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RESEARCH ARTICLE

Management of rice straw with relay cropping of Chinese milk vetch improved double-rice cropping system production in southern China

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Abstract

Improved utilization of rice (*Oryza sativa* L.) straw and Chinese milk vetch (*Astragalus sinicus* L., vetch) has positive effects on rice production. So far, few studies have investigated the productivity of vetch under different residue management practices in double-rice cropping system. The effects across seven years (2011–2017) of rice straw on growth and nutrient accumulation of vetch and the subsequent effects of rice straw and vetch on two succeeding rice crops in a vetch-rice-rice cropping system with establishment of vetch by relay cropping were examined. Treatments compared three practices for harvesting rice: use of low cutting height (low retained stubble) with either removal or retention of straw and high cutting height (high retained stubble) with retention of straw. Yields of the two rice crops after vetch were not affected by either the cutting height of stubble with retention of straw or by the management of straw (retention versus removal) with low cutting height of stubble. Yields of the two rice crops after vetch were significantly higher for high cutting height with retention of straw than for low cutting height with removal of straw, but the relative contributions of high cutting height and straw retention to the higher rice yield cannot be determined from this study. Higher cutting stubble with retention of straw can also increase yield stability of the double-rice grain as determined by a sustainable yield index. Significant increases in vetch biomass and nutrient uptake were observed in treatments fertilized during the rice season compared with unfertilized treatments. Improvements in the growing environment of the vetch by conserving soil water content, in plots by use of high cutting height (about 40 cm) with retention of straw were associated with the highest vetch biomass, nutrient uptake, and yield stability of vetch biomass. These increased nutrient inputs partially replaced the demand for chemical fertilizer and stimulated the rice yields. It can be concluded that retaining higher cutting stubble residues with retention of straw could be a better

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straw management practice for increasing the vetch biomass and nutrient use efficiency, thereby allowing utilization of high cutting height with retention of straw and vetch to improve the stability of rice productivity in a double-rice cropping system.

Keywords: double-rice cropping system, Chinese milk vetch, biomass productivity, rice straw, sustainable yield index

1. Introduction

Rice (*Oryza sativa* L.) is the staple food for the largest number of people on earth and maintaining the sustainable production of rice is therefore critical to global food security (Alexandratos and Bruinsma 2012). China is the largest rice producer in the world and contributed to 28.5% of the global rice production in 2016 (FAO 2016). Although rice grain yields have risen dramatically in recent decades, largely due to increased use of inorganic fertilizer, this has also coincided with the decreased nutrient use efficiency, leading to severe environmental impacts on soil, water and atmospheric quality (Le *et al.* 2010; Liu *et al.* 2010). Declining soil quality, e.g., soil acidification and structural damage, has already had negative effects on rice yield (Liu *et al.* 2013; Chen *et al.* 2016). Thus, a major challenge for sustainable rice production is to produce more grain yield with lower environmental impacts (Chen *et al.* 2014). Reducing the amount of chemical fertilizer with replenishment of organic materials offers a potential opportunity to deliver such improvements.

Future progress in narrowing yield gaps could be achieved largely through improvements in soil organic matter management *via* additions of organic materials such as crop residues and green manures (Fan *et al.* 2013). The subsequent utilisation of organic materials as nutrient sources depends on their quality, environmental factors, soil properties, and management (Singh *et al.* 2005). A number of studies have demonstrated that the return of crop residues is an effective way of increasing soil organic matter content, maintaining the productivity of soils and improving soil fertility (Malhi *et al.* 2011; Huang *et al.* 2013; Murphy *et al.* 2016). Rice straw, which is characterized by a high C/N ratio and abundant K, Si, often decomposes rapidly in soils but can result in the short-term immobilization of soil nutrients and anaerobism as the microbial population utlises the relatively available carbon substrates contained in the straw (Yang *et al.* 2017; Zhu *et al.* 2017). Legume green manures by contrast such as Chinese milk vetch (*Astragalus sinicus* L., hereafter vetch), are characterized by a lower C/N ratio, which often contributes to N mineralization and enhanced in paddy fields (Tejada *et al.* 2008; Yang *et al.* 2011; Piotrowska and Wilczewski 2012). Residues with high C/N ratio often decompose more slowly than those with a low C/N ratio or high N content (Magid *et al.* 1997; Trinsoutrot *et al.* 2000). And it has been reported that the decomposition of cereal straw could be accelerated by the addition of green manures (lowering the C/N ratio of the decomposing materials; Mishra *et al.* 2001). Co-incorporation of rice straw and leguminous green manures could therefore potentially improve the synchrony in N supply and demand thereby contributing to increases in crop yield and reductions in N losses from soil-plant system (Kaewpradit *et al.* 2009). However, it has not been possible to evaluate these potential effects of co-incorporation of rice straw and leguminous green manures given the lack of the effects on the stability of rice productivity in double-rice cropping systems. Especially, few studies have evaluated the effects of green-manure with contrasting management practices for rice straw on long-term yield.

The incorporation of crop residues is known to deliver multiple benefits on soil quality, such as increasing soil fertility, improving soil physical and chemical properties, reducing soil erosion and soil evaporation, and reducing soil sealing and crusting (Gangwar *et al.* 2006; Wilhelm *et al.* 2007; Blanco-Canqui and Lal 2008; Bandyopadhyay *et al.* 2016). In practice, straw management is currently changing from conventional return to high stubble retention because of the popularity of mechanized agricultural operations, which favor reduced tillage, and labor-saving approaches. Previous research found that keeping tall stubbles following rice production was an effective way to promote the productivity of succeeding legumes (Bandyopadhyay *et al.* 2016). This traditional system conserved soil moisture by increasing height of standing rice stubbles which improved productivity of succeeding crop substantially. In southern China, vetch as cover crop was broadcasted within the standing late rice without any tillage at 20–25 days prior to the harvest of late rice (Lin and Gu 2000). However, the influence of keeping stubbles height of rice on the vetch productivity and thereby co-incorporation of standing late rice residues and vetch on the stability of vetch-early rice-late rice rotation system is not fully understood. Therefore, the objectives of the present study were: 1) to evaluate the effect of different managements of rice residue on the production for vetch and the nutrient supply capacity of the vetch when used as green manure, and 2) to explore the influence of co-incorporation of rice straw and vetch on the stability of rice productivity under reduced fertilization in double-rice cropping system over seven consecutive years.

