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Full Length Research Paper

Interactions of a hairy vetch-corn rotation and P fertilizer on the NPK balance in an upland red soil of the Yunnan plateau

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A field experiment was conducted on an infertile red soil under a hairy vetch (*Vicia villosa* Roth) and corn (*Zea mays* L.) rotation system in a highland area of Yunnan Province, China. Effects of phosphate (P) fertilization, combined with hairy vetch returned to the soil, on crop yield and soil fertility were studied, and the balances of nitrogen (N), phosphorus (P) and potassium (K) in the rotation system were estimated. As P application increased from 135 to 315 kg ha^{-1}, the dry matter yield of hairy vetch increased by 900.6 to 1283.86 kg DM ha^{-1}, and also promoted P absorption by hairy vetch. When compared with CK, the corn and corn straw yield increased by 16.64 and 33.48%, respectively, from the crop rotation system, while it increased by 18.36 and 34.96% and 32.58 and 66.5%, from the integrated use of green manure and P fertilizer, respectively. Simple crop rotation proceeding could improve soil N content in the 0 to 20 cm soil layer, while the combined P application improved soil P content. After corn harvest, soil Olsen-P content under the different treatments increased by 35.31 and 122.15% and 19.70 and 63.63% in the 0 to 10 and 10 to 20 cm soil layers, respectively. The optimum P fertilizer rate for the hairy vetch-corn rotation system in Yunnan Province was 135 kg P_2O_5 ha^{-1}. At this P rate, the nutrient balance surpluses for N, P and K were 84.9, 18.9 and 26.4%, respectively.

Keywords: Rotation system, crop yield, green manure, NPK balance, P fertilizer, soil physical and chemical properties.

INTRODUCTION

Hairy vetch (*Vicia villosa* Roth) is a winter-hardy, leguminous green manure crop increasingly used in many countries (Brandsaeter and Netland, 1999; Caballero et al., 2001; Kui, 2003; Ruffo and Bollero, 2003; Teasdale et al., 2004). It can fix significant amounts of N to the soil, and provides early season weed control and moisture conservation (Teasdale, 1993; Enneking, 2001; Comis, 2008). As a green manure cover crop, vetches fit well into crop rotation systems. The hairy vetch-corn rotation system has received renewed interest in recent years and is suitable for the situation in China, playing an important role in improving the output efficiency of farming systems.

Red soil is the main soil type in south China, occupying about 22.7% of the total national land area (Shen, 1998). The red soil region is also important in Yunnan Province, accounting for 70% of the total provincial area (Wang, 1996). Due to its plentiful sunshine hours and abundant rainfall resources, the potential of the large highland area in the red soil region for agricultural production has been greatly emphasized. However, P deficiency and single crops have been a regional characteristic for a long time, which together with drought has resulted in soil structure compaction, soil fertility decline, crop yield decreases, and serious P nutrient degradation (Guan et al., 2007). Few studies of red soil physical and chemical properties and fertilization measures in the highland area have been reported internationally (Guan et al., 2008). Most Chinese studies focused on patterns of red soil utilization and

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cultivation in hilly areas of Southeast China (Zhao et al., 2000; Lu and Shi, 2001; Zhao and Li, 2005; Zeng et al., 2006), but few information about red soil fertility amendment and crop yield improvement by combining crop rotations with P fertilizer in highland areas was reported. Recently, N cycles in agricultural ecosystems have received much attention with the large consumption of N fertilizer in China (Richter and Roelcke, 2000), and agro-ecosystem nutrient balances have been an important index to evaluate whether NPK nutrient inputs are reasonable, or whether the agricultural development is sustainable in achieving the best environmental benefits (Wang et al., 2007). Therefore, it is important to investigate the NPK balance in south China to optimize crop yield and red soil fertility and reduce environmental pollution.

This study, incorporating a hairy vetch-corn rotation experiment with different P fertilization treatments, was conducted in the highland area of Yunnan province, and it had the following objectives: (1) to test the effect of different treatments on crop yield and NPK uptakes in crops; (2) to analyze changes in red soil physical and chemical properties; and (3) to compare NPK cycling and balance between the rotation system and conventional cultivation and propose useful measures to reduce nutrient loss to the environment.

The study intends to lay a foundation for optimum management in maintaining and improving P utilization efficiency and red soil fertility and NPK balance in the red soil region of south China.

MATERIALS AND METHODS

Experimental site

The study site is located in the highland area of Huize county, Yunnan province, Southwest China (20°45′N, 103°48′E; 2420–2525 m a.s.l), with a mean annual precipitation of 988.4 mm (with approximately 60% fall during June to August), an annual temperature of 14.3°C, 1978.4 h of sunshine annually, and a frost-free period of approximately 220 days. Climatic data of mean monthly precipitation and air temperature recorded from the study area in 2007 and 2008 are shown in Figure 1 (Huize weather bureau). The local soil was classified as red clay. The surface layer of the soil (0 to 20 cm) contained 3.2 g kg^{-1} soil organic matter, 0.26 g kg^{-1} total N, 159.2 mg kg^{-1} alkaline hydrolysis N, 9.93 mg kg^{-1} Olsen-P and 374.9 mg kg^{-1} available K, and it had a pH of 5.8 at the beginning of the trial in October 2007 (Huize Pasturage Bureau and Forage Monitoring Station).

Experimental design and management

The experiment was a randomized complete block design, which comprised five treatments with five replications. The five treatments were designated as: (1) CK, control (without hairy vetch and P fertilizer input); (2) P0 (0 kg P_2O_5 ha^{-1} applied to the hairy vetch); (3) P1 (135 kg P_2O_5 ha^{-1} applied to the hairy vetch); (4) P2 (225 kg P_2O_5 ha^{-1} applied to the hairy vetch); and (5) P3 (315 kg P_2O_5 ha^{-1} applied to the hairy vetch). The plot size was 132 m^2 (11 m × 12 m). However, adjacent plots were separated by ridges and the row spacing was 0.5 m.

