Impact of Soil Fertility in 92 Paddy Fields of Kanto Region

Dongpo Li, Teruaki Nanseki, Yosuke Chomei, and Shuichi Yokota

This chapter aimed to measure the determinants of rice yield, from the perspectives of fertilizer nitrogen and soil chemical properties. The data were sampled in 2014 and 2015, comprising 92 peat soil paddy fields, from a large-scale farm located in the Kanto Region of Japan. The rice variety was Koshihikari, which is most widely planted in Japan. The yield was measured by paddy with 15% moisture. The 12 soil chemical properties included pH, cation exchange capacity, content of pyridine base elements, phosphoric and silicic acids. The results indicated that fertilizer nitrogen affected the yield significantly, with a significant sustained effect to the subsequent year. In addition to silicic acid, magnesia positively affected the yield, in forms of its exchangeable content, saturation, ratios to potassium and lime; phosphoric acid affected the yield negatively. We measured soil chemical properties by the synthesized soil quality index and PCA. Positive effects were identified on the overall scores of both approaches, while the former performs better in explaining the rice yield. In soil quality index, the individual standardized soil properties and margins for improvement were indicated for each paddy field. Finally, multivariate regression on the principal components identified the most significant properties.

D. Li
Key Laboratory of Digital Economy and High Quality Development, School of Economics and Trade, Hunan University of Technology and Business, Changsha 410205, Hunan Province, People's Republic of China
e-mail: 791728448@qq.com

T. Nanseki (✉) · Y. Chomei
Faculty of Agriculture, Kyushu University, Fukuoka, Fukuoka Prefecture 819-0395, Japan
e-mail: nanseki@agr.kyushu-u.ac.jp

Y. Chomei
e-mail: chomei@agr.kyushu-u.ac.jp

S. Yokota
Yokota Farm Co. Ltd, Ryugasaki, Ibaraki Prefecture 301-0803, Japan
e-mail: shu@yokotanojo.co.jp

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1 Introduction

Soil is critical to crop growth in providing the growth locale and indispensable nutrients, and any degradation of soil quality may result in the decreased productivity, quality and thus profitability (Juhos et al. 2016; Li et al. 2012; Liu et al. 2014; Obade and Lal 2016). Soil properties can be measured from mainly the physical, chemical, and biological aspects (DFPJA 2011). The chemical properties typically relate more directly to the sustainability of agro-ecosystem, in addition to the variability of crop yield (Bouma 2002; Obade and Lal 2016; Qi et al. 2009). Meanwhile, comparing with the other aspects, the chemical properties are more feasibly to be improved, through proper fertilization and other farm managerial activities (Gray and Morant 2003). Thus, in narrow sense, the soil fertility refers to the chemical properties, drawing wide attentions from different aspects. Many researchers analyzed the relationship between soil chemical prosperities and rice yield. Juhos et al. (2016) constructed a soil quality index using three principal components derived from more than ten basic indicators, to evaluate the chemical and physical properties of soil and the impact on yields of maize, winter wheat and sunflower, sampled in 225 hectares farmland from east Hungary. Liu et al. (2014) analyzed the rice yield and the effect of eight soil chemical properties sampled in 13 provincial regions of south China, individually and synthetically using a soil quality index, based on PCA model adopted from Qi et al. (2009).

In Japan, rice (*Oryza sativa L.*) is the most important staple crop, and by 2015, it accounted for the largest proportion of 17% in gross agriculture output (MAFF 2016a). Japan is striving to improve the rice productivity and global competitiveness. By 2016, the total planted area of rice is estimated to be 1.57 million hectares, decreased roughly one third in the past three decades. At the same time, the aggregate production decreased by nearly 30% (MAFF 2017). Therefore, the accurate measurement of soil fertility and its yield effect is essential to promote the rice production in Japan. Some scholars have studied concerning the soil chemical properties of the paddy fields in Japan. In the estimation of the total CH_4 emission from rice paddies, Katayanagi et al. (2016) analyzed the soil chemical properties of 986 plots sampled across the country, through the individual indicators of pH (H_2O) and total carbon. Matsumoto et al. (2016) estimated the effects of iron materials applied in an experimental field at Shimane University, Matsue city of Shimane Prefecture, and the soil chemical properties were presented by the content of available arsenic and phosphorus, acid ammonium oxalate extractable iron and aluminum. To measure the effect of fermented bark as a soil amendment in the experimental site of Gunma Prefecture, Japan, Mori et al. (2016) measured the soil chemical properties using pH, CEC, oxidation-reduction potential, the content of heavy metals including cadmium, copper, and zinc. Judging from the literature, it is necessary to quantify the soil chemical properties through the adoption of synthesized indices, and the on-farm data sampled from individual paddy fields can provide more practical enlightenments.