2. Materials and methods

2.1. Site description

Field experiments were performed from 2011 to 2017 at Nan County, Hunan Province, China (29°13´N, 112°28´E and altitude 30.0 m). The soil is a typical purple calcareous loamy clay soil derived from lake sediment. The initial chemical properties of 0–20 cm soil layer in 2011 were as follows: pH (H_2O), 7.70; soil organic matter, 47.5 g kg^{-1}; total N, 3.28 g kg^{-1}; total P, 1.28 g kg^{-1}; total K, 22.2 g kg^{-1}; available nitrogen, 261 mg kg^{-1}; available phosphorus, 15.6 mg kg^{-1}; available potassium, 98.0 mg kg^{-1}. The annual mean temperature is 17.6°C and the yearly average precipitation is 1 293 mm at the experimental site. The annual sunshine is about 1 479 h (1 149 h during crop growing period). The monthly precipitation and mean temperature at the experimental site over the experimental years (2011–2017) are shown in Fig. 1.

2.2. Crop management and experimental design

The experiments were conducted in cropping system of early rice-late rice rotation in seven successive years (2011–2017). The key dates of early rice (*cv*. Yuanzao 1), late rice (*cv*. Huanghuazhan) and vetch of each season in each year including sowing date, transplanting seedling age and harvesting time listed in Table 1. Rice seedlings (both 30-days-old for early rice and late rice) were transplanted at a spacing of 20 cm×20 cm for double rice.

In this study, six treatments were established, as follows: (i) F-Con, control (no chemical fertilizer and vetch); (ii) F-F100, sole 100% chemical fertilizer; (iii) M-Con, only vetch without chemical fertilizer; (iv) M-F80, 80% chemical fertilizer plus vetch plus low cutting height (low retained stubble about 5 cm) with removal of rice straw; (v) M-F80-LR, 80% chemical fertilizer plus vetch plus low cutting height with retention of rice straw; (vi) M-F80-HR, 80% chemical fertilizer plus vetch plus high cutting height (high retained stubble about 40 cm, left after late rice harvest) with retention of rice straw. All treatments were arranged in a randomized complete block design with three replicates. The plot size was 20 m^2 (4 m×5 m) separated by a ridge (0.3 m wide and 15 cm aboveground).

The recommended fertilizer rates to rice of the experiment are: 150 kg ha^{-1} N (urea, 46% N), 75 kg ha^{-1}

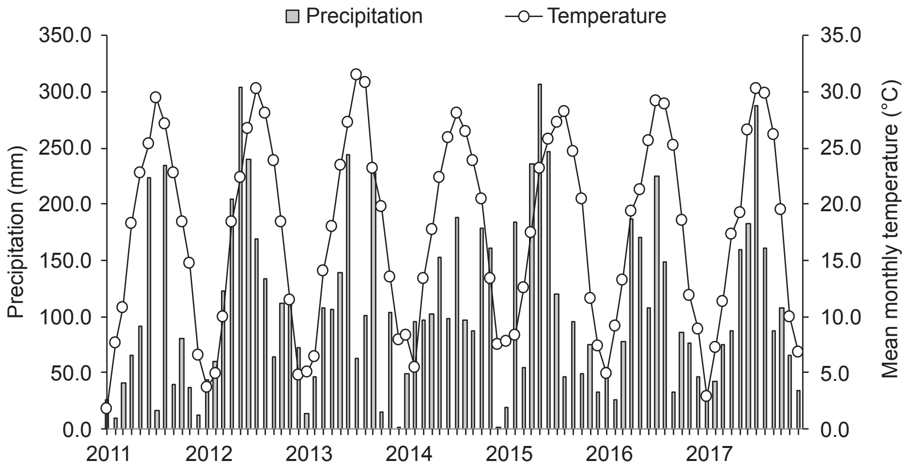

Fig. 1 The monthly rainfall and mean temperature at the experimental site from 2011 to 2017.

Table 1 The key dates of experimental crops in each year

Year	Vetch		Early rice			Late rice		
	Sowing	Returning	Sowing	Transplanting	Harvesting	Sowing	Transplanting	Harvesting
2010	Oct. 25th	–	–	–	–	–	–	–
2011	Oct. 10th	Apr. 8th	Mar. 10th	Apr. 17th	Jul. 1st	Jun. 7th	Jul. 4th	Oct. 29th
2012	Oct. 9th	Apr. 13th	Mar. 12th	Apr. 25th	Jul. 4th	Jun. 12th	Jul. 7th	Nov. 4th
2013	Oct. 9th	Apr. 10th	Mar. 10th	Apr. 23th	Jul. 2nd	Jun. 11th	Jul. 5th	Nov. 3rd
2014	Oct. 8th	Apr. 15th	Mar. 12th	Apr. 27th	Jul. 5th	Jun. 10th	Jul. 8th	Nov. 5th
2015	Oct. 10th	Apr. 12th	Mar. 11th	Apr. 20th	Jul. 1st	Jun. 7th	Jul. 4th	Oct. 29th
2016	Oct. 12th	Apr. 11th	Mar. 15th	Apr. 23th	Jul. 6th	Jun. 9th	Jul. 9th	Nov. 1st
2017	Oct. 7th	Apr. 13th	Mar. 14th	Apr. 26th	Jul. 8th	Jun. 13th	Jul. 11th	Nov. 3rd

P_2O_5 (superphosphate, 12% P_2O_5) and 90 kg ha^{-1} K_2O (potassium chloride, 60% K_2O) for early rice, and 180 kg ha^{-1} N, 45 kg ha^{-1} P_2O_5 and 120 kg ha^{-1} K_2O for late rice, respectively. It has been reported that the application of vetch plants as green manure could reduce partially the supply of chemical fertilizer (20–40%) due to it containing some nutrients (Zhou *et al.* 2015), so reduced 20% rate of chemical fertilizer in manure-amended treatments (M-F80, M-F80-LR and M-F80-HR). Half amount of the urea and all the superphosphate and potassium chloride were applied as basal fertilizer raked into a 5 cm soil depth manually by a smoothing harrow on 1 day prior to rice transplanting and the remaining nitrogen was top-dressed at the tillering stage of each rice season.

