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Influence of a flavonoid (formononetin) on mycorrhizal activity and potato crop productivity in the highlands of Peru

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Abstract

Mycorrhizal fungi serve as biofertilizers, reduce plant stress, and can increase plant productivity. Since the potato originated from the highlands of Peru and Bolivia, a goal of this research was to utilize indigenous Peruvian mycorrhizal populations to enhance crop productivity in a subsistence production site. The field study was also conducted to test the effectiveness of the flavonoid, formononetin, to stimulate native mycorrhizal activity and subsequent yield of six Andean potato (*Solanum tuberosum* L.) cultivars. The subsistence site was located at an altitude of 3900 m (61 kPa) in San Jose de Aymara (Department of Huancavelica), in the central highlands of Peru. This is approaching the highest altitude in the world that potatoes are grown. The site had a sandy-loam soil with pH 3.6, low phosphorus (P) availability and high aluminum (Al). Tubers were planted in November 1999, and grown during the rainy season. Minimal organic fertilizer was applied and the potato crop received no supplementary irrigation. Formononetin was applied as a soil drench when shoots from tubers began to emerge. At the end of the 6.5 month study, formononetin increased either potato tuber dry mass and/or Nos. 1 and 2 grade tubers in three of the six cultivars. Soil sporulation of

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indigenous mycorrhizae was increased more than three-fold by formononetin. There were differences in total mycorrhizal colonization among the six cultivars. The predominant arbuscular mycorrhiza genera at the site were *Gigaspora*, *Glomus* and *Scutellosporas*.

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Keywords: Aluminum (Al); Arbuscular mycorrhizal fungi (AMF); Biofertilizers; Formononetin; *Glomus* spp.; *Gigaspora* spp.; Isoflavonoid; Phosphorus (P); *Solanum tuberosum* L

1. Introduction

Potatoes are grown worldwide under a wider range of altitude, latitude, and climatic conditions than any other major food crop—from sea level to over 4000 m elevation. No other crop can match the potato in its production of food energy and food value per unit area (Sieczka and Thornton, 1993). It is also high in Vitamin C, niacin and Vitamin B₆. Yet, the potato plant has one of the heaviest production demands for fertilizer inputs of all vegetable crops, i.e., its nitrogen (N), phosphorus (P) and potassium (K) requirements are, respectively, 100, 100 and 33% greater than that required for tomato or pepper plant production (Maynard and Hochmuth, 1997). Normal fertilizer applications are around 1000 kg ha⁻¹ 10N–3P₂O₅–10K₂O applied in bands around the seed tuber. In high input potato production systems, N requirements can be as high as 336 kg N ha⁻¹ for an expected yield of 30 tonnes acre⁻¹ (67 Mg ha⁻¹) (Lang et al., 1999). Subsistence growers may not have access or be able to afford suitable organic or inorganic fertilizers. Modern sustainable agriculture systems are increasingly utilizing reduced fertility inputs. Hence, there are excellent opportunities to incorporate arbuscular mycorrhizal fungi (AMF) as biofertilizers to enhance crop productivity and reduce fertilizer inputs.

These symbiotic fungi increase nutrient and water uptake, alleviate cultural and environmental stresses and enhance disease resistance and plant health (Bethlenfalvay and Linderman, 1992; Davies et al., 1993, 1996; Pflieger and Linderman, 1994). AMF can enhance productivity of potatoes (Graham et al., 1976; Niemira et al., 1995). In part, this may be due to enhanced nutrient uptake of potato plants, particularly P (Black and Tinker, 1977; McArthur and Knowles, 1993), as well as enhanced disease resistance (Niemira et al., 1996). In Columbia, experiments show that a considerable amount of P fertilizer can be saved when potatoes are inoculated with effective AMF (Sieverding, 1991). In a greenhouse study conducted in Peru, a mycorrhizal isolate from Europe enhanced potato productivity and nutrient uptake (Moreno, 1988). However, native AMF isolates from Peru have yet to be characterized and tested in Peruvian potato production systems (Calderón, personnel communication).

