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Effects of ridge and furrow film mulching on soil environment and yield under potato continuous cropping system

*Yanling Fan, Weina Zhang, Yichen Kang, Zhangping Zhao, Kai Yao, Shuhao Qin**

College of Horticulture, Gansu Agricultural University, Lanzhou, P.R. China

**Corresponding author: qinsh@gsau.edu.cn*

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Abstract: The effect of ridge and furrow film mulching (RFFM) on soil microbial communities, physicochemical property, enzymatic activity, and tuber yield were studied under the potato (*Solanum tuberosum* L.) continuous cropping fields managed for one (CY-1), two (CY-2) and four years (CY-4). Experimental treatments included a conventional flat plot without film mulching (FP) and five RFFM treatments: (i) a flat plot with film mulching (T1); (ii) on-ridge planting with full film mulching (T2); (iii) on-furrow planting with full film mulching (T3); (iv) on-ridge planting with half film mulching (T4); and (v) on-furrow planting with half film mulching (T5). Compared with FP, RFFM increased microbial communities, soil electrical conductivity, and enzymatic activities, and decreased pH values to improve the soil environment. Microbial communities of T2 and T5 were relatively higher, while soil urease and alkaline phosphatase activities of T2 and T4 were higher in all the continuous cropping years. In addition, the tuber yields of T2 were also increased by 75.0, 46.4 and 97.3% than FP, respectively. Thus, on-ridge planting with full film mulching (T2) is recommended as an adaptive management strategy for potato cultivation in the semi-arid areas where continuous cropping is necessary.

Keywords: ridge tillage; plastic film; soil index; potato production; succession cropping

Potato (*Solanum tuberosum* L.) is widely planted in semi-arid areas, because of its geographical environment and natural conditions, including lower temperature and light, the larger temperature difference between day and night, as well as loose and fertile land. In addition, potato is considered as one of the principal economic and staple food crops by the local government (Wang et al. 2008), and the people here are fond of it. However, due to the restriction of land resources, continuous cropping is very common where fields grow only one crop annual season in these areas (Hou and Li 2018). Moreover, water use efficiency is low in semi-arid areas, only relying on natural precipitation, which limits the sustainable development of potato (Deng et al. 2006). More seriously, rainwater utilization efficiency is only 30–40% in these regions (Zhang et al. 2017).

Ridge and furrow film mulching (RFFM) tillage technique, which can effectively enhance water and fertilizer use efficiency and crop yield, is employed in these areas. This technique consists of two elements. One is the ridge mulched by the plastic film as the runoff area, and the other is the furrow, which acts in the planting area (Ren et al. 2016a). The greatest advantage of RFFM is that it can effectively improve the temperature and moisture of topsoil, increase water use efficiency, soil nitrate, and organic carbon, and consequently increase crop yields of wheat (Liu et al. 2018), maize (Wang et al. 2018) and winter oilseed rape (Gu et al. 2016) in the practice of agricultural production.

Good soil environment, which is the basis for plant growth and development, can support sufficient water, fertilizer, gas, and heat for plants (Mimura

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et al. 2008, Ma et al. 2017). Potato production faces numerous constraints, including lack of profitable rotation crops, diseases, high fertilizer and pesticide requirements, sequentially degrading soil quality during the growing season. Continuous cropping also further exacerbates this situation. The objectives of this research were to study (i) the effects of RFFM on soil microbial communities, physicochemical properties, enzymatic activities and yields in continuous cropping field, and (ii) explore an adaptive management strategy for potato cultivation in the semi-arid areas.

MATERIAL AND METHODS

Site description. The study site was conducted at the Dingxi Experimental Station (35°33'N, 104°35'E) of the Gansu Agricultural University, Lanzhou, China. The soil is locally classified as Huangmian, the typical semi-arid area soil in Chinese soil taxonomy (Chinese Soil Taxonomy Cooperative Research Group 1995). The soil has a deep layer, medium fertility, and high water storage capacity, which is widely distributed in China's Loess Plateau. The elevation, average annual rainfall and mean annual temperature are 1950 m a.s.l., 391 mm and 6.4°C, respectively. The basic soil properties of the topsoil layer (0~30 cm depth) of the experimental plot are shown in Table 1.