We fulfilled the following targets in the rest sections: presented the status of fertilizer nitrogen and soil chemical properties in the sampled paddy fields; revealed effect of the fertilizer nitrogen to the rice yield; measured impact of the soil chemical properties to rice yield, through the construction of soil quality index and standardized soil properties; identified the most significant properties using PCA and multivariate regression; and summarized the empirical findings and countermeasures to improve rice yield.

2 Materials and Methods

2.1 Sample and Data

The data were sampled in 2014 and 2015, comprising 92 peat soil paddy fields, from a large-scale farm located in the Kanto Region of Japan. The rice variety was Koshihikari, which enjoys highly appreciated taste and appearance at home and abroad. By 2015, it accounted for the largest share of 36% (Komenet 2020) in the domestic rice planting area, with its strong cold resistance and stable yield (Goto et al. 2000). The rice yield was measured by the grain weight of paddy with 15% moisture. The weight and moisture content of the raw paddy were monitored by combine harvesters equipped with advanced information technologies.

Fertilizer nitrogen was calculated using the amounts of chicken manure, chemical fertilizer, ammonium sulphate, urea fertilizers, and the corresponding nitrogen contents. Based on the local technical guidance (MAFF 2016b), we presented the soil chemical properties by 12 indicators, including the (1) pH specifying acidity (<7) or basicity (>7) of the soil; (2) CEC, number of negative ions, e.g., the loam and humus. It shows the capability of holding the positive ions, such as the ammonium NH4+, Ca2+, Mg2+ and K+ , and hence soil fertility, capacity to protect the groundwater from cation contamination (DFPJA 2011; Mori et al. 2016); (3) phosphoric acid, essential to ensure the grain quality, while superfluous content may bring about premature and decreased yield (Fujiwara et al. 1996); (4) silicic acids, indispensable for rice growth in preventing the soften stems and leaves, decayed roots; and (5) the contents and ratios of the pyridine base elements, including the potassium, lime and magnesia.

2.2 Analysis Framework

Firstly, we analyzed the effect of fertilizer nitrogen through regressions with the rice yield over the two years. We analyzed the synthesized effect of the soil chemical properties, by constructing the SQI (soil quality index). Using the standardized SQI of each paddy field, we identified the relative margins to improve the soil properties.

Furthermore, we conducted the PCA on the 12 soil chemical properties. We extracted five principal components of the total variance and analyzed their effects on rice yield. Finally, we identified the most significant properties using the multivariate regression on the principal components. The regression and PCA were performed using IBM SPSS 23.0 for windows.

3 Results and Discussion

3.1 Effect of the Fertilizer Nitrogen

Amount of the fertilizer nitrogen affected the yield significantly and positively, according to the aggregate estimation over the two years (Fig. 1a). In 2015, the linearity relationship between fertilizer nitrogen and rice yield was significant, while it was insignificant in 2014. It thus indicated that the fertilization was improved to increasing the rice yield over all the sampled paddy fields. Meanwhile, as illustrated by the scatting points, amounts of the fertilizer nitrogen of 2015 were larger than those of 2014. In fact, the average amounts per hectare were 50 kilograms and 69 kilograms in 2014 and 2015, respectively. As a result, a quadratic relationship was estimated to be significant in 2015, indicating that diminishing returns to scale held, when the fertilizer nitrogen transcended roughly 105 kilograms per hectare.

