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Effects of supplying silicon nutrient on utilization rate of nitrogen and phosphorus nutrients by rice and its soil ecological mechanism in a hybrid rice double-cropping system*

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Abstract: This study was conducted to reveal the effects of silicon (Si) application on nutrient utilization efficiency by rice and on soil nutrient availability and soil microorganisms in a hybrid rice double-cropping planting system. A series of field experiments were conducted during 2017 and 2018. The results showed that Si nutrient supply improved grain yield and the utilization rates of nitrogen (N) and phosphorus (P) to an appropriate level for both early and late plantings, reaching a maximum at 23.4 kg/ha Si. The same trends were found for the ratios of available N (AN) to total N (TN) and available P (AP) to total P (TP), the soil microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), microbial biomass phosphorus (MBP), and the ratios of MBN to TN and MBP to TP, at different levels of Si. Statistical analysis further revealed that Si application enhanced rice growth and increased the utilization rate of fertilizer due to an ecological mechanism, i.e., Si supply significantly increased the total amount of soil microorganisms in paddy soil compared to the control. This promoted the mineralization of soil nutrients and improved the availability and reserves of easily mineralized organic nutrients.

Key words: Silicon nutrient; Utilization rate of fertilizer; Ecological mechanism; Rice double-cropping system
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1 Introduction

Silicon (Si) is the second most abundant element in the Earth's crust after oxygen and is known to be beneficial for plants. It is the only element which is not detrimental when accumulated in excess (Ma and Yamaji, 2006; van Bockhaven et al., 2013). Many reports have shown that Si is an essential element for plant growth mainly because it promotes biomass production and grain yield and enhances tolerance to various abiotic and biotic stresses (Schaller et al., 2012; Cao et al., 2016; Fan et al., 2018). An adequate supply of Si can reduce pesticide and fertilizer inputs in agricultural production, thereby reducing agricultural non-point source pollution caused by unreasonable application of pesticides and fertilizers. In recent years, dozens of studies have proven the positive effects of Si fertilizer on soil nutrient efficiency

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ORCID: Min LIAO, https://orcid.org/0000-0001-9078-204X as used by plants (Eneji et al., 2008; Mehrabanjoubani et al., 2015; Pati et al., 2016; Schaller et al., 2016, 2019; Reithmaier et al., 2017). Neu et al. (2017) showed that a moderate Si nutrient supply promotes biomass production and grain yield and modifies nutrient use efficiency, while high levels induce a negative effect on these parameters. These benefits essentially mirror the positive effect of Si nutrient supply on the growth of *Phragmites australis* (Schaller et al., 2012). Some studies have demonstrated that Si not only enhances soil nitrogen (N) nutrient use efficiency, but also participates in soil phosphorus (P) metabolism (Saudy and Mubarak, 2015; Neu et al., 2017; Reithmaier et al., 2017; Schaller et al., 2019). These findings point to a possibility of Si influencing N and P availabilities and nutrient use efficiencies, resulting in increased aboveground biomass. Consequently, Si fertilization may reduce the demand for N and P fertilizers in agricultural soils for crop production.

N and P nutrient deprivation in paddy soil is a common phenomenon in southern China, which is characterized mainly by low N and P availabilities in soil and poor paddy field ecosystems. Currently, research on soil P is concentrated mainly on the availability of P in paddy soil. Several studies on hydroponically and soil grown rice and maize have demonstrated the role of Si in modifying plant growth under low-P conditions (Kostic et al., 2015, 2017). Few studies have assessed the effect of Si on the utilization rate of N and P fertilizers, or have attempted to reveal the possible mechanisms involved. Up to now, proposed explanations for beneficial effects of Si nutrient supply have focused on its effects on plant growth. Double- and triple-cropping are the main types of multiple-cropping systems in south China, which could significantly improve land-use efficiency and total crop yield. South China is a main area of rice planting, accounting for 83.5% of the total area of rice planted in China. Consequently, hybrid rice double-cropping systems are important for rice production and food security in China. However, little is known about the influence of Si nutrient on rice–soil ecosystems in hybrid rice double-cropping systems, especially their effects on soil microorganisms.

In a previous study (Qi et al., 2018), the influences of Si nutrient supply on the growth of rice and the agricultural soil ecosystems in double-cropping areas in South China were assessed with implications for the availability of soil nutrients and the total amount of soil microorganisms in paddy soil. In this study, we aimed to evaluate the potential of a moderate supply of available Si nutrient to enhance the availabilities of N and P, with subsequent increases of straw biomass and grain yield, and improvement in the rate of utilization of N and P. The results revealed the relationships among Si, N and P availabilities, and the total amount of soil microorganisms.

2 Materials and methods

2.1 Plant materials

An annual double-cropping rice system was selected as a field experimental system. Early season *indica* hybrid rice seedlings (cultivar: Lingliangyou 7717), grown by local agricultural cooperatives, were transplanted on Apr. 14 and harvested on July 17, 2017. Late season *indica* hybrid rice seedlings (cultivar: Xinliangyou-611), grown by local agricultural cooperatives, were transplanted on July 23 and harvested on Oct. 27, 2017. The experiment was repeated in 2018.

2.2 Research area and fertilization management

The research plots were located in a typical rice growing region in the middle reaches of the Yangtze River, in Yichun City, Jiangxi Province, China (28°16′15.79″ N, 115°07′04.41″ E). The research area has a typical subtropical monsoon climate with an annual average temperature of 17.6 °C, annual average precipitation of 1718.4 mm, and average frostless period of 276 d. The soil properties of the experimental site were: pH 5.03 (H_2O), organic matter 53.85 g/kg, total N (TN) 1.61 g/kg, available N (AN) 118.06 mg/kg, total P (TP) 528.40 mg/kg, and available P (AP) 40.83 mg/kg.

