Geostatistical Analysis of Yield, Soil Properties and Crop Management Practices in Paddy Rice Fields

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Abstract: We examined the possible benefit of rational site-specific crop management practices in 17 paddy fields located in an area of 2.0 ha for the prevalence of precision agriculture methods on a cooperatively managed large-scale farm in Sakurai, Nara Japan. Data on grain yield, soil physicochemical properties and farmer’s crop management practices were collected in each paddy field. Unhulled rice yield was estimated at a resolution of 5m × 5m in an area of 1.2 ha using a yield-monitoring combine. The spatial distribution of the variations for the collected data was characterized using geostatistical procedures. The kriged map of the unhulled rice yield drawn from the results of geostatistical analysis indicated the potential value of rational site-specific crop management using the yield-monitoring combine. The ratio of spatially structured variation to the total variation of brown rice yield, that is, the controllable proportion to total variation, was 75.4%. Each yield component i.e., the number of spikelets per square meter, filled-spikelet percentage and 1000-grain weight contributed 33.7%, 54.7% and 11.6%, respectively, to brown rice yield. These three yield components combined contributed to 96.5% of the brown rice yield variation. The agronomic factors (soil fertility factor, early growth factor, N dressing and uptake factor) contributed 79.7%, 52.1% and 41.8%, respectively, to the variation of these three yield components. Therefore these agronomic factors accounted for 58.1% of the total variation of the brown rice yield and 77.1% (i.e. 58.1% out of 75.4%) of the spatially structured variation of the brown rice yield. This controllable proportion may be a criterion for the prevalence of site-specific crop management in large-scale farm management in general, although only one case study was conducted.

Key words: Crop management, Geostatistics, Multivariate analysis, Nitrogen, Oryza sativa L., Precision agriculture, Soil physicochemical property, Spatial variability

The average age of the farmers in Japan is over 65 years, and 80 to 90% of the farmers over 65 will probably give up farming before 2010. In the large-scale farm management and the large paddy field practiced under government policies, there is a need for mechanization and automation far beyond the current situation. Moreover, in large-scale farm management, the spatial variability of the rice yield and the soil properties may be too high to justify the cost of equipment needed. An agricultural system with site-specific management, i.e., precision agriculture, can help to solve such problems (Cassman, 1999). Precision agriculture can compensate for the spatial variability of the yield according to within-field requirements to optimize profitability and the yield can be increased with less environmental load on agricultural activities. Such crop management practices should be based on diagnosis and prediction of the spatial variability of crop management parameters such as biomass, the amount of nitrogen in the crop, water status, and soil properties. Geostatistics is a method of diagnosing the spatial variability of soil properties (Trangmar et al., 1985; Webster, 1985). It provides the basis for describing spatial variation in soil quantitatively, for estimating soil properties and mapping them, and for planning rational sampling schemes that makes the best use of manpower (Webster, 1985). Geostatistics is useful for the studies not only on soil properties, but also been on the spatial patterns of plants (Vieira et al., 1983; Yanai et al., 2001) and other organisms living at the surface of the soil (Rossi et al., 1992).

The spatial variability of the soil physicochemical properties and the amount of N in paddy rice have been the major objectives in the top-dressing management practices for a target yield (Miyama, 1988; Miyama and Okabe, 1979; Inamura et al., 2003). However, only limited information is available on the proportion of variability controllable by farmer’s crop management practices for the spatial variability of the
rice yield not only in small-scale farm management but also in the large-scale farm management and in the large paddy field. We consider that this controllable proportion may be a criterion for the prevalence of site-specific crop management. The objectives of this study were, therefore, first to evaluate the spatial variability of the rice yield, secondly to extract the principal components of the soil physicochemical properties and farmer's crop management practices, and finally to analyze the controllable proportion of the spatially structured variability of rice yield caused by soil physicochemical properties and farmer's crop management practices based on a multivariate analysis.

Materials and Methods

1. Experimental field

An on-farm experiment was carried out in 2002 at the paddy fields (135°49'E, 34°32'N, 65 m above sea level) located in Ohnishi, Sakurai, Nara Japan with a mean annual temperature of 15.0°C and precipitation of 1,278 mm. The average terrain slope in the study area was 0.2%, although the paddy fields were almost flat (0.03 %), and the soil was Gray Lowland Soil.

