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ARTICLE

Effects of crop rotation on enhanced occurrence of arbuscular mycorrhizal fungi and soil carbon stocks of lowland paddy fields in seasonaly dry tropics

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Abstract

The impacts of crop rotation systems on the arbuscular mycorrhizal fungal (AMF) spore density, mycorrhizal colonization of rice roots, soil C fractions and C stocks in seasonally dry climatic zone of Sri Lanka were examined in Rice–Soybean (RS) and Rice–Onion (RO) crop rotation systems during the subsequent rice cultivation season and, compared these with a rice monoculture, *i.e*. Rice–Rice (RR). The study also examined the correlations between AMF occurrence and soil carbon stocks. Results revealed that RS crop rotation system significantly enhances the occurrence of AMF spores in soil with a higher fraction of large sized spores, the total organic C (TOC), microbial biomass C (MBC), water soluble C (WSC), labile C and a high AMF colonization in rice roots in the subsequent rice cultivation season. The diversity of AMF morphospecies were also the highest in RS. Reduction in AMF density in the soil in RR crop rotation system may be due to prolonged anaerobic conditions prevailed. The growth of onion has drastically reduced the AMF colonization in rice and soil C contents. Soil carbon stocks showed positive correlations with % root colonization and AMF spore number in soil. Thus, the study confirmed that C stocks in paddy soils can be improved by intercropping with AMF supporting plants like soya bean. This is the first report that shows positive correlations of AMF sporulation and % root colonization in lowland rice with soil carbon stocks.

Keywords Carbon sequestration · Mycorrhiza · Onion · Rice · Soybean · Sri lanka

Introduction

Being the major staple food of more than half of the world population (FAO 2004; FAO 2003), rice has become an economically important crop worldwide. Rice, (Genus *Oryza*) which belongs to the family Poaceae, is widely grown throughout the tropics, especially in Asian countries including Vietnam, Laos, Bangladesh, India, Sri Lanka, Myanmar, Cambodia as well as in West Africa and in South and Central America (Muthayya et al. 2012). The versatile distribution of this crop is due to its ability to perform well in diverse environmental conditions. It is of substantial importance for food security and socioeconomic development, especially in low-income-generating countries with food deficits (FAO 2004; FAO 2003). However, in the recent past, stagnation of rice yields has been reported from several Asian countries (FAO 2003). Depletion of nutrients due to prolonged cultivation and harvesting of high yields of rice from the same land could be a major reason behind this (FAO 2003; Talpur et al. 2013). Therefore, maintenance of soil fertility is essential for the sustenance of high paddy yields (Talpur et al. 2013). However, the continuous application of chemicals over a long period of time has contributed to the yield decreases via major issues such as soil infertility, hardening of soil (Pilbeam et al. 2005), drastic reduction in pH in paddy soil, changes in salt concentration (Adesemoye and Kloepper 2009) and drying up of soil (Liu et al. 2014).

Paddy ecosystems serve as one of the favored habitats for a large number of soil microorganisms. These microorganisms play a vital role in maintaining the nutrient cycles and soil fertility. However the continuous usage of chemicals destroy beneficial microbes such as entophytic fungi and bacteria that associated with the paddy ecosystem (Ab Rahman et al. 2018). Furthermore, even a minor alteration

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in the soil microbial biomass may directly influence the ecosystem health and crop productivity. This could be a major factor for the gradual reduction in rice yield with prolonged cultivation, which needs to be addressed through sustainable agriculture. Beneficial soil microbes are considered as a key component of soil fertility (Barea 1991). Therefore, it is a biological soil quality indicator to restore disturbed ecosystems.

Mycorrhizal fungi are reported to improve plant vigor and soil quality (Siddique and Futai 2008). They play a crucial role in plant nutrient uptake, water relations, ecosystem establishment and plant diversity (Siddique and Futai 2008). Therefore, promoting mutualistic associations between paddy crop with arbuscular mycorrhizal fungi (AMF) has found to be improving the rice yield by enhancing the uptake of nutrients such as phosphorous (Yeasmin et al. 2007; Hoseinzade et al. 2016) and several micronutrients (Javaid 2009). AMF colonization also improves plant N nutrition (Javaid 2009) as well as the C status of well-drained soil, by increasing organic matter and glomalin in soil (Wenget al. 2017). Thus, mycorrhizal fungi presumed to be mediated in enhancing plant growth, especially in nutrient-limited environments, by increasing net primary production and subsequent improvement of carbon sequestration, by fixing more atmospheric CO_2 (Rillig et al. 2001). In addition, Glomalin favors the formation of soil aggregates while protecting soil organic carbon (SOC) against mineralization and, thereby caused to increase the retention of nutrients (Cheng et al. 2013).