NPK fertilizer (N 148.35 kg/ha, P_2O_5 34.27 kg/ha, K_2O 65.36 kg/ha) was used as the base fertilizer for early and late rice before planting. For early planting, NPK fertilizer application was the only base fertilizer. However, for late planting, additional NPK fertilizer (N 11.25 kg/ha, P_2O_5 4.91 kg/ha, K_2O 9.34 kg/ha) was used as a top application at the tiller stage. The field experiment was conducted with five levels of Si nutrient treatments for both early and late plantings:

control (no Si supplement), S1 (Si 7.8 kg/ha), S2 (Si 15.6 kg/ha), S3 (Si 23.4 kg/ha), and S4 (Si 31.2 kg/ha). Si nutrient was applied in the form of Na_2SiO_3, and there were three replicates of each nutrient treatment. Each test area was ditched, ridged, and covered with plastic sheeting to prevent fertilizer flow from one test area into another. Other field management operations were maintained in line with the local custom.

2.3 Plant harvest sampling and determination of N and P content in plant tissues

At harvest, five rice samples were collected from random locations in each of the 15 experimental plots. The samples were soon dried to a constant weight in the laboratory for determination of economic characters. The roots, stems, leaves, brown rice, and rice glumes from those samples were then separated, crushed, and sieved to 0.3 mm prior to determination of their N and P content.

Plant tissue samples after crushing (0.1 g) were digested in 5 mL concentrated H_2SO_4 and dozens of drops of 30% H_2O_2 for about 2.5 h in a far-infrared temperature-controlled digestion furnace (LWY84B, GELAIMO Co., Ltd., Wuhan, China). Then the samples were transferred into 100-mL volumetric flasks, and the N concentration in the digested solution was analyzed using a total organic carbon (TOC) analyzer (Multi N/C 3100, Analytikjena Co., Ltd., Jena, Germany). The P concentration in the digested solution was determined by the colorimetric molybdenum blue method at 700 nm (Bao, 2011).

2.4 Soil sampling and physicochemical analysis

Soil samples were collected from the experimental field at the tiller and maturation stages from each of the 15 plots. In each plot, five soil cores were collected from random locations and then pooled to form a composite field plot sample. After returning to the laboratory, the soil samples were divided into two parts. One part was screened through a 2-mm sieve and stored at 4 °C for later determination of soil microbial biomass carbon (MBC), soil microbial biomass nitrogen (MBN), and soil microbial biomass phosphorus (MBP). The other fraction was air-dried for determination of soil physicochemical properties.

TN in 1 g soil samples digested with 5 mL of concentrated H_2SO_4 was determined using a TOC analyzer (Multi N/C 3100, Analytikjena). AN in 2 g samples of soil extracted by 10 mL 1 mol/L NaOH was determined by the alkali-diffusion method. TP in 1 g soil samples digested with 8 mL concentrated H_2SO_4 and 10 drops $HClO_4$ was determined by the colorimetric molybdenum blue method at 700 nm (Bao, 2011). AP in 1 g soil samples extracted by 7 mL 0.03 mol/L NH_4F and 0.025 mol/L HCl was determined by the colorimetric molybdenum blue method at 700 nm. Soil MBC, MBN, and MBP were determined by the chloroform ($CHCl_3$) fumigation extraction method (Vance et al., 1987; Qi et al., 2018).

2.5 Statistical analysis

Because the data from 2017 and 2018 showed the same trends and few differences between years, they were averaged and are presented as means with standard deviations. The data were subjected to analysis of variance (ANOVA) with least significant-difference (LSD) tests and correlation analysis using Microsoft Excel (Microsoft Co., Ltd., Redmond, WA, USA) and IBM SPSS Statistics 20 software (SPSS Inc., Chicago, IL, USA).

3 Results

3.1 Effects of supplying Si nutrient on rice growth and yield in a hybrid rice double-cropping system

The growth parameters of the rice with Si fertilizer application differed from those of controls with no supplementation (Table 1). Differences between treated and control plots in average plant height and straw biomass were not significant, but in plots with Si fertilizer application there were some significant increases in effective tiller rate, 1000-grain weight, and grain yields in both early and late plantings. Compared to the control group, the most significant increases were achieved by applying 23.4 kg/ha Si. In early plantings, the effective tiller rate increased by up to 83.8%, 1000-grain weight by up to 1.9% (21.9 g), and grain yield by up to 9.0% (9980 kg/ha). In late plantings, the effective tiller rate increased by up to 94.2%, 1000-grain weight by up to 3.2% (19.4 g), and grain yield by up to 13.7% (10708 kg/ha).

3.2 Effects of supplying Si nutrient on N and P nutrient uptakes from soil and N and P utilization rates of fertilizer by rice

The N and P nutrient uptakes from soil and N and P utilization rates of fertilizer of both early and

Table 1 Effects of different levels of Si nutrient application on growth and yield in a hybrid rice double-cropping system

Si treatment level	Early planting				
	Plant height (cm)	Straw biomass (g)	Effective tiller rate (%)	1000-Grain weight (g)	Grain yield (kg/ha)
CK	89.3±1.0^{b}	19.7±2.7^{a}	62.3±2.2^{c}	21.5±0.3^{a}	9156±138^{c}
S1	91.8±1.0^{a}	22.0±1.7^{a}	66.8±4.8^{c}	21.6±0.5^{a}	9324±201^{c}
S2	91.3±1.5^{a}	21.5±1.2^{a}	78.0±1.4^{ab}	21.7±0.3^{a}	9641±114^{b}
S3	90.5±0.6^{ab}	20.3±1.0^{a}	83.8±6.9^{a}	21.9±0.3^{a}	9980±117^{a}
S4	91.3±1.0^{a}	20.4±1.3^{a}	73.5±3.9^{b}	20.5±0.4^{b}	9303±189^{c}

