Fertilizer nitrogen, soil chemical properties, and their determinacy on rice yield: Evidence from 92 paddy fields of a large-scale farm in the Kanto Region of Japan

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Abstract. Rice, a staple crop in Japan, is at risk of decreasing production and its yield highly depends on soil fertility. This study aimed to investigate determinants of rice yield, from the perspectives of fertilizer nitrogen and soil chemical properties. The data were sampled in 2014 and 2015 from 92 peat soil paddy fields on a large-scale farm located in the Kanto Region of Japan. The rice variety used was the most widely planted Koshihikari in Japan. Regression analysis indicated that fertilizer nitrogen significantly affected the yield, with a significant sustained effect to the subsequent year. Twelve soil chemical properties, including pH, cation exchange capacity, content of pyridine base elements, phosphoric acid, and silicic acid, were estimated. In addition to silicic acid, magnesia, in forms of its exchangeable content, saturation, and ratios to potassium and lime, positively affected the yield, while phosphoric acid negatively affected the yield. We assessed the soil chemical properties by soil quality index and principal component analysis. Positive effects were identified for both approaches, with the former performing better in explaining the rice yield. For 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.

1. Introduction

Soil is critical to crop growth because it provides a growth environment and indispensable nutrients, and any degradation of soil quality may result in decreased productivity, quality, and thus profitability of the crop [1-4]. Soil properties can be determined primarily from physical, chemical, and biological aspects [5, 6]. The chemical properties typically relate more directly to the sustainability of the agro-ecosystem, in addition to variability in crop yield [2, 6, 7]. These properties can also be more easily improved than others, through proper fertilization and other farm management practices [8]. Thus, soil fertility may also refer to its chemical properties, with different aspects taken into consideration. Many researchers have analyzed the relationship between soil chemical prosperities and rice yield. Juhos *et al* [1] 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 from a 225 ha farmland in east Hungary. Liu *et al* [3] analyzed the rice yield and the effects of eight soil chemical properties sampled from 13 provincial regions of south China, individually and synthetically using a soil quality index, based on a principal component analysis model adapted from that published by Qi *et al* [8].

In Japan, rice (Oryza sativa L.) is the most important staple crop, and by 2015, it accounted for the largest proportion of 17% of gross agriculture output [9]. Japan is striving to improve rice productivity and global competitiveness. By 2016, the total planted area of rice was estimated to be 1.57 million ha, having decreased by approximately one third over the past three decades. At the same time, the total rice production decreased by nearly 30% [10]. Rice yield depends more on soil fertility than other crops, and loss of the crop may result from unbalanced soil fertility arising from improper fertilization and the nutrient deposited in the dammed rivers [5]. Thus, accurate measurement of soil fertility and its effect on yield is essential to promote rice production in Japan. Some scholars have investigated the chemical properties of paddy field soil in Japan. To estimate total CH_4 emission from rice paddies, Katayanagi *et al* [11] analyzed the soil chemical properties of 986 plots sampled across Japan, using the individual indicators of pH (H_2O) and total carbon. Matsumoto *et al* [12] estimated the effects of iron materials applied in an experimental field at Shimane University, Matsue city of Shimane Prefecture, and determined soil chemical properties in terms of the content of available arsenic and phosphorus and acid ammonium oxalate extractable iron and aluminum. To measure the effect of fermented bark as a soil amendment material in the experimental site of Gunma Prefecture, Japan, Mori *et al* [13] determined the soil chemical properties using pH, cation exchange capacity (CEC), oxidation-reduction potential, and the content of heavy metals, including cadmium, copper, and zinc. Thus, it is necessary to quantify the soil chemical properties using synthesized indices, and on-farm data from individual paddy fields can provide more practical information.

Here, we discuss the status of fertilizer nitrogen and soil chemical properties in the sampled paddy fields and demonstrate the effect of fertilizer nitrogen and soil chemical properties on rice yield, through the determination of soil quality index and standardized soil properties. We also examine the most significant properties using principal component analysis and multivariate regression, and summarize empirical findings and as well as countermeasures to improve rice yield.

