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Variation and Determinants of Rice Yields among Individual Paddy Fields: Case Study of a Large-Scale Farm in the Kanto Region of Japan

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This study aims to identify the variation and determinants of rice yield measured by IT combine, among different rice yields within large–scale farms. In addition to the yield of the paddy with 15% of moisture, unsorted and sorted brown rice, variations of concerning ratios are studied as well. The sample includes 351 paddy fields from a farm corporation scaled over 113 ha, locating in the Kanto region of Japan. The candidate determinants include the field area and condition, nitrogen amount, time of transplanting or seeding, stage–specific growth indictors for the contain of chlorophyll, number of panicles, plant height, and leaf plate value. In addition, soil properties, average temperature and solar radiation are incorporated. Meanwhile, varieties, cultivation methods and soil types are adopted as dummy variables. The empirical analysis is conducted using a multivariate linear regression, with logarithmic transformations of the continuous variables. The estimation result indicates that panicle numbers in full–heading stage and transplanting or sowing time are the most important continuous determinants, following by nitrogen amount, humus content, and so forth. Within the significant discrete determinants, Akidawara and Milky queen are measured as productive and unproductive variety, respectively; while the well–drained direct sowing method is identified as negatively affecting the yield.

Key words: Determinant, sorted brown rice, smart agriculture, variation, yield

INTRODUCTION

Since recapturing the regime in end of 2012, the LDP government has been pushing ahead serial policies of Proactive Agriculture, Forestry and Fisheries, to increase the efficiency and competitiveness with these sectors in Japan. As to agriculture, it is essential to reduce the production costs and improve the yields, through the fiscal subsides to adopt efficient technologies, equipments, managerial models, etc. To increase rice yield and hence reduce the average production costs, the government has declared that by 2018, the Acreage Reduction of rice adopted since early 1970s will be abolished, to expand efficient production and exports actively with improved international competitiveness (JEN, 2013).

As the staple crop in Japan, rice accounted for the largest proportion in gross agriculture output of 21.03% by 2013 (MAFF, 2014a). After the post–war high economic growth, the rapidly expanded western diet had changed Japanese food consumption with increasing animal products such as meat, dairy products, eggs, oils and fats. Together with the increasing percentage of the elderly and decreasing population, the average annual consumption of sorted brown rice had decreased from 111.7 kg per capita in 1965, to 55.2 kg per capita in 2014 (MAFF, 2014b). Simultaneously, rice production has been decreasing and dragged down the agricultural growth to a large extent (Ohizumi, 2014).

In Japan, rice yield is measured by the sorted brown rice grains with the thickness no less than a certain threshold, usually 1.70 mm as cited here. In 2014, the yield of sorted brown rice was 8.43 million ton, decreased by 40.27% from 11.83 million ton in 1985. Within the same period, the planted area of paddy has decreased by 45.58% from 2.29 million ha to 1.57 million ha. Since 2000, the average yield of the sorted brown rice has been stagnant on approximately 5300–5400 kg per hectare. In 2014, the average yield of the sorted brown rice was 5360 kg per hectare (MAFF, 2015), while the counterpart data in the US was 7263 kg per hectare (USDA, 2014). Meanwhile, the paddy production in Japan is faced with high costs. In 2013, the average production costs of the sorted rice in Japan was 258 JPY per kg (MAFF, 2014c), much higher than that of the US, which is merely 35 JPY per kg on average (USDA, 2014). To be noticed, different with Japan, rice yield is measured by paddy, the raw rice grain without threshing the hull, in many other countries include the US, China and Korea. Thus for better comparison, the above rice yield of the US has been transformed from paddy to sorted paddy rice, by 1: 0.8 (MAFF, 2014d; Yaguchi, 2012). According to the Japan Revitalization Strategy released in 2014, the costs of paddy production need to be reduced by 40% in the next 10 years, compared with the current national average level (PMJHC, 2014).

Within the latest decades, agricultural production corporations have made dramatic growth, from 2740 in 1970, to 14333 in 2014 (MAFF, 2014e), and have become important paddy producers. The major reasons of this boom include that different from family management, agricultural production corporations possess larger ara-

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ble lands and stronger managerial ability, easier access to credit, diversified business development, better welfare and hence sufficient HR. Nevertheless, such large–scale farms usually possess scattering paddy fields, with different scales, soil properties, altitude, humidity, day–lighting, etc (JSAI, 2014: p128). At the same time, in an effort to cope with the problems relate to agriculture, food and environment, GAP (Good Agriculture Practice) has spread in Japan. With respect to paddy production, GAP can improve people's working and consuming condition, environmental protection through appropriate application of agro–chemicals and proper concerns about biodiversity, and food safety free of contamination and being balanced in nutrition (Li *et al*., 2014). In this circumstance, to increase the yield with saved costs of paddy production subject to GAP, ICT (Information Communication Technology) has been adopted and promoted, to process the enormous amount of information in sectors of innovational cultivation, production and managerial technologies (Nanseki, 2015; JSAI, 2014).

This research is part of the NoshoNavi1000, a projects funded by the Japanese Ministry of Agriculture, Forestry and Fisheries (MAFF). Represented by Kyushu University, the project consortium includes four agricultural production corporations with 1000 paddy fields scaled over 330 ha in total, two technological companies, five institutes and two universities (Nanseki, 2015). It aims to develop and demonstrate the smart paddy agriculture models, implemented by agricultural production corporations, with the integration of ICT agro–machinery, field sensors, visualization farming and skill–transferring system. In this study, we investigate the variation and determinants of rice yield measured by IT combine, among 351 paddy fields of different planting conditions, within a large–scale farm from Ibaraki Prefecture, Kanto Region of Japan. Different from most the prior studies using experimental data, we use yield data measured by IT combine in the fields of a large–scale farm, with the cooperation of farm managers and field–work practitioners.

