Impact of Soil Fertility in 116 Paddy Fields of Kinki Region

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Japan is in urgent need of reducing its rice production costs through increasing yield, which is highly dependent on soil fertility. This chapter investigated the determinants of rice yield, from the perspective of nitrogen fertilizer and soil chemical properties. The data were collected in 2014 and 2015, from 116 paddy fields, on a large-scale farm located in the Kinki Region. The rice included Koshihikari and other seven varieties, cultivated using conventional, special, and organic methods. The nine soil chemical properties were: pH value, cation exchange capacity, ammonium nitrogen, effective phosphoric and silicic acid, saturation of base elements, exchangeable potassium, lime, and magnesia. Multiple regression analysis indicated that positive effects were found for silicic acid, exchangeable potassium, and ammonium nitrogen; while phosphoric acid affects yield negatively, while controlling rice variety, cultivation regime, and field area. Finally, countermeasures are put forward to improve soil fertility and rice yield.

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1 Introduction

Soil chemical properties are critical for growth, yield, quality, and market competitiveness of crops and their degradation results in decreased soil fertility, nutrients, and productivity (Juhos et al. 2016; Liu et al. 2014; Obade and Lal 2016). With respect to a sustainable agroecosystem, soil chemical properties can be improved through fertilization, cropping adjustment, and other farm managerial practices (Li et al. 2017a; Bouma 2002). Therefore, many researchers have studied the variability and impact of soil chemical properties on rice yield. Juhos et al. (2016) explored the yield determinants of crops by constructing a soil quality index (SQI) from more than ten chemical and physical indicators, on a farmland of 225 hectares in east Hungary. Obade and Lal (2016) tested four methods in constructing an SQI and identified the properties determining soil quality and crop yield, in the private fields of Ohio, the US.

In Japan, although rice still has the largest contribution in gross agriculture output, its share (Oryza sativa L.) has decreased from 27.8% in 1990 to 18.0% in 2016 (MAFF 2017a). Under the acreage reduction policy, the total planted area of rice decreased by 24% in the past two decades (MAFF 2017b). Compared with other crops, rice yield is determined more by soil fertility. For higher rice production, a precise measurement of soil properties and their impact on yield is needed in Japan, where most of the soil nutrients are drained by rain, or deposited in dams (DFPJA 2011). A large part of literature has focused on the soil chemical properties of paddy fields in Japan. Katayanagi et al. (2016) analyzed them in a nationwide sample of 986 plots, adopting the individual indicators of pH (H_2O) value and total carbon. To estimate the effect of soil chemical properties, Matsumoto et al. (2016) included the amount of available arsenic, phosphorus and acid ammonium oxalate, extractable iron, and aluminum. In addition to cadmium, copper, and zinc, Mori et al. (2016) represented the soil chemical properties by pH value, CEC, and oxidation-reduction potential. Li et al. (2017a) assessed the determinacy of soil chemical properties on rice yield, using on-farm data of individual paddy fields.

This chapter investigated the soil chemical properties and their determinacy on rice yield, using on-farm data of individual paddy fields, controlling for rice varieties, cultivation regimes, and field area.

2 Materials and Methods

2.1 Sample and Data

We collected the data of 116 paddy fields in 2014 and 2015, from a farm scaled over 170 hectares in Kinki Region. Rice yield is measured using paddy with 15% moisture. The paddy weight and moisture content were monitored using a combine harvester, through a matchbox-sized sensor fitted in the input slot of the grain tank.

The data was then conveyed by GNSS, via a cloud server connecting farms, institutes, and companies. The soil chemical properties, represented by nine indicators, were sampled and analyzed by a professional company (TAC 2018).

2.2 Analysis Framework

The significant soil chemical properties were identified using multivariate regression. We estimated the effects of the properties on rice yield by incorporating the natural features of the soil and rice production in Japan. The analyses were conducted using SPSS 23.0 for Windows, IBM Corp.