Table 1. Chemical properties of the soil before treatment application collected in March

Continuous cropping year	pH	Available N	Available P	Available K
		(mg/kg)		
CY-1	8.71	19.12	24.64	578.23
CY-2	8.48	16.66	20.30	441.50
CY-4	8.27	14.13	15.73	365.03

CY-1 – one-year, CY-2 – two-year, CY-4 – four-year continuous cropping

Experimental design. Flat plot without film mulching (FP, Figure 1) and five RFFM treatments were conducted in a random block design in 2015 (one-year continuous cropping, CY-1), 2016 (two-year continuous cropping, CY-2) and 2018 (four-year continuous cropping, CY-4). Five RFFM treatments were set out (Figure 1): (i) a flat plot with film mulching (T1); (ii) on-ridge planting with full film mulching (T2); (iii) on-furrow planting with full film mulching (T3); (iv) on-ridge planting with half film mulching (T4); and (v) on-furrow planting with half film mulching (T5). Each experimental plot was 7.7 m by 11.5 m with a plant spacing of 35 cm and row spacing at 55 cm. And each treatment included three replicated plots. The potato cv. Xindaping was planted with 0.01 mm thick plastic film in this experiment at the density of 45 460 plants per ha on April 25. Nitrogen, phos-

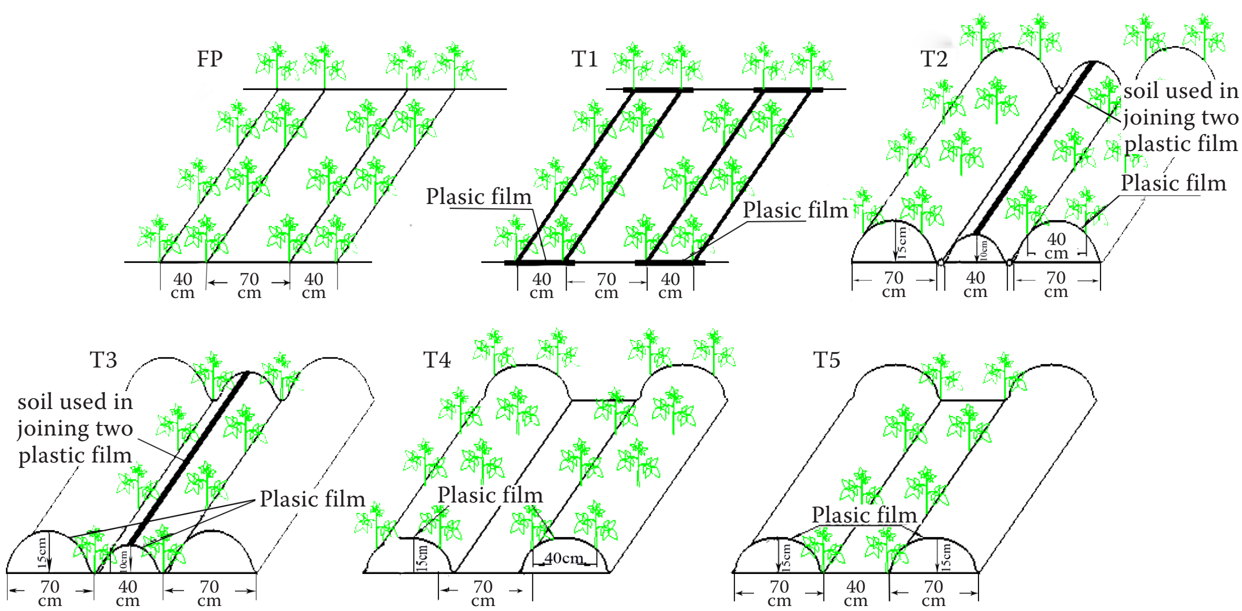

Figure 1. The schematic diagrams of different ridge and furrow film mulching treatments. FP – flat plot without film mulching; T1 – a flat plot with film mulching; T2 – on-ridge planting with full film mulching; T3 – on-furrow planting with full film mulching; T4 – on-ridge planting with half film mulching; T5 – on-furrow planting with half film mulching

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phorus, and potassium were fertilized in the plots at a rate of 44.8, 11.76, and 57.6 kg/ha, respectively.