Si treatment level	Late planting				
	Plant height (cm)	Straw biomass (g)	Effective tiller rate (%)	1000-Grain weight (g)	Grain yield (kg/ha)
CK	99.0±1.0^{a}	30.2±2.4^{a}	83.1±7.7^{b}	18.8±0.1^{c}	9417±781^{b}
S1	101.0±2.0^{a}	32.4±1.8^{a}	85.9±8.9^{ab}	19.0±0.1^{b}	9794±898^{ab}
S2	100.7±1.5^{a}	31.2±0.6^{a}	89.7±5.5^{ab}	19.3±0.1^{a}	10439±566^{ab}
S3	99.7±0.6^{a}	30.4±0.8^{a}	94.2±4.5^{a}	19.4±0.1^{a}	10708±460^{a}
S4	100.3±0.6^{a}	30.5±2.8^{a}	88.9±5.8^{ab}	19.2±0.1^{a}	10139±585^{ab}

Plants were cultivated without Si fertilizer (CK) or with application of Si nutrient at a dose of 7.8 kg/ha (S1), 15.6 kg/ha (S2), 23.4 kg/ha (S3), or 31.2 kg/ha (S4). Values are expressed as mean±standard deviation (SD; n=6; averaged over two years); different letters in the same column indicate significant differences between treatments at P<0.05

late plantings were clearly increased with the addition of Si compared with the control without Si addition (Table 2). The N and P uptakes and utilization rates of both early and late plantings first increased, peaking at 23.4 kg/ha additional Si, and then decreased as the level of Si addition increased. Compared to the control, in the early planting, the N uptake from soil increased by up to 15.0% and the P uptake by up to 6.4%. The N fertilizer utilization rate increased by up to 51.9% and the P utilization rate by up to 26.8%. In the late planting, the N uptake increased by up to 26.2% and the P uptake by up to 15.8%. The N fertilizer utilization rate increased by up to 65.0% and the P utilization rate by up to 77.7%. Accordingly, an appropriate application of Si to paddy soil in a hybrid rice double-cropping system could significantly increase the N and P fertilizer utilization rates, making it feasible to reduce the input of chemical fertilizers in agricultural production in the future.

3.3 Effects of supplying Si nutrient on availabilities of soil N and P nutrients

The amounts of AN and AP nutrients in proportion to the TN and TP in soil, respectively, can be used to evaluate the N and P nutrient status of soil. Within the five levels of Si application set in the experiment in each of the two years, the average ratios of AN/TN and AP/TP in the paddy soil increased first and then decreased with increasing levels of Si nutrient supplied during early or late planting in the hybrid rice double-cropping system (Table 3). Compared to the control, the most significant increases in mineralization of soil N and P were achieved by supplying 23.4 kg/ha Si. The effects were more obvious at the tiller stage than at the maturation stage. In the early planting, at the tiller stage the AN/TN ratio increased by up to 14.1% and the AP/TP ratio by up to 45.0%. At the maturation stage, the AN/TN ratio increased by 11.9% and the AP/TP ratio by 35.9%. In the late planting, at the tiller stage the AN/TN ratio increased by up to 19.6% and the AP/TP ratio by up to 103.6%. At the maturation stage, the AN/TN ratio increased by 14.3% and the AP/TP ratio by 90.0%.

3.4 Effects of supplying Si nutrient on soil microbial biomass C, N, and P

The average soil MBC, MBN, and MBP increased significantly with added Si fertilizer compared with the control at the tiller stage in the hybrid rice double-cropping system (Table 4). Within the five levels of Si application set in each year of the experiment, soil MBC, MBN, and MBP first increased and then decreased with increasing Si nutrient supplied following early or late planting. All three biomass parameters reached a maximum at an application of 23.4 kg/ha Si. In the early planting, the soil

Table 2 Effects of different levels of Si nutrient application on N and P nutrient uptakes from soil and N and P utilization rates of fertilizer by rice in a hybrid rice double-cropping system

Si treatment level	Early planting				Late planting			
	Nutrient uptake (kg/ha)		Utilization rate of fertilizer (%)		Nutrient uptake (kg/ha)		Utilization rate of fertilizer (%)	
	N	P	N	P	N	P	N	P
CK	136.2±2.3^{d}	31.2±0.4^{b}	28.7±1.7^{d}	24.6±1.3^{b}	147.5±3.7^{c}	50.5±1.0^{c}	28.0±1.1^{c}	21.1±0.4^{d}
S1	145.9±0.8^{c}	31.6±0.3^{b}	35.8±0.6^{c}	25.8±1.0^{b}	160.7±3.2^{b}	56.0±1.8^{b}	35.1±1.8^{b}	26.7±1.4^{c}
S2	150.6±0.3^{b}	31.9±0.5^{b}	39.2±0.3^{b}	26.7±1.7^{b}	163.1±1.6^{b}	56.3±1.5^{ab}	37.0±0.8^{b}	35.1±0.4^{b}
S3	156.6±1.3^{a}	33.2±0.5^{a}	43.6±1.0^{a}	31.2±1.6^{a}	186.2±11.0^{a}	58.5±1.2^{a}	46.2±0.8^{a}	37.5±1.1^{a}
S4	146.6±1.0^{c}	31.5±0.3^{bc}	36.3±0.8^{c}	25.4±1.0^{b}	159.1±4.0^{b}	47.6±0.2^{d}	36.1±0.6^{b}	26.5±1.3^{c}

Plants were cultivated without Si fertilizer (CK) or with application of Si nutrient at a dose of 7.8 kg/ha (S1), 15.6 kg/ha (S2), 23.4 kg/ha (S3), or 31.2 kg/ha (S4). Values are expressed as mean±standard deviation (SD; n=6; averaged over two years); different letters in the same column indicate significant differences between treatments at P<0.05

Table 3 Effects of different levels of Si nutrient application on mineralization of soil N and P nutrients in a hybrid rice double-cropping system