3 Results and Discussion

3.1 Rice Yield Analysis

In the two years, average yield decreased from 6347 kilograms to 5730 kilograms per hectare, with a smaller coefficient of variance. Over the same period, 85 paddy fields were planted with the same varieties, while 31 fields changed the rice varieties. Of the different rice varieties, Nakateshinsenbon had the highest average yield of 6652 kilograms per hectare with the least variance. The second highest yield was of Koshihikari, which accounted for the largest share (36.2% in 2016) of planted area in Japan (Komenet 2020), has an aesthetic appearance and good taste, strong cold resistance, and stable yield (Goto et al. 2000). Of all the methods, the conventional and special cultivation regimes yielded 6355 kilograms and 5910 kilograms per hectare, respectively, which were much higher than that of organic cultivation, 4734 kilograms per hectare on average (Table 1).

3.2 Soil Chemical Properties

As shown in Table 2, the paddy fields were scaled from 634 m^2 to 13562 m^2, with an average value of 4965 m^2. The pH value indicates soil acidity (<7) or basicity (>7). CEC shows soil fertility in the capacity to hold the positive ions of ammonium, calcium, magnesium, and potassium, for protecting groundwater from cation contamination (DFPJA 2011; Mori et al. 2016). Ammonium nitrogen, referring to the nitrogen directly absorbed by the rice plant, is essential for major plant components, such as proteins, nucleic acids, chlorophyll. It promotes growth by vigorously activating cell division, nutrient absorption, and anabolism (DFPJA 2011). Effective phosphoric acid refers to those that can be absorbed by the crops directly. Although

Table 1 Rice yield specified by variety and cultivation regime in 2014–2015

Specification	N	Paddy with 15% moisture (kg/ha)				CV[a] (%)
		Mini	Maxi	Mean	Std. D	
Total in two years	232	4040.60	8452.40	6038.63	1016.92	16.84
Year: 2014	116	4040.60	8452.40	6347.26	1129.74	17.80
2015	116	4070.00	8220.00	5730.00	780.23	13.62
Two-year variety: different	170	4040.60	8452.40	6057.80	1009.74	16.67
same	62	4230.00	7933.70	5986.07	1042.87	17.42
Variety: Koshihikari	9	4862.10	7483.30	6402.18	859.34	13.42
Milky queen	28	4090.00	7449.10	5663.57	745.52	13.16
Kinuhikari	9	4581.00	8452.40	6269.33	1529.22	24.39
Nipponbare	11	4134.90	7564.50	6259.53	1110.70	17.74
Nakateshinsenbon	29	5280.00	8298.30	6651.69	857.27	12.89
Yumeoumi	24	4040.60	8358.80	6189.56	1201.38	19.41
Nikomaru	30	4340.00	7999.90	5999.68	1052.49	17.54
Himenomoti	92	4070.00	7933.70	5848.31	937.95	16.04
Conventional cultivation	83	4040.60	8358.80	6355.10	1064.85	16.76
Special cultivation[b]	143	4070.00	8452.40	5909.69	934.54	15.81
Organic cultivation[c]	6	4090.00	5190.00	4733.80	442.29	9.34

[a]Coefficient of variance. [b]Nitrogen content is reduced by 50% in compost and chemical fertilizers and chemical pesticides according to the national guidelines. [c]soil fertility is improved by compost fertilizers, not by chemical fertilizers and chemical pesticides

essential for ensuring grain quality, its excessive content could lead to premature or low yield (Fujiwara et al. 1996). Silicic acid is indispensable for rice growth in reducing softened stems and leaves, and decayed roots (DFPJA 2011; Fujiwara et al. 1996). Of the exchangeable content of the base elements, lime is important for root growth, magnesia is necessary for photosynthesis, while potassium is crucial for anthesis and seed-setting (DFPJA 2011).

The correlation analysis indicated the significant properties—ammonium nitrogen, effective silicic acid, and exchangeable potassium affect yield positively, while effective phosphoric acid and CEC affect yield negatively (Table 2).