2. Materials and methods

2.1. Sampling and data

The data were sampled in 2014 and 2015 from 92 peat soil paddy fields on a large-scale farm located in the Kanto Region of Japan. The rice variety was Koshihikari, the taste and appearance of which make it desirable to consumers both in Japan and worldwide. By 2015, it accounted for the largest share (36%) [14] of the area planted with domestic rice, partly due to its strong cold resistance and stable yield [15]. Rice yield was measured as the grain weight of paddy with 15% moisture content. The weight and moisture content of the raw paddy were monitored by combine harvesters equipped with a matchbox-sized sensor set at the input slot of the grain tank, and the global navigation satellite system (GNSS) to convey data to the cloud server shared by companies, institutes, and farms.

Fertilizer nitrogen was calculated based on the amounts of chicken manure, chemical fertilizer, ammonium sulfate, and urea fertilizers applied and their corresponding nitrogen content. In accordance with local guidelines [16], we presented the soil chemical properties in terms of 12 indicators. The pH specifies the acidity (<7) or basicity (>7). CEC is a measure of soil fertility, i.e., the capacity of soil to hold positively charged ions of NH_4^+, Ca_2^+, Mg_2^+, and K^+, protecting the groundwater from cation contamination [5, 13]. Phosphoric acid is essential to ensure grain quality, while excessive content can lead to premature or low yield [17]. Silicic acid is indispensable for rice growth by preventing the softening of stems and leaves, and root decay. Contents and ratios of the pyridine base elements include lime that is indispensable for root growth, magnesia necessary for photosynthesis, and potassium essential for anthesis and seed-setting [5].

2.2. Analysis framework

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

soil properties. We also conducted a principal component analysis on the 12 soil chemical properties, extracted five principal components of the total variance, and analyzed their effects on rice yield. Finally, we identified the most significant properties using multivariate regression on the principal components. The regression and principal component analyses were performed using SPSS 23.0 for Windows (IBM Corp.).

3. Results and discussion

3.1. Effect of fertilizer nitrogen

The amount of fertilizer nitrogen affected yield significantly and positively, according to the results observed over the two years (figure 1(a)). In 2015, the linear relationship between fertilizer nitrogen and rice yield was significant, while it was non-significant in 2014. This indicated that fertilization was improved, thereby increasing rice yield across the sampled paddy fields. Meanwhile, as illustrated by the scatter plot, the amount of fertilizer nitrogen was greater in 2015 (69 kg ha^{-1}) than in 2014 (50 kg ha^{-1}). As a result, a quadratic relationship was estimated to be significant in 2015, indicating diminishing returns when the fertilizer nitrogen exceeded approximately 105 kg ha^{-1}.

We hypothesized that it might take some time for the fertilizer nitrogen to enrich the soil and thus improve plant growth. Hence, we identified the significant and positive effects of the amount of fertilizer nitrogen in 2014 on the rice yield of 2015. On average, a 1 kg increase in fertilizer nitrogen in 2014 resulted in 12.8 kg of paddy yield per hectare in 2015. This was higher than the effect of the fertilizer nitrogen in 2015, which was merely 8.3 kg (figure 1(b)). The results confirmed the sustained nature of the effect of fertilizer nitrogen on rice yield; it is therefore necessary to investigate the amount of residual nitrogen in the soil before fertilization [17]. Over the two years, ammonium sulfate fertilizer accounted of the largest ratio of fertilizer nitrogen by 40.8%, following by manure fertilizer (40.3%) and chemical compound fertilizer (18.9%).
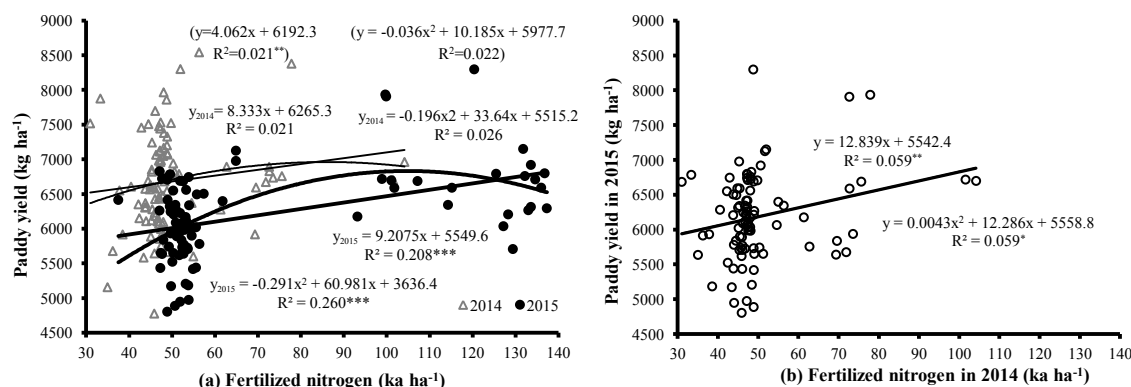

Figure 1. Relationship between (a) fertilizer nitrogen and rice yield in 2014-2015, and (b) fertilizer nitrogen in 2014 and rice yield in 2015.
Note: [***], [**] and [*] indicate significant at 1%, 5% and 10%, respectively.