It has also been reported that AMF may improve C sequestration of forest soils (Rillig et al. 2001; Moore et al. 2000; Godbold et al. 2006) and in mine soils (Qian et al. 2012). Further, an improved AMF colonization has been reported in upland paddy farming systems with crop rotation (Maiti et al. 2012). Although rice plants form mycorrhizal associations under upland conditions (Ilag et al. 1987), AMF colonization in lowland paddy fields is found to be low, because AMF may perform poorly in anaerobic conditions (Watanarojanaporn et al. 2013). Frequent flooding in paddy fields may create anaerobic soil conditions which results into reduce the population densities of all aerobic microbes, including AMF which has led to repute rice as a low mycorhizal plant (Ilag et al. 1987). However, artificial inoculation of AMF into paddy soil has shown to improve mycorrhizal colonization in rice (Barea 1991; Solaiman and Harita 1998). Moreover, with artificial inoculation of *Claroideoglomus etunicatum,* AMF colonization in rice roots had been increased and the survival under submerged conditions was improved after inoculation (Barea 1991; Solaiman and Harita 1998). However, such artificial inoculations measures are often associated with high cost and may not be successful under versatile environments.

Crop rotation appears to be a low-cost and easy farming practice which reported as enhancing the AMF sporulation among different upland farming systems. For instance, Oruru and Njeru (2016) have reported that, in a maize–common bean crop rotation system, the AMF sporulation has been increased than in a monoculture of maize and, the AMF sporulation correlates with the crop grown in the site previously. Similarly, both inoculation with AMF and crop rotation with mycorrhizal plants have been reported as improving the growth performance of maize in limed, acid sulfate soil (Higo et al. 2010). Moreover, crop rotations result into improve nutrient uptake by plants. For instance, nutrient uptake by maize plants in maize–common bean crop rotation system has been reported as increased (Oruru and Njeru 2016). Similarly, Ratnayake et al. (2017) have reported that rice grown in crop rotations in Sri Lanka tends to increase soil nutrient availability and to have higher C stocks than in rice monocultures. However, there are no records available on the effects of mycorrhizal colonizations in relation to soil C stocks in paddy soils.

As a measure of sustainable agriculture for the seasonally dry tropical areas, revealing the impacts of different rice cropping systems on AMF occurrences in rice and on soil carbon stocks would be beneficial as it enables to recommend suitable crop types to be rotated with lowland paddy. Therefore, the main objectives of this study is to determine the effects of paddy crop rotation systems with the upland mycorrhizal crops, soya and onion, on the AMF sporulation, soil carbon fractions and AMF colonization in rice roots under flooded condition and to compare these with a traditional lowland paddy monoculture. Further, the effect of AMF sporulation and root colonization was studied for C sequestration in lowland paddy soil. We hypothesized that crop rotation with mycorrhizal plants improve the AMF colonization of paddy roots and availability AMF spores in paddy soils and there by improve the soil organic C status. The findings would be applicable in all the seasonally dry tropical areas of the world where water is limited during some parts of the year, and low-cost sustainable agricultural practices are needed to be introduced.

Methodology

Field sites and rice cultivation systems

This study was carried out on Alfisols in the North Central province of dry zone in Sri Lanka (5° 54′ N—9° 52′ N latitude and 79° 39′ E—81° 53′ E longitude) where a typical monsoon climate prevails, with an annual rainfall of 900–1750 mm (FAO, 2017) and a mean annual temperature of 28–34 °C. These lands were cultivated twice a year with rice in the major rainy season and rice or another cash crop during the minor rainy season. Thus, rice, soya or onions are cultivated commonly in the study area, during the minor rainy season. Three different cropping systems of paddy, Rice/Rice (RR), Rice/Soya (RS) and Rice/Onion (RO), were selected for the present study (Fig. 1). The lands selected have been maintained the same crop for > 10 years. Inorganic fertilizers have been applied to examined paddy fields during the cultivation period, according to the dosages recommended by the Department of Agriculture, Sri Lanka. However, no organic fertilizers have been added to examined sites.

Field sampling

Both soil and plant materials were sampled from each cropping system using a corer, during the major rainy season when the fields were cultivated with paddy. For each cropping system, six plots, each of 20 m * 20 m area, were demarcated in farmer's fields scattered in an area over 4.04 ha. In each plot, six composite soil samples (altogether 12 soil samples) were collected from 0–15 cm soil depth using a soil corer of 5 cm width at randomly chosen points. Another 12 samples were collected from 15–30 cm soil depth and pooled to form another six composite samples. To study the AMF root colonization, one paddy plant from each plot were uprooted carefully at randomly chosen locations, without disturbing their root systems. Paddy plants were sampled just before tillering stage, when the growth requirements are very high.

AMF spore extraction from soil and spore counting

Spores were separated by wet sieving and decanting technique (Gerdemann and Nicolson, 1963) (Fig. 2), followed by sucrose centrifugation (2000 rpm). Spores were then washed onto a filter paper and the number of spores was determined under reflected light on stereomicroscope (Gerdemann and Nicholson 1963). The AMF spores were picked up with a Pasteur pipette, and they were observed under a binocular light microscope to identify the morphotypes (as glomoid, acaulosporoid and gigasporoid) where possible, using the International Culture Collection of Arbuscular and Vesicular–Arbuscular Mycorrhizal Fungi (INVAM) and mycorrhiza identification manual (Błaszkowski 2012).