3.3 *Significant Rice Yield Determinants*

In the multivariate regression analysis, the values of yield, soil properties, and field area were taken as the natural logarithmic transformations to capture linearity and interpret the regression coefficients in terms of elasticity. Dummy variables were included to control the effect of year (1 = 2015, 0 = 2014), rice varieties (1 = each, 0 = others), their changes in the two years (1 = same, 0 = different), and

Table 2 Field area and soil chemical properties of 116 paddy fields in 2014–2015

Variable	N	Min	Max	Mean	Std.D	CV[a] (%)	R[b]
Filed area (m^2)	232	634.00	13562.00	4964.91	2863.40	57.67	−0.105
pH	232	4.98	6.63	5.97	0.29	4.83	−0.102
CEC (meq/100 g)	232	5.89	18.21	10.67	1.92	18.04	−0.128*
Ammonium nitrogen (mg/100 g)	232	0.10	2.25	0.51	0.42	81.98	0.135**
Effective phosphoric acid (mg/100 g)	232	3.10	26.51	11.60	4.32	37.27	−0.254***
Effective silicic acid (mg/100 g)	232	6.38	69.13	16.14	10.14	62.82	0.147**
Saturation of base elements (%)	232	52.63	123.23	79.70	11.21	14.06	0.037
Exchangeable potassium (mg/100 g)	232	3.21	23.09	10.43	3.34	32.03	0.182***
Exchangeable lime (mg/100 g)	232	101.01	297.49	193.50	37.14	19.19	−0.108
Exchangeable magnesia (mg/100 g)	232	3.80	50.73	26.18	7.18	27.41	−0.009

[a]Coefficient of variance
[b]Pearson's correlation coefficient with yield of paddy with 15% moisture; ***, **, * indicate significance at 1, 5, and 10% levels, respectively

cultivation regimes (1 = each, 0 = others). Using backward procedure, the significant independent variables were selected. The result indicates that each regressor (t-test) and the entire model (F-test) are significant. All the VIFs are less than 10, indicating zero multicollinearity. The adjusted R^2 indicated that 24.4% of the yield variations are explained. White test eliminates the presence of heteroskedasticity and the bias of excluding variables that could affect the regressors significantly (Table 3).

Among the soil chemical properties, effective silicic acid, exchangeable potassium, and ammonium nitrogen affected yield positively, significant at 0.05 level and effective phosphoric acid and exchangeable lime affected the yield positively, significant at the 0.01 and 0.10 levels, respectively. With respect to the control variables, field area and organic cultivation related negatively to yield, while Nakateshinsenbon had a higher yield than the other varieties. These findings are in accordance with the correlation analyses. The estimated multiple coefficients indicated the change in yield with respect to each regressor, holding other variables fixed. For the continuous regressors, a coefficient indicates the elasticity, for example, a 1% increase in ammonium nitrogen increased yield by 0.034%, while a 1% increase in effective phosphoric acid decreases yield by 0.099%. For the dummy regressors, the average yield of Nakateshinsenbon was 16.6% higher than of the other varieties, and organic cultivation yielded 19.8% less than the other methods, *ceteris paribus* (Table 3).

Table 3 Result of multivariate regression on the significant rice yield determinants

Independent variable[a]	Unit	Unstandardized coefficient		t	Sig.	Collinearity statistics	
		B[b]	Std. E			Tolerance	VIF
Ln (Effective silicic acid)	mg/100 g	0.060**	0.024	2.482	0.014	0.678	1.476
Ln (Exchangeable potassium)	mg/100 g	0.068**	0.031	2.178	0.030	0.870	1.149
Ln (Ammonium nitrogen)	mg/100 g	0.034**	0.017	2.050	0.042	0.606	1.650
Ln (Effective phosphoric acid)	mg/100 g	−0.099***	0.026	−3.816	0.000	0.866	1.155
Ln (Exchangeable lime)	mg/100 g	−0.102*	0.057	−1.806	0.072	0.781	1.280
Ln (Filed area)	m^2	−0.030**	0.015	−2.092	0.038	0.912	1.097
Nakateshinsenbon	Dummy	0.166***	0.031	5.315	0.000	0.869	1.151
Organic cultivation	Dummy	−0.198***	0.063	−3.167	0.002	0.938	1.066
(Constant)	—	7.115***	0.315	22.588	0.000	—	—
N = 232, R = 0.519, R^2 = 0.270, Adj. R^2 = 0.244, F (8, 223) = 10.294*** (p = 0.000); White test: 0.228 × 232 = 52.896 < $\chi^2(8)$ = 20.090							