At every harvest season, both early and late rice were cut down manually using a sickle so that the remaining stubble after harvest would measure 5 or 40 cm, thereby simulating traditional low cutting stubble (traditional method for harvesting) or high cutting stubble harvest practices (harvested method by full feeding rice combine), respectively. The rice straw in the first four treatments at the harvesting stage (both early and late rice) and were removed with low cutting height (about 5 cm). The early rice straw in M-F80-LR and M-F80-HR with low cutting height (about 5 cm) was chopped into 5 cm and uniformly returned into 10 cm depth of surface soil mechanically after harvest. The late rice straw with low cutting height in M-F80-LR was uniformly mulched on the field surface, while in M-F80-HR retained with high-cutting stubble (about 40 cm, the cut straw spread uniformly as mulch on the field).

Vetch (*A. sinicus* L. Xiangzi 1) was broadcast uniformly manually at a density of 30 kg ha^{-1}, and directly seeded without tillage before the harvest of late rice in early October each year and was growing throughout the interval of the double-rice system (except for F-Con and F-F100 treatments), and was cultivated without additional fertilization during vetch's growth. The fresh vetch was harvested manually by cutting on the soil surface per plot and measured, and then ploughed back and mixed mechanically within 20 cm depth of the surface soil and flooded up to 5–7 cm depth, 10 days prior to early rice transplanting.

2.3. Plant sampling and analysis

Grain yield and yield components of double-cropping rice At the grain maturity stage, five representative hills of rice plant from 1 m^2 (25 hills) in each plot were collected to measure yield components, and rice grains were separated from straw using a plot thresher for each whole plot, where the grains were separately sun-dried, and rice yield was determined. Panicle number of each area was counted as efficient panicle number per 1 m^2. Panicles were hand-threshed, and filled and unfilled grain in a spikelet were separated by submerging in tap water. They were then weighted after oven drying at 60°C to constant weight. Filled and unfilled grains were used to calculate filled grains per panicle and filled grain percentages. 1 000-grain weight was determine by three subsamples of the1 000 filled grains.

Biomass, growth parameters and nutrient content of vetch At the full bloom stage, two 1-m^2 areas of fresh vetch were sampled diagonally from each plot to determine fresh aboveground and root biomass. Five representative vetch plants from 1 m^2 in each plot were collected to measure growth parameters of vetch. The growth parameters including plant height, number of compound leaves per plant, apparent leaf area, branches per plant and plant weight were measured. Plant samples were dried at 60°C to a constant weight after drying at 105°C. The plant materials were used to determine the C concentration by potassium dichromate oxidation method and N concentration by a modified Kjeldahl digestion method, the P concentration by molybdovanadate method, and K concentration by flame photometry (Lu 2000).

Soil water content of 0–20 cm soil layer Soil water content was measured gravimetrically from vetch plots, using a core sampler of 3 cm diameter and a length of 20 cm for the topsoil (0–20 cm). The soil water content was recorded 2 days in the successive two vetch seasons after each notable rainfall.

2.4. Statistical analyses

The productivity of vetch biomass and double-rice cropping system was calculated using a sustainable yield index (SYI). The SYI was calculated to counteract any annual variations in yield of the performance in each treatment throughout the test period. The SYI was calculated as follows (Singh *et al.* 1990):

$$SYI=(\overline{Y}-\sigma_{n-1})/Y_{max}$$

where $\overline{Y}$ is the mean yield or vetch biomass of a practice across the years, Y_{max} is the maximum yield or vetch biomass data obtained from the treatment in any year, σ_{n-1} is the standard deviation, measuring the variation and stability in yield caused by soil and climatic factors (Singh *et al.* 1990; Efthimiadou *et al.* 2010). The yield stability of various agricultural management practices in cropping systems is estimated through SYI (Shekhawat *et al.* 2016; Choudhary *et al.* 2018). The nearness of SYI to 1.0 suggests the closeness to an ideal situation which can sustain the maximum crop yield, while the deviation from 1.0 implies the loss to yield stability (Bhindhu and Gaikawad 1998).

Data obtained from various treatments were subjected to analysis of variance (ANOVA) using the SPSS 19.0 (IBM SPSS Statistics Version 19). The difference among treatments were tested using Duncan's test (P<0.05). Determination of differences between treatments, years and their interaction were performed *via* two-way ANOVA. Linear regression analyses (P<0.05) of vetch biomass and growth parameters (plant height, number of compound leaves per plant, apparent leaf area, branches per plant, plant weight) were performed to determine their relationships across years. The relationships among the rice yield and yield properties, vetch biomass input and nutrient inputs were evaluated by regression analysis using the Pearson correlation analyses in the SPSS 19.0., Sigmaplot 12.5 and MS Excel 2007.

3. Results

3.1. Rice productivity under different treatments

Grain yields of rice plants The grain yields of the double rice over the period 2011–2017 showed significant 'treatment×year' interactions in the early rice, not in the late rice and double rice. In addition, grain yields showed significant responses to treatments and year (Table 2).

The mean rice yields observed in control (F-Con) treatment suggests that the soil of the experimental field was capable of giving average grain yields in early and late rice of about 3.3 and 5.6 Mg ha^{-1}, respectively, without any fertilizer (Table 2). By comparison, the fertilized treatments produced significantly (P<0.05) greater yields, except for late rice in the M-Con treatment. Yields of the two rice crops after vetch were not affected by either the cutting height of stubble with retention of straw (M-F80-HR *vs*. M-F80-LR) or by the management of straw (retention versus removal) with low cutting height of stubble (M-F80-LR *vs*. M-F80), but yields of the two rice crops after vetch were significantly (P<0.05) higher for M-F80-HR than M-F80. Even, Rice yield were higher for M-F80-HR than for F-F100, early rice by 9.1%, late rice by 8.3%.? There was no significant difference between yields of the two rice in M-F80-LR and F-F100, indicating that the incorporation of vetch and rice straw with low cutting height could be able to maintain rice yield though reducing chemical fertilizer.

