Impact of soil chemical properties on rice yield in 116 paddy fields sampled from a large-scale farm in Kinki Region, Japan

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Abstract. Japan is in urgent need to reduce the production costs through increasing rice yield, which depends highly 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 116 paddy fields, on a large-scale farm located in the Kinki Region of Japan. The rice included Koshikihari and other seven varieties, cultivated in conventional, special and organic regimes. The nine soil chemical properties included pH, cation exchange capacity, ammonium nitrogen, effective phosphoric and silicic acid, saturation of base elements, exchangeable potassium, lime and magnesium. Multiple regression analysis indicated that positive effects were identified for silicic acid, exchangeable potassium, and ammonium nitrogen; while phosphoric acid affects the yield negatively, controlling the rice variety, cultivation regime, and field area. Finally, countermeasures were put forward to improve soil fertility and rice yield.

1. Introduction

Soil chemical properties are critical to the growth, yield, quality and market competitiveness of crop and their degradation will result in decreased soil fertility, nutrients and thus productivity [1-4]. Relating to sustainable agro-ecosystem as well, soil chemical properties can be improved through fertilization, cropping adjustment, and other farm managerial practices [2, 5-8]. Therefore, many researchers have studied variability and impact on rice yield of soil chemical properties. Juhos et al [1] explored the yield determinants of crops through constructing soil quality index out of more than ten chemical and physical indicators, on a farmland scaled 225 ha in east Hungary. Obade and Lal [4] tested four methods in constructing soil quality index (SQI), and identified the properties determining soil quality and crop yield, in the private fields of Ohio, US.

In Japan, although still be the largest among individual crops, ratio of rice (Oryza sativa L.) in gross agriculture output decreased from 27.8% in 1990 to 18.0% in 2016 [9]. Under the acreage reduction policy, the total planted area of rice decreased by 24% in the past two decades [10]. Comparing with other crops, rice yield is determined more by soil fertility. For higher rice production, precise measurement of soil properties and their impact on yield is more needed in Japan, where much soil nutrient is drained by rich, or deposited in the dammed rivers [5]. A large literature has focused on the soil chemical properties of paddy fields in Japan. Katayanagi et al [11] analyzed them in a nationwide sample of 986 plots, adopting the individual indicators of pH (H2O) and total carbon. To estimate the effect of soil chemical properties, Matsumoto et al [12] included content of available arsenic, phosphorus and acid ammonium oxalate extractable iron and aluminum. In addition to the content of cadmium, copper, and zinc, Mori et al [13] represented the soil chemical properties by pH,
cation exchange capacity (CEC), and oxidation-reduction potential. Li et al. [14] assessed the determinacy of soil chemical properties on rice yield, using on-farm data of individual paddy fields.

This study aimed to investigate the soil chemical properties and their determinacy on rice yield, using on-farm data of individual paddy fields, controlling the rice varieties, cultivation regimes, and field area, following by countermeasures for improved soil chemical properties and higher rice yield.

2. Materials and methods

2.1. Sample and data

We sampled the data of 116 paddy fields in 2014 and 2015, from a farm scaled over 170 ha in Kinki Region, Japan. Rice yield was measured using paddy of 15% moisture content. The paddy weight and moisture content were monitored by combine harvester, through a matchbox-sized sensor equipped at the input slot of the grain tank. The data was then conveyed by Global navigation satellite system (GNSS), via the cloud server connecting farms, institutes, and companies. Presented by nine indicators, the soil chemical properties were sampled and analyzed by professional company [15].