Soil samples collection. The soil samples were collected during flowering and the early tuber formation. The soils of six random points in each plot were sampled with a dry-sterile brush to brush the soil of potato root into sterile valve bags, mixed into one sample and then stored at −80°C for determination.

Determination of soil microbial community, physicochemical properties, and enzymatic activity. Bacteria and fungi were measured by soil dilution plating on agar media (Larkin et al. 2010). Modified Gaoshi No. 1 medium (pH 7.2–7.4) was used to detect the number of actinomycetes (Lin 2010). The soil pH and electrical conductivity (EC) were determined using a glass electrode pH meter (PHS-3E, Precision Scientific Instrument Co., Ltd, Shanghai, China) and a conductivity meter (DDSJ-308A, Precision Scientific Instrument Co., Ltd, Shanghai, China) (Qiu et al. 2012, Xiong et al. 2015). Catalase activity was calculated using a titration method (0.1 mol/L standard $KMnO_4$ solution titration). Urease activity was determined by the sodium hypochlorite-phenol sodium colorimetric method, and alkaline phosphatase was measured by a disodium phosphate-benzene colorimetric assay.

Data analyses. All data were represented by the mean value of three replicates. One-way ANOVA analysis of variance was performed using the Fisher's *LSD* (least significant difference) at a 5% probability in the SAS for Windows (v8) (SAS Institute Inc., North Carolina, USA). The standard error of the mean was calculated, and the result was indicated by vertical bars in the corresponding figures. AutoCAD 2007 (Autodesk Inc., San Rafael, USA) was used to create Figure 1, and Origin 8.0 (Originlab Corporation, Northampton, USA.) was utilized to create the other figures.

RESULTS AND DISCUSSION

Microbial communities. The numbers of bacteria, fungi, and actinomycetes under RFFM were generally greater than those of under FP during all continuous cropping years, and T2, T4, and T5 maintained greater bacterial populations than FP after four years of continuous cropping. In addition, T2 showed higher populations of fungi and actinomycetes than all the other treatments with the extended duration of continuous cropping, and all RFFM treatments had greater actinomycete populations than FP (Table 2). These results were consistent with Dong et al. (2017), who documented that the application of film mulching significantly increased the richness and diversity of bacteria and fungi. Many studies also indicated that film mulching provided a suitable environment for the growth of bacteria and fungi by effectively increasing topsoil temperature, moisture, water use efficiency, and reducing evapotranspiration (Qin et al. 2015, Liu et al. 2018).

Table 2. Microbial community of soil under the different ridge and furrow film mulching treatments under the continuous cropping potato field