Root clearing, staining and quantification of AM root colonization

The root samples were washed thoroughly and cleared by boiling in 10% KOH for 1 h at a temperature of 90 °C. KOH was poured off, and the roots were rinsed with tap water for 3 times. If the roots are dark in colour, these were bleached with 30% alkaline H_2O_2 by keeping for 10–20 min before acidifying with 1% HCl. Root segments of 1 cm long were stained with 0.05% cotton-blue in lactophenol. Stained root specimens were kept on a glass slide containing a drop of 70% glycerine and observed under the microscope. The gridline intersection method was used to quantify root colonization (Giovannetti and Mosse 1980).

Soil sample preparation and analyses

All visible organic debris, stones, plant roots were removed from soil samples. Then samples were sieved using a 2-mm mesh sieve. Microbial biomass C was analyzed using fresh soil. The rest of the samples were air dried and ground to a powder of < 0.15 mm. The determination of total organic C was carried out using acidified dichromate of organic carbon using modified Walkley's oxidation method (Baker 1976). Microbial biomass carbon was determined by using the chloroform fumigation and extraction method (Vance et al. 1987). The labile fraction of SOC was determined by the $KMnO_4$ oxidizable carbon estimation method (Weil et al. 2003). Water soluble organic carbon (WSC) was estimated by titration method using acidified ferrous ammonium sulfate (Anderson and Ingram, 1993).

Soil C stocks

Soil Carbon stock values for the same paddy fields had been estimated by Ratnayake et al. (2017) for soil samples collected during the same sampling time period using the method describe by Benbi et al. (2015). These C stock values were used in the present study to assess the relationship between AMF occurrences and C sequestration.

Data analyses

AMF spore abundance, root colonization data and soil carbon fractions were analyzed by performing General Linear Mixed Model (GLMM) using SAS (version 06) software and the mean separations were done using Tukey's test at 0.05 level of significance. The relationships between AMF occurrence, spore availability in soil and Soil C stocks were established through correlation and simple regression analyses. Detrended correspondence analysis (DCA) of total soil carbon and soil carbon fractions in 18 soil samples (from three cropping systems) were performed using Canoco 5 ® software (Microcomputer Power, Ithaca, NY), while a principal component analysis (PCA) was performed to detect the variation of size ranges of AMF spores in relation to the crop rotation systems, using the same software of ordination.