2.2. Analysis framework

Following the most significant soil chemical properties identified adopting multivariate regression. We estimated effects of the properties on rice yield, incorporating the natural features of paddy 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, the average yield decreased from 6347 kg to 5730 kg per ha, with smaller coefficient of variance. Over the two years, 85 paddy fields were planted the same varieties, while 31 fields changed. Within the either rice varieties, Nakateshinshenbon possessed the largest average yield of 6652 kg per ha with least variance. The second highly-yielded variety was Koshihikari, which accounts for the largest share, 36.2% by 2016, of planted area in Japan [16], with good taste and appearance, strong cold resistance and stable yield [17]. Within all the varieties, the conventional and special cultivation regimes yielded 6355 kg and 5910 kg per ha, respectively, which were much higher than that of the organic cultivation, 4734 kg per ha on average (Table 1).

| Specification | N  | Min   | Max   | Mean  | Std. D | CV (%) |
|---------------|----|-------|-------|-------|--------|--------|
| 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 same | 170 | 4040.60 | 8452.40 | 6057.80 | 1009.74 | 16.67  |
| Variety: Koshihikari | 9 | 4862.10 | 7483.30 | 5986.07 | 1042.87 | 17.42  |
| Milky queen | 28 | 4090.00 | 7449.10 | 5663.57 | 745.52  | 13.16  |
| Kinnuhikari | 9 | 4381.00 | 8452.40 | 6296.33 | 1529.22 | 24.39  |
| Nippobare | 11 | 4134.90 | 7564.50 | 6259.53 | 1110.70 | 17.74  |
| Nakateshinshenbon | 29 | 5280.00 | 8298.30 | 6651.69 | 857.27  | 12.89  |
| Yumeomi | 24 | 4040.60 | 8358.80 | 6189.56 | 1201.38 | 19.41  |
| Nikonaru | 30 | 4340.00 | 7999.90 | 5999.68 | 1052.49 | 17.54  |
| Himenomoto | 92 | 4070.00 | 7933.70 | 5848.31 | 937.95  | 16.04  |
| Cultivation: conventional special | 83 | 4040.60 | 8358.80 | 6355.10 | 1064.85 | 16.76  |
| organic | 143 | 4070.00 | 8452.40 | 5909.69 | 934.54  | 15.81  |
| 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.

Data source: on-farm survey by the authors.
3.2. Soil chemical properties
As shown in Table 2, the paddy fields scaled from 634 m² to 13562 m², with an average value of 4965 m². The pH indicates soil acidity (<7) or basicity (>7). CEC showcases soil fertility from the capacity to hold the positive ions of NH₄⁺, Ca²⁺, Mg²⁺, and K⁺, thus protecting the groundwater from cation contamination [5, 13]. Ammonium nitrogen, referring the nitrogen directly absorbable by rice plant, is essential to constituent the major plant components such as proteins, nucleic acids, chlorophyll. It promotes growth by vigorously activating cell division, nutrient absorption, and anabolism [5]. The effective phosphoric acid refers to those can be absorbed by the crops directly. Although essential to ensure grain quality, its excessive content may lead to premature or low yield [18]. Silicic acid is indispensable for rice growth in reducing softened stem and leaf, and decayed root [5, 18]. Within the exchangeable contents of base elements, lime is important for root growth, magnesia is necessary for photosynthesis, while potassium is crucial for anthesis and seed-setting [5].

Correlation analysis indicated the significant properties, i.e., ammonium nitrogen, effective silicic acid and exchangeable potassium affected the yield positively; while effective phosphoric acid and CEC affected the yield positively (Table 2).

| Variable | N     | Min   | Max   | Mean   | Std.D | CV (%) | Corr a |
|----------|-------|-------|-------|--------|-------|--------|--------|
| Filed area (m²) | 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⁻¹)   | 232   | 5.89  | 18.21 | 10.67  | 1.92  | 18.04  | -0.128 |
| Ammonium nitrogen (mg 100 g⁻¹) | 232 | 0.10  | 2.25  | 0.51   | 0.42  | 81.98  | 0.135  |
| Effective phosphoric acid (mg 100 g⁻¹) | 232 | 3.10  | 26.51 | 11.60  | 4.32  | 37.27  | -0.254 |
| Effective silicic acid (mg 100 g⁻¹) | 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⁻¹) | 232 | 3.21  | 23.09 | 10.43  | 3.34  | 32.03  | 0.182  |
| Exchangeable lime (mg 100 g⁻¹) | 232 | 101.01 | 297.49 | 193.50 | 37.14 | 19.19  | -0.108 |
| Exchangeable magnesia (mg 100 g⁻¹) | 232 | 3.80  | 50.73 | 26.18  | 7.18  | 27.41  | -0.009 |

a Coefficient of variance.

b Pearson correlation coefficient with paddy yield of 15% moisture; ***. *** indicate significance at 1%, 5% and 10%, respectively.