Table 2 Mean grain yields influenced by various treatments over seven years (2011–2017)

Treatment[1)]	Mean grain yield (Mg ha^{-1})		
	Early rice	Late rice	Double-rice system
F-Con	3.3 d	5.6 c	8.8 e
F-F100	5.5 b	7.2 b	12.7 c
M-Con	4.1 c	5.5 c	9.5 d
M-F80	5.7 b	7.3b	13.0 bc
M-F80-LR	5.8 ab	7.5 ab	13.3 ab
M-F80-HR	6.0 a	7.8 a	13.8 a
Analysis of variance			
Treatment	***	***	***
Year	***	***	***
Treatment×Year	*	ns	ns

1) F-Con, control (no chemical fertilizer or vetch); F-F100, sole 100% chemical fertilizer; M-Con, only vetch without chemical fertilizer; M-F80, 80% chemical fertilizer plus vetch plus low cutting height with removal of rice straw; M-F80-LR, 80% chemical fertilizer plus vetch plus low cutting height with retention of rice straw; M-F80-HR, 80% chemical fertilizer plus vetch plus high cutting height with retention of rice straw.

Values presented are means (n=3). Lowercase letters in the same column indicate significant differences between treatments at P<0.05. ns, not significant, *, P<0.05, **, P<0.01, ***, P<0.001.

In addition, the yield response trend of early rice with various treatments was similar to the late rice (Table 2 and Fig. 2). However, the variation ranges of early rice were more obvious (yield in vetch fertilized treatments increased by 3.6 to 9.1% compared to the F-F100) than late rice (increased by 1.4 to 8.3%). Yields of two rice with the same straw management practice (straw removal) were not affected by vetch (F-F100 *vs*. M-F80), suggesting no decrease in rice yield from vetch with 20% less fertilizer.

Furthermore, grain yields of the double-rice cropping system fluctuated over the experimental period. The grain yield gap of early rice between F-Con and M-Con progressively narrowed over the years; but the gap between synergistic treatment (M-F80-HR or M-F80-LR) and conventional fertilizer treatment (F-F100) reversed the trends (Fig. 2). The comparable trends in yield during seven years between F-F100 and M-F80-HR or M-F80-LR suggested that vetch might maintain high rice yields.

Rice yield components Combined analysis of variance using data obtained over the experimental period of 2011–2017 indicated that the effects of year and treatment were significant for rice grain yield components except for 1 000-grain weight (Table 3). In addition, only the effects of interactions of treatment and year were significant for filled grains per panicle of yield components in the early rice and late rice. When compared with the grain yields of unfertilized treatments (F-Con or M-Con), yield changed in fertilized treatments mainly due to the changes in the panicle number, filled grains per panicle and filled grain percentage. However, yield increases in treatments received vetch (M-F80, M-F80-LR and M-F80-HR) were mainly due to the increase of filled grains per panicle.

Stability of double-rice system productivity The SYI provided a consistent framework for comparing treatments because it allowed an assessment of individual treatment performance over the experimental years. The SYI for the double-rice cropping system reveals that there was a higher sustainability for late rice than for early rice in all plots, due to the erratic weather conditions in the early rice season

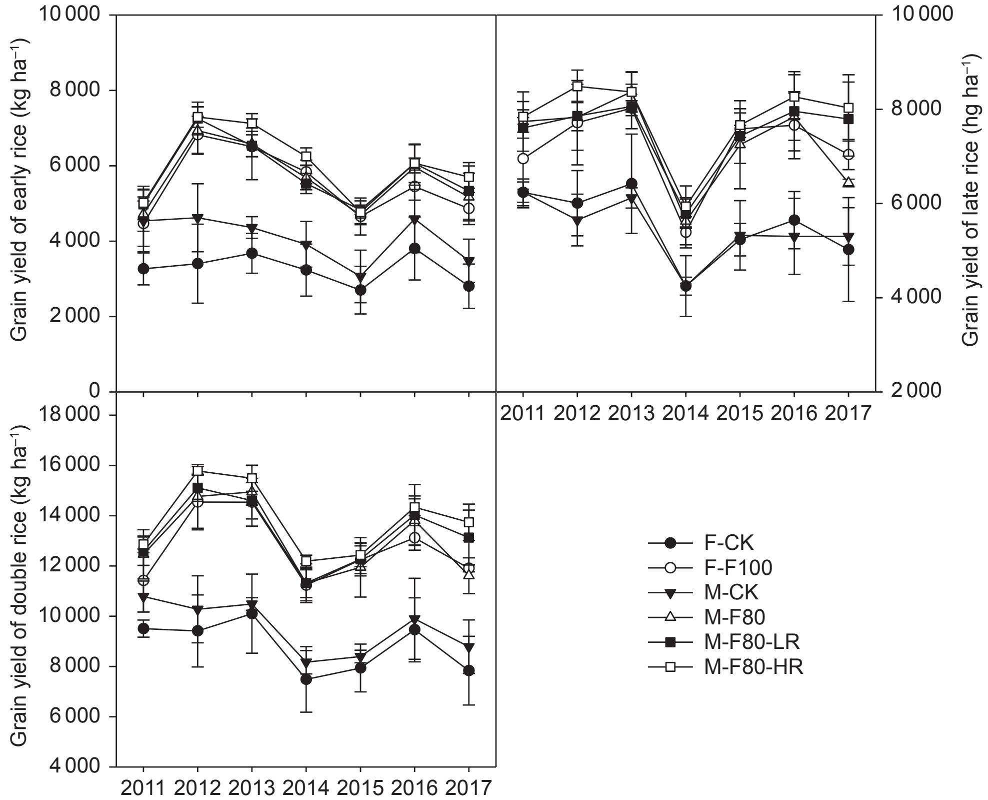

Fig. 2 Sequential changes of rice grain yields under various treatments from 2011 to 2017. F-Con, control (no chemical fertilizer or vetch); F-F100, sole 100% chemical fertilizer; M-Con, only vetch without chemical fertilizer; M-F80, 80% chemical fertilizer plus vetch plus low cutting height with removal of rice straw; M-F80-LR, 80% chemical fertilizer plus vetch plus low cutting height with retention of rice straw; M-F80-HR, 80% chemical fertilizer plus vetch plus high cutting height with retention of rice straw. Error bars represent the standard error of mean (n=3).