Si treatment level	Early planting				Late planting			
	Tiller stage		Maturation stage		Tiller stage		Maturation stage	
	AN/TN (%)	AP/TP (%)	AN/TN (%)	AP/TP (%)	AN/TN (%)	AP/TP (%)	AN/TN (%)	AP/TP (%)
CK	7.1±0.1^{c}	8.0±0.4^{d}	6.7±0.2^{d}	7.8±0.3^{d}	9.8±0.1^{b}	8.3±0.5^{d}	8.4±0.4^{b}	8.0±0.2^{e}
S1	7.3±0.2^{bc}	9.9±0.2^{c}	7.1±0.1^{bc}	9.0±0.5^{c}	10.3±0.4^{b}	12.3±1.2^{c}	8.7±0.3^{ab}	11.3±0.8^{d}
S2	7.6±0.3^{b}	10.9±0.6^{ab}	7.3±0.1^{b}	9.8±0.2^{b}	11.3±0.7^{a}	15.0±0.6^{b}	9.3±0.8^{a}	14.5±0.4^{b}
S3	8.1±0.2^{a}	11.6±0.3^{a}	7.5±0.1^{a}	10.6±0.5^{a}	11.8±0.4^{a}	16.9±1.2^{a}	9.6±0.1^{a}	15.2±0.1^{a}
S4	7.3±0.2^{bc}	10.1±0.7^{bc}	7.1±0.1^{c}	9.3±0.2^{bc}	11.0±0.4^{b}	13.5±3.2^{bc}	9.1±0.3^{ab}	12.8±0.6^{c}

Plants were cultivated without Si fertilizer (CK) or with application of Si nutrient at a dose of 7.8 kg/ha (S1), 15.6 kg/ha (S2), 23.4 kg/ha (S3), or 31.2 kg/ha (S4). Values are expressed as mean±standard deviation (SD; n=6; averaged over two years); different letters in the same column indicate significant differences between treatments at P<0.05. AN: available nitrogen; TN: total nitrogen; AP: available phosphorus; TP: total phosphorus

Table 4 Effects of different levels of Si nutrient application on soil MBC, MBN, and MBP at the tiller stage in a hybrid rice double-cropping system

Si treatment level	Early planting				
	MBC (mg/kg)	MBN (mg/kg)	MBP (mg/kg)	MBN/TN (%)	MBP/TP (%)
CK	682.5±12.1^{c}	30.2±1.2^{d}	8.6±0.4^{e}	1.8±0.0^{c}	1.6±0.1^{e}
S1	699.9±6.7^{c}	34.8±0.9^{c}	11.0±1.4^{d}	2.1±0.1^{c}	2.3±0.2^{d}
S2	774.6±5.0^{b}	41.7±0.9^{b}	16.7±0.6^{b}	2.7±0.3^{b}	3.4±0.2^{b}
S3	843.4±10.3^{a}	54.4±1.2^{a}	19.9±1.0^{a}	3.2±0.1^{a}	3.9±0.3^{a}
S4	688.2±11.8^{d}	36.0±0.5^{c}	13.3±1.3^{c}	2.4±0.0^{b}	2.9±0.3^{c}

Si treatment level	Late planting				
	MBC (mg/kg)	MBN (mg/kg)	MBP (mg/kg)	MBN/TN (%)	MBP/TP (%)
CK	772.3±10.3^{d}	35.7±1.7^{d}	9.4±0.6^{d}	1.7±0.1^{d}	1.1±0.1^{c}
S1	808.4±13.7^{c}	42.8±4.8^{c}	12.7±1.8^{c}	2.0±0.3^{cd}	1.5±0.2^{c}
S2	843.8±6.6^{b}	47.5±3.2^{c}	19.1±0.8^{b}	2.3±0.2^{bc}	2.2±0.1^{b}
S3	871.7±16.4^{a}	61.6±3.9^{a}	23.6±3.3^{a}	3.0±0.2^{a}	2.8±0.4^{a}
S4	804.7±10.3^{c}	55.0±3.0^{b}	10.8±1.3^{cd}	2.6±0.2^{b}	1.3±0.2^{c}

Plants were cultivated without Si fertilizer (CK) or with application of Si nutrient at a dose of 7.8 kg/ha (S1), 15.6 kg/ha (S2), 23.4 kg/ha (S3), or 31.2 kg/ha (S4). Values are expressed as mean±standard deviation (SD; n=6; averaged over two years); different letters in the same column indicate significant differences between treatments at P<0.05. MBC: microbial biomass carbon; MBN: microbial biomass nitrogen; MBP: microbial biomass phosphorus; TN: total nitrogen; TP: total phosphorus

MBC increased by up to 23.6%, MBN by up to 80.1%, and MBP by up to 131.4% compared with the control. In the late planting, the soil MBC increased by up to 12.9%, MBN by up to 72.5%, and MBP by up to 151.0%. Similar trends were found for the ratios of MBN/TN and MBP/TP following different levels of Si fertilizer application. The results showed that Si nutrient application could enhance the immobilization of soil N and P by soil microorganisms to form reserves of organic N and P nutrients, which could decrease the risk of N and P loss in runoff from paddy fields.

3.5 Correlation analysis

Correlation analysis was used to reveal the relationships among factors responding to Si application during early or late planting in the hybrid rice double-cropping system (Tables 5 and 6). Table 5 shows clear positive correlations between yield and the efficiency of N and P fertilizer uses, AN/TN, MBN/TN, AP/TP, MBP/TP, and MBC, with correlation coefficients (r) ranging from 0.830 to 0.995. Strong correlations between N utilization rates of fertilizer and the AN/TN and MBN/TN ratios (r=0.918–0.952), P utilization rates of fertilizer and AP/TP and MBP/TP (r=0.811–0.974), and N and P utilization rates of fertilizer and MBC (r=0.868–0.990), showed a clear link between fertilizer use efficiency, the mineralization of soil nutrients, and the reserves of organic nutrients. These findings provide evidence that Si nutrient application could promote soil N and P mineralization and increase reserves of organic N and P nutrients that are easy to mineralize, thereby increasing the fertilizer use efficiency and grain yield of rice.