In Ohnishi, the unit area of the paddy fields that are cooperatively managed by farmers is about 38 ha, and there are about 38 sections (“Tsubo”, in Japanese) and about 380 paddy fields (Fig. 1). The cropping system of these fields has been three croppings in two years from 1988, with some variation. Paddy rice (cv. Hinohikari) is grown from June to October, wheat (cv. Kinuiroha) from December to the next June, and soybean (cv. Nishimusume) in the next year from late June to December. In the summer cropping season in 2002, paddy rice was grown in half of these fields, and soybean in the other half (Fig. 1). This cropping system is called paddy-upland rotation, and has been used since the 18th century in Japan (Miyamoto, 1994).

Fig. 1 shows the study area that included 17 paddy fields cultivated by 13 farmers. These paddy fields were selected as the representative of paddy fields in Ohnishi. The study area was about 2.0 ha and divided into two sections. The basic size of each section was 109m×109m. Each section was surrounded by a farm road and/or creek. The width of farm road was 1 to 4 m, and that of creek was 0.5 to 2m. In Ohnishi, the unit of the management practice of the cropping system, which consists of the choice of principal
crops and crop rotation employed on a farm, has been each section. The section has been a unit of farmland consolidation and irrigation. A section was primarily composed of 10 paddy fields. The basic size of each paddy field was 10.9m x 109m. Each paddy field was surrounded by levee. The width of levee was about 0.2 to 0.3m. The unit of the farmer's cropping management, i.e., soil leveling operation and application of fertilizer, has been each paddy field.

2. Yield monitoring
Grain yield as unhulled rice with a 15% moisture content was estimated at a resolution of 5m x 5m for a 1.2 ha portion (Fig. 1) at maturity (October 12 to 18) using a yield-monitoring combine (Mitsubishi Agricultural Machinery Co., Ltd. Shimane). This combine is equipped with an impact-type grain flow-rate sensor and a global positioning hardware (RTK-GPS MS750, Trimble Japan CO., LTD.), and provides real-time measurement of yield for localized areas. The standard error of difference between the actual yield and the yield within the field (Lee et al., 2000). The sensitivity of weight per square meter of this yield-monitoring combine was 0.05 to 1.0 kg sec⁻¹, when the combine harvests the rice at the ordinary speed of 0.8 m/s.

3. Data collection of each farmer's crop management practices
The amount of N basal-dressing and the amount of N top-dressing were recorded after interviewing the owners of the paddy fields. One week after transplanting, planting density and the number of rice seedlings per hill in an area of 1 m x 1 m with three replications were measured at 2 places on each paddy field. The depth of plow layer was measured at 2 places on each paddy field with three replications after harvesting.

4. Sampling and analysis of soil
Soil samples were collected before the application of N basal-dressing. The paddy field was divided equally into two or three sub-plots and soil sample was collected as a composite of 3 sub-samples taken from the surface soil (0 to 15 cm deep) within a 2 m circular area centered on each sub-plot. All soil samples were air-dried and ground to pass through a 1-mm sieve before analysis. Soil pH was measured in 1:2.5 (w/w) soil: water suspensions with a pH meter. The concentration of total N (T-N) and total carbon (T-C) was analyzed by using a trace mass spectrophotometer (Tracer MAT, Thermo Quest Co. Ltd., Tokyo). The amount of T-N and T-C per square meter was determined as the product of the concentration (g kg⁻¹), the depth of plow layer (m) and the apparent specific gravity of soil in the plow layer. In our study, the apparent specific gravity of soil in each paddy field was assumed to be 1.0. Mineralizable N of soil (Nm) was determined as the difference between the amount of N extractable with 2 M KCl solution before and after incubation at 30ºC for 4 weeks under waterlogged conditions. The concentration of NH₄⁺ was determined by the indophenol blue method. The amount of Nm per square meter was determined as the product of Nm (mg kg⁻¹), the depth of plow layer (m) and the apparent specific gravity of soil.

5. Plant sampling and analysis
One hundred rice seedlings were collected from two seedling-raising boxes used on each paddy field. Variation of crop growth was examined by including the plants in three plots (10m x 10m) without N basal-dressing in the study area. Each paddy field was divided equally into two or three sub-plots and plants from 12 hills (20 hills at maturity) were randomly collected by two replications on each sub-plot and each plot without N basal-dressing at panicle formation stages (August 5 to 7), heading stage (August 28 to 30) and maturity stage (October 9 to 12). Thereafter, unless mentioned otherwise, the data do not include that of the three plots without N basal-dressing. The aboveground biomass of those paddy rice at panicle formation and heading was determined after oven drying at 70ºC to constant weight, and N concentration was analyzed by the Kjeldahl method using an ion analyzer (Hiranuma FIA Ion Analyzer WIS-2000, Hiranuma Sangyo Co., Ltd. Mito). Rice yield was calculated as brown rice at a moisture content of 15%. The brown rice yield was divided into 3 components (number of spikelets per square meter, filled-spikelet percentage and 1000-grain weight).