Table 3 Yield components in double-rice system under different treatments over seven years (2011–2017)

Treatment[1)]	Efficient panicle number (no. m^{-2})		Filled grains per panicle (no./panicle)		1 000-grain weight (g)		Filled grain percentage (%)	
	Early rice	Late rice	Early rice	Late rice	Early rice	Late rice	Early rice	Late rice
F-Con	155 c	200 b	62 d	80 d	25.0 a	22.3 a	86.6 a	89.1 a
F-F100	222 a	290 a	77 c	94 c	24.7 a	22.2 a	77.5 b	79.7 b
M-Con	183 b	238 b	72 c	83 d	25.0 a	22.4 a	86.7 a	88.2 a
M-F80	220 a	308 a	84 b	92 c	24.9 a	22.2 a	80.6 b	80.2 b
M-F80-LR	233 a	312 a	89 a	98 b	25.1 a	22.4 a	80.7 b	79.3 b
M-F80-HR	243 a	320 a	94 a	108 a	25.1 a	22.7 a	82.2 b	80.2 b
Variance analysis								
Treatment	***	***	***	***	ns	ns	**	***
Year	**	***	***	***	ns	ns	**	***
Treatment×Year	ns	ns	*	***	ns	ns	ns	ns

1) F-Con, control (no chemical fertilizer or vetch); F-F100, sole 100% chemical fertilizer; M-Con, only vetch without chemical fertilizer; M-F80, 80% chemical fertilizer plus vetch plus low cutting height with removal of rice straw; M-F80-LR, 80% chemical fertilizer plus vetch plus low cutting height with retention of rice straw; M-F80-HR, 80% chemical fertilizer plus vetch plus high cutting height with retention of rice straw.
Values indicate means (n=3), which followed by the same letters within the same column denote not significantly different according to Duncan's new multiple range test at 0.05 level of probability. ns, not significant; *, P<0.05; **, P<0.01; ***, P<0.001.

(Table 4). The SYI for early rice, late rice was thr highest in the M-F80-HR plot, whereas the lowest SYI was in the F-Con plot. The SYI for vetch-amended plots tended to be higher than that of the F-F100 treatment. Thus, the results imply that the effective management of straw combined with milk vetch incorporation has the potential to promote sustainable production for rice grain yields in double-rice cropping system of Central-South China.

3.2. Vetch biomass productivity

Biomass production of vetch in full-bloom stage During the 7-year field study, the weather conditions and particularly rainfall at the experimental site varied considerably (Fig. 1). These resulted in large inter-annual variations in the vetch biomass production (Fig. 3). While treatments also caused significant impacts on vetch aboveground biomass, plant height, number of leaves, branches per plant and plant weight (P<0.05) (Table 5). However, there were no significant 'treatment×year' interactions which indicated that the treatment in different years independently affected the vetch biomass productivity.

The mean biomass yields of vetch were 15.9–24.2 Mg ha^{-1} on a fresh weight basis (the mean moisture content is 85%; Table 5). Fertilization treatments in the rice season significantly increased the biomass yields of vetch by 15–52% compared with the only vetch treatment (M-Con). This implies that the fertilizer applied in the rice season had a positive residual effect on vetch production. The highest mean biomass yield was observed in the high-cutting stubble with retention of straw plots (M-F80-HR), which was 29% higher than low cutting height with removal of straw (M-F80, P<0.05); M-F80-HR also resulted in a significantly higher vetch biomass production than the low cutting height with retention of straw (M-F80-LR, by 32%,

Table 4 Sustainable yield index (SYI) for vetch biomass cultivated with different utilization patterns of rice straw and grain yield in double-rice cropping system over seven years (2011–2017)

Treatment[1)]	SYI for vetch biomass[2)]	SYI for early rice	SYI for late rice	SYI for double-rice system
F-Con	–	0.49 e	0.56 c	0.57 c
F-F100	–	0.57 c	0.64 b	0.64 b
M-Con	0.57 c	0.53 d	0.65 b	0.63 b
M-F80	0.69 b	0.58 bc	0.64 b	0.65 b
M-F80-LR	0.69 ab	0.58 b	0.67 ab	0.68 a
M-F80-HR	0.79 a	0.61 a	0.70 a	0.69 a

[1)] F-Con, control (no chemical fertilizer or vetch); F-F100, sole 100% chemical fertilizer; M-Con, only vetch without chemical fertilizer; M-F80, 80% chemical fertilizer plus vetch plus low cutting height with removal of rice straw; M-F80-LR, 80% chemical fertilizer plus vetch plus low cutting height with retention of rice straw; M-F80-HR, 80% chemical fertilizer plus vetch plus high cutting height with retention of rice straw.
[2)] – indicates there was no vetch in F-Con and F-F100 treatment so that the SYI doesn't need to be calculated.
Values denote means (n=3). Lowercase letters in the same column indicate significant differences between treatments at P<0.05.

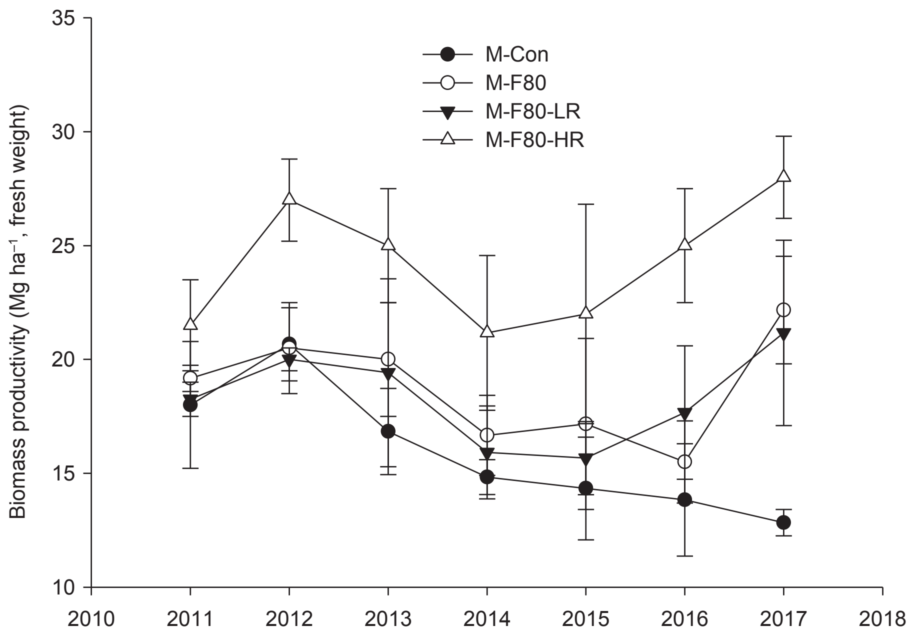

Fig. 3 Sequential changes of vetch biomass yield in full-bloom stage under different treatments in the vetch-rice-rice rotation system from 2011 to 2017, Central-South China. M-Con, only vetch without chemical fertilizer; M-F80, 80% chemical fertilizer plus vetch plus low cutting height with removal of rice straw; M-F80-LR, 80% chemical fertilizer plus vetch plus low cutting height with retention of rice straw; M-F80-HR, 80% chemical fertilizer plus vetch plus high cutting height with retention of rice straw. Error bars represent the standard error of mean (n=3).