Data source: on-farm survey by the authors.

3.3. Significant rice yield determinants
In the multivariate regression analysis, values of the yield, soil properties and field area were taken natural logarithmic transformations, to capture the 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) and their changes in the two years (1=same, 0=different), cultivation regimes (1=each, 0=others). Using backward procedure, the significant independent variables were selected. The result indicated that each regressor (t-test) and the whole model (F-test) are significant. All the VIFs less than 10 thus no multicollinearity was identified. The Adj. R² indicates that 24.4% of the yield variations were explained. White test eliminates the existence of heteroskedasticity, and hence the bias of excluding variables that may affect the regressors significantly (Table 3).

Among the soil chemical properties, effective silicic acid, exchangeable potassium, and ammonium nitrogen affected the yield positively, significant at 0.05; while effective phosphoric acid and exchangeable lime affected the yield positively, significant at 0.01 and 0.10, respectively. With respect to the control variables, field area and organic cultivation negatively relate to yield, while Nakateshinsenbon is found yielded higher than the other varieties. These findings are in accordance with the correlation analyses. The estimated multiple coefficients indicated the change of yield with respect to each regressor, holding the other variables fixed. For the continuous regressors, a coefficient indicates the elasticity, e.g., 1% increase of ammonium nitrogen increased the yield by 0.034%, while a 1% increase of effective phosphoric acid decreased the yield by 0.0999%. For the dummy regressors, average yield of Nakateshinsenbon is 16.6% higher than the other varieties, and organic cultivation yielded 19.8% lower than the other regimes, ceteris paribus (Table 3).
Table 3. Result of multivariate regression on the significant rice yield determinants.

| Independent variable * | Unit          | Unstandardized coefficient B | Std. E | t      | Sig. | Collinearity statistics |
|------------------------|---------------|-----------------------------|--------|--------|------|-------------------------|
| Ln (Effective silicic acid) | mg 100 g⁻¹ | 0.060*** | 0.024 | 2.482 | 0.014 | 0.678 1.476 |
| Ln (Exchangeable potassium) | mg 100 g⁻¹ | 0.068**  | 0.031 | 2.178 | 0.030 | 0.870 1.149 |
| Ln (Ammonium nitrogen) | mg 100 g⁻¹ | 0.034**  | 0.017 | 2.050 | 0.042 | 0.606 1.650 |
| Ln (Effective phosphoric acid) | mg 100 g⁻¹ | -0.099*** | 0.026 | -3.816 | 0.000 | 0.866 1.155 |
| Ln (Exchangeable lime) | mg 100 g⁻¹ | -0.102*** | 0.057 | -1.806 | 0.072 | 0.781 1.280 |
| Ln (Filed area) | m²       | -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 |  |  |  |  |  |  |
| (Constant) |  | 7.115*** | 0.315 | 22.588 | 0.000 |  |

N = 232, R² = 0.519, Adj. R² = 0.270, F(8, 223) = 10.294 (p<0.000). White test: 0.226 x 232 = 52.896. (8) = 20.090

* Selected using the Backward procedure, and the excluded variables included year, two-year same/different varieties, rice varieties except for Nakateshinsenbon, conventional and special cultivation, ln(pH), ln(CEC), ln(exchangeable magnesium), and ln(Saturation of base elements). Dependent variable: ln(paddy yield at 15% moisture content per ha).

** *** : significant correlation at 1%, 5% and 10%, respectively.

Data source: on-farm survey by the authors.