The highlands of Peru and Bolivia comprise the center of origin and diversity of the cultivated potato. Potato is the main staple crop in the highlands and accounts for 63% gross value of all crop production (Devaux et al., 1997). Average potato yields are very low (between 5 and 8 tonnes/ha) and limited by low fertility. While small producers apply organic N as animal or green manure, P is applied via chemical fertilizers, which is costly and not always available. For subsistence and modern sustainable potato production in Peru, it is important that native mycorrhizal isolates be utilized. A limitation of mycorrhiza application is its commercial availability and the added production cost.

The flavonoid, formononetin, has been reported to enhance AMF sporulation and effectivity of mycorrhizal plants (Nair et al., 1997; Davies et al., 1999; Koide et al., 1999), i.e., this could allow for lower, more cost-effective levels of AMF inoculum to be incorporated or to rely solely on stimulating indigenous AMF present in the soil of the crop production site. It is highly desirable and more economically viable to utilize native rather than exotic AMF in sustainable agriculture systems. Since the potato originated from the highlands of Peru and Bolivia—a goal of this research was to utilize indigenous Peruvian AMF populations to enhance crop productivity in a subsistence production site. The field study was also conducted to test the effectiveness of formononetin, to stimulate native mycorrhizal activity and subsequent yield of six Andean potato (*Solanum tuberosum* L.) cultivars.

2. Materials and methods

2.1. Field site

The site was located at an altitude of 3900 m with an atmospheric pressure of 61 kPa in San Jose de Aymara (Department of Huancavelica; Province: Tayacaja; District: Pazos; latitude: 12°13'S; longitude: 75°04'W, in the central highlands of Peru. This is approaching the highest altitude in the world that potatoes are grown. The soil texture of the site was sandy-loam and classified as an Entisol (Table 1). The soil had a pH of 3.6 with low P availability. Prior to planting, the farmer's field had been fallow for 5 years. Tubers were planted in November 4, 1999, just before the beginning of the rainy season. Tubers were planted on 30 cm spacing. Minimal organic fertilizer (estiércol) was applied (about 1 kg manure per m²) and the potato crop received no supplementary irrigation. The experiment was terminated 6.5 months later on May 16, 2000.

2.2. Environmental conditions

From November 1999 through May 2000, the environmental conditions were as follows: average minimum/maximum temperature of 3.5 °C/16.4 °C, precipitation average of 88.7 mm month⁻¹, range of 27–132 mm month⁻¹, monthly average radiation of 18,643 kJ m⁻² day⁻¹, and a monthly range of 17,178–20,305 kJ m⁻² day⁻¹ (Table 2).

Table 1
Soil analysis of potato field production site in Huancavelica, Peru at 3900 m

Soluble salts (dS m ⁻¹)	1.2	P (ppm)	18.2
Sand (%)	64	K ₂ O (kg ha ⁻¹)	180.0
Silt (%)	33	Cation exchange capacity (Cmol+ kg ⁻¹)	5.1
Clay (%)	3	Ca ²⁺ (Cmol+ kg ⁻¹)	1.2
Soil texture	Sandy-loam	Mg ²⁺ (Cmol+ kg ⁻¹)	0.2
pH	3.6	K ⁺ (Cmol+ kg ⁻¹)	0.2
CaCO ₃ (%)	3.5	Na ⁺ (Cmol+ kg ⁻¹)	0.1
Organic matter (%)	5.8	Al ²⁺ + H (Cmol+ kg ⁻¹)	3.5

Table 2

Environmental Conditions at San Jose de Aymara, District of Pazos, Province of Tayacaja, Department of Huancavelica, Peru at an altitude of 3900 m, atmospheric pressure of 61 kPa, Latitude 12°13'S, Longitude 75°04'W from November 1999 to May 2000

Date	Avg min temp (°C)	Avg max temp (°C)	Precipitation (mm)	Radiation (kJ m ⁻² day ⁻¹)	Potential evapotranspiration (mm/day)
November 1999	3.6	17.8	67	20,305	3.5
December 1999	3.9	17.1	103	19,814	3.4
January 2000	4.7	15.7	132	18,783	3.2
February 2000	4.6	15.6	115	18,388	3.1
March 2000	3.9	15.7	120	18,124	3.0
April 2000	2.7	16.5	57	17,906	3.0
May 2000	1.0	16.6	27	17,178	2.8
Avg.	3.5	16.4	88.7	18,643	3.1

The monthly photoperiod average was from 12.6 h in November 1999 to 11.4 h in May 2000.