As analyzed in, we hypothesized that it may take some time for the fertilizer nitrogen to enrich the soil and thus plant growth. Hence, we identified the significant and positive effect of the amount of fertilizer nitrogen of 2014 on the rice yield of 2015. On average, one-kilogram increase of fertilizer nitrogen in 2014 resulted in 12.8 kilograms of paddy yielded per hectare in 2015. It was higher than the effect of the fertilizer nitrogen in 2015, which was merely 8.3 kilograms as shown in Fig. 1b. The results hereby confirmed the existence of the sustained effect of fertilizer nitrogen, and it is necessary to investigate the amount of nitrogen residuals in the soil before fertilization (Fujiwara et al. 1996).

3.2 Effect of the Individual Soil Properties

In Japan, the soil tends to be acid, due to the rich precipitation that washing away the alkaline components of calcium and magnesium (Fujiwara et al. 1996). CEC of the sampled fields was slightly lower than the local criterion, indicating that the soil fertility needed to be improved. The negative correlation to rice yield may indicated that in Japan, phosphoric acid is easier to be fixed by the rich volcano ash soil, and supplied through the overused organic fertilizers (DFPJA 2011). Silicic acid increases the yield and a positive correlation was observed in Table 1. Within the pyridine base elements, significant and positive effects were observed in magnesia,

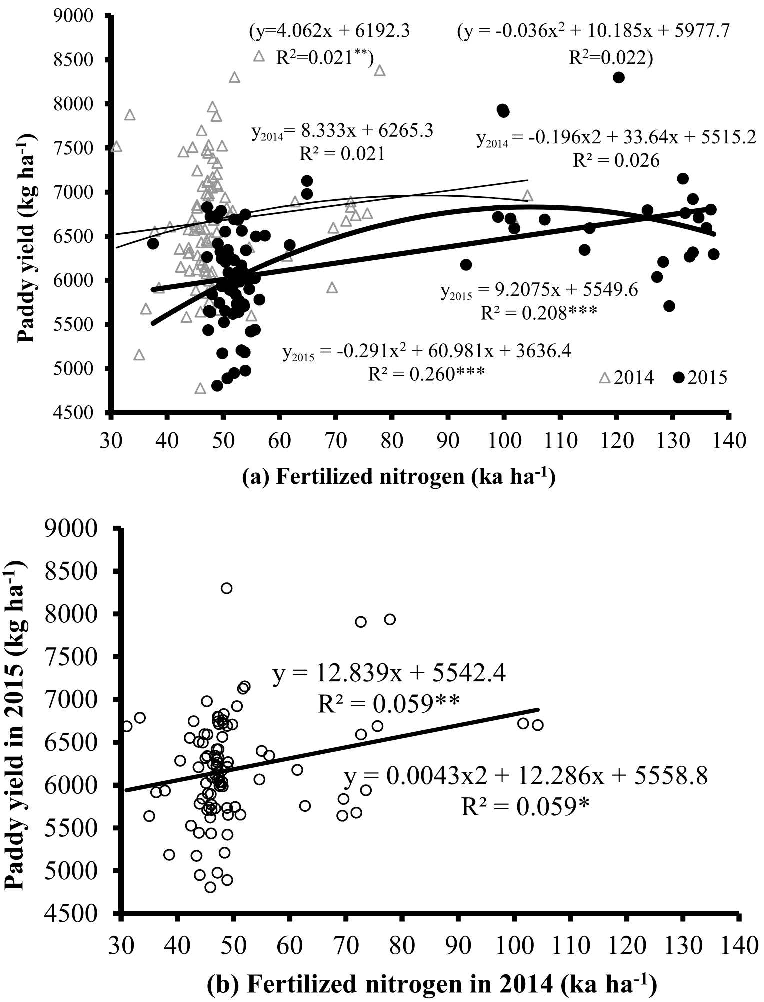


Fig. 1 Fertilizer nitrogen and rice yield (a) within 2014–2015 and (b) from 2014 to 2015. **a** Fertilized nitrogen (ka ha^{-1}). **b** Fertilized nitrogen in 2014 (ka ha^{-1}) (*Note* ***, ** and * indicate significant at 1, 5 and 10%, respectively)

from the perspectives of its exchangeable content, saturation, ratios to potassium and lime (Table 1).