Treatment	Bacteria (× 10^6 CFU/g)			Fungi (× 10^3 CFU/g)			Actinomycetes (× 10^5 CFU/g)		
	CY-1	CY-2	CY-4	CY-1	CY-2	CY-4	CY-1	CY-2	CY-4
FP	3.93 ± 0.40^{c}	4.18 ± 0.30^{b}	8.84 ± 0.53^{bc}	4.38 ± 0.22^{c}	1.84 ± 0.34^{b}	0.48 ± 0.04^{b}	6.42 ± 0.16^{d}	0.68 ± 0.05^{e}	4.29 ± 0.23^{c}
T1	5.13 ± 0.39^{c}	5.02 ± 0.45^{b}	7.46 ± 0.63^{c}	5.41 ± 0.43^{bc}	3.39 ± 0.39^{ab}	0.70 ± 0.05^{b}	6.60 ± 0.29^{d}	2.82 ± 0.24^{d}	5.74 ± 0.25^{b}
T2	10.28 ± 0.44^{b}	4.42 ± 0.18^{b}	13.85 ± 0.58^{a}	11.78 ± 0.12^{a}	3.63 ± 0.47^{ab}	4.48 ± 0.50^{a}	12.26 ± 0.15^{a}	3.89 ± 0.14^{c}	7.45 ± 0.24^{a}
T3	4.98 ± 0.61^{c}	10.68 ± 0.43^{a}	9.89 ± 0.28^{bc}	3.87 ± 0.27^{c}	2.89 ± 0.38^{ab}	1.47 ± 0.22^{b}	9.26 ± 0.08^{c}	9.00 ± 0.14^{a}	5.82 ± 0.30^{b}
T4	4.38 ± 0.29^{c}	5.86 ± 0.39^{b}	11.23 ± 0.36^{ab}	1.84 ± 0.36^{d}	3.03 ± 0.29^{ab}	0.92 ± 0.06^{b}	8.83 ± 0.10^{c}	4.57 ± 0.13^{c}	6.43 ± 0.25^{ab}
T5	12.96 ± 0.49^{a}	11.77 ± 0.36^{a}	12.70 ± 0.61^{a}	6.63 ± 0.21^{b}	3.89 ± 0.11^{a}	1.3 ± 0.15^{b}	10.60 ± 0.06^{b}	7.66 ± 0.15^{b}	6.22 ± 0.30^{ab}

Data are mean ± standard error of the three replicates. Different small letters within a column indicate significant differences among treatments at P = 0.05 level. CFU – colony-forming unit; CY-1 – one-year, CY-2 – two-year, CY-4 – four-year continuous cropping; FP – flat plot without film mulching; T1 – a flat plot with film mulching; T2 – on-ridge planting with full film mulching; T3 – on-furrow planting with full film mulching; T4 – on-ridge planting with half film mulching; T5 – on-furrow planting with half film mulching

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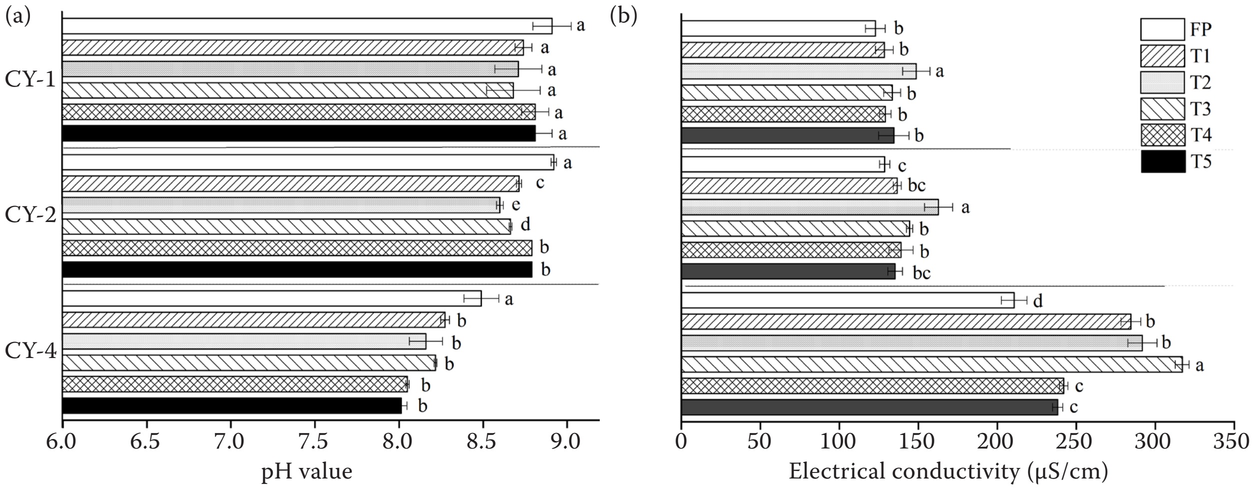