Table 5 The mean biomass production and growth parameters at full-bloom stage of Chinese milk vetch (vetch) cultivated with different treatments over seven years in the vetch-rice-rice rotation (M-R-R) system, central south of China (2011–2017)

Treatment[1)]	Aboveground biomass yield (Mg ha^{-1}, fresh weight)	Plant height (m)	Number of compound leaves per plant (no./plant)	Apparent leaf area (cm^2)	Branches per plant (no./plant)	Plant weight (g)
M-Con	15.9 c	0.70 c	7.2 c	1.97 a	1.8 a	5.5 c
M-F80	18.7 b	0.87 b	9.3 b	1.96 a	2.1 a	7.1 b
M-F80-LR	18.3 b	0.84 b	10.1 b	1.97 a	2.2 a	6.7 b
M-F80-HR	24.2 a	1.06 a	12.6 a	1.97 a	2.3 a	9.5 a
Analysis of variance						
Treatment	***	***	***	ns	***	***
Year	***	***	***	ns	ns	***
Treatment×Year	ns	ns	ns	ns	ns	ns

[1)] M-Con, only vetch without chemical fertilizer; M-F80, 80% chemical fertilizer plus vetch plus low cutting height with removal of rice straw; M-F80-LR, 80% chemical fertilizer plus vetch plus low cutting height with retention of rice straw; M-F80-HR, 80% chemical fertilizer plus vetch plus high cutting height with retention of rice straw.
Values indicate means (n=3), which followed by the same letters denote not significantly different according to Duncan's new multiple range test at 0.05 level of probability. ns, not significant; *, P<0.05; **, P<0.01; ***, P<0.001.

P<0.05). Furthermore, there was no significant difference between M-F80-LR and M-F80.

As far as vetch biomass productivity is concerned, the SYI was the highest in the M-F80-HR plot, while the lowest SYI was in the M-Con treatment (Table 4). No distinct trend of SYI was observed between M-F80-LR and M-F80. It indicates that the effective management of stubbles and incorporated residues could maintain stable production for Chinese milk vetch.

Growth parameters of vetch at full-bloom stage The parameters describing vetch growth over seven years showed no significant 'treatment×year' interactions at full-bloom stage (Table 5). But growth parameters of vetch (except apparent leaf area and branches per plant) changed significantly in different years and treatments. By comparison with M-Con treatment, the M-F80-LR and M-F80 treatments showed significant higher plant height, more compound leaves and greater plant weight, by 19, 41 and 22%, and 23, 30 and 30%, respectively, while no significant differences of the three parameters were observed between M-F80-LR and M-F80. Meanwhile, these three parameters in the M-F80-HR treatment increased significantly than the M-Con treatment by 50, 76 and 74%, respectively, even significantly higher than that of in M-F80- LR and M-F80.

3.3. Milk vetch nutrient enrichment

At the full bloom stage of the vetch prior to being returned to the soil as green manure, more than 80% of the C, N, P_2O_5 and K_2O accumulation had occurred in the aboveground biomass (Table 6). The C, N, P_2O_5 and K_2O accumulation of the experiment changed over various years, but again there was no significant 'treatment×year' interaction for biomass nutrient accumulation. In addition, different treatments had a significant effect on the accumulation of C, N, P_2O_5 and K_2O relative to the M-Con (Table 6).

The accumulation of C, N, P_2O_5 and K_2O (Table 6) clearly indicate the higher nutrient content of M-F80-HR treatment by comparison to M-Con. The vetch biomass at the flowering stage in the M-F80-HR treatment was approximately 25.8 Mg ha^{-1} (fresh weight) contained 105 kg ha^{-1} N, 12 kg ha^{-1} P_2O_5 and 100 kg ha^{-1} K_2O, however, this was insufficient to fully satisfy the recommended levels of nutrition (N-P_2O_5-K_2O=150–33–75 kg ha^{-1}) for early rice in a double-rice cropping system, and was well below what would be required by later rice crop. However, the accumulation decreased significantly with decreasing vetch biomass productivity in M-F80-LR and M-F80.

3.4. Correlation between rice grain yield, yield components and vetch biomass input properties

By analyzing the correlation between rice grain yield, yield components and vetch biomass inputs properties (Table 7), it showed that the grain yield of early rice and late rice was positively correlated with the vetch biomass input and nutrient inputs. The increase of grain yield can be explained by the observation that the increasing nutrient inputs from the vetch simulated the increase of the filled grains per panicle and panicle number in the double-rice cropping system.

4. Discussion

4.1. Effect of incorporation of vetch and rice straw on double-rice system productivity

The capacity of cover crops to accumulate nutrients so that they could be made available to subsequent crops through straw decomposition is an important feature of cover crops

Table 6 Annual mean biomass nutrient accumulation of milk vetch cultivated under different treatments

Treatment[1)]	Aboveground biomass nutrient accumulation (kg ha^{-1})				Root biomass nutrient accumulation (kg ha^{-1})			
	C	N	P_2O_5	K_2O	C	N	P_2O_5	K_2O
M-Con	1 136 c	72 c	7.5 c	31 d	125 b	6.6 b	1.3 b	1.9 d
M-F80	1 315 b	81 b	10.2 a	44 c	129 b	7.3 b	1.6 a	2.5 c
M-F80-LR	1 241 bc	78 b	8.7 b	60 b	153 a	8.3 a	1.6 a	4.3 b
M-F80-HR	1 577 a	96 a	10.6 a	94 a	158 a	8.3 a	1.7 a	5.4 a
Analysis of variance								
Treatment	***	***	***	***	***	***	***	***
Year	*	*	*	*	**	**	**	*
Treatment×Year	ns	ns	ns	ns	ns	ns	ns	ns