Table 1 Rice yield, fertilizer nitrogen and soil chemical properties of 92 peat soil paddy fields in 2014–2015. Each property is evaluated based on the average and ideal values

Variable	N[a]	Min	Max	Mean	CV[b] (%)	Optimum[c]	Score[d]	R[e]
Paddy with 15% moisture (kg/ha)	184	4778.10	8544.40	6434.38	10.86	—	—	1.000
Fertilizer nitrogen (FN, kg/ha)	184	30.96	137.30	59.61	42.27	—	—	0.150**
pH	184	5.66	6.50	6.16	2.93	6	1.03	−0.072
CEC (meq/100 g)	184	5.69	31.00	18.61	30.25	27	0.69	0.015
Effective phosphoric acid (mg/100 g)	184	1.04	31.10	9.61	54.99	10–30	0.96	−0.289***
Effective silicic acid (mg/100 g)	184	6.70	56.27	20.75	55.93	30–40	0.69	0.414***
Exchangeable potassium (mg/100 g)	184	8.43	34.92	19.14	29.04	25–30	0.77	0.055
Exchangeable lime (mg/100 g)	184	93.73	472.50	303.71	28.71	300–350	1.00	0.033
Exchangeable magnesia (mg/100 g)	184	18.31	115.57	58.43	31.80	35–40	1.46	0.291***
Potassium saturation (%)	184	0.86	6.16	2.31	31.58	2.0–2.5	1.00	0.013
Lime saturation (%)	184	34.02	96.80	58.82	12.23	40–45	1.31	0.015
Magnesia saturation (%)	184	8.57	36.29	16.04	26.14	6–7	2.29	0.317***
Lime/magnesia	184	2.19	6.84	3.85	22.30	5.4–7.1	0.71	−0.347***
Magnesia/potassium	184	2.75	18.12	7.52	37.78	2.7–3.8	1.98	0.209***

[a]92 paddy fields in two years
[b]Coefficient of variance
[c]MAFF (2016b)
[d]Equals to 1 when the mean falls into the optimal range, or dividing the mean by the corresponding nearer bound, lower or upper, of the optimal range
[e]Correlation coefficient with the yield of paddy with 15% moisture in 2014–2015, while *** and ** * indicate significant at 1 and 5%, respectively
Data source Survey by the authors conducted in 2014–2015

3.3 Soil Quality Index

Referring to the Hungarian soil quality index adopted by Juhos et al. (2016) and using the 12 chemical properties analyzed above, we constructed an SQI for each paddy field *i* as:

$$SQI_i = \sum_{j=1}^{12} SSP_i \times w_j$$

$$SSP_i = \sum_{j=1}^{12} \frac{SP_{ij} - \min(SP_j)}{\max(SP_j) - \min(SP_j)},\ w_j = \frac{R_j}{\sum_{j=1}^{12} |R_j|}\ (i = 1, 2, \ldots, n), \quad (1)$$

where SSP means the standardized soil property; w_i is the weight of soil property j (SP_j); $|R_j|$ is the absolute value of correlation coefficient of SP_j with the paddy yield, as indicated in Table 1; n is the number of paddy fields.

Due to the normalization using the extreme values, the values of both SSP and SQI ranged from 0 to 1. A significant correlation was observed between SQI and the rice yield (Fig. 2). The determination coefficient (R^2) indicates that 24% of the yield was explained by the soil quality defined in Eq. (1). This result thus supported that good soil chemical property is essential to increase the rice yield (Liu et al. 2014). In addition, comparison of the SQIs showcased the difference of soil quality among the sampled paddy fields. In this chapter, the two-year average SQI was 0.536,