Table 6 shows the correlations between the mineralization of soil N and P and the reserves of organic N and P (MBN, MBP) and the total amount of soil microorganisms (MBC). The results showed strong correlations (r=0.836–0.973) between MBC and the AN/TN and AP/TP ratios in the paddy soil at the tiller stage following early or late planting. This suggests that the increase in the total amount of soil microorganisms could promote mineralization of soil nutrients, thereby improving their availability. There were also strong correlations (r=0.868–0.994) between MBN, MBP and the AN/TN and AP/TP ratios in the paddy soil at the tiller stage following early or late planting, demonstrating that MBN and MBP had made important contributions to the contents of AN and AP in the paddy soil, and that MBN and MBP were important reserves of organic N and P, respecitvely, in the soil in this hybrid rice double-cropping system.

Table 5 Coefficients (*r*) of correlation between grain yield and N and P use efficiencies of fertilizer, mineralization of soil N and P nutrients, and the reserves of organic N and P nutrients in a hybrid rice double-cropping system

Factor	Early planting			Late planting		
	N use efficiency	P use efficiency	Grain yield	N use efficiency	P use efficiency	Grain yield
N use efficiency			0.925*			0.925*
P use efficiency			0.959*			0.958*
AN/TN	0.952**		0.995**	0.918*		0.993**
MBN/TN	0.951**		0.957**	0.935*		0.948*
AP/TP		0.811	0.891*		0.944*	0.969**
MBP/TP		0.828	0.915*		0.974**	0.830
MBC	0.868	0.948*	0.991**	0.945*	0.990**	0.956*

** $P<0.01$, * $P<0.05$ (n=6). N: nitrogen; P: phosphorus; AN: available N; TN: total N; MBN: microbial biomass N; AP: available P; TP: total P; MBP: microbial biomass P; MBC: microbial biomass carbon

Table 6 Coefficients (*r*) of correlation between the reserves of organic N and P nutrients and mineralization of soil N and P nutrients in a hybrid rice double-cropping system at the tiller stage

Factor	Early planting		Late planting	
	AN/TN	AP/TP	AN/TN	AP/TP
MBN	0.994**		0.897*	
MBP		0.942*		0.868
MBC	0.973**	0.836	0.943*	0.956*

** $P<0.01$, * $P<0.05$ (n=6). N: nitrogen; P: phosphorus; AN: available N; TN: total N; AP: available P; TP: total P; MBN: microbial biomass N; MBP: microbial biomass P; MBC: microbial biomass carbon

In summary, our results indicate that the key ecological mechanism for the improvement of N and P uptakes by rice with Si application involved a significant increase of the total amount of soil microorganisms in the paddy soil compared to the control in the hybrid rice double-cropping system. This contributed to the mineralization of N and P and the increased contents of organic N and P (MBN and MBP). Application of Si increased the total amount of soil microorganisms, thereby enhancing the mineralization, availability, and reserves of soil organic N and P in microorganisms. These effects consequently enhanced rice growth and increased the utilization rates of N and P.

4 Discussion

As a beneficial element, many studies have led to the conclusion that an optimum Si nutrient supply enhances nutrient use efficiency by plants at the whole-plant level and in such way that vegetative and generative biomass are improved simultaneously (Schaller et al., 2012, 2016, 2019; Mehrabanjoubani et al., 2015; Pati et al., 2016; Neu et al., 2017; Reithmaier et al., 2017). Under a normal base fertilizer regime, our results revealed that grain yield was increased as a function of Si nutrient supply during 2017 and 2018. However, when the application of Si nutrient was 23.4 kg/ha, grain yield was higher while straw biomass was lower than those under lower applications of Si (Table 1). This was in agreement with the results of Neu et al. (2017) who showed that with an appropriate Si nutrient supply, a change in resource allocation could lead to improved generative biomass at the expense of vegetative biomass. However, higher levels of Si nutrient supply might lead to a stress response with a negative impact on plant growth and nutrient accumulation (Eneji et al., 2008; Schaller et al., 2012). This may explain the decreased grain yield at higher levels of Si nutrient supply observed in our study (Table 1). Taken together, these results suggest that Si exerts either a positive or negative influence depending on the amount of Si applied (Eneji et al., 2008; Schaller et al., 2012).

The utilization rate of fertilizer and productivity of rice can be influenced by many factors, such as soil nutrient status, fertilization custom, and rice genotype. Several studies conducted in soil and hydroponic systems have revealed the effect of Si nutrient in enhancing plant growth. Several kinds of mechanism have been proposed to explain this phenomenon, including a change of soil pH, decreasing rhizosphere toxic aluminum (Al) species reducing root damage, increased availability of P by P replacement from binding sites of soil minerals, up-regulation of the expression of transporter genes for P uptake, and the induction of root responses including the promotion of organic acid secretion (Pavlovic et al., 2013; Ryan et al., 2014; Kostic et al., 2015, 2017; Huang et al., 2016). However, experimental evidence for the ecological mechanisms underlying the effect of Si on enhancing plant growth and nutrient accumulation is still extremely scarce. Previous studies have demonstrated that Si nutrient as the sole stimulating effect promotes shoot P accumulation even without a soil pH change, and as P has a higher affinity than Si to possible binding sites, Si could not displace P from such sites in soil (Ma and Yamaji, 2008, 2015; Kostic et al., 2017). Studies conducted with *P. australis* have proved that Si nutrient supply might not only influence the Si cycle, but also the P cycle in soil ecosystems (Vance et al., 1987; Debona et al., 2017). Si nutrient supply might increase the utilization rate of fertilizer by promoting N and P nutrient cycles in the plant–soil ecosystem (Reithmaier et al., 2017; Schaller et al., 2019). Our study revealed for the first time the ecological mechanism of an active effect of Si on a plant–soil ecosystem in a double-cropping rice area (Tables 5 and 6). Si nutrient was shown to have an indirect effect by improving the total amount of soil microorganisms, enhancing the immobilization of soil N and P as reserves of organic N and P nutrients, and promoting the mineralization of N and P, therefore enhancing their subsequent availability in soil.