[a]Selected using backward procedure, and the excluded variables include year, two-year same/different varieties, rice varieties except for Nakateshinsenbon, conventional and special cultivation regime, ln(pH), ln(CEC), ln(exchangeable magnesia), and ln(saturation of base elements). Dependent variable: ln(yield of paddy with 15% moisture per hectare)
[b]***, **, * significant correlation at 1, 5, and 10% levels, respectively

3.4 Further Discussion

To confirm and supplement the result of the multivariate regression, Fig. 1 illustrates the soil properties identified as statistically significant at the 0.05 level in Table 3.

1. Silicic acid accounts for 10–15% of dry straw and 2–3% of paddy grain due to the high silicon accumulation ability of rice (DFPJA 2011; Fujiwara et al. 1996). Its deficiency results in declining growth, delayed heading, poor grain-filling, softened stems and leaves, and increased risks of pest damage and lodging. Although it is unlikely to occur, excessive silicic acid could cause changes in soil pH, alkalization disorder, and decreased yield (Fujiwara et al. 1996). Compared with the national minimum criterion of 15 mg per 100 grams (DFPJA 2011), a higher content of silicic acid can also increase rice yield. However, a significant quadratic relation is found as well, indicating an optimal amount of 39.8 mg per 100 grams.
2. In Japan, potassium and other base elements are drained by the ample rainfall (DFPJA 2011). For soils rich in humus, like surface gray lowland soil, the optimal

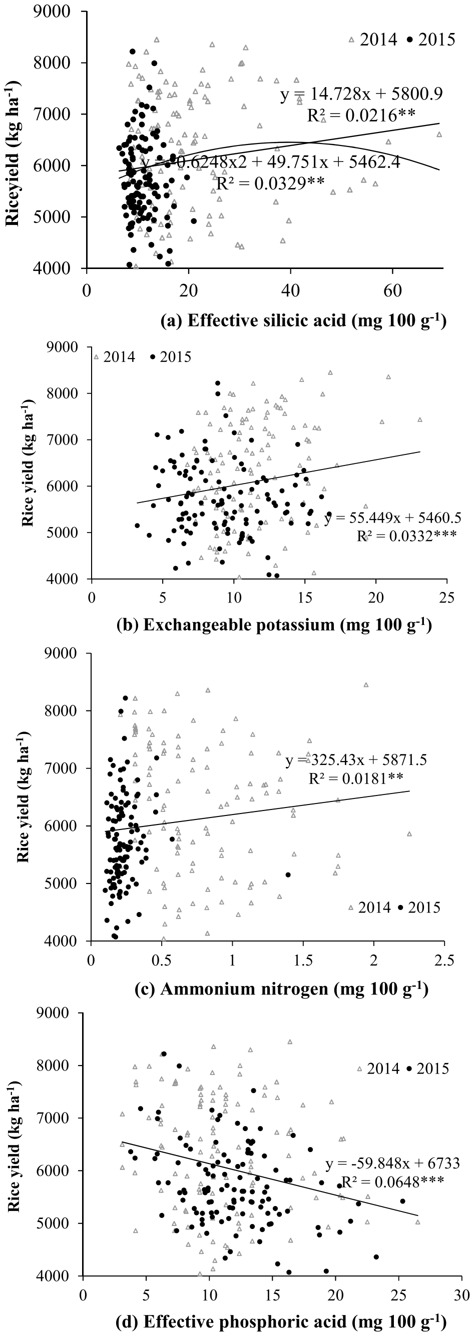

Fig. 1 Relationship of rice yield and the significant soil chemical properties.
a Effective silicic acid (mg 100 g^{-1}). **b** Exchangeable potassium (mg 100 g^{-1}).
c Ammonium nitrogen (mg 100 g^{-1}). **d** Effective phosphoric acid (mg 100 g^{-1}) ($N = 232$, ***and ** indicate significant correlation at 1 and 5% levels, respectively)

range of exchangeable potassium was 20–30 mg per 100 grams. It was higher when CEC was lower than 30 milliequivalents per 100 grams (DFPJA 2011). In the sampled fields, average exchangeable potassium was 10.43 milligrams per 100 grams, with a maximum CEC of 18.21 milliequivalents per 100 grams; thus, its increase undermined the rice yield.