Hairy vetch (*Vicia villosa* Roth *var glabrescens* cv.Yunguangzao) was seeded at a seeding rate of 45 kg ha^{-1} within one week of corn harvest in the 3rd week of October 2007, and was harvested in the 2nd week of March 2008. The plots were tilled with harrow and plow to a depth of 25 to 30 cm before seeding the hairy vetch. Goat manure and P fertilizer (calcium magnesium phosphate), as a basal fertilization, were applied to all the treatments except the control before seeding. The goat manure (3675 kg ha^{-1}) was obtained from the Tianba Goat Farm and applied to the soil before tillage. The nutrient composition of the goat manure was 0.84% N, 0.21% P and 1.04% K. The P fertilizer was broadcast and incorporated into the soil when the hairy vetch was seeded.

Corn (cv. Quchen 3) was seeded at a rate of 30 kg ha^{-1} in the 3rd week of March 2008, about one week after the hairy vetch was returned into the ground as green manure. A mulch cover of plastic film was used for the corn crop. Urea (207 kg N ha^{-1}), a compound fertilizer (33.8 kg N ha^{-1}, 11.3 kg P_2O_5 ha^{-1} and 56.3 kg K_2O ha^{-1}) and farmyard manure (56.3 kg N ha^{-1}, 18.3 kg P_2O_5 ha^{-1} and 59.0 kg K_2O ha^{-1}) were broadcast-applied to the cultivation layer in all plots before seeding. The corn was harvested in the 2nd week of October 2008.

The hairy vetch and corn crops were managed according to common local practice. No irrigation was used for the hairy vetch and corn crops in all plots during each growing season. Weeds were controlled by hand and no crop diseases and insect pests were found during the experimental periods.

Sample collection and analysis

Fresh hairy vetch samples were collected from three 1 m^2 frames in mid March, 2008 from representative areas of each plot and were composited by plot. Forage samples were cut by hand clipper to ground level, weighed and dried to constant weight in a forced-air oven at 65°C for 48 h. In early October 2008, corn crops were hand-harvested. The corn straw and corncobs were air dried after harvest, and dry weights were measured. The dry crop samples were milled and then sampled for chemical analysis.

Soil samples from the 0 to 10 and 10 to 20 cm soil layers of each area (five composite samples) were collected by soil auger before hairy vetch planting, after hairy vetch harvest and after the corn harvest. Part of the soil samples were used to measure gravimetric water contents (by oven drying at 105°C for 24 h). Another part was air dried, gravel and plant roots were removed, and then it was ground to pass through 1, 0.25 and 0.15 mm sieves, respectively, before being stored in sealed bags for soil analysis.

Samples of goat manure were obtained from each load spread on the experimental plots. The nutrient contents of farmyard manure were determined by using parameters from the organic fertilizers in Yunnan province (Che, 1996). Plant samples and goat manure samples were digested by H_2O_2-H_2SO_4 to determine total N, total P and total K concentrations. The soil samples were analyzed for total N, alkaline hydrolysis N, Olsen-P and available K using conventional soil test methods (Bao, 2000).

Statistical analysis, nutrient balance analysis and calculations

Data were analyzed using SPSS 13.0 (SPSS Inc., Chicago, IL, USA), and significance was declared at $P < 0.05$. Mean separations were performed using Duncan's Multiple Range Test.

Nutrient inputs included hairy vetch (green manure), urea, calcium magnesium phosphate fertilizer, compound fertilizer, farmyard manure and goat manure. N, P and K uptake in the hairy vetch were calculated by multiplying the yield and dry weight percentages of N, P and K; while N, P and K uptake in farmyard and goat manure were calculated similarly by multiplying the rate of manure addition and the respective N, P and K contents.

Table 1. Effect of crop rotation combined with P fertilizer application on yields of hairy vetch (kg DM ha^{-1}), corn and corn straw (kg ha^{-1}) (Means ± SE).

Treatment	Hairy vetch	Corn	Corn straw
CK	—	6795.50 ± 272.45^{Ac}	6600.16 ± 282.71^{Ac}
P0	2270.80 ± 96.66^{A}	7926.02 ± 428.59^{ABb}	8810.06 ± 401.56^{Bb}
P1	3171.40 ± 117.26^{B}	9171.19 ± 332.10^{Ba}	10988.98 ± 449.7^{Ca}
P2	3554.66 ± 129.07^{B}	8850.99 ± 416.09^{Bab}	9990.26 ± 392.50^{BCa}
P3	3490.19 ± 145.41^{B}	8042.83 ±434.52^{ABab}	8750.43 ± 447.74^{Bb}
F value	22.985 * *	5.873 * *	16.903 * *

Within a row, means without a common superscript differ (P<0.05). *P<0.05; * *P<0.01; ns not significant (P>0.05).

Nutrient outputs included corn, corn straw and corncobs. N, P and K uptake in the corn crop was calculated by multiplying the corn yield by the respective N, P and K contents. The nutrient surplus or deficit was calculated as the difference between total nutrient inputs and total nutrient outputs, while the nutrient balance was calculated according to the formula of Lu et al. (2000) and Li et al. (2005):

Nutrient balance (%) = [(total nutrient input/total nutrient output) – 1] × 100.