In this study, grain yields of both early and late rice plantings showed a significant improvement with application of Si. The grain yields of both plantings were maximized when 23.4 kg/ha Si was applied (Table 1). The AN/TN, AP/TP, MBN, and MBP showed marked increases with Si nutrient application, and similar trends were found for MBN/TN and MBP/TP ratios under the same conditions. When 23.4 kg/ha Si was applied to early plantings, AN/TN increased by 14.1%, AP/TP by 45.0%, MBN by 80.1%, MBP by 131.4%, MBN/TN by 77.7%, and MBP/TP by 143.8% compared with the control (Tables 3 and 4). Late planted rice showed the same trend, which indicated that Si application could lead to increased availabilities of N and P and the reserves of organic N and P in the soil (Tables 3 and 4). Correlations between grain yield and N and P fertilizer utilization rates and AN/TN, AP/TP, MBN/TN, and MBP/TP, and between grain yield and N and P fertilizer utilization rates were all significant (Table 5). This provided further evidence that the increased availabilities of soil N and P and reserves of organic N and P that are easy to mineralize were important factors contributing to improved fertilizer use efficiency and grain yield of rice in this hybrid rice double-cropping system.

Soil microorganisms are the main drivers of material circulation in soil–plant systems. Through their metabolism, they have the power to transform and circulate soil organic matter and nutrients, and provide a storehouse of available nutrients in soil. MBC, determined by $CHCl_3$ fumigation extraction method, as an indicator of the total amount of soil microorganisms, was increased by Si application. When 23.4 kg/ha Si was applied, MBC peaked, with increases of 23.6% following early planting and 12.9% following late planting, compared with the control (Table 4). Other studies have demonstrated that soil microorganisms play an important role in the decomposition and synthesis of soil organic matter, which is a significant source of the reserves of soil nutrients available for plant growth (Sinha et al., 2009; Canakci et al., 2015; Kalantary and Kahani, 2015; Khaleghi and Rowshanzamir, 2019). There were strong correlations (r=0.836–0.994) among MBC, AN/TN, and AP/TP and among MBN, MBP, AN/TN, and AP/TP, indicating that the increase in the total amount of soil microorganisms with Si nutrient supply was an important factor for increasing the availabilities of soil N and P, and that MBN and MBP as reserves of organic N and P made important contributions to the content of AN and AP. Correlations between MBC, AN/TN, and AP/TP were also strong (r=0.836–0.973; Table 6), indicating that increasing the total amount of soil microorganisms was effective in enhancing the availabilities of soil N and P. Taken together, the increase in the total amount of soil microorganisms with Si nutrient supply effectively improved the soil nutrient status, resulting in increased rice yield and N and P fertilizer utilization rates in this hybrid rice double-cropping system. Moreover, root exudates could influence the microbial community structure in the rhizosphere (Huang et al., 2014). Conversely, a change in the rhizosphere microbial community structure could have an important influence on the secretion of plant root exudates, soil nutrient cycling, energy flow, and information transmission (Eisenhauer et al., 2012). Some studies suggested that Si supply could promote organic acid secretion from roots to activate soil nutrients by changing the rhizosphere environment (Toyama et al., 2011; Karunakaran et al., 2013). A previous study by Kostic et al. (2017) attributed better wheat growth in low-P soil following application of Si to increased malate and citrate exudation rates and up-regulated expression of transporter genes for P uptake. Some studies have shown that root exudates extracted from corn seeds play a role in promoting transformation of soil N from inorganic N to organic N (Raza et al., 2016). However, except for the organic acids of root exudates, little is known about the components and the interaction between Si, roots of rice, and soil, under conditions with varied Si nutrient supply. The effects of Si nutrient supply on the ecological structure of soil microorganisms and the amount of functional microorganisms related to soil N and P biological fixation and metabolism might be the key ecological mechanisms for improving N and P uptake by rice. In our study, Si nutrient application increased Si nutrient supply, resulting in a significant increase in the total amount of soil microorganisms in paddy soil compared to the control, in a hybrid rice double-cropping system.

5 Conclusions

An appropriate Si nutrient supply could significantly improve the yield of rice and the utilization rates of N and P fertilizers. Within the five levels of Si application set in the experiment, the grain yield and N and P utilization rates all reached a maximum at an Si supply level of 23.4 kg/ha. On average, grain yield increased by 11.4%, N utilization rate by 58.5%, and P utilization rate by 52.3% compared to the control without supplementary Si, for both early and late plantings in the hybrid rice double-cropping system.

An appropriate Si nutrient supply could significantly promote the mineralization of soil N and P and improve the reserves of organic N and P (MBN and

MBP). Within the five levels of Si application set in the experiment, AN/TN, AP/TP, MBC, MBN, and MBP first increased and then decreased as Si nutrient supply increased, and all reached a maximum at the application of 23.4 kg/ha Si in paddy soil during plantings of early and late rice in the hybrid rice double-cropping system.

The correlation coefficients among N and P fertilizer utilization rates and AN/TN, AP/TP, MBN/TN, and MBP/TP were in the range of 0.811–0.974 (Table 5), and those among MBC, MBN, and MBP and AN/TN and AP/TP were in the range of 0.836–0.994 (Table 6). This suggests that the stimulatory effect of increasing Si nutrient supply on growth in a hybrid rice double-cropping system and the increases in N and P fertilizer utilization rates might primarily be attributable to an increase in the content of available nutrients and improvement in the reserves of organic nutrients that resulted from an increase in the total amount of soil microorganisms.