2.3. Potato cultivars

Virus-free tubers of Andean cultivars of *Solanum tuberosum* L. from the potato germplasm collection of the International Potato Center (CIP), Lima, Peru were used: #1: CIP700724, #2: CIP703531, #3: CIP704058, #4: CIP704483, #5: CIP704994, #6: CIP705131. These cultivars were selected by CIP scientists from farmers' fields in the Peruvian highlands and clonally propagated as single genotypes.

2.4. Application of formononetin

On January 6, 2000 [8 weeks after planting], shoots had emerged and half of the Andean potato cultivars received a 1000 ml soil drench containing 15 mg l⁻¹ Myconate (VAMTech L.L.C., Lansing, MI, USA), which is a water-soluble formulation of the flavonoid, formononetin (Nair et al., 1997).

2.5. Assessment of tuber development

Plants were evaluated for tuber grade (Nos. 1, 2, 3, or culls) and total tuber dry mass (dm) was determined. Tubers were dried at 70 °C for 5 days in a forced air oven. The formononetin effect (FE) was determined by $FE (\%) = (\text{dm of formononetin-treated plant} - \text{dm of non-formononetin-treated plant}) \times 100 \times (\text{dm non-inoculated plant})^{-1}$.

2.6. Assessment of mycorrhizal development

For spore counts—samples consisted of soil from the rhizosphere of treated and untreated plants. From five 1000 g samples per \pm formononetin treatment, five 100 g subsamples per 1000 g sample ($n = 25$) were processed through glycerol flotation and spore extraction methods (Furlan and Fortin, 1975; Schenck, 1982). The supernatant was

resuspended in 25 ml of distilled water and three replicates of 1.0 ml were taken in order to perform spore counts. The samples were wet sieved from 212 to 45 μm . The results were recorded as number of spores per 1 g soil.

For AMF analysis of roots, 1-cm root segments from 5 plants per treatment were sampled at harvest and pooled to assess colonization percentage through clearing and staining of the root samples (Phillips and Hayman, 1970). Ten 1-cm stained root pieces were placed on each slide and three microscopic observations per 1-cm root piece at 400 \times was made at the top, the middle and the bottom of each root piece. There were 10 slides per treatment ($n = 300$ observations per treatment). Roots were evaluated for the presence of mycorrhiza.

2.7. Soil analysis

Standard soil textural and mineral analysis was done at the Soil Testing Laboratory, Universidad Nacional Agraria La Molina, Lima, Peru.

2.8. Statistical design

The factorial experiment was composed of $2 \pm$ formononetin \times 6 Andean potato cultivars in a completely randomized design. There were three replications per treatment, with each replication consisting of 5 “seed” tubers per replication; $n = 15$ “seed” tubers per treatment. All data were analyzed using analysis of variance (ANOVA) [SAS Institute Inc., 2000].

3. Results

3.1. Soil conditions

The soil texture was a sandy-loam and is classified as an Entisol (Table 1). The cation exchange capacity (CEC) was low at 1.2 dS m^{-1} . The soil pH was 3.6, classified as very acid, and organic matter was relatively high (5.8%). Soil P was 18.2 ppm, however, P-availability to plants was low since the soil had a very low pH (3.6), limiting P-availability. Furthermore, the Olson method extracts P at pH 8.5, which would give a higher soil P value than is available to the plant.

Soil calcium (Ca) levels were low and aluminum (Al) was high. Hence, low soil pH contributed to low P availability and high extractable Al.