RESULTS AND DISCUSSION

Effect of different treatments on crop yield

Application of P fertilizer significantly (P<0.01) affected the dry matter yield of hairy vetch in the low fertility red soil (Table 1). When compared with P0 treatment, as the P application rate increased from 135 to 315 kg P_2O_5 ha^{-1}, the dry matter yield increased by 39.66 to 56.54% in the order P2>P3>P1>P0, respectively. Comparatively, no differences for dry matter yields were found between P1, P2 and P3 treatments (P>0.05). Regression analysis (Figure 2) indicated that the dry matter yield of hairy vetch was significantly related to P fertilizer application rate as:

$$Y = 2260.773 + 9.401x - 0.017x^2 \quad (R^2 = 0.808,\ F = 35.697,\ P<0.001)$$

Where, x is the P fertilizer application rate (kg ha^{-1}) and Y is the dry matter yield (kg ha^{-1}). This quadratic relationship between forage yield and P fertilizer application rate showed that dry matter yield initially increased as the P rate increased and then decreased, with a maximum yield of 3560.46 kg ha^{-1} achieved at a P rate of 276.5 kg P_2O_5 ha^{-1}, and the forage moisture content was about 79%, while the fresh yield was about 16954.57 kg ha^{-1}. This result was lower than that found by Yang et al. (2007), who reported that the maximum fresh yield of hairy vetch was 22992 kg ha^{-1}, at a P application rate of 152.85 kg ha^{-1}. However, annual climatic factors affected the stability of crop yields (Wassenaar et al., 1999) and forage production was mostly related to precipitation (Willms et al., 1985; Holst et al., 2006). It is likely that the relatively low rainfall and non-irrigation during October and February, 2007 (Figure 1) resulted in forage yield decline. Huang et al. (2009) found a linear relationship between P rate and the dry matter yield of hairy vetch, in contrast to this study's result. The reason for this difference could be as a result of the different P levels used and the absence of K_2SO_4 and lime interference in this study's experiment.

Corn yields increased markedly (P<0.05) with increasing P fertilizer application combined with green manure returned to the red soil (Table 1). When compared with CK, corn yields in the P1 and P2 treatments increased very significantly by 2375.69 (34.96%) and 2055.49 kg ha^{-1} (30.25%), respectively, while corn yields in the P0 and P3 treatments increased significantly by 1130.52 (16.64%) and 1247.33 kg ha^{-1} (18.36%), respectively. Furthermore, significant differences for corn straw yields were observed between the different treatments (P<0.01) in the order: CK<P3<P0<P2<P1. When compared with the CK plots, corn straw yields in the P0, P1, P2 and P3 treatments increased by 2209.90 (33.48%), 4388.81 (66.50%), 3390.10 (51.36%) and 2150.27 kg ha^{-1} (32.58%), respectively. The results indicated that legume-based cropping with biological nitrogen fixation improved soil fertility and increased crop production. When fertilizer P was applied along with the leguminous plant phase of the rotation, the corresponding yields of forage, corn and corn straw increased significantly, suggesting that P deficiency was also an important factor restricting crop yield. From the crop yield responses to P rates, maximum corn and corn straw yields were both attained in the P1 treatment, declining at higher fertilizer-P application rates. Thus, proper P fertilization measures are needed to assure sustainable crop yield, and phosphorus is potentially wasted if applied at high P rates. A P rate of 135 kg P_2O_5 ha^{-1} is recommended for optimum crop yield in the hairy vetch-corn rotation system in Yunnan Province.

N, P and K concentrations in hairy vetch and corn crops

Concentrations of N, P and K in the hairy vetch and corn

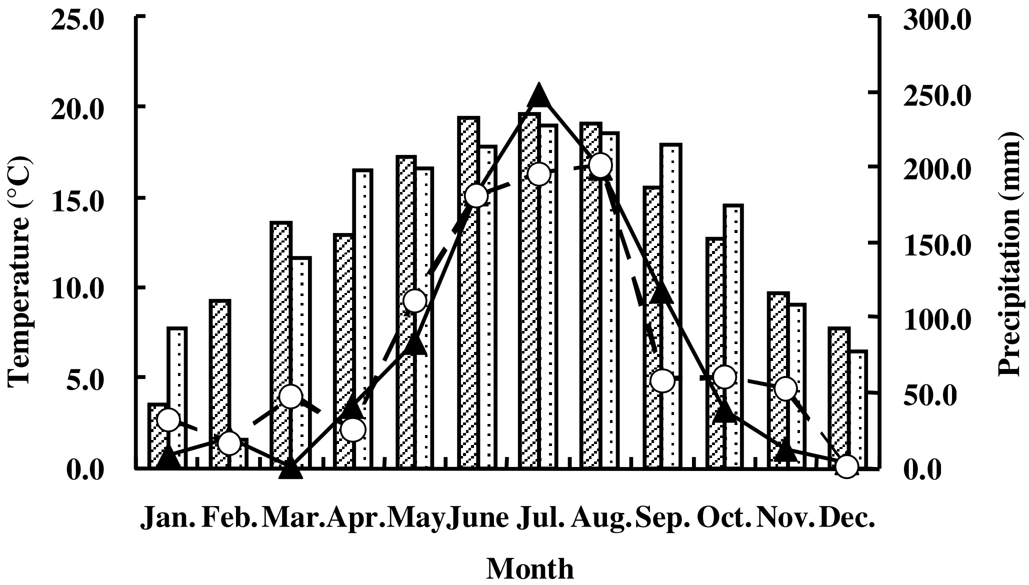

Figure 1. Mean monthly temperature (bars, °C) and precipitation (lines, mm) of the experimental site during the growing periods (2007 to 2008). Shadow and dot bars represent 2007 and 2008 temperatures, respectively; lines with black triangles and white circles represent 2007 and 2008 precipitation, respectively.