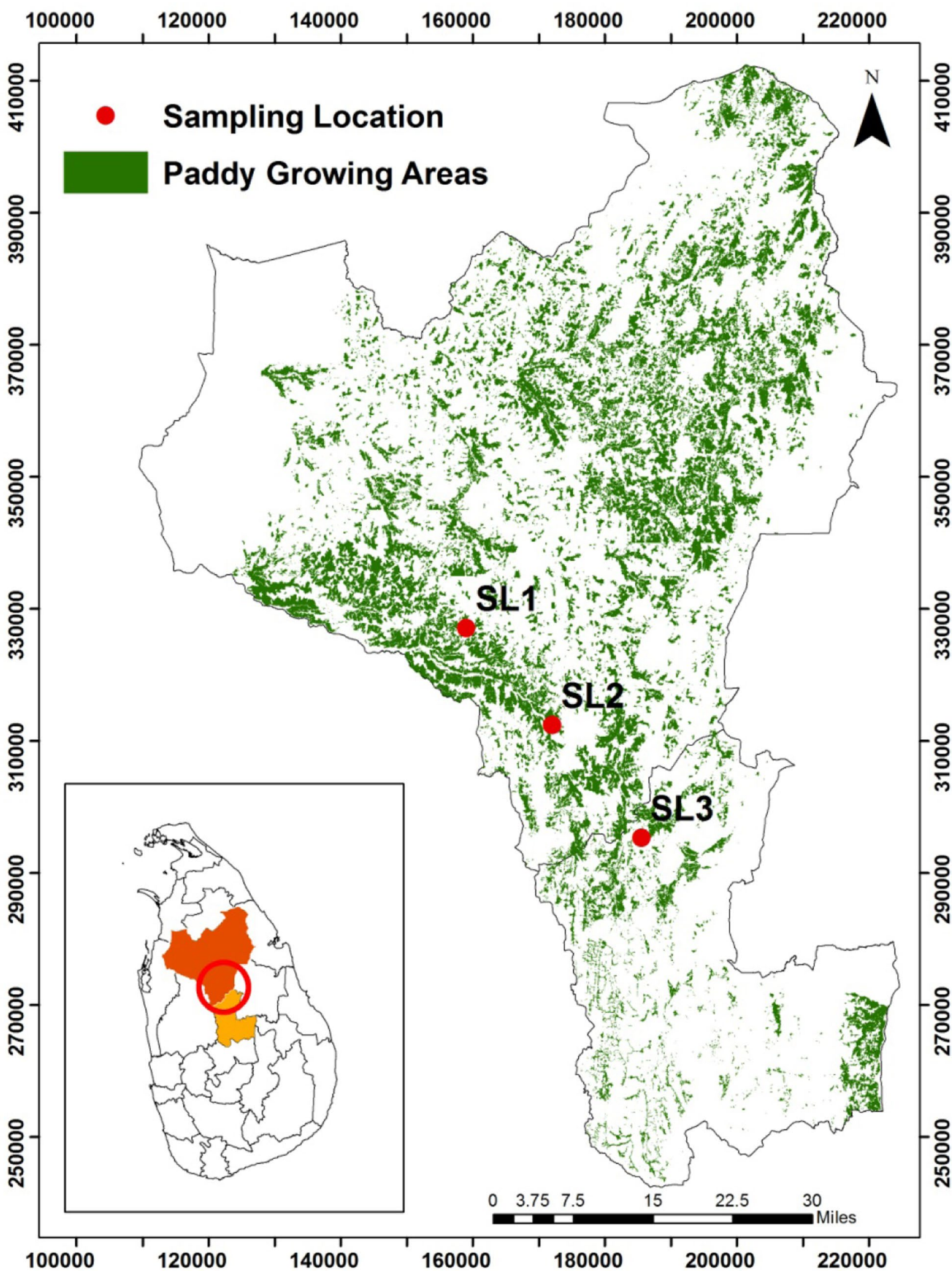

Fig. 1 Sampling locations of the study area

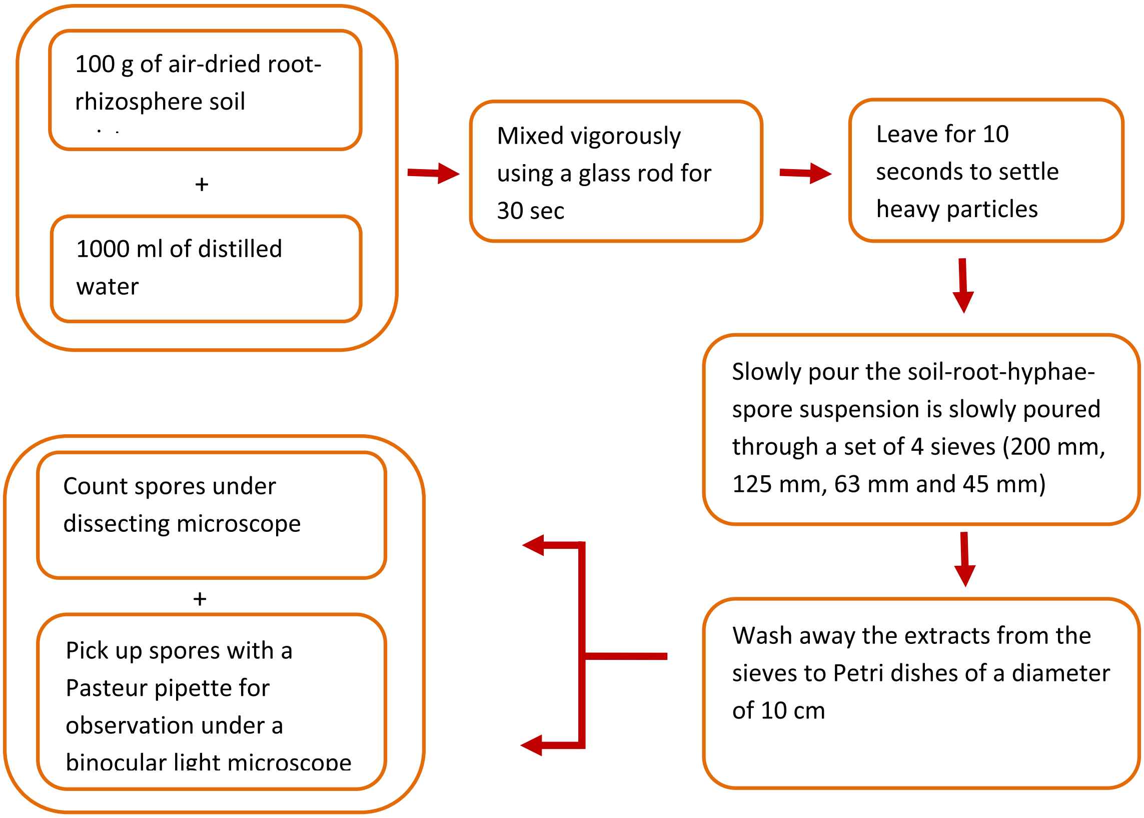

Fig. 2 Flowchart to indicate the wet sieving and decanting method described by Gerdemann and Nicolson (1963)

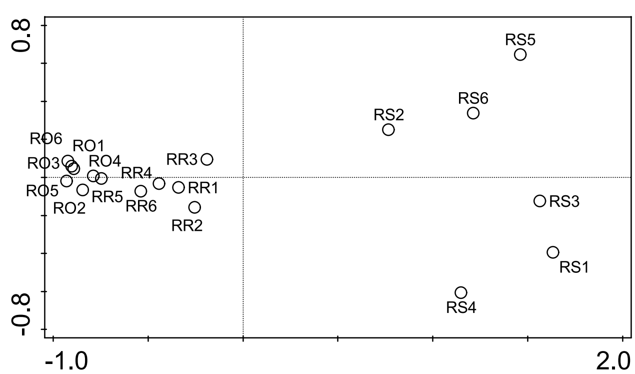

Fig. 3 Scattergram produced by PCA of the abundance of mycorrhizal spores in three size classes that isolated from 18 soil samples