3.2. Tuber yield

At the end of the 6.5 month study, three of the six Andean cultivars treated with formononetin had either increased potato tuber DM and/or greater Nos. 1 and 2 grade tubers, i.e., #1: CIP700724, #5: CIP704994 and #6: CIP705131 (Table 3). Formononetin had the greatest effect on cultivar #1 (CIP700724), increasing its tuber dm, Nos. 1 and 2 tubers and formononetin effect (FE) [+115%] compared to the non-formononetin-treated control. Formononetin also enhanced the FE of cultivars #2 (CIP703531) and #6

Table 3
Effects of formononetin on tuber development of six Andean potato cultivars in a field experiment in Huancavelica, Peru (Mean and \pm S.E., $n = 15$)

Cultivar	Formononetin	Tuber dm (g)	No. 1 tubers	No. 2 tubers	No. 3 tubers	Culls	AMF colon. (%)	FE (%) ^a
#1: CIP700724	Yes	52.8 \pm 8.8	1.1 \pm 0.3	4.3 \pm 0.8	3.8 \pm 0.4	9.0 \pm 2.5	33 \pm 4	+115
	No	24.6 \pm 4.2	0.1 \pm 0.1	1.3 \pm 0.3	2.7 \pm 0.4	8.8 \pm 1.4	31 \pm 2	
#2: CIP703531	Yes	47.1 \pm 4.6	0.6 \pm 0.2	2.1 \pm 0.3	2.3 \pm 0.4	5.6 \pm 0.8	21 \pm 4	+28
	No	36.8 \pm 6.2	0.6 \pm 0.2	1.6 \pm 0.3	2.3 \pm 0.5	2.9 \pm 0.6	14 \pm 3	
#3: CIP704058	Yes	15.4 \pm 2.2	0 \pm 0	0.4 \pm 0.2	1.3 \pm 0.3	9.4 \pm 1.3	39 \pm 3	-12
	No	17.5 \pm 3.6	0 \pm 0	0.9 \pm 0.3	2.3 \pm 0.4	11.1 \pm 1.4	41 \pm 2	
#4: CIP704483	Yes	62.8 \pm 8.4	1.0 \pm 0.5	2.6 \pm 0.4	2.9 \pm 0.5	6.2 \pm 0.6	15 \pm 2	-9
	No	69.1 \pm 7.5	2.2 \pm 0.5	3.8 \pm 0.5	2.9 \pm 0.5	5.1 \pm 0.8	14 \pm 3	
#5: CIP704994	Yes	40.1 \pm 8.7	0.6 \pm 0.2	1.0 \pm 0.3	1.6 \pm 0.4	4.3 \pm 0.6	33 \pm 3	+4
	No	38.5 \pm 4.1	0.1 \pm 0.1	1.5 \pm 0.3	2.6 \pm 0.4	4.4 \pm 0.7	28 \pm 3	
#6: CIP705131	Yes	29.7 \pm 5.6	0.4 \pm 0.2	0.3 \pm 0.2	2.5 \pm 0.5	9.2 \pm 1.2	18 \pm 3	+23
	No	24.2 \pm 3.6	0 \pm 0	1.2 \pm 0.4	2.1 \pm 0.3	10.3 \pm 0.9	23 \pm 1	
Significance	Formononetin (F)	0.0776	NS	NS	NS	NS	NS	
	Cultivar (C)	0.0001	0.0001	0.0001	0.0104	0.0001	0.0001	
	F \times C	0.0755	0.0001	0.0001	NS	NS	NS	

^a FE (%) = formononetin treatment effect = (tuber dm of formononetin-treated plants – dm non-formononetin-treated plants) \times 100 \times (dm non-formononetin-treated plants)⁻¹.

(CIP705131) by +28% and +23%, respectively (Table 3). Formononetin did not enhance cultivar #4 (CIP704483) which had among the greatest tuber mass and lowest FE, nor cultivar #3 (CIP704058) which had lowest tuber yield, FE, and fewest Nos. 1 and 2 tubers.