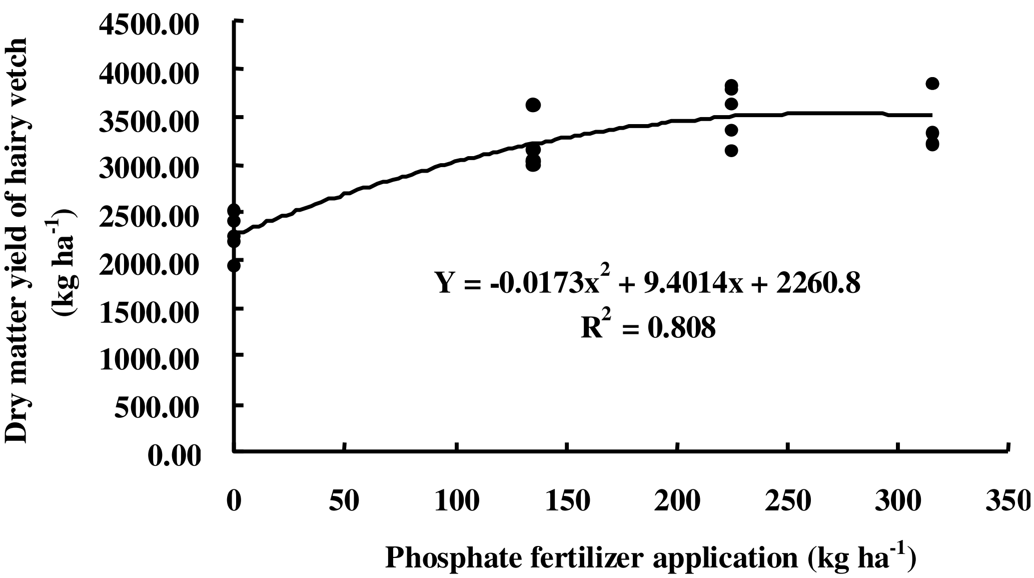

Figure 2. The relationship between phosphate fertilizer application rate (x, kg ha^{-1}) and dry matter yield of hairy vetch (Y, kg DM ha^{-1}).

crops in the rotation are shown in Figure 3. Application of P fertilizer significantly ($P<0.01$) affected the total P uptake in hairy vetch. Total P contents in hairy vetch were significantly higher in P1 and P2 treatments than in P0 and P3 treatments ($P<0.01$), while the P content in P0 treatment was significantly higher than that in P3 treatment ($P<0.05$), and the values were: 0.221, 0.280, 0.246 and 0.172%, respectively. However, no significant differences in total N and K concentrations were found in hairy vetch between the different treatments ($P>0.05$). This may be as a result of the fact that the hairy vetch can directly fix atmospheric N by utilizing rhizobium and so was less sensitive to N than P. Contrasting with the P1 and P2 treatments, P uptake in the P0 treatment decreased by 28.51 and 11.31%, and in P3 treatment, it significantly decreased by 65.12 and 43.02%,

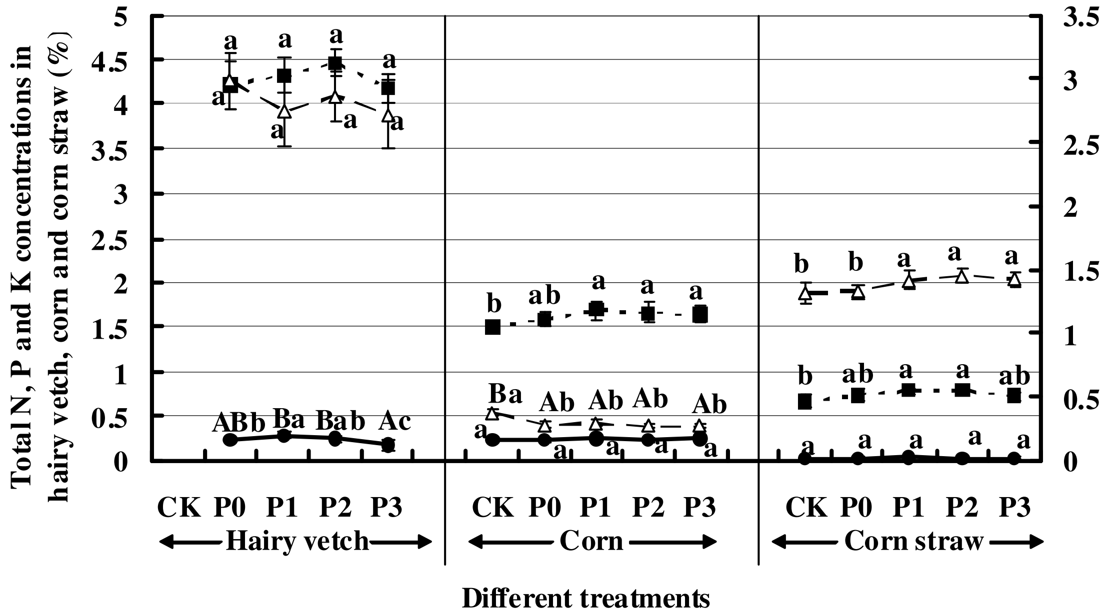

Figure 3. Effect of different treatments on total N (-■-), P (-●-) and K (-▵-) concentrations in hairy vetch, corn and corn straw (Data are mean ± SE). Different capital letters indicate very significant difference (P<0.01); different lowercases indicate significant difference (P<0.05).

respectively. Thus, P application can promote P absorption by hairy vetch, while too much of it will inhibit P absorption.