3.2. Effects of the individual soil properties

In Japan, the soil tends to be acidic owing to a substantial amount of precipitation, which washes away the alkaline calcium and magnesium components [17]. The CEC of the sampled fields was slightly lower than the local standard, indicating that the soil fertility needed to be improved. The negative correlation with rice yield may indicate that, in Japan, phosphoric acid can be more easily fixed by rich volcanic ash soil and supplied through overused organic fertilizers [5]. Higher content of silicic acid increased yield, and a positive correlation was observed between them (table 1). Of the pyridine base elements, significant and positive effects were observed for magnesia, from the perspectives of its exchangeable content, saturation, and its 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.

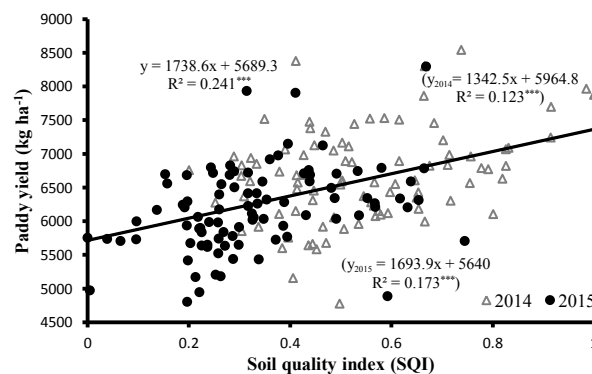| Variable	N	Mean	CV[a] (%)	Optimum	Score[b]	Corr.[c]
Paddy yield of 15% moisture (kg ha^{-1})	184	6434.38	10.86	—	—	1.000
Fertilizer nitrogen (kg ha^{-1})	184	59.61	42.27	—	—	0.150[**]
pH	184	6.16	2.93	6	1.03	-0.072
CEC (meq 100 g^{-1})	184	18.61	30.25	27	0.69	0.015
Effective phosphoric acid (mg 100 g^{-1})	184	9.61	54.99	10~30	0.96	-0.289[***]
Effective silicic acid (mg 100 g^{-1})	184	20.75	55.93	30~40	0.69	0.414[***]
Exchangeable potassium (mg 100 g^{-1})	184	19.14	29.04	25~30	0.77	0.055
Exchangeable lime (mg 100 g^{-1})	184	303.71	28.71	300~350	1.00	0.033
Exchangeable magnesia (mg 100 g^{-1})	184	58.43	31.80	35~40	1.46	0.291[***]
Potassium saturation (%)	184	2.31	31.58	2.0~2.5	1.00	0.013
Lime saturation (%)	184	58.82	12.23	40~45	1.31	0.015
Magnesia saturation (%)	184	16.04	26.14	6~7	2.29	0.317[***]
Lime/magnesia	184	3.85	22.30	5.4~7.1	0.71	-0.347[***]
Magnesia/potassium	184	7.52	37.78	2.7~3.8	1.98	0.209[***]

[a] Coefficient of variance.
[b] 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.
[c] Correlation coefficient for yield determined using paddy of 15% moisture content in 2014-2015, while [***] and [**]
[*] indicate significant correlation at 1% and 5%, respectively.
Data source: survey by the authors conducted in 2014-2015, and the optimum was MAFF [9].

3.3. Soil quality index
Based on to the Hungarian soil quality index adopted by Juhos *et al* [1], and using the 12 chemical properties discussed above, we determined the SQI for each paddy field *i* as:

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

Figure 2. Regression analysis between the rice yield and the SQI in 2014-2015.
Note: [***] indicates significant correlation at 1%.

where SSP is the standardized soil property; w_j 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; and *n* is the number of paddy fields. To calculate the relative position between the corresponding minimum and maximum values of the paddy fields (equation (1)), we standardized both the soil property (SSP) and the SQI from 0 to 1. A significant correlation was observed between SQI and rice yield (figure 2).

