954. *Estimation of available phosphorus in soils by extraction with sodium bicarbonate* (USDA Circular No. 939). Washington, D.C.: U.S. Government Printing Office.

Pattanayak, S. K., P. Sureshkumar, and J. C. Tarafdar. 2009. New vista in phosphorus research. *Journal of the Indian Society of Soil Science* 57:536–545.

Paul, J., V. K. Suri, S. K. Sandal, and A. K. Choudhary. 2011. Evaluation of targeted yield precision model for soybean and toria crops on farmers' fields under sub-humid sub-tropical northwestern Himalayas. *Communications in Soil Science and Plant Analysis* 42:2452–2460.

Piper, C. S. 1950. *Soil and plant analysis*. New York: Scientific Publishers.

Prasad, R. N., and A. Prasad. 1998. Effect of *Rhizobium*, P, and GA_3 on protein, carbohydrate, and P content in garden pea (*Pisum sativum*). *Indian Journal of Horticulture* 55:164–167.

Rangana, S. 1976. *Hand book of analysis and quality control for fruit and vegetable products*. New Delhi: Tata McGraw-Hill.

Sharma, P. K., S. P. Verma, and D. R. Bhumbla. 1980. Transformation of added phosphorus into inorganic fractions in some acid soils of Himachal Pradesh. *Journal of Indian Society of Soil Science* 28:450.

Sieverding, E. 1991. Vesicular arbuscular mycorrhiza management in tropical agrosystems. *Technical Cooperation Federal Republic of Germany Eschborn* 3:460–462.

Subbiah, B. V., and G. L. Asija. 1956. A rapid procedure for the determination of available nitrogen in soils. *Current Science* 25:259–260.

Suri, V. K., A. K. Choudhary, G. Chander, and T. S. Verma. 2011a. Influence of VAM fungi and applied P on root colonization in wheat and plant nutrient dynamics in a P-deficient acid Alfisol of western Himalayas. *Communications in Soil Science and Plant Analysis* 42 (10): 1177–1186.

Suri, V. K., A. K. Choudhary, G. Chander, M. K. Gupta, and N. Dutt. 2011b. Improving phosphorus use through co-inoculation of vesicular arbuscular mycorrhizal fungi and PSB in maize in an acid Alfisol. *Communications in Soil Science and Plant Analysis* 42 (18): 2265–2273.

Suri, V. K., and A. K. Choudhary. 2012. Fertilizer economy through VAM fungi under STCR targeted yield model in maize–wheat–maize crop sequence in Himalayan acid Alfisol. *Communications in Soil Science and Plant Analysis* 43 (21): 2735–2743.

Tisdall, J. M. 1991. Fungal hyphae and structural stability of soil. *Australian Journal of Soil Research* 29:729–743.

Tisdall, J. M., and J. M. Oades. 1982. Organic matter and water stable aggregates in soils. *Journal of Soil Science* 33:141–163.

Utkhede, R. 2006. Increased growth and yield of hydroponically grown greenhouse tomato plants inoculated with arbuscular mycorrhizal fungi and *Fusarium oxysporum* sp. radicis-lycopersici. *Biocontrol* 59:393–400.

Walkley, A., and I. A. Black. 1934. An examination of the Dagtjareff (wet acid) method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science* 37:29–38.

Waring, R. H., and B. D. Clearly. 1967. Plant moisture stress evaluation by pressure bomb. *Science* 155:1248–1254.

Weatherley, P. E. 1950. Studies in the relations of the cotton plants, the field measurement of water deficits in leaves. *New Phytologist* 49:36–51.

Zou, X., D. Binkley, and B. A. Caldwell. 1995. Effects of dinitrogen-fixing trees on phosphorus biogeochemical cycling in contrasting forests. *Journal of American Society of Soil Science* 59:1452–1458.