In the hairy vetch-corn rotation system, P fertilizer addition caused a significant response in total N and K concentrations in both corn and corn straw but a non-significant response in P concentration (Figure 3). Total N concentrations in corn and corn straw increased as the P application rate increased. Relative to the CK treatment, N concentrations in corn were significantly higher in the P1, P2 and P3 treatments, which increased by 9.75 to 12.42%, but no significant difference was found between the CK and P0 treatments (P>0.05). For corn straw, N concentrations in the P1 and P2 treatments were higher than in the CK treatment, but no significant difference was found between the CK, P0 and P3 treatments (P>0.05). The results showed that application of both P fertilizer and green manure to the soil may accelerate N absorbability in a later crop. When compared with the CK, the K concentrations in corn markedly decreased as the P rate increased from 0 to 315 kg P_2O_5 ha^{-1} (P<0.01) and decreased by 26.21, 23.68, 27.95 and 28.53%, respectively, whereas it increased in corn straw. In a comparison of the CK and P0 treatments, it was found that K concentrations in the corn straw were higher in the P1, P2 and P3 treatments. N concentrations were highest in the hairy vetch and corn, whereas K concentrations were highest in corn straw. This means that for normal growth, the crop needs to absorb large amounts of N and K, and that the soil nutrient content is responsible for limiting crop growth. Therefore, crop rotation combined with P fertilizer cannot only result in higher crop yields but also benefit crop uptake of nutrients.

Effect of different treatments on soil water content

After the hairy vetch harvest, soil water content in the 0 to 20 cm soil layer decreased significantly with increasing P application rate (P<0.01) (Table 2). In 0 to 10 cm soil layer, soil water content in CK and P0 treatments was significantly higher than that in P1, P2 and P3 treatment (P<0.01). In the 10 to 20 cm soil layer, soil water content in CK and P0 treatment was significantly higher than that in P2 and P3 treatments (P<0.01), in that no significant difference was found between CK, P0 and P1 treatments (P>0.05). When compared with the CK treatment, soil water content in the other treatments decreased by 4.55 to 26.99% and 6.88 to 19.56% in the 0 to 10 cm and 10 to 20 cm soil layers, respectively. Some researches have shown that hairy vetch depletes soil moisture stored in winter and spring, thus increasing drought stress (Xin et al., 1990; Mischler et al., 2010). In this study, soil water content was similar in the CK and P0 treatments in the 0 to 10 cm and 10 to 20 cm soil layers. Low rainfall (Figure 1) prior to P fertilizer application and subsequent non-irrigation probably contributed to the decline in soil water content.

After the corn crop harvest, the soil water content considerably increased in the 0 to 20 cm soil layer, but no significant difference was observed in the individual soil layers (P>0.05). In the 0 to 10 cm soil layer, P application

Table 2. Changes of soil water content and fertility in the 0 to 20 cm layer under different treatments (Means ± SE).

Treatment	Soil water content (%)			
	March 2008		October 2008	
	0 to 10 cm	10 to 20 cm	0 to 10 cm	10 to 20 cm
CK	20.86 ± 0.60^{Ca}	21.52 ± 0.62^{Ba}	21.68 ± 0.99	19.87 ± 1.12
P0	19.91 ± 0.20^{Ca}	21.69 ± 0.87^{Ba}	21.12 ± 1.25	21.36 ± 1.05
P1	18.04 ± 0.87^{Bb}	20.04 ± 0.36^{ABab}	22.91 ± 0.91	22.57 ± 0.81
P2	16.70± 0.49^{ABc}	18.47 ± 0.99^{Abc}	22.42 ± 0.75	21.58 ± 1.28
P3	15.23 ± 0.61^{Ad}	17.31 ± 0.52^{Ac}	19.79 ± 1.48	19.44 ± 1.01
F value	38.824* *	7.222* *	1.206ns	1.460ns
Total-N (%, g kg^{-1})				
CK	0.275 ± 0.011^{b}	0.242 ± 0.008^{Ab}	0.278 ± 0.005	0.226±0.01^{b}
P0	0.324 ± 0.015^{a}	0.304 ± 0.013^{Ba}	0.298 ± 0.017	0.278±0.01^{a}
P1	0.300± 0.013^{ab}	0.264±0.012^{ABb}	0.293 ± 0.014	0.277±0.01^{a}
P2	0.295± 0.012^{ab}	0.253±0.012^{Ab}	0.265 ± 0.013	0.248±0.01^{ab}
P3	0.272 ± 0.010^{b}	0.250±0.006^{Ab}	0.258 ± 0.010	0.244± 0.008^{ab}
F value	3.008 *	5.617 * *	1.931ns	4.085 *
NaOH-hydrolyzable N (mg kg^{-1})				
CK	171.06 ±11.20	146.40 ± 7.20^{b}	189.39 ± 4.08^{ab}	179.38± 7.90^{ab}
P0	169.27 ± 12.36	171.34 ± 5.59^{a}	191.24 ± 5.01^{ab}	194.46 ± 2.18^{a}
P1	151.38 ± 6.50	142.57 ± 3.10^{b}	206.41 ± 6.66^{a}	197.36 ± 8.16^{a}
P2	165.14 ± 7.04	150.56 ± 6.55^{b}	189.03 ± 6.39^{ab}	176.91± 8.41^{ab}
P3	156.89 ± 7.27	147.25 ± 4.67^{b}	177.46 ± 7.05^{b}	166.78 ± 8.29^{b}
F value	0.830ns	4.116 *	3.021 *	2.978 *
Olsen-P (mg kg^{-1})				
CK	10.28 ± 1.09^{Ac}	7.52 ± 0.96^{Ac}	9.12 ± 1.08^{Ab}	7.26 ± 1.06^{b}
P0	12.73 ± 1.44^{ABc}	7.15 ± 0.63^{Ac}	12.34 ± 0.81^{ABb}	8.69 ± 1.10^{ab}
P1	14.15 ± 1.44^{ABc}	10.90 ± 0.65^{Bb}	17.39 ± 1.21^{BCa}	10.18 ± 0.50^{ab}
P2	21.23 ± 1.93^{Bb}	13.29 ± 0.08^{Ba}	20.26 ± 1.43^{Ca}	11.62 ± 1.14^{a}
P3	34.39 ± 2.65^{Ca}	13.61 ± 0.96^{Ba}	16.73 ± 1.45^{BCa}	11.88 ± 1.44^{a}
F value	29.427 * *	17.680 * *	13.100 * *	3.217 *
Available K (mg kg^{-1})				
CK	435.27 ± 17.78	345.05 ± 27.98	373.71 ± 28.74	349.15 ± 31.05
P0	466.80 ± 29.07	368.92 ± 37.67	397.73 ± 30.69	351.24 ± 36.38
P1	453.64 ± 21.86	373.25 ± 7.74	396.73 ± 40.70	357.16 ± 14.95
P2	435.28 ± 35.81	317.30 ± 43.52	371.11 ± 16.59	336.64 ± 20.05
P3	450.31 ± 27.97	361.41 ± 24.43	369.82 ± 37.06	345.81 ± 34.78
F value	0.241ns	0.545ns	0.197ns	0.070ns