3.3. Mycorrhiza

Formononetin increased soil sporulation of indigenous AMF more than three-fold. In rhizosphere soil of control plants, there were 6.3 ± 1.2 spores g^{-1} soil, whereas formononetin treatments had 19.4 ± 1.1 spores g^{-1} soil ($P \leq .0001$). There were

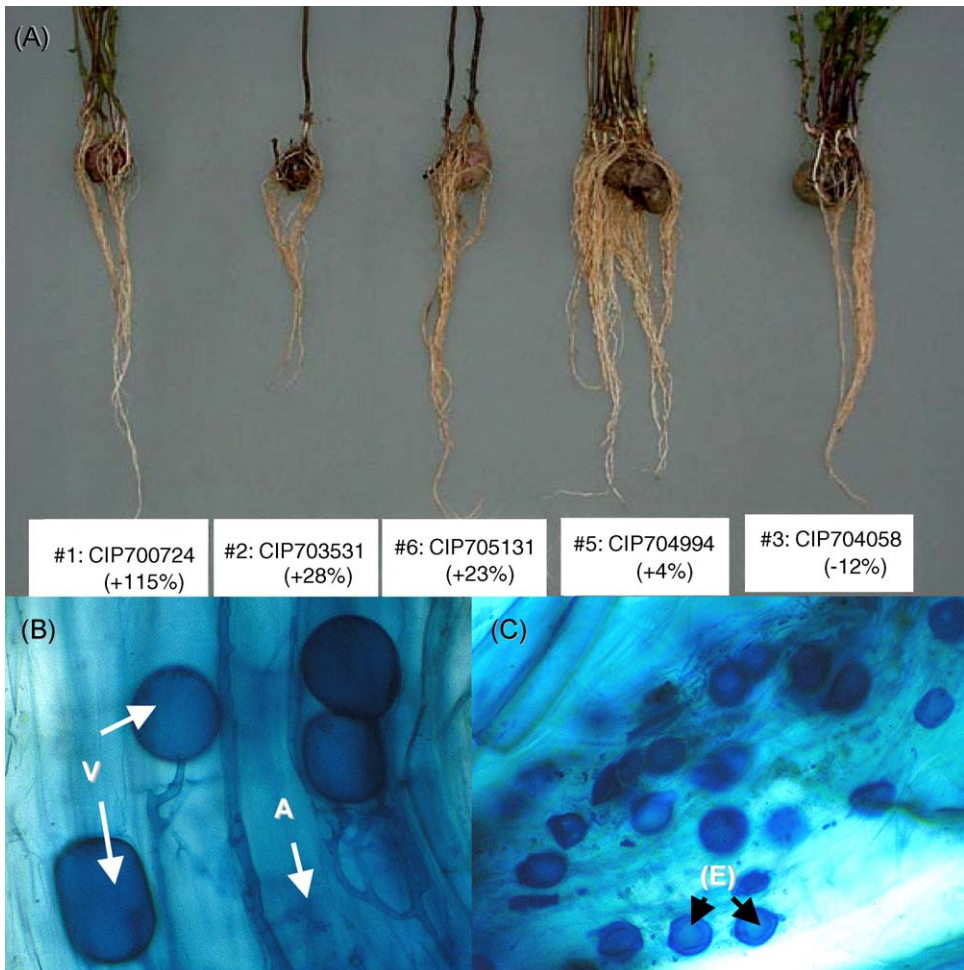


Fig. 1. (A) Root systems of CIP Andean potato cultivars. The cultivar number and formononetin effect (% FE) is in parentheses. (B) Photomicrographs of vesicles (v) and arbuscules (a), and (C) endospores (e) in root cortical cells (400 \times) of indigenous arbuscular mycorrhiza (AMF) from the subsistence production site at San Jose de Aymara, Department of Huancavelica, Peru.

differences in mycorrhizal colonization among the six Andean cultivars, which ranged from 14 to 41%. Formononetin did not have a significant effect on total mycorrhizal colonization. The predominant mycorrhizal genera were *Gigaspora* spp., *Glomus* spp. and *Scutellosporas* spp. with spore size ranging from 45 to 180 μm . In the formononetin treatment, *Scutellosporas* was also observed. Vesicles, arbuscules and endospores were observed in root cortical samples (Fig. 1B and C). Formononetin had the greatest effect on spore production of *Gigaspora*, whereas *Glomus* spp. was more abundant in the non-formononetin treatment (C. Calderón, personal observation).

Of the six potato selections, five representative samples were analyzed for root development in a separate containerized greenhouse study at CIP, in Lima, Peru (Fig. 1A). Cultivars #3 and #5 had the more extensive root systems, while cultivars #1 (CIP700724) and #2 (CIP703531) had among the smallest root systems (Fig. 1A). Tubers from cultivar #4: CIP704483 did not sprout, hence its root system was not observed.