The determination coefficient (R^2) indicated that 24% of the yield was explained by the soil quality defined in equation (1). This result thus supported the hypothesis that good soil chemical properties

are essential to increase rice yield [3]. In addition, comparison of the SQIs demonstrated the differences in soil quality among the sampled paddy fields. In this study, the two-year average SQI was 0.536, which was higher than the SQI of 0.323 observed in 2015. This might have contributed to the reduced average rice yield per hectare, from 6683 kg to 6186 kg, over the two years. However, with respect to its correlation with rice yield, the determination coefficient R^2 in 2015 was higher than that in 2014, indicating that soil quality had a higher contribution to rice yield in 2015 (figure 2).

Using indicator-specific SSPs for each paddy field, we determined relative soil quality based on different aspects, for use as a standard for soil quality improvement through optimal fertilization and other management strategies. In the paddy fields with SQI values of 1 and 0, the highest SSPs were observed for the exchangeable magnesia (figure 3(a)) and the ratio of lime to magnesia (Figure 3(b)), while the SSPs were more balanced in paddy fields with average SQI values (Figure 3(c)). Similar radar charts were available for all the other paddy fields.
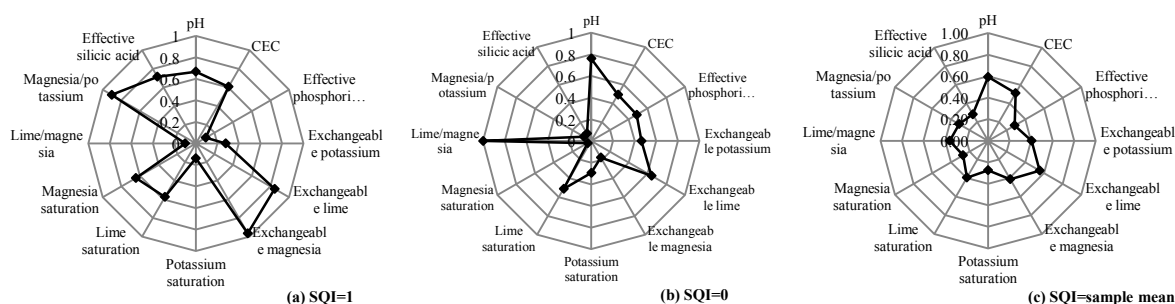

Figure 3. Relative soil quality of paddy fields with different standardized soil properties (SSPs).
Note: [***] indicates significance at 1%.

3.4. Principal component analysis (PCA)

PCA has been used in several studies to identify and separate soil quality indicators [1, 2, 7]. In this study, we conducted the PCA on the 12 soil chemical properties with varimax rotation. Using a cutoff of over 1 for the eigenvalues indicating components variances, we extracted five principal components, which explained 91.34% of the total variance. The KMO measurement (0.61) of sample adequacy and Bartlett's test of sphericity (sig. at 0.01) indicated that the PCA was appropriate [18].

Table 2. Rotated component matrices of five principal components of the soil quality indicators.

Soil quality indicator	PC1	PC2	PC3	PC4	PC5
pH (SP1)	0.103	0.192	0.177	**0.784**	-0.112
CEC (meq 100 g^{-1})	**0.952**	-0.152	-0.036	-0.206	-0.104
Effective phosphoric acid (mg 100 g^{-1})	0.136	-0.096	0.05	0.053	**-0.901**
Effective silicic acid (mg 100 g^{-1})	0.235	0.282	0.161	0.309	**0.713**
Exchangeable potassium (mg 100 g^{-1})	**0.567**	-0.062	**0.805**	0.032	0.057
Exchangeable lime (mg 100 g^{-1})	**0.959**	-0.175	-0.064	0.159	0.011
Exchangeable magnesia (mg 100 g^{-1})	**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) = 019.791[***].
Rotation method: varimax with Kaiser normalization converged in six iterations, and the high factor loadings are bolded.
Software: IBM SPSS 23.0 for windows.