Within a row, means without a common superscript differ (P<0.05). *P<0.05; * *P<0.01; ns, not significant (P>0.05).

at the P0 and P3 rates decreased the soil water content by 2.58 and 8.72%, respectively, when compared with the CK treatment while and P1 and P2 increased it by 5.67 and 3.41%, respectively. A comparison with the CK treatment showed that soil water content in the 10 to 20 cm layer decreased by 2.16% in the P3 treatment, but increased by 7.50, 13.59 and 8.61% in the P0, P1 and P2 treatments, respectively. This is in agreement with previous findings that proper fertilization can improve soil water use efficiency (Pala et al., 2007; Sun et al., 2007). Haynes and Naidu, (1998) also reported that considerable aluminum exists in acidic red soils, which can react with phosphorus to generate colloidal aluminum phosphate and enhance the capacity to absorb soil water. The higher soil water content in the P1 and P2 treatments suggests that the crop had covered the ground well, increasing the soil water infiltration rate (%), and reducing water, soil and fertility losses (Gao and Liu, 2007). Yu et al. (2005) showed that the physiological activities of forage roots changed the soil texture from tight to loose, and greatly reduced the soil hardening rate which helped conserve soil water and fertility resources in a rotation system.

Changes of soil fertility

There were significant differences in soil total N and alkaline hydrolysis N concentrations in the 0 to 20 cm soil layer under the different treatments (Table 2). Before the hairy vetch was incorporated into the soil, total N concentrations increased significantly in the P0 treatment, and increased by 17.82 and 25.62%, respectively, relative to the CK treatment in the 0 to 10 and 10 to 20 cm soil layers. In contrast, alkaline hydrolysis N concentrations under the different treatments showed varying degrees of decline, and no significant difference was found between them. After the corn harvest, alkaline hydrolysis N concentrations increased as the P application rate increased, but total N concentrations gradually decreased. This may be because, after the hairy vetch had been returned to the soil as green manure, soil organic matter increased as a result of decomposition and mineralization by soil microorganisms, which therefore enhanced alkaline hydrolysis N concentrations. During the period of the rotation, total N and alkaline hydrolysis N concentrations showed a higher increment in the P0 and P1 treatments. Consequently, integrated use of a crop rotation and P fertilizer is an efficient way of improving soil total N and alkaline hydrolysis N concentrations. This result is consistent with the findings of Tian et al. (2007) who reported that crop rotation can improve N nutrition in soils.

Application of P fertilizer and organic manure can significantly increase soil Olsen-P contents (Liu and Zhang, 2000). In this study, the combination of P fertilizer with green manure significantly increased the soil Olsen-P content in the 0 to 20 cm soil layer (Table 2). Before return, the hairy vetch into soil as green manure, the soil Olsen-P content in the 0 to 10 and 10 to 20 cm layers increased from 23.83 to 234.53% and 44.95 to 80.98%, respectively, as the P application rate increased. After the corn harvest, soil Olsen-P contents in both the 0 to 10 and 10 to 20 cm layers showed an overall decrease. When compared with the CK treatment, P fertilizer application at the P0, P1, P2 and P3 rates increased soil Olsen-P by 35.31 to 122.15 and 19.70 to 63.64%, respectively, in the 0 to 10 cm and 10 to 20 cm soil layers. Planting hairy vetch (green manure) may therefore increase the soil Olsen-P content. One reason is that green manure contains many activated and moderately activated organic phosphorus compounds which are readily decomposed and released. On the other hand, application of green manure enhances the accumulation of soil organic matter and humic acids, reducing phosphorus absorption by iron and aluminum oxides (Zhao and Lu, 1991), thereby improving soil exchange ability and the efficient use of residual phosphorus. In the 0 to 10 cm soil layer, Olsen-P contents in the P2 and P3 treatments were 2.1 and 3.3 times higher, respectively, than in the CK treatment, indicating that a great deal of the P fertilizer application quickly increased available P concentrations in the topsoil.