6. Geostatistical analysis
In the geostatistical analysis, a semivariogram was used to evaluate the spatial variability of the properties. It represents the relationship between the lag or any integral multiple of the sampling interval and the semivariance (Goovaerts, 1998). Semivariance \( \gamma(h) \) is theoretically shown as follows:

\[
\gamma(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} [Z(x_i + h) - Z(x_i)]^2
\]

where, \( n(h) \) is the number of pairs separated by a distance \( h \), and \( Z(x_i) \) and \( Z(x_i + h) \) are the sampled values at location \( x_i \) and \( x_i + h \). The quantity \( \gamma(h) \) is a function only of the increment \( h \). The function is called a semivariogram (Fig. 2).

In this study, two indices were used to evaluate the spatial dependence of the properties. One is the \( Q \) value, which indicates the spatial structure for the sampling scale (Goerres et al., 1997). This value is


\[ Q = \frac{(S - N)}{S} \]

where \( S \) and \( N \) are the sill variance and nugget variance, respectively. The sill variance \( S \) is the structural variance, roughly equal to the sample variance. The nugget variance \( N \) is \( \gamma(h) \) at a zero separation distance (intercept of semivariogram) and arises from measurement errors or spatial sources of variation at distances smaller than the shortest sampling interval or both. The \( Q \) value ranges between 0 and 1. If the \( Q \) value is 0, no spatial structure is detected on the sampling and crop management scale used. As the \( Q \) value approaches 1, the spatial structure is more developed. The other is the range \( (R) \) which indicates the limit of spatial dependence (Fig. 2). The \( \gamma(h) \) stops increasing at the range, and fluctuates around the same sill variance.

For the analysis, we used the semivariogram model with the greatest \( r^2 \) value for the estimation of semivariogram parameters. Geostatistical software, GS+ Version 3.1 for Windows (Gamma Design Software), was used for the analysis (Robertson, 1998).

### Table 1. Descriptive statistics of five physicochemical properties of soil, six properties of rice seedling, four properties of crop management practices, the amount of N accumulated in the aboveground biomass of rice at panicle formation stage (Npf) and heading stage (Nh), and yield and yield components.

| Variable                        | unit                  | n  | Mean  | Maximum | Minimum | C.V. |
|---------------------------------|-----------------------|----|-------|---------|---------|------|
| **Soil property**               |                       |    |       |         |         |      |
| Depth of plow layer            | cm                    | 17 | 15.86 | 20.54   | 9.82    | 21   |
| pH                              |                       | 17 | 6.13  | 6.63    | 5.45    | 6    |
| Amount of T-N                  | kg m\(^{-2}\)         | 17 | 0.218 | 0.255   | 0.156   | 14   |
| Amount of T-C                   | kg m\(^{-2}\)         | 17 | 2.50  | 2.96    | 1.69    | 14   |
| Amount of mineralizable N       | g m\(^{-2}\)         | 17 | 10.90 | 17.68   | 7.09    | 27   |
| **Rice seedling property**     |                       |    |       |         |         |      |
| Plant length                    | cm                    | 17 | 18.35 | 23.04   | 13.10   | 14   |
| Aboveground biomass            | mg plant\(^{-1}\)     | 17 | 27.65 | 48.00   | 16.80   | 31   |
| Leaf area                       | cm\(^2\) plant\(^{-1}\)| 17 | 3.79  | 7.63    | 1.70    | 45   |
| Amount of N in seedling         | mg plant\(^{-1}\)     | 17 | 0.358 | 0.598   | 0.218   | 33   |
| No. of rice seedlings per hill  |                       | 17 | 4.43  | 5.55    | 3.00    | 17   |
| No. of rice seedlings per m\(^2\)|                       | 17 | 73.20 | 98.87   | 46.53   | 17   |
| **Crop management practice**   |                       |    |       |         |         |      |
| Plowing frequency              | cropping season\(^{-1}\)| 17 | 3.71  | 6.00    | 0.00    | 45   |
| Planting density               | hills m\(^{-2}\)      | 17 | 16.61 | 20.45   | 13.87   | 10   |
| N basal-dressing               | g m\(^{-2}\)         | 17 | 7.34  | 9.00    | 4.80    | 14   |
| N top-dressing                 | g m\(^{-2}\)         | 17 | 3.71  | 6.40    | 2.40    | 28   |
| **Amount of N in rice**        |                       |    |       |         |         |      |
| Npf                            | g m\(^{-2}\)         | 17 | 10.44 | 11.95   | 8.54    | 10   |
| Nh                             | g m\(^{-2}\)         | 17 | 11.92 | 15.09   | 9.32    | 17   |
| **Rice yield and yield component** |                   |    |       |         |         |      |
| Unhulled rice yield * * *      | g m\(^{-2}\)         | 10 | 691.2 | 750.5   | 634.5   | 6    |
| Brown rice yield               | g m\(^{-2}\)         | 17 | 554.3 | 622.0   | 461.5   | 9    |
| number of spikelets            | m\(^{-2}\)           | 17 | 34990 | 38557   | 31363   | 5    |
| filled-spikelet percentage     | %                    | 17 | 73.6  | 80.9    | 57.9    | 8    |
| 1000-grain weight              | g                    | 17 | 21.45 | 22.92   | 20.69   | 3    |