Figure 2. Effect of different ridge and furrow film mulching treatments on (a) soil pH and (b) soil electrical conductivity under continuous cropping potato field. The error bar represents the standard error. Different lowercase letters indicate significant differences (P < 0.05) among treatments under continuous cropping years. CY-1 – one-year, CY-2 – two-year, CY-4 – four-year continuous cropping; FP – flat plot without film mulching; T1 – a flat plot with film mulching; T2 – on-ridge planting with full film mulching; T3 – on-furrow planting with full film mulching; T4 – on-ridge planting with half film mulching; T5 – on-furrow planting with half film mulching

Physicochemical properties. Soil pH and EC are two important chemical characteristics of crop soil, which play a vital role in maintaining the sustainability of agricultural production systems. RFFM treatments had lower pH value and higher soil electrical conductivity (EC) than FP in continuous cropping (Figure 2). The lowest pH of CY-1, CY-2 and CY-4 were separately found in T3 (pH = 8.68), T2 (pH = 8.60), and T5 (pH = 8.01), and the highest EC value were shown in T2 (148.7 µS/cm), T2 (162.7 µS/cm) and T3 (317.0 µS/cm). What's more, in CY-4, the soil EC of all RFFM treatments had a significant increase, and T2 was still the highest (291.8 µS/cm) except lower than T3. Li et al. (2016) found that the contents of phenolic acids, such as *p*-hydroxybenzoic acid, cinnamic acid, and *p*-coumaric acid, were accumulated in strawberry soil under continuous cropping, then H^+ was released to make the drop of pH. RFFM treatments improved the soil EC, and the effects in CY-4 were more pronounced. We speculated that the higher the value of the EC increased the number of free ions in the soil and accelerated physiological metabolism.

Enzymatic activities. Soil enzymatic activities play a crucial role in soil biochemical processes, and the changes observed in enzymatic activity may be used to show the effectiveness of soil restoration of some ecosystems. Here, we found that the activities of catalase had no difference between RFFM and FP in CY-1 and CY-2, but in CY-4, significantly differences (P < 0.05) were measured from FP except T1 (Figure 3a). RFFM treatments could improve soil urease activities, revealing no significant differences from that of FP in CY-1, but significant differences (P < 0.05) in CY-2 and CY-4, and the highest alkaline phosphatase activity was found in T2, followed by T4 in all the continuous cropping years (Figure 3b,c). Previous studies had shown that film-mulched continuous ridge-furrow planting could increase enzymatic activity in soil (Gu et al. 2019), which supported our findings on the soil enzymatic activities under the RFFM treatments. A'Bear et al. (2014) found that activities of the enzyme in wet soil were significantly higher than those in dry soil. López et al. (2014) indicated the relationship between soil moisture content and enzymatic activity might be positively linearly correlated. Thus, our observation of greater activity in RFFM was probably due to the higher soil moisture contents under the RFFM treatments.

Tuber yield. The results of this study demonstrated that tuber yields of RFFM were significantly higher than those of FP, and the highest yields were shown in T2, which were 75.0, 46.4, and 97.3% higher than FP, respectively (Figure 4). In CY-1, the order of tuber yields was T2 > T5 > T4 > T3 > T1 > FP, but it was T2 > T4 > T1 > T5 > T3 > FP in CY-2, While in CY-4, it became T2 > T3 > T5 > T4 > T1 > FP (Figure 4). Ren et al. (2016b) reported that the 4-year