MATERIALS AND METHODS

Yield measurement and estimation

According to the national standards of brown rice inspection of Japan (MAFF, 2014f), the paddy yield used in the following analyses is converted by 15% of moisture content. By contrast, the paddy before the conversion is named as *raw paddy*, weight and moisture content of which applied here are monitored directly by IT combine equipped with the GNSS (Global Navigation Satellite System, H. Isemura *et al*., 2015), and hereby with higher accuracy, comparing with the estimated weight of brown rice by sampling. Calculation of the rice yield with all of the 351 fields is shown in Table 1. Incidentally, rice yield is determined by the following four factors: panicle number, spikelet number per panicle, ratio of filled grains and grain weight (CSSJ, 2002: p522).

In Japan, rice yield, as summarized above, refers to the weight of sorted brown grains, while it is presented by weight of paddy grains in most of the other countries. The difference is generated from a complex process of measuring the rice yield, incorporating different conceptions and ratios. As shown in Fig. 1, we estimated the paddy yield of 15% of moisture, using the data of raw paddy and average moisture, measured by on–farm IT combines. Then, samples about 2 kg from each paddy field was gathered and hulled, based on which the weight of the brown rice were measured. In succession, the ratio of brown rice and hence the yield of the unsorted brown rice were estimated for each paddy field. At the same time, the hulled samples were sent to the laboratory in Kyushu University, where the brown rice grains thicker than 1.85 mm were sorted out using grain–sorting machine, using another sample of 0.6 kg. Finally, yield of the sorted brown rice was estimated by multiplying the yield of brown rice and ratio of sorted grains. For each paddy field, calculation of rice yields and the summary statistics of concerning indices are shown in Table 1.

Continuous explanatory variables

To outline the production and present the candidate yield determinants in the sampled paddy fields, we build an indicator system of 48 continuous variables, from the perspectives of field area and condition, nitrogen amount, time of transplanting or seeding, to the stage–based growth indictors. In addition, soil properties, average temperature and solar radiation are incorpo-

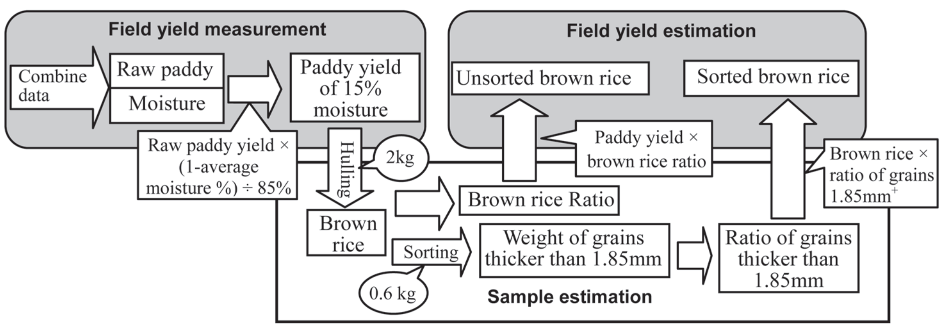

Fig. 1. Process of estimating the sorted brown rice yield.

Table 1. Calculation of rice yields and the summary statistics

Field	Raw yield (kg)	Average moisture (%)	Total paddy yield[a] (kg)	Field area (ha)	Average paddy yield[a] (kg/ha)	Unsorted brown rice/ paddy (%)	Unsorted brown rice (kg/ha)	Sorted/ Unsorted brown rice (%)	Sorted brown rice (kg/ha)
	(a)	(b)	(c)=a(100–b)/85	(d)	(e)=c/d	(f)	(g)=e×f/100	(h)	(i) =g×h/100
No.1	7894.10	20.80	7355.40	1.03	7079.99	75.80	5366.64	90.88	4877.20
No.2	7555.40	23.30	6817.50	1.04	6557.18	75.00	4917.90	91.00	4475.29
…	…	…	…	…	…	…	…	…	…
N	351	351	351	351	351	345	345	349	344
Min.	103.60	1.61	100.10	0.02	3484.44	70.61	3427.81	79.42	3074.65
Max.	13388.40	31.60	12871.60	2.11	9945.93	83.80	7918.93	97.52	7462.00
Mean	2383.68	21.91	2189.89	0.32	6904.42	77.87	5383.80	92.44	4976.76
Std.D.	2384.19	3.26	2191.54	0.34	833.32	2.50	666.00	2.93	624.58
CV (%)[b]	100.02	14.89	100.08	105.88	12.07	3.22	12.37	3.17	12.55

a: Converted yield by the moisture content of 15%; b: The CV (coefficient of variation) represents the ratio of the standard deviation to the mean, and it is a useful statistic for comparing the degree of variation among data series
Source: survey conducted by the authors in 2014

rated to showcase impact of natural condition. The summary statistics are shown in Table 2.