3.4. Further discussion

To confirm and supplement the result of the multivariate regression, Figure 1 illustrates the soil properties identified as statistically significant at the level of 0.05 in Table 3. (1) Silicic acid accounts for 10-15% of the dry straw and 2-3 for paddy grain, due to the high silicon accumulation ability of rice [5, 18]. Its deficiency may result in declining growth, delayed heading, and hence worse grain-filling, softened stems and leaves, and increased risks of pest damage and lodging. Although unlikely to occur, excessive contents may cause changed soil pH, alkalization disorder and decreased yield [18]. Comparing with the national minimum criterion of 15 mg 100 g⁻¹ [5], higher content of silicic acid can also increase rice yield. However, significant quadratic relation was identified as well, indicating the optimal amount of 39.8 mg 100 g⁻¹. (2) In Japan, potassium and other base elements easily be drained by rich precipitation [5]. For soils rich in humus, like surface gray lowland soil sampled here, the optimal range of exchangeable potassium is 20-30 mg 100 g⁻¹. It is higher when CEC is lower than 30 meq 100 g⁻¹ [5]. In the sampled fields, average exchangeable potassium was 10.43 mg 100 g⁻¹, with a maximum CEC of 18.21 meq 100 g⁻¹, thus its increase undermine the yield. (3) Rice growth relies heavily on nitrogen, 60% of which is supplied by soil [5, 18]. Ammonium nitrogen, directly absorbable by crops, is essential for high rice yield. Here, its highest content was merely 2.25 mg 100g⁻¹, much lower than the optimal range of 10-20 mg 100g⁻¹ [18]. Therefore, its increased content benefit higher rice yield. (4) In Japan, soil of the paddy fields is easy to be acidic, as shown by the average pH of 5.97 in this sample, attributing to drained calcium and magnesium [5]. In acidic soil, more iron and aluminum are dissolved and phosphoric acid is easily fixed and less applicable to crops. Moreover, difficult to be observed, as brown streaks on leaf blade, whitened leaf tip [5], phosphoric acid is easily over-supplied, through organic fertilizer and compost, as indicated by the negative correlation with rice yield here.

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*** | 0.100 | — | — |
| 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%, respectively.

Data source: on-farm survey by the authors.

In practice, significant correlations exist between some chemical properties (Table 4). Thus it is essential to consider and adjust them collectively through, say, creating soil improvement prescription and deciding proper fertilization rate by professional agencies, in different paddy fields [5].
Figure 1. Relationship of rice yield and the significant soil chemical properties.
(N=232, **" and ***" indicate significant correlation at 1% and 5%, respectively)
Data source: on-farm survey by the authors.

As a high-yield and lodging-resistant variety, Nakateshinsenbon is widely planted in Kinki Region. With no application of pesticides and chemical fertilizers, although reduces agro-pollutions, organic cultivation tends to suffer lower yield from increased pest damages and insufficient fertility. Overscaled paddy field may undermine rice yield, in terms of unbalanced fertilization hence soil fertility and irrigation. A quadratic relation indicates the optimal scale of 0.38 ha in this sample.

4. Conclusion and suggestions
This study provided a case study of estimating the soil properties and their impact on rice yield. Based on the nine soil chemical properties and control variables, the regression model explained 24.4% of the yield variation. The significant chemical properties included were generally in accordance with the direct correlation analysis. Positive and significant impacts were identified for the contents of silicic acid, exchangeable potassium and ammonium nitrogen, while phosphoric acid affects the rice yield negatively, ceteris paribus. Further discussion indicated that these empirical findings were in accordance with the soil property, and rice production in Japan. In addition, the yield was significantly affected by rice variety and cultivation regime, while smaller paddy field tended to relate to higher yield.

Accordingly, soil fertility is improvable 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 the balance with other base elements. Ammonium nitrogen can be increased through enhanced nitrogen mineralization, which is promotable by accelerated microbial activities due to irrigating the dried soil after spring-plowing, irrigation after silicate-calcium fertilizers were applied, and when ground temperature rises over 30°C. To decrease the content of phosphoric acid, fertilizer-free farming is adoptable when it is over-supplied, say, over 30 mg 100 g⁻¹.

In future studies, this model can be expanded to accommodate more soil types and rice varieties. For precise analyses on soil chemical properties and soil fertility improvement, regularly soil testing and local technical guidance are necessary as well. Proper selection of rice variety and cultivation regime is of great importance to increase rice yield.
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