* with a 15% moisture content. **estimated by the yield-monitoring combine.
the principal components with eigenvalues higher than 1.0. Multiple regression analysis was carried out to elucidate each yield component-determining factor, using the standardized scores of the extracted principal components. The Principal component analysis and multiple regression analysis were carried out using the data of 17 paddy fields and the data of three plots without N basal-dressing.

Results and Discussion

1. Descriptive statistics of collected data

Table 1 gives the descriptive statistics (the mean, maximum, minimum, and coefficient of variance (CV)). The soil chemical properties with a moderate acidity and almost neutral pH range, relatively high Nm, and relatively large amount of T-N were representative of typical soil in Nara Prefecture (Nara Prefectural Agricultural Experiment Station, 1978). The amount of N basal dressing at 7.34 gm⁻² exceeded the standard level of N application at 5.00 gm⁻² in Nara Prefecture (Nara Prefectural Agricultural Experiment Station, 2002), and Nh might have increased. The CV values of soil properties, rice seedling properties and crop management practices properties ranged from 6 to 27, 14 to 45 and 10 to 45, respectively, whereas, the CV value for brown rice yield was 9, suggesting a lower variability among the fields.

2. Spatial dependence of collected data

The Q values of the depth of plow layer, amount of T-N, amount of aboveground biomass of rice at panicle formation stage (Npf) and rice at heading stage (Nh), and yield and yield components.

Table 2. Geostatistical parameters of five physicochemical properties of soil, six properties of rice seedling, four properties of crop management practices, the amount of N accumulated in the aboveground biomass of rice at panicle formation stage (Npf) and heading stage (Nh), and yield and yield components.

| Variable                  | unit         | Nugget (N) | Sill (S) | Range (R) | Q value | r²  |
|---------------------------|--------------|------------|----------|-----------|---------|-----|
| Soil property             |              |            |          |           |         |     |
| Depth of plow layer       | cm           | 0.574      | 3.205    | 10.78     | 0.821   | 0.692|
| pH                        |              | 0.091      | 0.118    | 9.00      | -       | 0.178|
| Amount of T-N             | kg m⁻²       | 0.0003     | 0.0013   | 97.6      | 0.769   | 0.608|
| Amount of T-C             | kg m⁻²       | 0.0001     | 0.1252   | 10.0      | -       | 0.000|
| Amount of Nm              | g m⁻²        | 0.860      | 8.330    | 13.9      | -       | 0.052|
| Rice seedling property    |              |            |          |           |         |     |
| Plant length              | cm           | 0.030      | 6.270    | 25.3      | -       | 0.067|
| Aboveground biomass       | mg plant⁻¹   | 0.100      | 65.700   | 10.0      | -       | 0.000|
| Leaf area                 | cm² plant⁻¹  | 0.090      | 3.726    | 89.0      | -       | 0.191|
| Amount of N in seedling   | mg plant⁻¹   | 0.0002     | 0.104    | 10.0      | -       | 0.000|
| No. of rice seedlings per hill |            | 0.001     | 0.603    | 11.5      | -       | 0.001|
| No. of rice seedlings per m² |            | 0.400     | 158.10   | 10.0      | -       | 0.000|
| Crop management and Npf   |              |            |          |           |         |     |
| Plowing frequency         | cropping season⁻¹ | 0.001 | 2.613    | 10.0      | -       | 0.000|
| Planting density          | hills m⁻²    | 0.001      | 2.635    | 10.0      | -       | 0.000|
| N basal-dressing          | g m⁻²        | 0.086      | 1.022    | 12.0      | -       | 0.003|
| N top-dressing            | g m⁻²        | 0.001      | 1.106    | 14.5      | -       | 0.020|
| Amount of N in rice       | g m⁻²        | 0.488      | 2.158    | 107.5     | 0.774   | 0.883|
| Nh                        | g m⁻³        | 0.010      | 3.754    | 13.1      | -       | 0.007|
| Rice yield and yield component |         |            |          |           |         |     |
| Unhulled rice yield       | g m⁻²        | 2980       | 12070    | 30.6      | 0.753   | 0.742|
| Brown rice yield          | g m⁻²        | 676        | 2748     | 39.3      | 0.754   | 0.416|