(1) Fields property. The paddy fields vary in a large scope of area as revealed by the coefficient of variance, from 200 to 21148 m^2 with an average of 3238 m^2. Scores of field are evaluated by farm managers, considering the differences in height, water depth, water leakage, former crop, inletting water, soil fertility, illumination, and herbicides application. (2) Production management. The proxy variable of transplanting date is transformed through defining April 14 as 1 and June 22 as 70 for the all the 351 paddy fields. The nitrogen amounts are weighted means calculated according to the amounts and corresponding nitrogen contents of compost, compound chemical fertilizer, ammonium sulfate, and urea fertilizers. (3) Stage–specific growth indices. The stage covers from panicle–forming, full–heading, 10 days after full–heading and maturity. The growth indictors include the chlorophyll meter value of the soil and plant analyzer development (SPAD), number of stems or panicles per hill, plant height, and individual and community leaf plate value (LPV) by stage of panicle growth for the forming, heading, 10 days after full–heading, and maturity stages, as well as panicle length for the maturity stage only. (4) Temperature and solar radiation. With the global warming–up and climate changes, impacts of temperature and solar radiation on crop growth and yield have become increasingly concerned among scholars, e.g., Ohsumi *et al.* (2014), Deng *et al.* (2015). In our research project, we adopt the precision devices to collect continuous data of temperature and solar radiation in each hour. The data shown in Table 2 is the average of 20 days since heading, as this span of time is vital for starch accumulation (Asaoka *et al.*, 1985). (5) Soil property analysis. Soil has been measured as an important determinant for paddy yield by many prior studies, e.g., Tsujimoto *et al.* (2009), from the function of permeability, heat–preservation, and the large amounts of fertilizing materials closely correlated with rice grain yields, from the surface to the deep soil layers. Based on the analysis results of specialist agencies, the soil properties are represented from five aspects: 1) fertility and texture include pH, EC (electrical conduction), CEC (cation exchange capacity), humus, and phosphate absorption coefficient; 2) saturation, constitution and exchangeable amount of the base, by potassium, lime and magnesia; 3) inorganic nitrogen in forms of ammonium and nitrate; 4) effective phosphoric and silicic acid; 5) contents of other elements, including manganese, free iron oxide, soluble zinc and copper.

Discrete explanatory variables

In this research, we include the *variety* and *cultivation method*, to analyze determinants of rice yield, similar with some of the prior studies, include Nishiura and Wada (2012), Muazu *et al.* (2014), Ju *et al.* (2015). In addition, soil properties may affect rice growth and yield from the perspectives of nutrition content, water drainage and conservation, aeration, etc (CSSJ, 2002: p210). Therefore, we investigated the soil types of the sampled paddy fields, through referring to the Soil Information Navigation System of NIAES. A dummy variable named *soil type* is formulated, with the binary values of *gray lowland soil and peat soil*. The summary statistics of these variables are to be provided in the follow section.

Statistical analysis

Impact of the independent variables, including the discrete and continuous variables, on yield of sorted brown rice is analyzed using a multivariate regression. Values of the yield and the continuous variables are taken natural logarithmic transformations, to make easier interpretation of the regression coefficients in terms of elasticity (Gujarati, 2015: p44). All these analyses are performed using SPSS 23.0 for Windows, and the Backward procedure is used to select the significant determinants of the ultimate model.

Table 2. Summary statistics of the continuous explanatory variables

Variable	N	Min	Max	Mean	Std. D.	CV (%)	R [e]
Field area (m^2)	351	200.00	21148.00	3237.70	3428.18	105.88	–0.165 ***
Score of field evaluation [a]	349	0.00	38.90	32.13	4.56	14.18	–0.076
Date of transplanting/sowing [b]	351	1.00	70.00	33.66	13.98	41.55	–0.221 ***
Nitrogen from fertilizers (kg/ha) [c]	349	14.00	148.83	66.09	20.02	30.29	0.065
SPAD in panicle–forming stage	351	26.30	63.30	36.06	4.26	11.82	0.185 ***
Stems per hill in panicle–forming stage	351	13.80	34.60	24.34	4.18	17.15	0.236 ***
Plant height in panicle–forming stage (cm)	351	57.70	112.70	86.66	10.38	11.98	–0.226 ***
Individual LPV in panicle–forming stage	351	2.60	6.00	4.39	0.58	13.31	0.248 ***
Community LPV in panicle–forming stage	351	2.00	6.00	4.29	0.73	17.05	0.231 ***
SPAD in full–heading stage	347	24.60	50.70	35.60	4.17	11.72	0.142 ***
Panicles per hill in full–heading stage	347	13.30	42.40	23.52	4.36	18.55	0.191 ***
Plant height in full–heading stage (cm)	347	79.50	117.60	102.61	6.71	6.54	0.157 ***
Individual LPV in full–heading stage	347	2.60	6.20	4.47	0.67	14.98	0.121 **
Community LPV in full–heading stage	344	2.00	6.00	4.31	0.73	17.02	0.225 ***
SPAD 10 days after full–heading	350	20.10	46.80	34.93	3.86	11.05	0.207 ***
Panicles per hill 10 days after full–heading	350	12.60	33.30	23.23	3.92	16.89	0.037
Plant height 10 days after full–heading (cm)	350	80.90	124.20	106.08	6.27	5.91	0.282 ***
Individual LPV 10 days after full–heading	350	2.00	6.00	4.05	0.75	18.42	0.265 ***
Community LPV 10 days after full–heading	350	2.00	6.00	4.02	0.74	18.40	0.299 ***
SPAD in maturity stage	350	12.80	42.30	31.31	4.71	15.04	0.305 ***
Individual LPV in maturity stage	350	1.00	6.40	3.18	0.79	24.79	0.254 ***
Community LPV in maturity stage	350	1.00	6.00	3.13	0.82	26.22	0.198 ***
Panicles per hill in maturity stage	350	12.80	33.50	23.12	3.86	16.72	0.072
Panicle length in maturity stage (cm)	349	16.90	23.80	19.99	1.23	6.14	–0.067
Plant height in maturity stage	350	65.60	99.30	83.95	5.87	7.00	–0.076
Average temperature (°C) [d]	351	23.42	27.49	25.91	1.01	3.88	–0.173 ***
Average solar radiation (MJ/m^2) [d]	351	12.80	22.91	18.81	3.00	15.94	–0.032
pH	347	5.42	6.56	6.12	0.18	3.01	–0.134 **
EC (ms/cm)	347	0.03	0.18	0.08	0.03	34.77	0.149 ***
Humus (%)	345	1.46	12.33	5.63	1.81	32.15	0.127 **
Phosphate absorption coefficient (mg/100g)	347	574.08	2689.26	1464.16	301.57	20.60	0.086
CEC (meq/100g)	347	5.69	31.43	18.29	4.64	25.34	0.073
Ammonium nitrogen (mg/100g)	347	0.16	2.27	0.65	0.28	42.63	–0.080
Nitrate nitrogen (mg/100g)	347	0.21	3.15	1.25	0.63	50.49	–0.034
Effective phosphoric acid (mg/100g)	347	1.02	29.45	7.74	5.26	67.90	0.213 ***
Exchangeable potassium (mg/100g)	347	9.07	54.09	21.62	6.91	31.96	–0.077
Exchangeable lime (mg/100g)	347	90.91	561.62	303.25	79.77	26.30	0.046
Exchangeable magnesia (meq/100g)	347	18.40	128.24	65.07	17.92	27.55	0.092 *
Potassium saturation (%)	347	0.94	6.16	2.60	0.80	30.70	–0.166 ***
Lime saturation (%)	347	28.43	96.80	59.45	7.28	12.24	–0.082
Magnesia saturation (%)	347	9.97	36.29	17.97	3.91	21.74	–0.004
Lime/magnesia	347	1.96	5.41	3.41	0.62	18.03	–0.092 *
Magnesia/potassium	347	2.64	18.62	7.54	2.74	36.35	0.110 **
Exchangeable manganese (%)	347	0.13	19.76	5.03	3.11	61.89	0.060
Soluble zinc (%)	347	2.50	76.69	8.70	6.37	73.15	–0.137 **
Soluble copper (%)	347	0.54	10.99	5.84	1.97	33.65	–0.026
Free iron oxide (%)	347	0.32	3.42	1.73	0.57	32.71	0.073
Available silicic acid (mg/100g)	347	6.70	68.54	29.54	11.47	38.84	–0.086