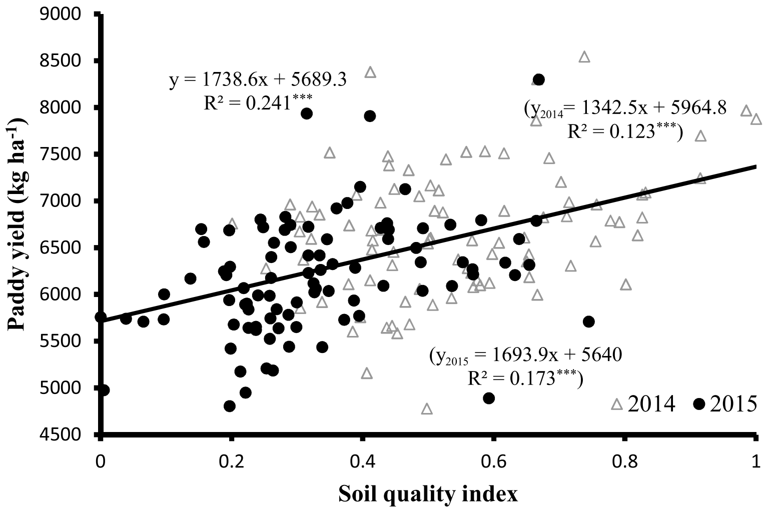
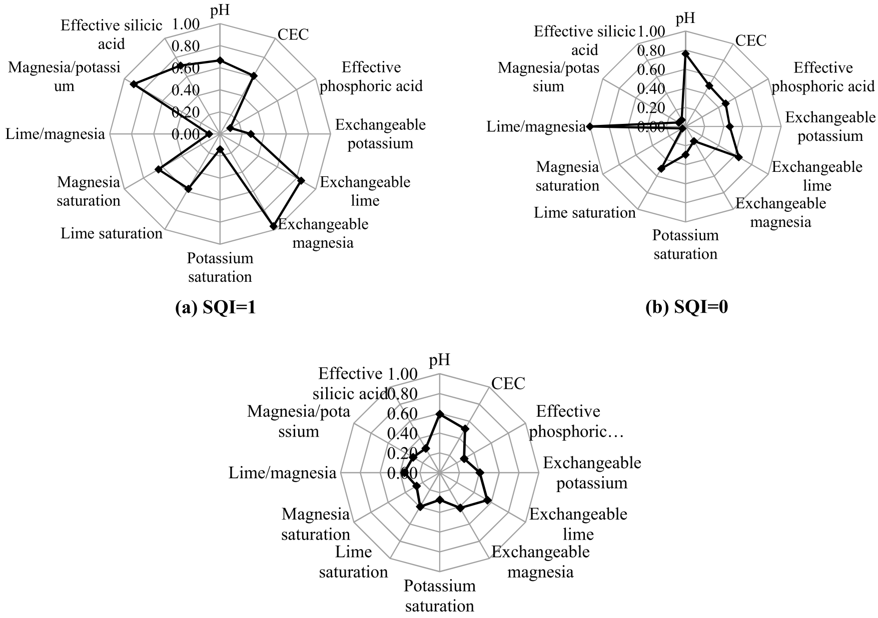


Fig. 2 Regression analysis between the rice yield and the SQI in 2014–2015 (*Note* *** indicates significant at 1%)



(c) SQI=sample mean

Fig. 3 Relative soil quality of paddy fields with different SSP. **a** SQI=1. **b** SQI=0. **c** SQI=sample mean (*Note* *** indicates significant at 1%)

higher than that of 0.323 in 2015. It may contribute to the reduced average rice yield per hectare, from 6683 kilograms to 6186 kilograms, within the two years. However, with respect to its correlation with rice yield, the determination coefficient R^2 in 2015 was higher than that of 2014, thus indicating the soil quality was more important to explain the rice yield in 2015 (Fig. 2).

Using the indicator specific SSPs of each paddy field, we identified the relative soil quality from different aspects, which were referential for soil quality improvement through optimal fertilization, etc. In the paddy fields with SQIs valued as 1 and 0, the highest SSPs was observed in the exchangeable magnesia (Fig. 3a) and the ratio of lime to magnesia (Fig. 3b), respectively; while the SSPs were much balanced in the paddy fields with the average SQI of the sample (Fig. 3c). Similar radar charts were available for all the other paddy fields.