3. Rice growth relies heavily on nitrogen, 60% of which is supplied by the soil (DFPJA 2011; Fujiwara et al. 1996). Ammonium nitrogen, directly absorbable by crops, is essential for a high rice yield. Here, its highest content was merely 2.25 milligrams per 100 grams, much lower than the optimal range of 10–20 milligrams per 100 grams (Fujiwara et al. 1996). Therefore, an increase in its content benefited higher rice yield.
4. In Japan, the soil of the paddy fields is usually acidic, as shown by the average pH value of 5.97 in this sample, because of drained calcium and magnesium. In an acidic soil, more iron and aluminum are dissolved, and phosphoric acid is easily fixed and less applicable to crops. Moreover, phosphoric acid can be easily over-supplied, through organic fertilizer and compost, as indicated by the negative correlation with rice yield here. Excess phosphoric acid shows up as brown streaks on the leaf blade and whitened leaf tips (DFPJA 2011), which cannot be easily observed.

In practice, there are significant correlations between some chemical properties (Table 4). Thus, it is important to consider and adjust them collectively through, say, soil improvement and an appropriate fertilization rate determined by professional agencies, in different paddy fields (DFPJA 2011).

As Nakateshinsenbon is a high-yielding and lodging-resistant variety, it is widely planted in the Kinki Region of Japan. Although a zero application of pesticides and chemical fertilizers reduces agricultural pollution, organic cultivation has a lower yield due to increased pest damages and insufficient fertility. Over-scaled paddy fields may undermine rice yield, in terms of unbalanced fertilization; hence soil fertility and irrigation management are important factors. The quadratic relation indicated an optimal scale of 0.38 hectares in this sample.

Table 4 Correlations between the soil properties significant to rice yield

Variable	Effective silicic acid	Exchangeable potassium	Ammonium nitrogen	Effective phosphoric acid
Effective silicic acid	1.000	—	—	—
Exchangeable potassium	0.117	1.000	—	—
Ammonium nitrogen	0.306^{***}	0.206^{***}	1.000	—
Effective phosphoric acid	0.170^{***}	−0.111	0.146^{**}	1.000

N = 232, *** and ** indicate significant correlation at 1 and 5% levels, respectively

4 Conclusion and Suggestion

This chapter provided a case study of estimating the soil properties and their impact on rice yield. Based on nine soil chemical properties and control variables, the regression model explained 24.4% of yield variation. The significant chemical properties were generally in accordance with the direct correlation analysis. Positive and significant impacts were identified for silicic acid, exchangeable potassium, and ammonium nitrogen, while phosphoric acid affects rice yield negatively, *ceteris paribus*. These empirical findings were in accordance with the soil properties, and rice production in Japan. In addition, yield was significantly affected by rice variety and cultivation regime, while smaller paddy fields tend to have a higher yield.

Accordingly, soil fertility can be improved to increase rice yield in the sampled paddy fields. Soil silicic acid can be supplemented through the application of silicate-calcium and other siliceous fertilizers. Potassium can be directly supplemented by chloride or sulfate potassium that do not contain other base elements or by sulfate potassium magnesia and silicate potassium, considering a balance with other base elements. Ammonium nitrogen can be increased through enhanced nitrogen mineralization, which can be promoted by accelerated microbial activity caused by irrigating of the dry soil after spring-plowing, irrigation after the application of silicate-calcium fertilizers, and when ground temperature rises over 30 °C. To decrease the phosphoric acid content, say, over 30 milligrams per 100 grams, fertilizer-free farming should be adopted.

In future studies, this model should be extended to accommodate more soil types and rice varieties. For precise analyses on soil chemical properties and soil fertility improvement, regular soil testing and local technical guidance are necessary as well. Proper selection of rice variety and cultivation regime is especially important for increasing rice yield.

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