a: Evaluation items include variable concerning height difference, water depth, water leakage, former crop, water inletting, unevenness of soil fertility, illumination, and herbicides application; b: The earliest date of April 14=1, while the latest date of June 22=70; c: Calculation based on the amounts of chicken manure, chemical fertilizer, Ammonium sulfate and urea fertilizers, and the corresponding contents of nitrogen; d: Data of 20 days since full–heading; e: Pearson correlation with sorted brown rice; ***, **, * denote significant at 0.01, 0.05 and 0.10, respectively
Source: survey conducted by the authors in 2014

VARIATION OF THE YIELDS AND RATIOS

General correlation and variation

As shown in Table 1, CVs (Coefficients of variance) of the average yield per hectare, including those of the paddy with 15% moisture, unsorted and sorted brown rice, vary in the scope of 12–13%. By contrast, the ratio CVs, of both the unsorted brown rice against the paddy and the unsorted brown rice over the sorted brown rice, range around 3%. Thus the yields fluctuate with much more variation than that of the ratios. With respect to the correlation correlations, the yield of sorted brown rice is identified as significantly correlating with the other four indicators shown in Table 3. Among them, coefficients with the two yields are larger than 0.95, much higher than those with the two ratios. It indicates that comparing the ratios, yield of sorted brown rice is much linearly related to the yield of paddy and unsorted brown rice. Fig. 1 plots the yield of the sorted brown rice and other yields and ratios, and it is clear that the yields scatter much closely to the estimated regression line, relate to the yield of the sorted brown rice.

Variation among varieties

Akidawara possesses the largest value of both the paddy yield converted by 15% of moisture, 7303 kg per hectare, and ratio of the unsorted brown rice in the paddy, 81%. Consequently, its yield of unsorted brown rice is the highest valued amounting to 5934 kg per hectare. Simultaneously, Akidawara yields the highest amount of sorted brown rice with 5426 kg per hectare, despite the lowest ratio of sorted brown rice against unsorted brown rice, which is merely 91%. In succession, the following higher yields are ranked as Akitakomachi, Ichibanboshi, Koshihikari and Yumehitachi. Being the relatively low–yielding varieties,

Table 3. Pearson correlation of the yields and ratios

Yield and ratio	Paddy of 15% moisture (kg/ha)	Unsorted brown rice/paddy (%)	Unsorted brown rice (kg/ha)	Sorted/Unsorted brown rice (%)	Sorted brown rice (kg/ha)
Paddy yield of 15% moisture (kg/ha)	1.000				
Unsorted brown rice/paddy (%)	0.071	1.000			
Yield of unsorted brown rice (kg/ha)	0.963*** [a]	0.334***	1.000		
Sorted/Unsorted brown rice (%)	0.001	–0.267***	–0.067	1.000	
Sorted brown rice (kg/ha)	0.951***	0.263***	0.969***	0.178***	1.000

a: *** implies significant at the level of 0.01 Source: survey conducted by the authors in 2014

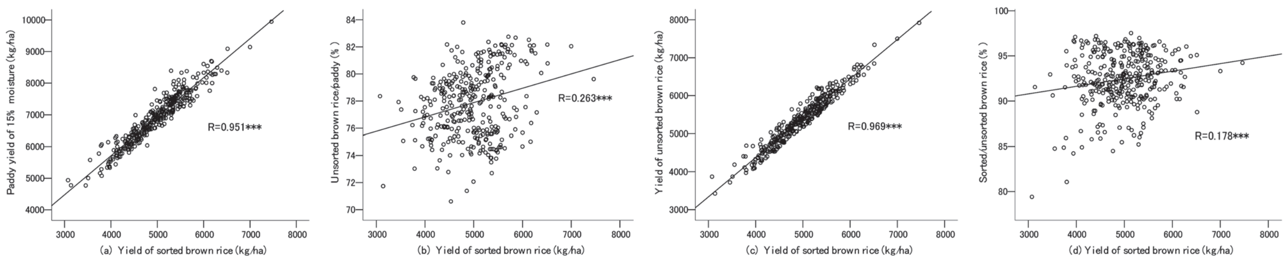

Fig. 2. Scatters of sorted brown rice yield and other yields and ratios.
(***: Pearson coefficient significant at 0.01)