Table 1 Summary table of the PCA of mycorrhizal spore abundance for each size ranges

Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.9189	0.0665	0.0146	–
Explained variation (cumulative)	91.89	98.54	100.00	

Results

Density of AMF spores and diversity of AMF morphospecies in examined cropping systems

The scattergram that produced from the PCA of AMF spore abundances in the surface soil layer (Fig. 3), indicates that the RS crop rotation systems is contrastingly different from the rest by having a high number of large sized spores. As given in Table 1, the variation is mainly arranged alone the axis 1 (Eigenvalue = 0.918). Further, AMF spore density at this soil depth (0–15 cm) was significantly different (GLMM; $p < 0.0001$) among different crop rotation systems, with the lowest AMF spore density recorded in RO farmland (Fig. 4).

However, the AMF spore density at the depth of 15–30 cm was lower compared to that of the 0–15 cm layer, in all three cropping systems. Despite it is significantly higher in the RS cropping system than the rest (GLMM: $p < 0.003$), in contrast, the density of AMF spores found at the subsurface soil layer (15–30 cm) of the RO cropping system was slightly higher than that in its surface soil layer (Fig. 4).

Altogether, 20 spore morpho types were observed in the examined soil samples of which, 12 were identified to the

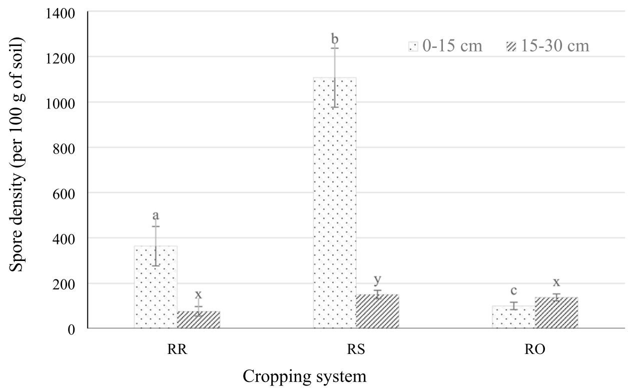

Fig. 4 AMF spore density in examined crop rotations at the depth of 0–15 and 15–30 cm soil depths (Similar letters next to error bars indicate no significant difference among treatments at $p = 0.0001$ significant level)

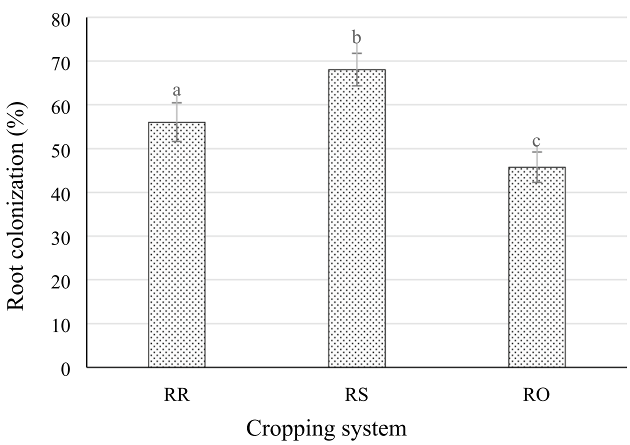

Fig. 5 Percentage root colonization by AMF in rice root samples obtained from RR, RS and RO crop rotation systems (Similar letters next to error bars indicate no significant difference among treatments at $p = 0.0001$ significant level)

genus level. As depicts in Table 3, in all three examined cropping systems, AMF species with Glomoid spores occur in high proportions. In the RS cropping system, the number of AMF morpho-species at both 0–15 and 15–30 cm soil depths were the highest compared to other two cropping systems. In the RS cropping system, nineteen AMF morpho-species were found from each soil layers and of these Glomoid and Acaulosporoid spores showed a high abundance in soil (Table 3).

Root colonization percentage of AMF in examined cropping systems

Root colonization percentage of paddy plants were significantly different (GLMM: $p < 0.0001$) among different cropping systems (Fig. 5). Percentage colonization of

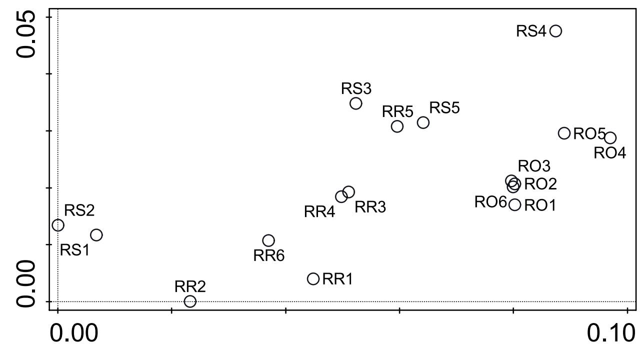

Fig. 6 Sample scattergram produced by DCA of 18 soil samples and four soil variables (Total C, Labile C, MBC and WSC)

Table 2 Summary table of DCA of 18 soil samples

Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.0050	0.0003	0.0000	
Explained variation (cumulative)	86.54	91.16	91.64	
Gradient length	0.10	0.05	0.03	
Total variation	0.00582			

AMF in rice roots was the highest in RS cropping system, while the lowest value recorded in RO crop rotation system.