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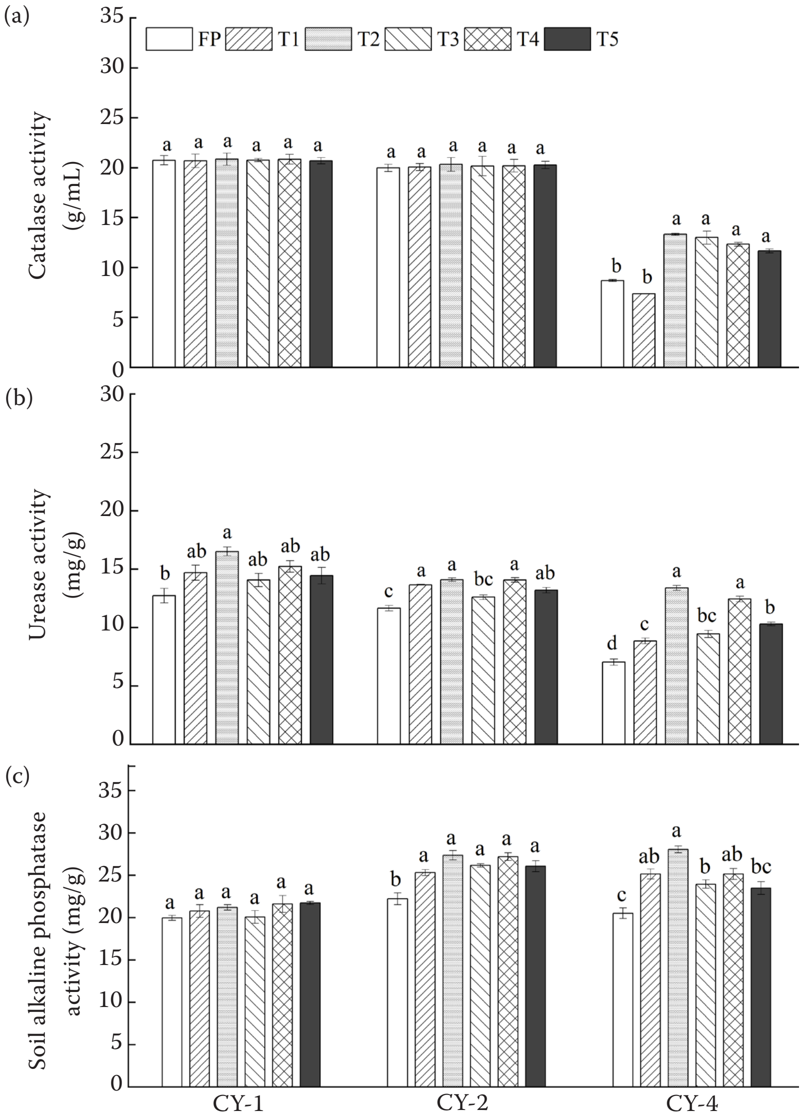

Figure 3. Effect of different ridge and furrow film mulching treatments on (a) catalase activity; (b) urease activity and (c) soil alkaline phosphatase activity under continuous cropping years. CY-1 – one-year, CY-2 – two-year, CY-4 – four-year continuous cropping; FP – flat plot without film mulching; T1 – a flat plot with film mulching; T2 – on-ridge planting with full film mulching; T3 – on-furrow planting with full film mulching; T4 – on-ridge planting with half film mulching; T5 – on-furrow planting with half film mulching

average total dry matter amount per plant covered with biodegradable films and liquid film in RFFM systems increased by 42.1% and 30.8%, and the corn yield increased by 59.7% and 53.4% compared to FP,