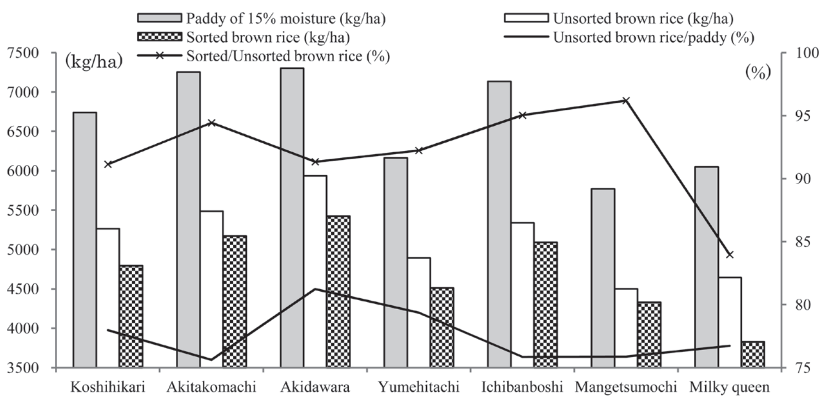

Fig. 3. Rice yields and ratios among varieties.

Mangetsumochi has the lower yield of both the paddy and unsorted brown rice than Milky queen. Nevertheless, the former yields more sorted brown rice per hectare than the latter, thanks to the highest ratio of sorted brown rice to the unsorted brown rice (Fig. 3).

Variation among cultivation methods

The conventional transplant has the highest yields of both paddy and sorted brown rice per hectare, with the amount of 7053 kg and 5105 kg, respectively. The two yields per hectare are ranked secondly with submerged direct sowing, and the values are 6940 kg and 5057 kg, respectively. Meanwhile, it yields the highest amount of unsorted brown rice, 5619 kg per hectare, thanks to the highest ratio of 81% of the unsorted brown rice in the paddy. Well–drained direct sowing possesses the highest ratio of 97% sorted brown rice within the unsorted grains; while its average yield of 4846 kg sorted brown rice per hectare is ranked the third, due to the lowest paddy yield (Fig. 4).

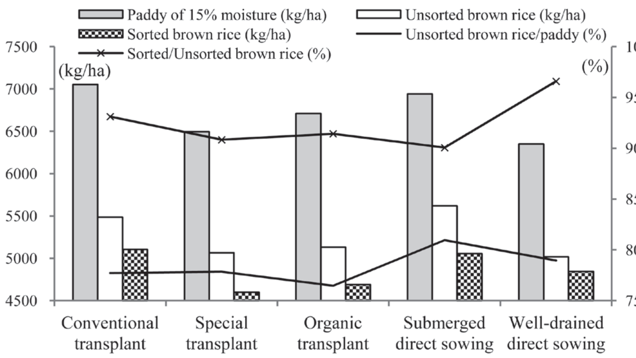

Fig. 4. Rice yields and ratios among cultivation methods.

Variation among soil types

Little discrepancy can be identified between the two soil types, with respect to all the yields and ratios. In general, rice planted in the gray lowland soil yields more than that of the peat soil, while the average ratios of the latter are higher than the former. In the paddy fields with gray lowland soil, yields per hectare of the paddy, unsorted and sorted brown rice are 7069 kg, 5464 kg and 5030 kg, 2.6%, 1.6% and 1.2% higher than that of the peat soil, respectively. At the same time, in the former type of soil, there is 77.5% of the unsorted brown rice within paddy and 92.2% of sorted brown rice in the unsorted ones, on average. Both of the two ratios are lower than that of the paddy fields of peat soil, although the differences are no more than 0.5% (Fig. 5).

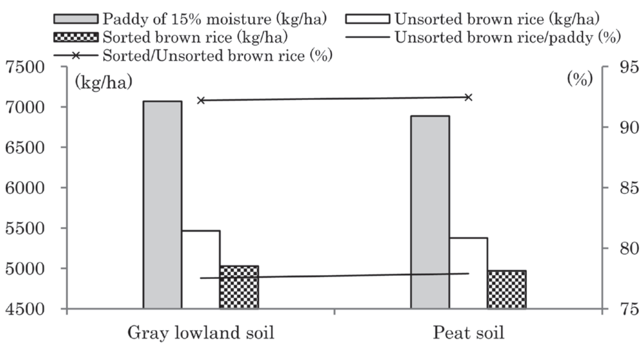

Fig. 5. Rice yields and ratios among soil types.

RESULT AND DISCUSSION

As mentioned above, rice yield in Japan is mainly measured by the weight of sorted brown grain, which is directly relating to the milled rice sold in the market. For each continuous variable, we present the Pearson correlation coefficient and the significance with sorted brown rice yield in Table 2. These coefficients measure linear association between each determinant and the yield, showcasing how strongly the two variables are linearly related and be referential to identify the determinants of some variables. However, correlation coefficient may lead to illusive results as it showcases only the bilateral relationship, without considering the influence of other variables. Thus to identify the yield determinants of the sorted brown rice, we need to conduct multivariate regression analysis. Hereby, we can get significant models and determinants, partial correlation coefficients of which showcase the pure impact holding the influence of other variables constant (Gujarati and Porter, 2010: p254). To amplify the relationships among yield and the determinants, logarithmic transformation is adopted to the continuous variables.