4. Discussion

To our knowledge this is one of the first reports of mycorrhizal activity and crop enhancement in a potato field at such high altitude—3900 m (12,795 ft). AMF are known to tolerate a wide variety of soil pH conditions and mineral ion conditions (Smith and Read, 1997). Formononetin caused a stimulation of native mycorrhiza (three-fold greater sporulation) and subsequent increase in tuber development in three of the six Andean potato cultivars.

The Andean cultivars, we grew are late maturing and plant development at 3900 m is much slower than at lower altitudes. These cultivars at the CIP germplasm repository are local, single genotypes of generally unknown Indian names, collected by CIP scientists from farmers' fields. Farmers select and preserve these cultivars via clonal propagation of tubers. From November 1999 through May 2000, the average minimum/maximum temperature was 3.5 °C/16.4 °C and plants received no supplementary irrigation. As is the custom in these subsistence production systems in the highlands, the potatoes were planted in November and grown during the rainy season.

As would be expected, there were differences in tuber production among the six cultivars and their response to formononetin. At the end of the 6.5 month study, three of the six cultivars treated with formononetin had either increased potato tuber DM and/or a greater Nos. 1 and 2 grade tubers (Table 3). Cultivar #1: CIP700724, #2: CIP703531 and #6: CIP705131 had the greatest response to formononetin. Formononetin had no effect on selection #4: CIP704483 or #3: CIP704058 which had ranged from among the highest to lowest in tuber yield. Formononetin had no effect on the lower value No. 3 grade tubers and culls, however, differences did occur among cultivars. Cultivar #1: CIP700724 had the highest tuber DM, Nos. 1 and 2 tubers and among the highest No. 3 tubers and culls.

Of the five cultivars analyzed for root development in a separate containerized greenhouse study at CIP, in Lima, Peru, there was a general trend: cultivars: #1: CIP700724 (+115% FE), #2: CIP703531 (+28% FE) and #6: CIP705131 (+23% FE) tended to have fewer and less coarse roots, while cultivars #5: CIP704994 (+4% FE) and #3: CIP704058 (−12% FE) tended to have more extensive and courser roots.

While above ground biomass and root DM were not determined in this study, frequently the root:shoot ratio is higher in AMF than non-inoculated plants. Greater carbon allocation to the root system allows for more extensive root development (relative to shoot growth). In our field study, non-formononetin-treated plants also became colonized with native AMF and colonization levels were not significantly different. In a containerized study, AMF plants had greater root:shoot ratio than non-inoculated ‘Yungay’ potato plants, but root:shoot ratios were generally comparable between AMF inoculated plants and AMF inoculated + formononetin (Davies et al., 2005). Irrespective of formononetin treatment, colonization was highest with #3 cultivar (CIP704058), which had the lowest FE effect, lowest tuber DM and premium grade #1 potatoes. Higher colonization levels are not always indicative of enhanced drought (Davies et al., 1996) or growth responses (Smith and Read, 1997).

Potato plants are not known for high colonization levels, even though trace levels [0.4% colonization] are reported to enhance growth (Niemira et al., 1995). The low colonization levels in commercial production systems is likely due to high fertility inputs, as opposed to traditional, low-input subsistence systems where fields remain fallow for a several years prior to planting. At the Peruvian subsistence site, the predominant vegetation that grows in fields at this elevation is ichu grass (*Stipa ichu* [Gramineae] (Ruiz and Pavon) Kunth). Arroz-arroz (*Rumex* spp.) [Polygonaceae] was another grass species at the site, which is an indicator plant of soil acidity (Rene Gomez, personnel communication). In our study, the farmer’s field in Huancavelica was fallow for 5 years and only around 1 kg m⁻² of manure (estercol) was used. Hence in this experiment, relatively high colonization levels of 14–41% occurred among all treatments, depending on the Andean cultivar.