Si nutrient supplementation could be an effective and sustainable method for improving the efficiencies of N and P fertilizer uses and alleviating agricultural non-point source pollution caused by the input of chemical fertilizers in a hybrid rice double-cropping system.

Contributors

Min LIAO and Xiao-mei XIE participated in the study design, data analysis, writing and editing of the manuscript. Zhi-ping FANG, Yu-qi LIANG, Xiao-hui HUANG, Xu YANG, Shu-sen CHEN, Chang-xu XU, and Jia-wen GUO performed the experimental research and data analysis. All authors have read and approved the final manuscript and, therefore, have full access to all the data in the study and take responsibility for the integrity and security of the data.

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Compliance with ethics guidelines

Min LIAO, Zhi-ping FANG, Yu-qi LIANG, Xiao-hui HUANG, Xu YANG, Shu-sen CHEN, Xiao-mei XIE, Chang-xu XU, and Jia-wen GUO declare that they have no conflict of interest.

This article does not contain any studies with human or animal subjects performed by any of the authors.

References

Bao SD, 2011. Soil Agrochemical Analysis. China Agriculture Press, Beijing, China, p.39-61, 264-268 (in Chinese).

Canakci H, Sidik W, Kilic IH, 2015. Effect of bacterial calcium carbonate precipitation on compressibility and shear strength of organic soil. *Soils Found*, 55(5):1211-1221. https://doi.org/10.1016/j.sandf.2015.09.020

Cao HS, Zhou L, Su Y, et al., 2016. Non-specific phospholipase C1 affects silicon distribution and mechanical strength in stem nodes of rice. *Plant J*, 86(4):308-321. https://doi.org/10.1111/tpj.13165

Debona D, Rodrigues FA, Datnoff LE, 2017. Silicon's role in abiotic and biotic plant stresses. *Annu Rev Phytopathol*, 55:85-107. https://doi.org/10.1146/annurev-phyto-080516-035312

Eisenhauer N, Scheu S, Jousset A, 2012. Bacterial diversity stabilizes community productivity. *PLoS ONE*, 7(3):e34517. https://doi.org/10.1371/journal.pone.0034517

Eneji AE, Inanaga S, Muranaka S, et al., 2008. Growth and nutrient use in four grasses under drought stress as mediated by silicon fertilizers. *J Plant Nutr*, 31(2):355-365. https://doi.org/10.1080/01904160801894913

Fan XY, Lin WP, Liu R, et al., 2018. Physiological response and phenolic metabolism in tomato (*Solanum lycopersicum*) mediated by silicon under *Ralstonia solanacearum* infection. *J Integr Agric*, 17(10):2160-2171. https://doi.org/10.1016/S2095-3119(18)62036-2

Huang GY, Guo GG, Yao SY, 2016. Organic acids, amino acids compositions in the root exudates and Cu-accumulation in castor (*Ricinus communis* L.) under Cu stress. *Int J Phytoremediat*, 18(1):33-40. https://doi.org/10.1080/15226514.2015.1058333

Huang XF, Chaparro JM, Reardon KF, et al., 2014. Rhizosphere interactions: root exudates, microbes, and microbial communities. *Botany*, 92(4):267-275. https://doi.org/10.1139/cjb-2013-0225

Kalantary F, Kahani M, 2015. Evaluation of the ability to control biological precipitation to improve sandy soils. *Procedia Earth Planet Sci*, 15:278-284. https://doi.org/10.1016/j.proeps.2015.08.067

Karunakaran G, Suriyaprabha R, Manivasakan P, et al., 2013. Effect of nanosilica and silicon sources on plant growth promoting rhizobacteria, soil nutrients and maize seed germination. *IET Nanobiotechnol*, 7(3):70-77. https://doi.org/10.1049/iet-nbt.2012.0048

Khaleghi M, Rowshanzamir MA, 2019. Biologic improvement of a sandy soil using single and mixed cultures: a comparison study. *Soil Till Res*, 186:112-119. https://doi.org/10.1016/j.still.2018.10.010

Kostic L, Nikolic N, Samardzic J, et al., 2015. Liming of anthropogenically acidified soil promotes phosphorus acquisition in the rhizosphere of wheat. *Biol Fertil Soils*, 51(3):289-298. https://doi.org/10.1007/s00374-014-0975-y

Kostic L, Nikolic N, Bosnic D, et al., 2017. Silicon increases phosphorus (P) uptake by wheat under low P acid soil

conditions. *Plant Soil*, 419(1-2):447-455.
https://doi.org/10.1007/s11104-017-3364-0

Ma JF, Yamaji N, 2006. Silicon uptake and accumulation in higher plants. *Trends Plant Sci*, 11(8):392-397.
https://doi.org/10.1016/j.tplants.2006.06.007

Ma JF, Yamaji N, 2008. Functions and transport of silicon in plants. *Cell Mol Life Sci*, 65(19):3049-3057.
https://doi.org/10.1007/s00018-008-7580-x

Ma JF, Yamaji N, 2015. A cooperative system of silicon transport in plants. *Trends Plant Sci*, 20(7):435-442.
https://doi.org/10.1016/j.tplants.2015.04.007

Mehrabanjoubani P, Abdolzadeh A, Sadeghipour HR, et al., 2015. Impacts of silicon nutrition on growth and nutrient status of rice plants grown under varying zinc regimes. *Theor Exp Plant Physiol*, 27:19-29.
https://doi.org/10.1007/s40626-014-0028-9

Neu S, Schaller J, Dudel EG, 2017. Silicon availability modifies nutrient use efficiency and content, C:N:P stoichiometry, and productivity of winter wheat (*Triticum aestivum* L.). *Sci Rep*, 7:40829.
https://doi.org/10.1038/srep40829