Results of the multivariate regression

In the initial multivariate regression model, the independent variables included all the continuous and discrete variables shown in Table 2 and Table 3. For each discrete variable, a dummy variable is formulated taking the value 1 or 0 to indicate the presence or absence of the categorical effect. According to the estimation result of the final model, nine continuous and three discrete variables are included in the final model (Table 4). Value of the adjusted R^2 denotes that 37.5% of the variation of the independent variable can be explained by the 12 significant independent variables, for this sample of 334 paddy fields. The significant values of F and t show that, both the model and each dependent variable made difference in identifying the variation. VIFs of all the dependent variables are less than 10, hence eliminated the probability of Collinearity. In the plot of regression standardized residual shown in Fig. 6, the expected cumulated probability increases closely as the observed cumulated probability increases. Thus it indicates that heteroscedasticity does not exist in the final model (Carter *et al.*, 2012).

In Table 4, column B contains the unstandardized estimated regression coefficients. For each continuous variable (X_i), the coefficient is the elasticity of yield with respect to X_i. For instance, the plus coefficient of X_1 and the minus coefficient of X_2 imply that yield can be increased by either more panicles per hill in the full–heading stage or earlier transplanting or sowing. For a certain level, 1% increase of panicle number can increase

Table 4. Result of the Log–linear Multivariate Regression estimation

Independent variable [a]	B [b]		Δ% [c]	Std. B	Contribution (%) [d]	t	VIF
(Constant)	7.803					37.053	
Panicles per hill in full–heading stage (X_1)	0.196	***	0.195	0.297	14.558	4.860	1.995
Date of transplanting/sowing (X_2)	–0.053	***	–0.053	–0.212	10.371	–2.931	2.785
Lime/magnesia (X_3)	–0.100	***	–0.100	–0.145	7.120	–2.830	1.408
Nitrogen from fertilizers per ha (X_4)	0.046	**	0.046	0.107	5.232	1.983	1.549
Community LPV in panicle–forming stage (X_5)	0.065	**	0.065	0.100	4.880	2.120	1.178
Humus (X_6)	0.036	*	0.036	0.098	4.811	1.657	1.875
Field area (X_7)	0.014	*	0.014	0.090	4.415	1.719	1.467
Exchangeable potassium (X_8)	–0.034	*	–0.034	–0.086	4.194	–1.661	1.417
Exchangeable manganese (X_9)	0.014	*	0.014	0.079	3.847	1.670	1.180
Akidawara (D_1)	0.153	***	16.537	0.484	23.706	9.102	1.509
Milky queen (D_2)	–0.201	***	–18.198	–0.197	9.658	–4.174	1.191
Well–drained direct sowing (D_3)	–0.236	**	–21.025	–0.147	7.210	–2.422	1.971

Dependent Variable (Y): Natural log of the sorted brown rice yield; Valid N =334
R=0.631, R^2=0.398, Adjusted R^2=0.375; F(12, 321)=17.682***

a: Natural log values of X_i, b: ***, ** and *imply significant at the level of 0.01, 0.05 and 0.10, respectively; c: percentage of paddy yield changes due to a 1% increase of X_i by=100*(1.01^B–1); and due to value of D shifting from 0 to 1 by 100*(e^B–1); d: calculated based on Std. B.
Software: SPSS 23.0; Variable selection: the Backward procedure

the yield by 0.196%, while 1% decrease of the transforming or sowing date value can increase the yield by 0.053%, holding other variables fixed. For exacter calculation, the estimated yield increases by $1.01^{0.196}$–1=0.195% and $1.01^{-0.053}$–1=–0.053%, respectively (Wooldridge, 2013: p183). Similarly, as the other significant determinants, 1% increase of the nitrogen amount, community LPV in panicle–forming stage, humus contains, field area and exchangeable manganese are estimated to increase the yield by roughly 0.046%, 0.065%, 0.036%, 0.014% and 0.014%, respectively. Meanwhile, 1% decrease of ratio of the lime to magnesia and exchangeable potassium, *ceteris paribus*, are measured as increasing the yield by roughly 0.1% and 0.034%, respectively. Table 4 shows the exacter percentage of yield changes due to 1% increase of each X_i as well. For a dummy independent variable D_i, the coefficient B implies yield changes by e^B–1 when D_i switches from 0 to 1, keeping other explanatory variables constant (Wooldridge, 2013: pp224–225). Thus for Akidawara, the coefficient of 0.153 denotes a roughly 15.3% higher yield, while the exact increase is 16.537%. By the same token, milky queen and well–drained direct sowing showcase roughly 20.1%, and 23.6% less of yield on average, respectively, holding other factors fixed (Table 4).

Within the continuous variables, an unstandardized coefficient B is affected by the units of measurement. We need to calculate standardized coefficient, absolute values of which show relative importance of the explanatory variables. For example, according to data of column Std. B in Table 4, the panicle number in full–heading stage is measured as the most effective continuous factor to affect yield of the sorted brown rice. Variables in Table 4 are presented in the ascending rank of the absolute values of the Std. B, grouped in continuous and discrete variables.

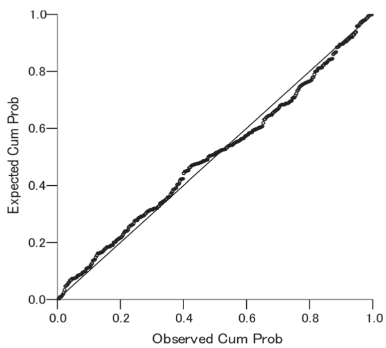

Fig. 6. Plot of regression standardized residual.