Principal component 1 (PC1) was identified as CEC and content of exchangeable pyridine base elements, due to their high loadings. PC1 accounted for 27.07% of the total variance. Similarly, the other PCs were labeled as magnesia (PC2), potassium (PC3), pH and lime (PC4), and phosphoric and silicic acids (PC5), respectively, considering their high loadings of the related properties. Accordingly, the variance explained by these PCs decreased from 19.82% to 12.65% (table 2). Weighting the five principal components using the corresponding percentage of variance explained, we determined the principal component and regressed it with the paddy yield. As shown in figure 4(a), the determination coefficient ($R^2 = 0.092$) was significant, but less than that of the regression with SQI as the independent variable (figure 2). Similar results were obtained with the models of the other year. Thus, the SQI performed better as an indicator for increase in rice yield.
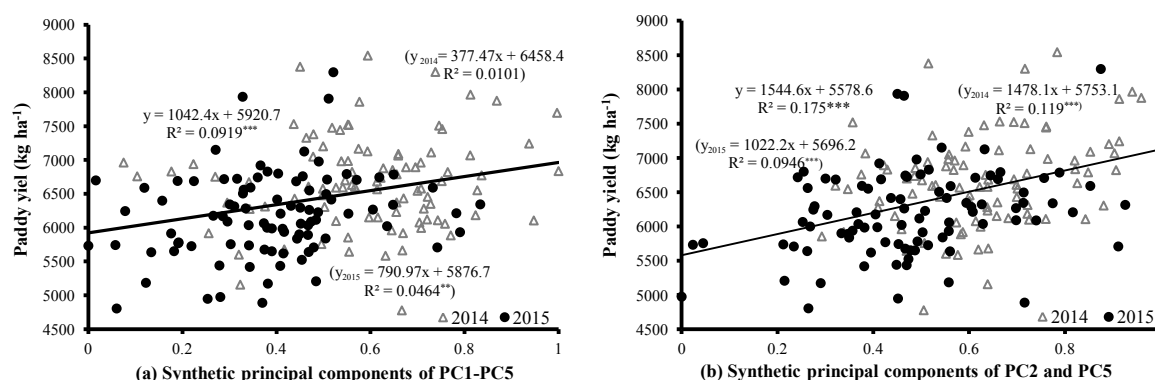

Figure 4. Synthetic scores of five principal components (SPC) and rice yield in 2014-2015.
Note: [***] and [**] indicate significance at 1% and 5%, respectively.

To explore the possible reasons, we conducted principal component regression analysis [1, 4], using the stepwise method to select the variable. The result indicated that only PC2 and PC5 were significant (table 3). Accordingly, as illustrated in figure 4(b), the determination coefficients increased when regression analysis was performed on the determined principal components of PC2 and PC5. Thus, integrating with the respective high loadings, bold values in table 2, the significant properties included magnesia and phosphoric and silicic acids contents.

Table 3. Results of multivariate regression on the five principal components.

Independent variable	Unstandardized coefficient		Standardized coefficient	t	Sig	Collinearity statistics	
	B	Std. E	Beta			Tolerance	VIF
PC2	227.622	45.383	0.326	5.016	0.000	1.000	1.000
PC5	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: paddy yield at 15% moisture content (kg ha^{-1}).
Independent variables selecting method: stepwise out of PC1 through PC5; [***] indicates significance at 1%.
Software: IBM SPSS 23.0 for windows.

4. Conclusions

The amount of fertilizer nitrogen affected the yield significantly and positively over the two years, while a turning point was observed when the fertilizer nitrogen was approximately 105 kg ha^{-1}. The sustained nature of the effect of fertilizer nitrogen was confirmed. Thus, the effects of residual nitrogen on rice yields in the subsequent years need to be investigated to ensure proper fertilization.

Based on the 12 chemical properties, the constructed SQIs were found to be significantly related to the rice yield. The higher determination coefficient R^2 in 2015 indicated that soil quality was more

important in explaining rice yield than that in 2014. Using the SSP of each paddy field, we identified the relative soil quality in terms of different properties, providing a reference for soil quality improvement through improved fertilization and other management practices. Comparison of the paddy fields with the highest and lowest SSPs demonstrated that magnesia was an essential soil indicator. Similarly, PCA and stepwise multivariate regression indicated that the most significant soil properties included magnesia and phosphoric and silicic acid content. The SQIs and SSPs provided important indices to monitor both the overall and individual soil properties of paddy fields. When considering measures to improve rice yield, SQIs and SSPs should be included in the panel database of rice yield and soil properties. Thus, the analysis framework can be adapted for multiple farms of different regions and soil types, incorporating several more soil properties.

Acknowledgments

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