Pati S, Pal B, Badole S, et al., 2016. Effect of silicon fertilization on growth, yield, and nutrient uptake of rice. *Commun Soil Sci Plan Anal*, 47(3):284-290.
https://doi.org/10.1080/00103624.2015.1122797

Pavlovic J, Samardzic J, Maksimovic V, et al., 2013. Silicon alleviates iron deficiency in cucumber by promoting mobilization of iron in the root apoplast. *New Phytol*, 198(4):1096-1107.
https://doi.org/10.1111/nph.12213

Qi YB, Chen T, Pu J, et al., 2018. Response of soil physical, chemical and microbial biomass properties to land use changes in fixed desertified land. *CATENA*, 160:339-344.
https://doi.org/10.1016/j.catena.2017.10.007

Raza W, Wang JC, Wu YC, 2016. Effects of volatile organic compounds produced by *Bacillus amyloliquefaciens* on the growth and virulence traits of tomato bacterial wilt pathogen *Ralstonia solanacearum*. *Appl Microbiol Biotechnol*, 100(17):7639-7650.
https://doi.org/10.1007/s00253-016-7584-7

Reithmaier GMS, Knorr KH, Arnhold S, et al., 2017. Enhanced silicon availability leads to increased methane production, nutrient and toxicant mobility in peatlands. *Sci Rep*, 7:8728.
https://doi.org/10.1038/s41598-017-09130-3

Ryan PR, James RA, Weligama C, et al., 2014. Can citrate efflux from roots improve phosphorus uptake by plants? Testing the hypothesis with near-isogenic lines of wheat. *Physiol Plant*, 151(3):230-242.
https://doi.org/10.1111/ppl.12150

Saudy HS, Mubarak M, 2015. Mitigating the detrimental impacts of nitrogen deficit and fenoxaprop-p-ethyl herbicide on wheat using silicon. *Commun Soil Sci Plan*, 46(7): 897-907.
https://doi.org/10.1080/00103624.2015.1011753

Schaller J, Brackhage C, Gessner MO, et al., 2012. Silicon supply modifies C:N:P stoichiometry and growth of *Phragmites australis*. *Plant Biol*, 14(2):392-396.
https://doi.org/10.1111/j.1438-8677.2011.00537.x

Schaller J, Schoelynck J, Struyf E, et al., 2016. Silicon affects nutrient content and ratios of wetland plants. *Silicon*, 8(4): 479-485.
https://doi.org/10.1007/s12633-015-9302-y

Schaller J, Faucherre S, Joss H, et al., 2019. Silicon increases the phosphorus availability of Arctic soils. *Sci Rep*, 9:449.
https://doi.org/10.1038/s41598-018-37104-6

Sinha S, Masto RE, Ram LC, et al., 2009. Rhizosphere soil microbial index of tree species in a coal mining ecosystem. *Soil Biol Biochem*, 41(9):1824-1832.
https://doi.org/10.1016/j.soilbio.2008.11.022

Toyama T, Furukawa T, Maeda N, et al., 2011. Accelerated biodegradation of pyrene and benzo[*a*]pyrene in the *Phragmites australis* rhizosphere by bacteria–root exudate interactions. *Water Res*, 45(4):1629-1638.
https://doi.org/10.1016/j.watres.2010.11.044

van Bockhaven J, de Vleesschauwer D, Höfte M, 2013. Towards establishing broad-spectrum disease resistance in plants: silicon leads the way. *J Exp Bot*, 64(5):1281-1293.
https://doi.org/10.1093/jxb/ers329

Vance ED, Brookes PC, Jenkinson DS, 1987. An extraction method for measuring soil microbial biomass C. *Soil Biol Biochem*, 19(6):703-707.
https://doi.org/10.1016/0038-0717(87)90052-6

中文概要

题　目：硅养分补充对双季杂交稻系统水稻氮磷养分利用率的影响及其土壤生态机制

目　的：揭示双季杂交稻系统中硅（Si）养分补充对水稻养分利用率与对土壤养分有效性影响的相应关系及其生态机制。

创新点：发现一定量的 Si 养分补充可提高稻田土壤氮（N）和磷（P）养分的有效性，并促进水稻根系对养分的吸收，从而提高水稻产量及肥料利用率。其核心生态机制是补充 Si 养分可显著增加稻田土壤的微生物总量，从而促进土壤养分同化固定，提高土壤中 N 和 P 的矿化以及易矿化的土壤微生物量氮（MBN）和土壤微生物量磷（MBP）的储备。

方　法：2017 和 2018 连续两年，在双季稻作区设计了系列田间试验，统一常规养分管理，于早稻和晚稻种植期间设置五个有效 Si 用量梯度处理（即 0（对照）、7.8、15.6、23.4 和 31.2 kg/ha Si），分析收获后的水稻生长性状（株高、籽粒产量、植株生物量等），水稻根、茎、叶和籽粒中 N 和 P 的含量，土壤有效态 N 和 P 的含量以及土壤微生物量碳（MBC）、MBN 和 MBP 的含量，最后统计分析 Si 的供应与对水稻 N 和 P 养分利用率、土

壤养分有效性、MBC、MBN和MBP的影响及其相互关系。

结　论：Si养分补充可增加双季杂交稻系统土壤微生物总量，促进土壤养分同化固定，提高土壤养分的有效性以及易矿化的有机养分的储备，使得土壤养分易于被水稻根系吸收利用，从而提高水稻肥料利用率，促进水稻的生长发育，提高水稻产量。其中Si施用量为23.4 kg/ha时双季水稻产量及N和P肥利用率均达到最大值，此时土壤有效态氮与总氮比（AN/TN）、有效态磷与总磷比（AP/TP）以及MBN和MBP也均达到最大值。上述结果表明，通过Si养分补充可适当削减双季杂交稻系统因过多化学肥料投入带来的面源污染问题。

关键词：硅养分；肥料利用率；生态机制；双季稻系统