Fundamentally, no significant differences of available K were observed between different treatments ($P>0.05$, Table 2). Before the hairy vetch was returned to the soil as green manure, soil available K concentrations increased with the increasing P fertilizer application. When compared with the CK treatment, available K concentrations were increased by 0 to 7.24 and 4.74 to 8.17% in the 0 to 10 and 10 to 20 cm soil layers, respectively. After the corn harvest, the available K concentration in the CK treatment was lower than that in the P0 and P1 treatments, but was higher than that in the P2 and P3 treatments. Obviously, the improvement in soil available K concentrations was directly related to the total K content of the green manure. Zhou et al. (1997) also found that successive applications of green manure could markedly increase soil available K contents, and that it was effective in maintaining soil K balance. As such, no significant effects on soil available K contents were found between the different treatments, showing that potassium deficiency was not present in this area. Therefore, optimizing the rotation system and P fertilizer level are pivotal steps in rehabilitating the low fertility red soil ecosystem in this highland area.

NPK cycling and balance under the different treatments

N cycling and balance analysis

The N balance under the different treatments was estimated by calculating N inputs to and outputs from the cropland. Table 3 shows that 73.4% of the total N input in the CK treatment was obtained from chemical fertilizer with 26.6% obtained from the organic fertilizer. In the crop rotation system, 22.6 to 32.4% of the total N inputs were obtained from N fixation by plants, and 49.5 to 56.8% of the total N inputs were obtained from chemical fertilizer. This shows that the rotation cannot only be economized on chemical fertilizer resources, therefore reducing the cost of agricultural production, but can also improve the recycling rate of organic N. N in corn is the major output in both the traditional agriculture and crop rotation systems, accounting for 61.3 to 65.7% of the total N output. Amounts of N removed by corn straw and

Table 3. Balance of N, P and K in hairy vetch-corn rotation.

Treatment	CK	P0	P1	P2	P3
Balance of N in rotation system					
A) N input (kg ha^{-1})					
(1) Hairy vetch	0	95.6	137.2	158.7	145.9
(2) Urea	207	207	207	207	207
(3) Composite fertilizer	33.8	33.8	33.8	33.8	33.8
(4) Farmyard Manure	56.3	56.3	56.3	56.3	56.3
(5) Goat manure	30.9	30.9	30.9	30.9	30.9
Total N input	328.0	423.6	465.2	486.6	473.8
B) N output (kg ha^{-1})					
(1) Corn	101.7	126.1	154.3	146.9	132.1
(2) Corncob	8.9	10.4	11.9	11.5	10.5
(3) Corn straw	44.1	64.7	85.4	77.8	63.8
Total N output	154.7	201.2	251.6	236.1	206.4
N surplus, kg ha^{-1}:A)–B)	173.3	222.4	213.5	250.5	267.4
N balance (%)	112.0	110.5	84.9	106.1	129.5
Balance of P in rotation system					
A) P input (kg ha^{-1})					
(1) Hairy vetch	0	5.0	9.0	8.7	6.0
(2) Ca-Mg-P fertilizer	0	0	135	225	315
(3) Composite fertilizer	11.3	11.3	11.3	11.3	11.3
(4) Farmyard Manure	18.3	18.3	18.3	18.3	18.3
(5) Goat manure	7.7	7.7	7.7	7.7	7.7
Total P input[1)]	6.5	7.4	31.7	47.4	62.7
B) P output (kg ha^{-1})					
(1) Corn	15.1	18.1	21.6	20.7	19.4
(2) Corncob	1.6	1.9	2.1	2.0	1.9
(3) Corn straw	1.4	2.3	3.0	2.5	2.3
Total P output	18.0	22.2	26.7	25.2	23.5
P surplus, kg ha^{-1}:A)–B)	-11.5[2)]	-14.8[2)]	5.0	22.2	39.2
P balance (%)	-63.8[2)]	-66.6[2)]	18.9	88.2	166.6
Balance of K in rotation system					
A) K input (kg ha^{-1})					
(1) Hairy vetch	0	67.8	86.9	101.9	94.8
(2) Composite fertilizer	56.3	56.3	56.3	56.3	56.3
(3) Farmyard Manure	59.0	59.0	59.0	59.0	59.0
(4) Goat manure	38.2	38.2	38.2	38.2	38.2
Total K input	153.4	221.2	240.4	255.3	248.2
B) K output (kg ha^{-1})					
(1) Corn	25.8	22.2	26.6	24.2	21.8
Bv (2) Corncob	6.0	7.1	8.1	7.8	7.1
(3) Corn straw	87.0	116.5	155.5	144.9	124.4
Total K output	118.8	145.8	190.2	176.9	153.3
K surplus, kg ha^{-1}:A)–B)	34.6	75.4	50.2	78.4	94.9
K balance (%)	29.1	51.7	26.4	44.3	61.9

[1)]Total P input = (1 + 2 + 3 + 4 + 5) × 17.5%. [2)]— means nutrient losses.

corncobs are also important, accounting for 34.3 to 38.7% of the total N output. N cycling and balance analysis can reduce N losses and improve fertilizer-N use efficiency from farmland (Zhang and Ju, 2002).

The results of the nutrient balance analysis (Table 3) showed a large surplus in the N balance for the different treatments, ranging from 84.9 to 129.5%, and amounts of surplus N from 173.3 to 267.4 kg ha^{-1}. The N balance surplus was lowest in P1 treatment, probably because this treatment had the highest crop yields and total N output. Generally, when the N balance surplus exceeds 20%, it can cause potential threats to the environment (Lu et al., 1996). In this study, the large surplus N balance was mainly due to increases in N fertilizer nutrient inputs. In order to maximize crop yield, farmers often apply superfluous N fertilizer exceeding the minimum required for crop growth, thereby wasting N resources, reducing the fertilizer use efficiency, causing potential environmental harm and affecting the functioning of the agro-ecosystem. This clearly suggests that growing legume crops is a suitable alternative which would reduce the need for N from chemical fertilizers. Thus, there is an urgent need to decrease rates of N application and increase organic manure inputs under current cropping in Yunnan Province.