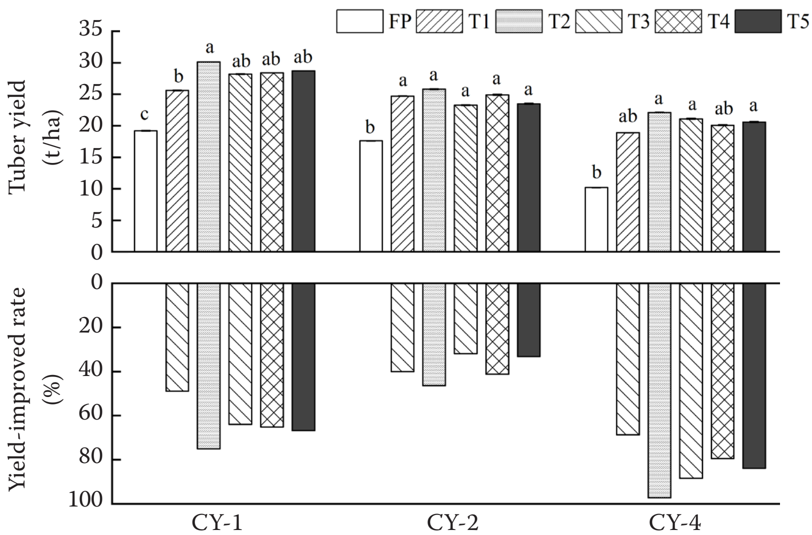

Figure 4. Effects of different ridge and furrow film mulching treatments on potato tuber yield and yield-increase rate under continuous cropping years. CY-1 – one-year, CY-2 – two-year, CY-4 – four-year continuous cropping; FP – flat plot without film mulching; T1 – a flat plot with film mulching; T2 – on-ridge planting with full film mulching; T3 – on-furrow planting with full film mulching; T4 – on-ridge planting with half film mulching; T5 – on-furrow planting with half film mulching

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Table 3. Pearson correlations coefficients among soil factors of the fourth continuous cropping year under different ridge and furrow film mulching treatments

	BN	FN	AN	pH	EC	CA	UA	APA	Y
BN	1.000								
FN	0.746	1.000							
AN	0.757	0.783	1.000						
pH	–0.659	–0.273	–0.762	1.000					
EC	0.029	0.463	0.490	–0.170	1.000				
CA	0.809	0.619	0.679	–0.613	0.351	1.000			
UA	0.792	0.721	0.946**	–0.743	0.294	0.735	1.000		
APA	0.514	0.767	0.933**	–0.546	0.621	0.470	0.856*	1.000	
Y	0.545	0.539	0.886*	–0.825*	0.687	0.647	0.761	0.813*	1.000

BN – bacterial number (10^6 CFU (colony-forming unit)/g); FN – fungi number (10^3 CFU/g); AN – actinomycetes number (10^5 CFU/g); pH – pH value; EC – electrical conductivity; CA – catalase activity (g/mL); UA – urease activity (mg/g); APA – alkaline phosphatase activity (mg/g); Y – tuber yield (t/ha). *$P < 0.05$, **$P < 0.01$

respectively. These results were similar to our results as well as those obtained from previous studies in crops like potato (Zhao et al. 2012), maize (Deng et al. 2019), and wheat (Qin et al. 2015). In addition, tuber yields of T2 and T3 only decreased by 25.6% and 25.2% over four years of continuous cropping, relative to 34.9% of FP (Figure 4). Although the trend of decreasing yield with continuous cropping was consistent, regardless of film mulching treatment, yet RFFM could effectively relieve the loss of production. This indicated that only film mulching couldn't eliminate the crop yield reduction caused by continuous cropping obstacles. To maintain a higher yield in short-term continuous cropping of potatoes, other cultivation measures (such as the increasing application of organic fertilizer, strengthening irrigation, etc.) should be combined with film mulching.

Pearson correlations among microbial communities, physicochemical properties, soil enzymatic activities, and tuber yield. pH value was negatively correlated with all the measured experimental indices and was significantly ($P < 0.05$) negatively correlated with yield (Table 3). Actinomycetes number (AN) was significantly positively correlated ($P < 0.01$) with urease activity (UA) and alkaline phosphatase activity (APA). Moreover, we found that tuber yields were significantly positively correlated ($P < 0.05$) with AN and APA. In conclusion, ridge and furrow film mulching (RFFM) could increase microbial communities, EC and soil enzymatic activities, and decreased pH values to improve the soil environment. Different RFFM treatments could enhance the tuber yields compared with FP treatment, the yield-improved rate of T2 was 97.3%, compared with 68.7, 88.4, 79.5, and 83.9% of T1, T3, T4, and T5 in CY-4, respectively, and greatly alleviate the loss of yields caused by poor soil environment under continuous cropping. On-ridge planting with full mulching (T2) produced a comparatively higher microbial communities, soil urease, and alkaline phosphatase activities and tuber yield under the potato continuous cropping system. Thus T2 is recommended as an appropriate tillage practice for short-period continuous cropping of potato cultivation in the semi-arid areas.

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