Total C and soil C fractions in collected soil samples

As depicted in the sample scattergram produced by DCA of four soil variables in 18 soil samples (Fig. 6), the soil samples of RO cropping system are clustered together but somewhat separated from the rest. However, very low eigenvalue indicates (Table 2) that this spatial variation is not much significant. This low variation of soil carbon fractions among the soil samples in three crop rotation systems are due to overlapping ranges of total carbon and labile carbon contents. However, soils in RR and RS crop rotation systems are highly variable or heterogeneous in terms of total C, labile C, microbial biomass C and water soluble C contents so that these samples are much scattered in the DCA diagram. However, the soils in the RS crop rotation system showed not only the highest soil heterogeneity (Fig. 6), but also a significantly higher TOC % (GLMM, $p = 0.016$), microbial biomass C (GLMM, $p > 0.001$), water soluble C (GLMM, $p > 0.001$) and Labile C (GLMM, $p = 0.027$) contents. Also, the MBC % was very low in the surface soils of both RR and RO crop rotating systems.

Correlation between AMF root colonization and soil C stocks

As reported by Ratnayake et al. (2017), total organic carbon stocks detected for the same study sites varied significantly with different cropping systems and ranged between 43.41 and 65.18 T/ha. RR and RS showed the highest C stocks while the lowest stock values were observed in RO cropping system (Ratnayake et al. 2017). Correlation analysis runs between these soil C stock values and AMF root colonization showed a significant correlation ($r^2 = 0.58$) (Fig. 7a) between the parameters. Similarly, a significant correlation ($R^2 = 0.59$) was also observed between soil C stocks and AMF spores (Fig. 7b).

Discussion

The present study reveals the increasing AMF sporulation and root colonization of lowland paddy with the crop rotation with soya bean, an upland crop species in seasonally dry regions in Sri Lanka. This observation is in parallel with the report by Vallino et al. (2014) for an upland cropping system of soya. Further, the present study agrees with Oruru and Njeru (2016) and Higo et al. (2010) that AMF sporulation and root colonization in seasonally dry climates may vary with the plant species that associated with. As Maiti et al. (2011 and 2012) stated, rice-legume crop rotations cause to increase incidence of AMF in soil (Fig. 8).

In the present study, the abundance and diversity of AMF spore morpho-species in the soils at both 0–15 cm and 15–30 cm soil depths and % AMF colonization in rice roots were high in RS crop rotation system. In the RS crop rotation system, the soil contains comparatively high total C % WSC and MBC and labile C contents though it appears to be highly heterogenous.

In contrast, low TOC %, WSC, MBC and Labile C were reported in the RO crop rotation system and onion do not appear to be favoring AMF spore occurrences in the soil so that low amount of AMF spores with comparatively a high fraction of smaller sized spores and low rates of AMF colonization in rice roots were recorded in the RO crop rotation system. Onion is reported to be low mycorrhizal and improved only with inoculation (Charron et al. 2001) though, as Ijdo et al. (2011) reported, this could be highly dependent on the type of mycorrhizal fungi too. Root architecture and distribution may have also affected onion to have low mycorrhizal colonization and resulted low AMF spore count in the examined RO croplands (Pearson and Jakobsen, 1993). Onion plants possess shallow feeding root systems than rice, distributed in upper soil layer and less branched (Charron et al. 2001). As a result, growing of onion as a