P cycling **and balance analysis**

Phosphorus is readily fixed by acid red soils used for dryland farming in south China, and 10 to 25% of the P fertilizer applied is used by the crop during the crop growing season (ISSCAS, 1978). Some studies have reported that using hairy vetch in a corn crop rotation system decreases the degree of P absorption and improves P utilization efficiency in red soils (Lu and Shi, 2001). In this study, we used a mean value of 17.5% as the P utilization rate with P inputs, and then calculated it by multiplying the total P input by 17.5%. Table 3 shows that 69.7 and 61.5% of the P input was derived from organic manure in the CK and P0 treatments, respectively. In contrast, P fertilizer was the main source of P for P1, P2 and P3 treatments, accounting for 80.7, 87.2 and 91.1%, respectively. Corn was the main P output in both the traditional agriculture and crop rotation systems, accounting for 80.9 to 83.9% of the total P output.

Under the different treatments, P deficiency was only observed in the CK and P0 treatments with accumulated deficits of 11.5 and 14.8 kg P_2O_5 ha^{-1}, respectively while the surplus was 5.0 kg P_2O_5 ha^{-1} in the P1 treatment with a P rate of 135 kg P_2O_5 ha^{-1}; with hairy vetch in the rotation, the P fertilizer application increased by 225 and 315 kg P_2O_5 ha^{-1}, and the surplus increased by 22.2 and 39.2 kg P_2O_5 ha^{-1}, respectively. No significant increase in crop yield was observed when the P rate exceeded 225 kg P_2O_5 ha^{-1} (Table 1), but the imbalance of P fertilization led to P accumulation in the soil and increased the environmental risk. Therefore, the yield response of P fertilization and the environmental pollution arising from P accumulation must be considered in determining the optimum P fertilization rate. Generally, in red soils of lower P fertility, a critical P balance value of 100 to 150% is accepted. When P fertilizer addition increases the crop yield by 10 to 25%, a P balance below 20% is considered to be reasonable (Lu et al., 1996). Obviously, when the P balance reached 166.6% in the P3 treatment, it incurred an environmental risk. Although the P balance reached 88.2% (< 100%) in the P2 treatment, long-term P fertilezation will increase soil P accumulation and also lead to environmental pollution. Hence, the P balance of 18.9% in the P1 treatment was reasonable (Table 3).

K cycling **and balance analysis**

K cycling and balance in the experiment is shown in Table 3. The results indicated that hairy vetch returned to the soil plays an important role in K balance. In the CK treatment, 36.7% of the K input was derived from chemical fertilizer, while 63.4% of the K input was derived from organic manure, and there was an apparent K surplus of 34.6 kg ha^{-1}. In contrast, a K surplus ranging from 50.2 to 94.9 kg K ha^{-1} was observed in the P0, P1, P2 and P3 treatments. This difference was attributed to the return of the hairy vetch to the soil as green manure accounting for 22.6 to 32.6% of the total K input. Corn straw is the major K output in both traditional agriculture and crop rotation systems, which is different from the N and P outputs. K outputs from corn straw accounted for 73.2 to 81.9% of the total K output which seems to be a considerable proportion. From 2001 to 2003, the total corn straw yield was 2.3×10^8 t K y^{-1} in China, and about 50% of the corn straw was directly burned in the fields to remove large quantities of nutrients from the farm system (Cao et al., 2006). According to the numeric value of straw K content in this study, there were about 1.52 to 1.67×10^8 t K y^{-1} loss from the straw burning, which is a waste of resources and may contribute to greenhouse effects and other environmental issues (Duan et al., 2004).

Under the experimental conditions in this study, soil available K contents were high, been above 300 kg ha^{-1} in the 0 to 20 cm soil layer (Table 2). Short-term K losses in the CK treatment showed no great impact on soil fertility. On the other hand, the K surplus was higher in the P0, P2 and P3 treatments in contrast to the P1 treatment, but the crop yield was lower in the P1 treatment. Short-term K inputs may be reasonable in increasing crop production in the P1 treatment, but they are unfavorable to system nutrient balance from a long term consideration. Gustafson et al. (2003) also found that an imbalance of K had harmful impacts on crop yield, long-term soil fertility, and the surrounding environment.

Straw is a very important K fertilizer resource in China. Nowadays, to maintain the balance of K and to increase crop yield, reducing K fertilization rates or without K fertilizer and at the same time increasing amounts of straw returned to the soil have become indispensable measures in agricultural systems.

Conclusions

1) There is ample evidence showing that appropriate P fertilizer rates in combination with crop rotations can increase fertilizer use efficiency, thereby increasing crop yield, enhancing NPK uptake by plants, and maintaining and improving red soil fertility and the NPK balance of the rotation system. The optimum P fertilization rate in the hairy vetch-corn rotation system in Yunnan Province was 135 kg P_2O_5 ha^{-1}.
2) Dry matter yield of hairy vetch (Y, kg ha^{-1}) was significantly related to the P fertilizer application rate (x, kg ha^{-1}) with the relationship being:

$Y = 2260.773 + 9.401x - 0.017x^2$ ($R^2 = 0.808$, $F = 35.697$, $P<0.001$).

3) Crop nutrient outputs were the main pathway of NPK loss in the hairy vetch-corn rotation cropping system, but nutrient loss from soil erosion and water runoff and volatilization were not considered in the calculation. Farmyard manure and livestock manure were the main nutrient sources for farmland nutrient cycling. Nitrogen in the manure may volatilize ammonia and release carbon dioxide and methane into the atmosphere, bringing some environmental problems and even influencing global climate (Qian and Lu, 1994). This suggests that further nutrient recycling research is not only necessary to enhance sustainable crop productivity, but also to minimize environmental damage.

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