Discussion on impact of the continuous determinants

(1) Full–heading stage refers to when 40–50% of the stalks have finished sprouting panicles. It is an important stage to judge the growth, variety properties of the whole year (Goto *et al.*, 2000). Thereafter, focus of cultivation management shifts from the growth of stem and leaves, to panicle growth and grain filling. In this stage, more panicles help to increase the yield directly according to the determining of rice yield. It is proofed by Fig. 7–(a), where the yield of sorted brown rice is plotted to go upward with larger panicle numbers. (2) Relatively earlier transplanting or sowing benefits high yielding. Generally, earlier transplanting or sowing is followed by

longer vegetation period to accumulate more nutrients and benefit the growth in the following stages. In another study (Li *et al*., 2015), we have identified that growth duration goes shortened, when the transplanting or sowing time goes relatively later. e.g., the paddy transplanted during April 11–20 can grow for 109 days before heading, while those transplanted or sowed during June 21–30 can grow only for 58.5 days on average. The shortened vegetative growth usually results in reduced panicles, spikelet and poor ripening ratio, etc (NARO, 2011). Fig. 7–(b) verified the trend of downward yield when transplanting or sowing time goes later. (3) Magnesia is the key ingredient of chlorophyll and thus indispensible for photosynthesis, in addition to balance the soil minerals. Nevertheless, its absorption efficiency is suppressed when soil contains excessive lime. As shown in Fig. 7–(c), a positive correlation relationship, with the significant level of 0.01, exists between the magnesia saturation and the yield of sorted brown rice. (4) As an essential element for paddy growth, nitrogen exists mainly in forms of protein especially Rubisco, which accounts for 20–30% of total nitrogen amount (CSSJ, 2002: p126). Generally, sufficient nitrogen helps to increase the yield, as shown in Fig. 7–(d), through the enhancement of photosynthesis. More than 90% of crop biomass is derived from photosynthesis, and rice has been found possessing high photosynthesis rate 10 times of some evergreen trees (Makino, 2011). Therefore, it positively relates to yield through increasing nitrogen appropriately, with the amount leading to no lodging and other negative consequences. (5) The panicle–forming stage refers to when the young panicle growth to the length of 1–2 mm that visible by naked eye. It is a very important stage in determining the optimum fertilizer amount and conducting the panicle–length diagnosis. In addition, the importance of prevention cold injury increases after this stage. To judge the nutrition contains and hence decide the top dressing amount, there is a quick way of reading the leaf plate value (LPV), higher grade of which indicates more nutrition contains in the plant. Thus this indicator is positive relate to yield, as plotted in Fig. 7–(e). (6) As kind of polymeric compound transformed from organic matter, humus composes an important source of supplying the paddy plant with carbon, hydrogen, oxygen, nitrogen, sulfur, phosphorus and other nutrient elements (Makino, 1998). Humus can significantly improve the soil's cation exchange capacity, hence contributes to store nutrient against leached by rain or irrigation. On the other hand, humus can hold moisture up to 80–90% of its weight, and thus makes the soil strong to withstand drought conditions. The biochemical structure enables humus to improve soil aeration, block the toxic substances excess nutrients, and excessive acid or alkaline (Kono, 1993). Thus as shown in Fig. 7–(f), humus is positively correlating to the yield of sorted brown rice, significant at 0.05. (7) The inverse impact of exchangeable potassium, as shown in Fig. 7–(g), reveals the reality that over the latest years, surplus potassium is accumulated in paddy field of Japan, due to the over–application of fertilizers (Watanabe *et al*., 2015). Within the sampled paddy fields, the average potassium saturation amounts to 2.6%, higher than the maximum threshold of 2.5% of paddy field in Ibaraki Prefecture (MAFF, 2008). (8) As an essential trace element for plant growth, manganese is involved in photosynthesis and the transformation of nitrogen, and being active in the catalysis of many enzymes and redox processes. It can promote the synthesis of chlorophyll and the operation of carbohydrates. The deficiency of manganese in soil may lead to withered plants, dysplasia, and eventually declined production. Thus, a positively relationship exists between the amount of exchangeable manganese and the yield of sorted brown rice, as shown in Fig. 7–(h).

Within this sample, 312 fields are less than 0.7 ha, up to which positive correlation coefficients are observed

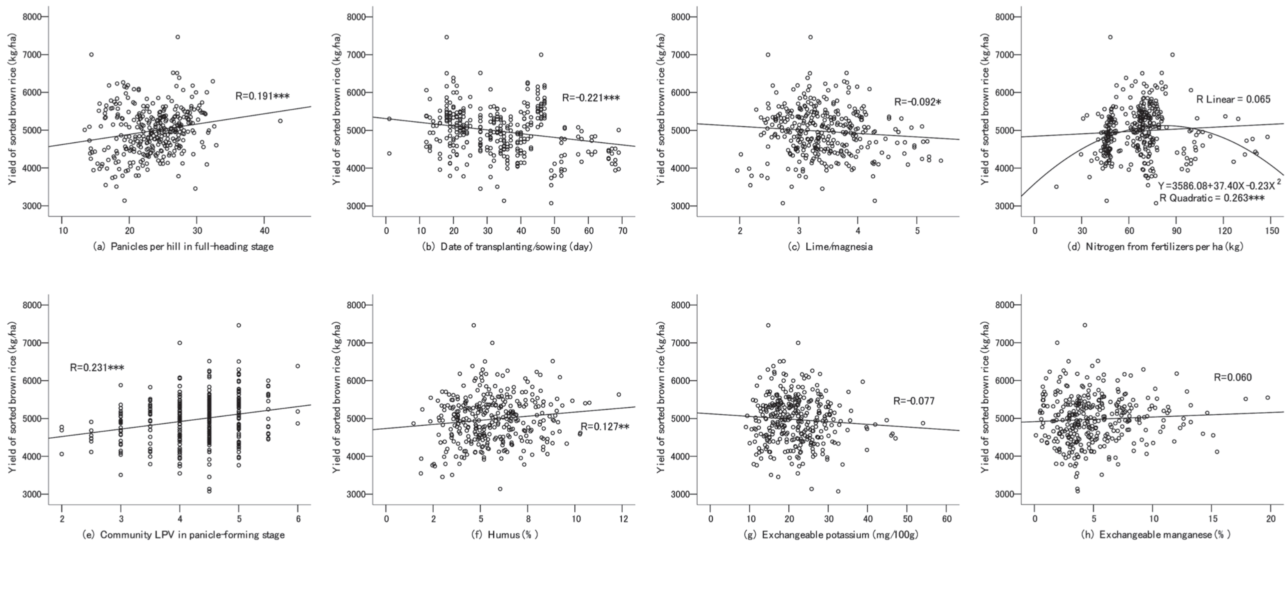

Fig. 7. Scatters of sorted brown rice yield and determinants.
(***, **, *: Pearson coefficient significant at 0.01, 0.05 and 0.10, respectively)