While there were no formononetin differences in total colonization in this current study—in a greenhouse, containerized study, formononetin stimulated greater extraradical development, net photosynthesis, stomatal conductance and shoot development in Russet Norkotah potatoes (Davies et al., 1999). In another containerized study in Lima, Peru—formononetin enhanced extraradical hyphae formation (but not total root colonization), and increased tuber yield in ‘Yungay’ potatoes (Davies et al., 2005). However, extraradical hyphae formation development was beyond the scope of this current field study, and consequently, was not evaluated.

Formononetin increased soil sporulation levels three-fold from 6.3 to 19.4 spores g⁻¹. All spores, young and old, were counted in this study. At higher altitudes temperature is much lower, and sporulation of mycorrhiza and plant growth are reduced. There is only limited information on mycorrhizal species and soil spore levels in selected production sites in Peru (Calderón, 1994). Soil spore number is a function of AMF species, climate, soil characteristics and seasonality. Soil spore numbers in undisturbed sites have ranged from 50 to 800 spores g⁻¹ soil to 1 to 40 spores g⁻¹ soil (Smith and Read, 1997). The predominant mycorrhizal genera in our study were *Gigaspora*, *Glomus* and *Scutellosporas*. It is well known that dominant AMF species vary with differing ecological and edaphic conditions (Smith and Read, 1997). Formononetin had the greatest effect on spore production of *Gigaspora* spp., while *Glomus* spp. was more abundant in the non-formononetin treatment.

The production site had very acid soil (pH 3.6), with low P availability and high Al. Aluminum toxicity at this pH can be a problem. Ideally, the soil should be amended with

calcium [dolomite ($\text{Mg}\cdot\text{CO}_3 + \text{CaCO}_3$) or lime (CaOH)] to increase Ca levels, raise the pH, decrease extractable Al levels and increase soil P availability. However, this was not cost-effective in subsistence farming conditions. AMF can enhance the host plants ability to produce biomass and withstand acid soil induced stresses (Killham and Firestone, 1983; Clark and Zeto, 2000). There are differences among AMF isolates in their effectiveness on plant growth and root colonization in acidic soil. Although percentage root colonization was not directly related to tuber DM, in other studies, enhancement of biomass did not occur unless total root colonization exceeded 20% in acidic soils (Clark et al., 1999).

In a *Zea mays*–*Glomus etunicatum*, *G. diaphanum* and *G. intraradicis* systems, roots with arbuscules or vesicles were nonexistent or very low for plants grown on acid soil and relatively high for plants grown on alkaline soil (Clark and Zeto, 1996); root hyphal infection was more important than arbuscules for growth enhancement of plants on acid soil. In our experiment, arbuscules and vesicles of native AMF were prevalent under very acid conditions (pH 3.6).

Mycorrhizal fungi can increase plant tolerance to Al toxicity. Mycorrhizal fungi (ericoid) can reduce short-term Al uptake and increase root cation exchange capacity of highbush blueberry plants (Yang and Goulart, 2000). AMF can increase plant dry mass and decrease Al content under relatively high Al concentrations (Koslowsky and Boerner, 1989). The Al ions are sequestered in the mycorrhizal symbionts, resulting in less Al uptake with mycorrhizal roots (Maddox and Soileau, 1991; Yang and Goulart, 2000). Mycorrhizal enhancement of P and tuber yield in potato plants has been reported in Peru with indigenous and introduced AMF (Davies et al., 2005).

5. Conclusion

It can also be very costly to apply sufficient levels of AMF to subsistence level potato production systems. One of the strengths of this paper is that it shows potential benefits of applying formononetin to stimulate the effectivity of native, ecotypically adapted AMF at lower inoculum levels under field production conditions. Formononetin used in combination, could also allow for lower, more cost-effective levels of indigenous AMF inoculum to be utilized. Hence, there are excellent opportunities to utilize and manipulate AMF to enhance crop productivity and reduce agricultural chemical inputs.

Beneficial mycorrhizal fungi are one of the important cornerstones of sustainable agricultural systems. They can make plants more efficient in utilizing available soil water and fertility, i.e., they serve as biofertilizers and increase drought resistance and plant productivity. A long-term goal of our research is to utilize formononetin with native AMF populations to enhance potato crop productivity in a cost-effective manner.

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