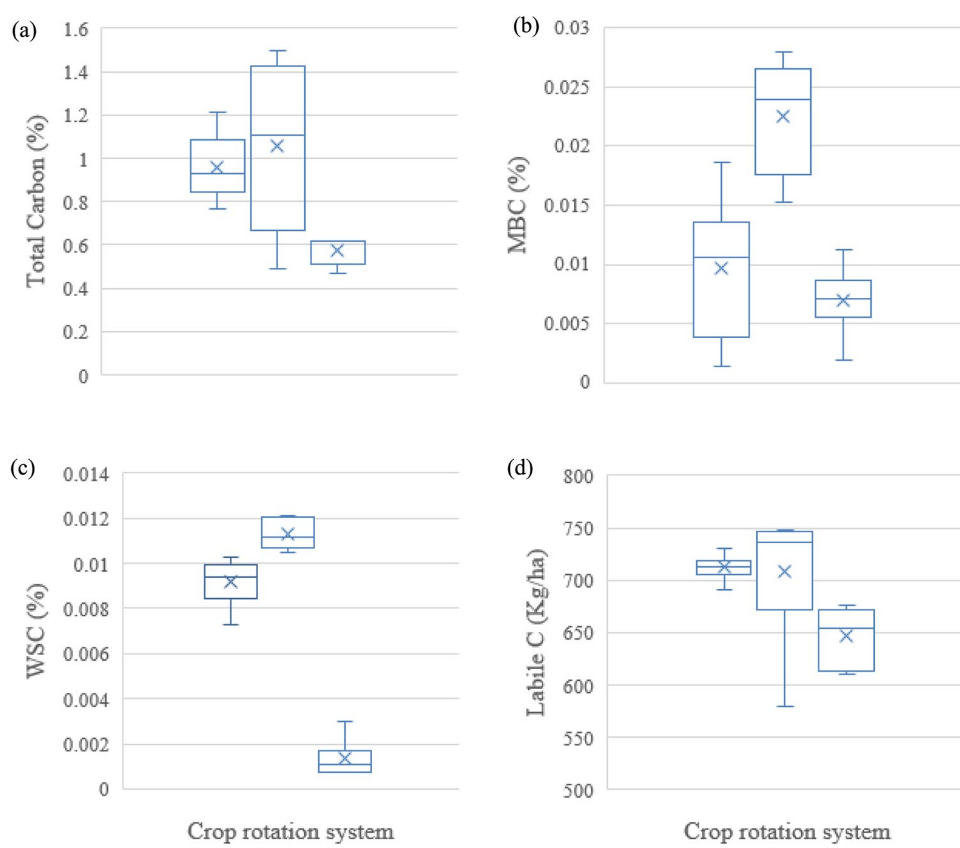

Fig. 7 Box plot diagrams for **a** Total Carbon, **b** MBC, **c** WSC and **d** Labile C contents in three examined crop rotation systems. The median is marked with x mark

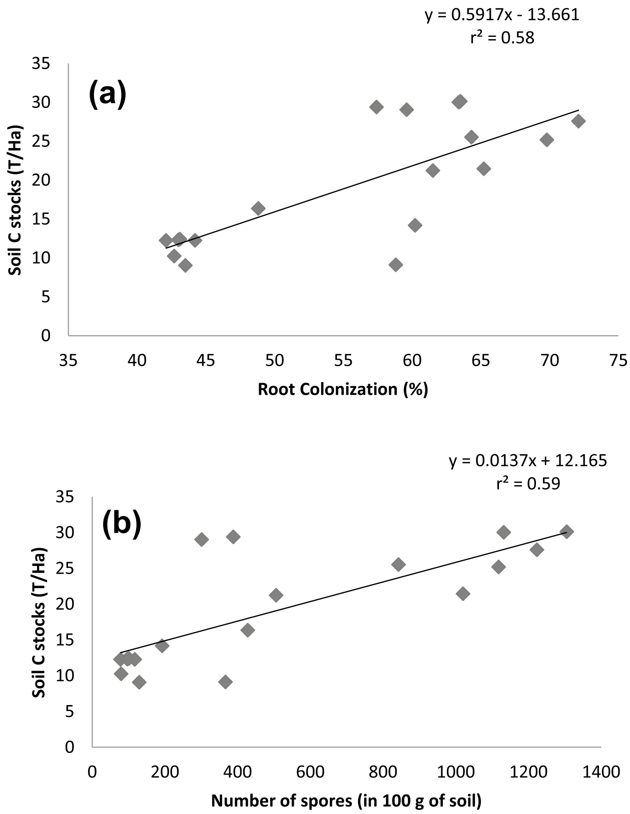

Fig. 8 Correlation between **a** soil C stocks and root colonization %and **b** number of AMF spores and soil C stocks in RR, RS and RO crop rotation systems

rotational crop may not support much for mycorrhizal colonization in rice in the RO cropping system. It is also reported that Onion has a low AMF diversity and colonization in croplands due to the selection pressure imposed by cultivation practices and species that are able to tolerate stresses like tillage, fertilizer and biocide applications will be survived (Priyadharsini 2012).

However, the surface soils of examined paddy monoculture (RR) contains moderately high TOC %, WSC and labile C contents and possesses a little higher soil AMF spore abundances and % root colonization values, compared to RO crop rotation system. However, the MBC % is as low as RO crop rotation system. These findings also agree with others who reported low- or medium-level mychorrhizal colonization in lowland rice (Ilag et al. 1987) due to reduced microbial growth under frequently flooded environment (Watanarojanaporn et al. 2013). Further, ethylene that produced under flooded and anaerobic conditions may adversely affects plant-mycorrhizal interactions in RR cropping systems (Morgan and Drew 1997).

The present study proves that soya bean is an ideal crop for intercropping with rice than onion or rice monoculture at seasonally dry tropics. As soya has a deep feeding root system and many root tips due to higher root branching (Sartori et al. 2016), it can support a high AMF flora not only on the surface soil but also in deep soil layers of the RS cropping system (Wang et al. 2011). It has been reported that factors such as depth of the root systems, root architecture and root branching patterns of soya favors the occurrence of mycorrhiza and spores in soil (Vallino et al. 2014). Further, soya bean is a legume which bare Rhizobium nodules on their roots. Rhizobitoxine (Yuhashi et al. 2000) and the enzyme ACC deaminase (Penrose and Glick 2003) produced by rhizobia strains may inhibit the rise in ethylene in the soil and subsequently reduce the inhibitory effects imposed on mycorrhiza (Morgan and Drew 1997). As a result, the extent of mycorrhizal colonization of rice and the amount of AMF spores in the paddy soil of RS cropping system may have increased.