3.4 Principal Component Analysis (PCA)

To reduce and synthesize the soil quality indicators, the PCA has been used in many studies (Qi et al. 2009; Liu et al. 2014; Juhos et al. 2016). In this chapter, we conducted the PCA on 12 soil chemical properties with varimax rotation. Using the criteria of eigenvalues greater than 1, we extracted five principal components, explaining 91.34% of the total variance. The KMO (Kaiser-Meyer-Olkin) measurement (0.610) of sample adequacy and Bartlett's test of sphericity (significant at 0.01) indicated the PCA was appropriate (Hutcheson and Sofroniou 1999).

Principal component 1 (PC_1) was identified as CEC and content of exchangeable pyridine base elements, due to the high loadings of the concerning items. The PC1 accounts for 27.07% of the total variance. Similarly, the other PCs were labelled as magnesia (PC_2), potassium (PC_3), pH and lime (PC_4), phosphoric and silicic acids (PC_5), respectively, considering their high loadings of the relating properties. Accordingly, the variance explained by these PCs decrease from 19.82 to 12.65% (Table 2). Weighting the five principal components using the corresponding percentage of variance explained, we synthetic principal component and regress it with the paddy yield. As shown in Fig. 4a, the determination coefficient ($R^2 = 0.092$) was significant but less than that of the regression taking SQI as the independent (Fig. 2). Same results hold comparing the models of the either year. Thus, the SQI performed better as indicators to explicate the increased rice yield.

To explore the possible reasons, we conducted the analysis of principal component regression (Juhos et al. 2016; Obade and Lal 2016), using the stepwise method to select the variable. The result indicated that only PC_2 and PC_5 were significant (Table 3). Accordingly, as illustrated in Fig. 4b, the determination coefficients

Table 2 Rotated component matrix of the five principal components on the soil quality indicators

Soil quality indicator	PC_1	PC_2	PC_3	PC_4	PC_5
pH	0.103	0.192	0.177	**0.784**	−0.112
CEC (meq/100 g)	**0.952**	−0.152	−0.036	−0.206	−0.104
Effective phosphoric acid (mg/100 g)	0.136	−0.096	0.05	0.053	**−0.901**
Effective silicic acid (mg/100 g)	0.235	0.282	0.161	0.309	**0.713**
Exchangeable potassium (mg/100 g)	**0.567**	−0.062	**0.805**	0.032	0.057
Exchangeable lime (mg/100 g)	**0.959**	−0.175	−0.064	0.159	0.011
Exchangeable magnesia (mg/100 g)	**0.799**	**0.527**	−0.127	0.143	0.148
Potassium saturation (%)	−0.506	0.097	**0.795**	0.186	0.105
Lime saturation (%)	−0.08	−0.014	−0.081	**0.905**	0.24
Magnesia saturation (%)	−0.134	**0.819**	−0.119	0.445	0.229
Lime/magnesia	0.125	**−0.971**	0.037	0.046	−0.133
Magnesia/potassium	0.282	**0.543**	**−0.755**	0.085	0.102
Explained variance after rotation (%)	27.069	19.821	16.275	15.526	12.653
Cumulated %	27.069	46.890	63.166	78.692	91.344

KMO measurement of sample adequacy: 0.610; Bartlett's test of sphericity: Chi-Square (66) = 3019.791***

Rotation method Varimax with Kaiser normalization converged in 6 iterations; bolded factor loadings are considered as high