[1)] M-Con, only vetch without chemical fertilizer; M-F80, 80% chemical fertilizer plus vetch plus low cutting height with removal of rice straw; M-F80-LR, 80% chemical fertilizer plus vetch plus low cutting height with retention of rice straw; M-F80-HR, 80% chemical fertilizer plus vetch plus high cutting height with retention of rice straw.
Values indicate means(n=3),, which followed by the same letters denote not significantly different according to Duncan's new multiple range test at 0.05 level of probability. ns, not significant; *, P<0.05; **, P<0.01; ***, P<0.001.

in rotations. Legume cover crops are particularly important in this context (such as Chinese milk vetch), since they can fix atmospheric N with rhizobia. Consequently, when compared with the conventional fertilizer treatment (F-F100), the vetch only treatments with less 20% fertilizer (M-F80) were able to maintain the productivity of the double-rice system even though reducing the fertilizer application rate was reduced by 20% (Table 2). In the experiment, the lowest mean nutrient accumulation of pure vetch without fertilizer in the rice season (M-Con) reached 81 kg ha^{-1} N, 9 kg ha^{-1} P_2O_5 and 33 kg ha^{-1} K_2O. This demonstrates that nutrients such as N, P, K and other minerals contained in the vetch biomass application would have been able to enhance the availability of nutrient to rice production (Zhou *et al.* 2015). In some studies, the effects of rice straw on the subsequent crop production were significantly negative due to the high C/N ratio of the straw (Yang *et al.* 2017; Zhu *et al.* 2017). Such effects provide evidence of high rates of microbial immobilization, as soil microbial populations compete for ammonium-N (Muhammad *et al.* 2011; Takakai *et al.* 2018). The oxygen demand associated with this process often leads to the production of toxic substrates and anaerobic conditions as microbes switch away from oxygen as a terminal electron acceptor. In the experiment, the use of vetch under rice straw with 20% less chemical fertilizer produced a much higher level of rice productivity than the pure chemical fertilizer, particularly where tall rice stubbles was retained, which in turn, significantly improved the grain yield of the double-rice system (Table 2). The higher nutrient content provided by the vetch was able to support production of the tall rice stubble and could partially replace the chemical fertilizers, thus improving the rice productivity. The combination of fresh vetch with low C/N ratios and standing rice stubbles with high C/N ratios help to reduce N immobilization and N losses from the application of pure rice straw (Kaewpradit *et al.* 2009). Moreover, adding rice straw delayed decomposition of the vetch may therefore have resulted in a more stable N supply over year compared with the pure rice straw and vetch because of the complementarity of the two materials (Kaewpradit *et al.* 2009).

However, there were some differences in rice yield between two residue treatments (M-F80-LR and M-F80-HR). Kaewpradit *et al.* (2009) found that improvement of rice yield could already had been achieved by adding 2.5 Mg ha^{-1} rice straw to 5 Mg ha^{-1} legume crop (groundnut). It is possible that such changes in yield may occur as a consequence of improved synchrony between the release and uptake of nutrients. In a study that incorporated a mixture of legume and cereal straw, increased nutrient recovery was observed in a subsequent maize crop, which was ascribed to such improved synchrony (Myers *et al.* 1994). However, the impacts of green manures on soil microbial activity are complex and can influence the nature and abundance of ammonia oxidizing bacteria which play a key role in soil N transformations in rice cropping systems (Gao *et al.* 2018). Further research is therefore required to fully understand the influence of rice straw and legume cover crop mixtures in different proportions on growth and yield of rice.

Furthermore, the sustainability of a cropping system is dependent on the combination of soil, climate and cropping system (Manna *et al.* 2005). So, the yield trend is a complex phenomenon and may not be answered precisely on the basis of present fertilizer treatment set. Climate changes have already been widespread concerned by all walks of life. The change might be affecting yield trends due to changes in photo-synthesis, respiration in the vegetative and grain filling period (Manna *et al.* 2005; Yuji *et al.* 2009). In the present study, the yield of late rice in all

Table 7 Correlation between rice grain yield and yield properties and milk vetch biomass input properties

Parameters	Filled grains per panicle of early rice	Filled grains per panicle of late rice	Efficient panicle number of early rice	Efficient panicle number of late rice	1000-grain weight of early rice	1000-grain weight of late rice	Filled grain percentage of early rice	Filled grain percentage of late rice	Grain yield of early rice	Grain yield of late rice
Milk vetch biomass input	0.464**	0.552**	0.584**	0.510**	0.027	0.021	−0.393*	−0.564**	0.626**	0.521**
C input	0.413*	0.491**	0.546**	0.489**	0.010	−0.019	−0.414*	−0.563**	0.601**	0.475**
N input	0.332*	0.396*	0.485**	0.445**	−0.003	−0.071	−0.435**	−0.552**	0.541**	0.403*
P input	0.395*	0.338*	0.553**	0.494**	−0.007	−0.081	−0.489**	−0.615**	0.637**	0.480**
K input	0.607**	0.439**	0.676**	0.544**	0.093	0.157	−0.404*	−0.543**	0.665**	0.651**
C/N ratio input	0.703**	0.598**	0.674**	0.533**	0.069	0.203	−0.444**	−0.466**	0.715**	0.710**

ns, not significant, *, $P<0.05$, **, $P<0.01$, ***, $P<0.001$.

treatments decreased due to rainy continuously for weeks in the grain filling period in 2014 (Fig. 2). Farm yields are usually influenced by seasonal rainfall, particularly in dry-farming region, where the amount of rainfall received at critical growth stages of the crop. In addition to soil, climate and cropping system, the change of yield trends in long-term experiments could occur because of adversity of other factors such as imbalanced fertilizer use, cultivar, and insect pest.

4.2. Effect of rice straw management methods on succeeding Chinese milk vetch productivity

Previous studies have demonstrated that the application of rice straw with low rice stubble can have a larger effect on a succeeding legume (mung bean) production than other planting methods (removal) in rice-based lowland areas in the Mekong region (Bunna *et al.* 2011). The main reason for this is that retention of rice straw has the potential beneficial effect of reducing soil surface crusting and evaporation of moisture in the study area (Van den Berg and Lestari 2001). But the results of this study showed that rice straw mulched on the field surface (M-F80-LR) had no significant effects on succeeding vetch growth in a double-rice cropping system when compared with a conventional system of vetch cultivation without rice straw (M-F80, Table 5). Although retention of rice straw provides insulation for vetch growth in winter, it may also cause shading and therefore have a negative effect on vetch at the seeding stage leading to more slender stems that lodge easily (Jiang *et al.* 2001). In the experiment, the vetch biomass production where high stubble was maintained (M-F80-HR) was significantly greater than that of the conventional cultivation of vetch without rice straw (M-F80) and vetch with a low stubble retention of rice straw (M-F80-LR). This is likely to have been due to direct effect of higher temperature regulation and moisture status under keeping high stubbles to increase root proliferation and thus enhanced availability of nutrients to succeeding crop roots (Bandyopadhyay *et al.* 2016), thereby reflecting higher plant biomass yield and better growth parameters (Table 5).