between the yield of sorted brown rice and field area (Fig. 2). It can be interpreted by that when fields scaled less than approximately 0.7 ha, larger area usually can increase yield through enlarged sink size, i.e., spikelet number per unit land area. Meanwhile, the correlation coefficient of the field area and amount of nitrogen from fertilization is 0.46, significant at 0.01, indicating that larger field facilitates the application of fertilizer. Nevertheless, both of the factors indicate the existence of diminishing returns when being inputted over certain threshold values. As shown in Fig. 4–(d) and Fig. 8, yield per hectare decreases in the paddy fields more than roughly 0.7 ha, or when the amount of nitrogen amount exceeds approximately 80 kg per hectare.

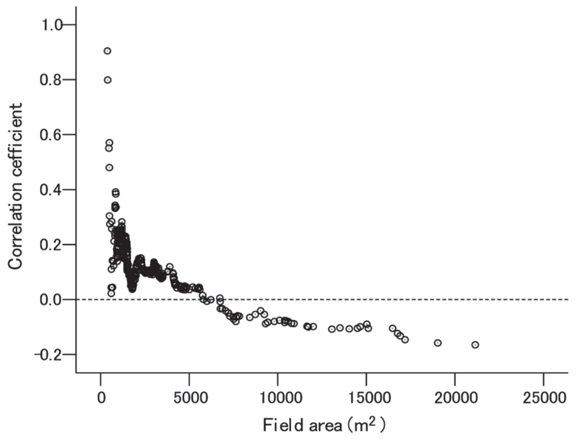

Fig. 8. Correlation coefficient of field area and sorted brown rice yield.

Discussion on impact of the discrete determinants

As we have measured in another study (Li *et al.*, 2015), variety is a significant factor affecting paddy yield of this sample. Being a new, lodging–resistant and high–yielding variety, Akidawara is suitable to be cultivated in the Kanto region. In this study, Akidawara yields 7303 kg per hectare on average, the highest among the seven varieties. The average yield of other six varieties is 6812 kg per hectare, 7.21% lower than that of Akidawara (Table 3). Meanwhile, Akidawara has the longest growth of 80 days from transplanting to heading, almost 10 day longer than that of the other varieties on average. Thus as analyzed above, it has advantage in prolonged vegetative growth with more panicles, spikelet and enlarged ripening ratio, etc. By contrast, milky queen is a new rice variety bred from Koshihikari, with low amylose content in the endosperm. Milky queen was not adapted to heavy chemical fertilizer use in paddy fields, because it was susceptible to lodging after heading and to leaf–blast and panicle–blast disease. In addition, milky queen is weak in resistance to rice blast disease (Isei *et al.*, 2001). Therefore, as shown in Fig. 3, the sorted brown rice yield of milky queen is 3829 kg per hectare, the lowest among the seven varieties.

Direct sowing is one of the traditional cultivation methods, and it is outstanding in saving the input of labors and energy. However, due to the defects of instable establishment, poor resistance to weed damage and lodging occurrence, directly sowed rice yields lower than the transplanting ones, in general cases. With respect to the well–drained direct sowing, it possesses more defects of sowing time is dominated by the weather, nutrient loss from cracked soil, etc (CSSJ, 2002: p326–329). Viewing back to the survey data, yield of the paddy cultivated using well–drained direct sowing is the lowest, with the largest data dispersion denoted by CV, among the five cultivation methods. In addition, it has the smallest number of panicles in the heading stage. Submerged direct sowing is used only to cultivate Akidawara, within which the average yield of submerged direct sowing is less than the other cultivation methods.

CONCLUSION

In the initial multivariate regression analysis, the candidate determinants included a variety of continuous variables of the yield, field characteristics, transplanting time, nitrogen amounts from fertilizing, and growth data of different stages. In addition, three discrete variables are included, from the perspectives of variety, cultivation method and soil type. Result of the multivariate regression analysis shows that, the panicle numbers in heading stage and earlier transplanting date are the most important determinants to increase rice yield. The other significant determinants include nitrogen amount, humus content, exchangeable manganese, and community LPV in panicle–forming stage, all of which have positive impact on yield of sorted brown rice; ratio of lime to magnesia and exchangeable potassium are positive with yield of sorted brown rice. Within the discrete determinants, Akidawara and Milky queen are measured as high–yield and low–yield variety, respectively; while the well–drained direct sowing is identified as negatively affecting the yield of sorted brown rice. The regression coefficients indicate positive impacts of field area to yield, while the correlation coefficient and further analysis from scatter plot denote over–large values may lead to yield reduction.

These empirical findings are referential to increase yield in farm management. Nevertheless, paddy production within large–scale farms is a systematic procedure, subject to constraints of the labors, funds, machinery, etc. For instance, although earlier transplanting or sowing has been measured as favorite higher yield, it may be unrealistic or uneconomic to conduct transplanting or sowing in many fields simultaneously. Thus optimal planning is necessary to conduct transplanting or sowing in different time and makes full use of the limited machinery, labors and funds (Chomei *et al.*, 2015). Meanwhile, the appropriate amount of fertilizer, and the rational allocation of fields with different areas need to be optimized in the following studies, considering the property of different varieties. As analyzed above, the adoption of direct sowing negatively relates to yield increasing, but it possesses attributes in agreement with the sustainable development. Hence, much more paddy varieties suitable for direct sowing needed to be bred and adopted.

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