Software IBM SPSS 23.0 for windows

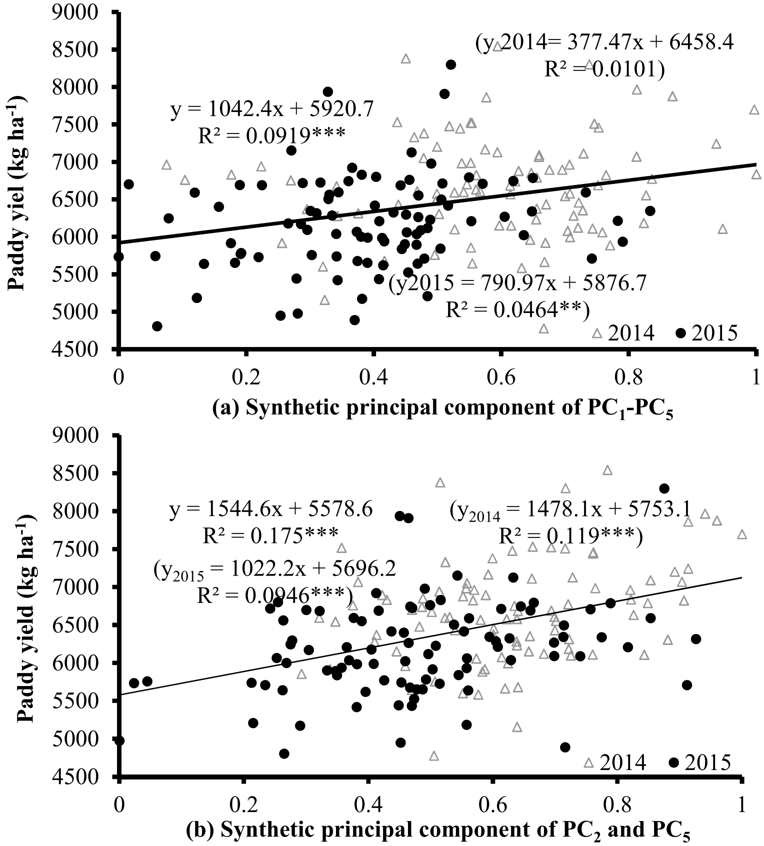


Fig. 4 Synthetic sore of five principal components and rice yield in 2014–2015. **a** Synthetic principal component of PC_1–PC_5. **b** Synthetic principal component of PC_2 and PC_5 (*Note* *** and ** indicate significant at 1 and 5%, respectively)

Table 3 Result of multivariate regression on the five principal components

Independent	Unstandardized coefficient		Standardized coefficient	t	Sig	Collinearity statistics	
	B	Std. E	Beta			Tolerance	VIF
PC_2	227.622	45.383	0.326	5.016	0.000	1.000	1.000
PC_5	252.772	45.383	0.362	5.570	0.000	1.000	1.000
(Constant)	6434.376	45.259	0.362	142.167	0.000	1.000	1.000
N = 184, R = 0.487, R^2 = 0.237, Adj. R^2 = 0.228, F (2, 181) = 28.089***							

Dependent variable Yield of paddy with 15% moisture (kg/ha); independent selecting method: stepwise out of PC_1 through PC_5

*** indicates significant at 1%

Software IBM SPSS 23.0 for windows

increased, when regressing on the synthesized principal component of PC_2 and PC_5. Thus, integrating with the respective high loadings, the significant properties included those concerning magnesia, phosphoric and silicic acids.

4 Conclusion

Amount of fertilizer nitrogen affected the yield significantly and positively over the two years, while diminishing returns to scale held, when the fertilizer nitrogen was roughly 105 kilograms per hectare. In addition, the existence of the sustained effect of fertilizer nitrogen was confirmed. Thus, the effects on the subsequent years need to be investigated in planning the proper fertilization.

Based on the 12 chemical properties, the constructed SQIs were observed as significantly related to the rice yield, in the sampled paddy fields. The higher determination coefficient R^2 in 2015 indicated the soil quality was more important to explain the rice yield than that in 2014. Using the SSP of each paddy field, we identified the relative soil quality on different properties, and thus be referential for soil quality through improved fertilization. Comparison on the paddy fields of highest and lowest SSP showcased that magnesia was an essential soil indicator. Similarly, the following PCA and stepwise multivariate regression indicated that, the most significant soil properties included concerning magnesia, phosphoric and silicic acids. The SQIs and SSPs constructed in this chapter provided important indices to monitor both the overall and individual soil property of the paddy fields. To improve the rice yield, SQIs and SSPs should be included in the panel database of rice yield and soil prosperities. Thereby in future studies, the analyze framework can be adapted for multiple farms of different regions and soil types, incorporating much more soil properties.

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