In previous studies, both retaining tall rice stubbles and retention of rice straw with low stubbles have been shown to have a positive effect on mitigating soil moisture stress and increasing productivity of the succeeding crop (Bunna *et al.* 2011; Bandyopadhyay *et al.* 2016). In this context, the average moisture content of the topsoil (0–20 cm) during the vetch growing period in winter in the experiment was observed for 2 days following periods without rainfall (over 5 days; Fig. 4). The results showed that under the short stubbles with no rice straw (M-Con and M-F80), soils were exposed earlier during the growth of vetch and deep cracks were then created during the mature phase of the late rice, which led to greater evaporation of residual soil moisture. Although low cutting stubbles with retention of rice straw (M-F80-LR) has been showed to prevent soil water loss (Mulumba and Lal 2008; Zhao *et al.* 2014), in this study there were no consistent effects. This was mainly because surface mulching shaded the soil allowing it to retain more moisture at the seeding stage (Huang *et al.* 2007), but then about 50–60% of returned straw was decomposed 2 months after harvest of the late rice (Li *et al.* 2006; Guo *et al.* 2018) and gradually lost the capacity to retain moisture. Retaining tall rice stubble conserves plenty of soil moisture (Bandyopadhyay *et al.* 2016), preventing soil water loss by reducing evaporation and thus helping to retain moisture during the succeeding crop growing. As expected, keeping tall rice stubbles plots (M-F80-HR) significantly and consistently increased soil water content of the topsoil (Fig. 4). One reason for these differences is that taller rice stubble residue creates a more complex micro-climate which could directly affect the distribution of surface soil moisture (Hu *et al.* 2015).

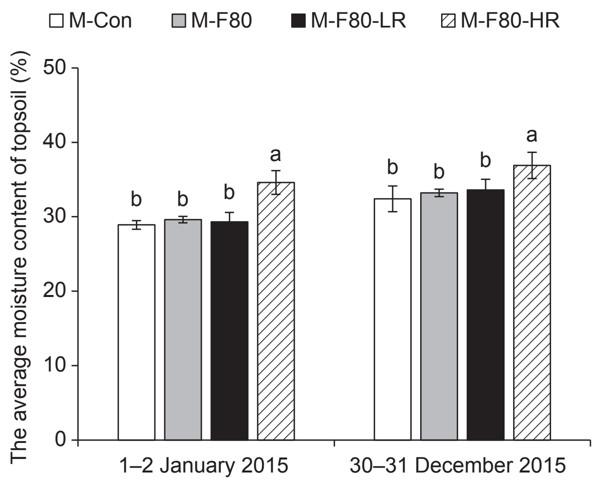

Fig. 4 The average soil water content of topsoil (0–20 cm) in different treatments was recorded for 2 days in the successive 2 vetch seasons. M-Con, only vetch without chemical fertilizer; M-F80, 80% chemical fertilizer plus vetch plus low cutting height with removal of rice straw; M-F80-LR, 80% chemical fertilizer plus vetch plus low cutting height with retention of rice straw; M-F80-HR, 80% chemical fertilizer plus vetch plus high cutting height with retention of rice straw. Error bars represent the standard error of mean (n=3). Lower case letters in the same time indicate significant differences between treatments at P<0.05.

4.3. The stability of vetch–rice–rice rotation system

The SYI is considered to represent an important indicator for measuring the yield stability of crop production system (Srinivasarao *et al*. 2012; Li *et al*. 2016). Generally speaking, higher values of SYI indicate indicate that the system is in a more sustainable stage. In the experiment, fertilizer application in the rice season improved the SYI of vetch biomass production compared with the no-fertilizer treatment in the rice season (Table 4). Increases in the SYI of vetch production could be mainly attributed to the residual effects from fertilizer applied in the rice season on the succeeding crop (Pan *et al.* 2012). The highest SYI for vetch biomass production was observed in the treatment in which tall late rice stubble was retained. Essentially, retaining tall late rice stubble improved the environment for vetch growth, particularly in relation to moisture status and temperature (Bandyopadhyay *et al.* 2016), resulting in a positive effect on the sustainability of vetch biomass production. In addition, the SYI for the double-rice cropping system reveals that there was higher yield stability for late rice than for early rice in all plots, due to the erratic weather conditions in the early rice season. Fertilizer application improved the SYI of double-cropping rice grain production when compared with treatments without fertilizer application. The SYI of double-cropping rice grain increased by applying organic and inorganic fertilizer, especially where co-incorporation of vetch and tall rice stubbles was included (M-F80-HR, Table 4). It is possible that adding rice straw might delay decomposition of vetch and therefore result in a more stable N supply across years because of the complementarity of the two materials (Kaewpradit *et al.* 2009). Thus, rice straw and incorporated vetch biomass were able to improve the system's soil N-supplying capacity thereby enhancing the yield stability of vetch–rice–rice rotation system.

5. Conclusion

Chinese milk vetch was once very commonly as green manure used in China. However, its use has virtually disappeared due to low direct economic benefit of itself, increase in labor cost and increased use of chemical fertilizer. The study investigated that improved rice straw management during the vetch phase of a vetch–rice–rice rotation could help to enhance the stability. Keeping high cutting height of late rice stubble with retention of straw may conserve plenty of soil moisture to improve the growing environment for vetch in winter allowing significant increases in the total biomass and nutrient retention by vetch, thereby retaining more nutrient within the system. The increased nutrient input and co-incorporation of high cutting height of late rice stubble with the vetch stimulated the double-rice growth and significantly increased the double-rice grain yield. Thus, effective management of rice straw by keeping high-cutting stubble could improve the value of vetch and promote double-rice system production. Such systems will be required fuse of vetch by farmers in the future.

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