The positive correlation between mycorrhizal colonization and soil C stocks revealed by the present study lead to presume that the improvement of C stocks in paddy soil can be an effect of improved AMF occurrences which is influenced by the crop rotation. Ratnayake et al. (2017) have shown the contribution of soil carbon stock due to increased addition of leaf litter by the plants used in crop rotation. Both plant roots and mycorrhizal fungi demand more carbon for their growth, plants tend to fix more atmospheric CO_2 via

Table 3 Number of morpho-species (bold) and the proportional abundance of different morpho-species (given in brackets) at 0–15 cm and 15–30 cm soil depths in examined cropping systems

Cropping system	Total no of spores	*Glomoid*	*Acaulosporoid*	*Gigasporoid*	Unidentified morphospecies	Total no of morphospecies
0–15 cm						
RR	2181	**4**(40.26%)	**3**(12.24%)	**3**(1.60%)	**4**(45.90%)	**14**
RS	6647	**4**(59.19%)	**4**(18.78%)	**4**(2.62%)	**7**(19.42%)	**19**
RO	600	**3**(37.83%)	**1**(16.83%)	**3**(2.00%)	**3**(43.33%)	**10**
15–30 cm						
RR	458	**4**(36.90%)	**3**(14.19%)	**4**(4.15%)	**3**(44.76%)	**14**
RS	1156	**4**(42.92%)	**4**(14.49%)	**4**(7.63%)	**7**(34.96%)	**19**
RO	961	**3**(49.33%)	**2**(22.85%)	**3**(3.39%)	**3**(24.43%)	**11**

the natural process of photosynthesis and provide C to the soil and its biota (Rillig et al. 2001). However, Godbold et al. (2006) have stated that mycorrhizal external mycelium act as a dominant pathway (62%) through which, C enters the soil organic matter (SOM) pool, exceeding the input via leaf litter, contributing to efficient C sequestration. Mycorrhiza play a key role in the formation of soil aggregates (Cheng et al. 2012) by excretion of Glomalin (Wilson et al.2009) in which C is conserved (Cheng et al. 2012).

Decline in paddy yield has been observed in many seasonally dry areas of the tropics over the years and, as a result, farmers tend to apply more inorganic chemical fertilizers to their paddy fields than in the past. always This accompany with a high production cost and linked with environmental pollution (Ratnayake et al. 2017). In some areas, farmers convert paddy fields in to permanent crop lands with banana or merely abandon the area from time to time. Improved effective AMF occurrences in paddy with crop rotations will provide positive benefits in mitigating environment pollution and enhancing yield per unit area of land. Thus, as revealed from the present study, crop rotation can be recommended to improve AMF occurrences in paddy fields in seasonally dry climates in the tropics which may increase rice yield, reduces environmental pollution and enhances soil carbon sequestration but the crops that used in rotation with rice should be selected with caution. However, as the presence of AMF spores does not guarantee the effectivity in enhancing crop yield and therefore further studies are needed to distinguish effective AMF strains from parasitic or ineffective ones. Further, it is necessary to examine the AMF diversity, sporulation and root colonization in lowland paddy with other upland crop species (e.g. tobacco, vegetables) which practiced in various different regions not only in Sri Lanka but also in other parts of the world. The study confirmed that the diversity and sporulation, root colonization of AMF and soil carbon fractions in lowland paddy fields in seasonally dry tropics can be enhanced by crop rotations with favorable species like Soya bean (Table 3).

Conclusions

Cultivation of soya bean as a rotation crop in rice cropping systems during the minor rainy period caused to enhance the TOC, MBC, WSC and Labile C contents and AMF spore abundances and their sizes in the surface soil (0–15 cm) as well as to increase the % of AMF colonization in roots of rice that grow in the subsequent major rainy season, compared to other rotation crops such as onion. Therefore, soya bean can be recommended as an ideal rotation crop that can be used in sustainable paddy cultivation in seasonally dry tropics. The use of onion in crop rotation, however, may cause to deprive the AMF spore abundances and to reduce AMF root colonizations in rice in the next cultivating season, which might cause to gradual reduction of rice yield with time or demand more investments to increase soil fertility in rice fields. Compared to RO crop rotation system, the Rice monocultures are better in many aspects (except MBC), but inferior to RS crop rotation system, in terms of all examined variables. Further, this study reports a positive correlation between AMF sporulation in lowland rice in seasonally dry tropics with soil carbon stocks and confirms that C stocks in paddy soils can be improved by intercropping with AMF supporting crop plants such as soya. As such, RS cropping system could contribute to world's food security in the dry tropics and sustainable agriculture.

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