* with a 15% moisture content. **estimated by the yield-monitoring combine.
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The kriged map of the unhulled rice yield estimated using the yield-monitoring combine was drawn by block kriging using the data within the range (Fig. 3). The parts with higher yield in Figure 3, along the farm roads, and especially northing about 100 m and easting from 40 to 80 m, were the places where the rice plants grew bigger by a border effect. In the paddy field with lower yield in Figure 4, the sixth fields from the south, the topsoil was removed to be used as raw material of roof tiles about 50 years ago. The average depth of plow layer of the 17 paddy fields was 15.86 cm, but that of this paddy field was 9.82 cm (Table 1). In another part with higher yield in Figure 3, northing about 45 m and easting about 10 m, the reason for the higher yield was uncertain.

Considerable spatial variability was clearly observed for the yield in accordance with the semivariograms, even though farmer's crop management practices, i.e., soil leveling operation, application of fertilizer, and planting, were different among the paddy fields. These results indicate the potential value of site-specific crop management based on the kriged maps drawn using the yield-monitoring combine on a rational management scale within the range.

3. Relative importance of yield components

The relative importance of yield components was analyzed according to Yoshida and Parao (1976). The relative importance of each yield component for brown rice yield was shown by each correlation coefficient in the multiple regression of brown rice yield with three yield components. Brown rice yield based on a log scale was used as a dependent variable, and standardized scores of the yield components based on a log scale were used as independent variables.

\[
\text{Ln(Brown rice yield)} = 6.32 + 0.0563 \times N + 0.0915 \times F + 0.0194 \times W
\]

\[R^2 = 0.965\]

N : Standardized score of the number of spikelets per square meter based on a log scale
F : Standardized score of filled-spikelet percentage based on a log scale
W : Standardized score of 1000-grain weight based on a log scale

The relative contribution of spikelets per square meter to the brown rice yield variation was 33.7% (i.e. 0.0563 out of \((0.0563 + 0.0915 + 0.0194)\)), that to the filled-spikelet percentage was 54.7%, and that to the 1000-grain weight was 11.6%. The combined three yield components explained for 96.5% of the brown rice yield variation.
The most important yield-limiting component was usually the number of spikelets per square meter. However, in this experiment it was the filled-spikelet percentage. The number of spikelets per square meter was increased through improved crop management practices, but the amount of solar radiation during ripening per spikelet might be limited, and a considerable portion of the spikelets produced remained unfilled. Practically, the filled-spikelet percentage decreased as the number of spikelets per square meter increased (Fig. 4). Thus, there appeared to be an optimum number of spikelets for maximum grain yield under limited solar radiation (Fig. 5), and increase in spikelet number per square meter could not result in increased grain yield. Thus, the filled-spikelet percentage would contribute to the brown rice yield with a larger magnitude than the number of spikelets per square meter in this experiment.

Table 3. Component loading, eigenvalue and percentage of total variance explained for the first five principal components.

| Variable                      | PC1   | PC2   | PC3   | PC4   | PC5   |
|-------------------------------|-------|-------|-------|-------|-------|
| Soil property                 |       |       |       |       |       |
| Depth of plow layer           | 0.958 | 0.044 | 0.166 | -0.134| 0.046 |
| pH                            | 0.306 | 0.045 | 0.060 | 0.081 | -0.667|
| Amount of T–N                 | 0.941 | 0.211 | -0.134| -0.017| -0.180|
| Amount of T–C                 | 0.910 | 0.211 | 0.237 | -0.038| -0.180|
| Amount of Nm                  | 0.789 | -0.065| 0.053 | 0.207 | 0.188 |
| Rice seeding property         |       |       |       |       |       |
| Plant length                  | 0.052 | 0.876 | -0.071| 0.151 | -0.108|
| Aboveground biomass           | 0.116 | 0.868 | 0.056 | -0.174| 0.038 |
| Leaf area                     | 0.008 | 0.900 | -0.113| -0.051| 0.061 |
| Amount of N in seedling       | 0.080 | 0.943 | 0.080 | -0.041| 0.008 |
| No. of rice seedlings per hill| 0.018 | 0.030 | 0.120 | 0.919 | -0.236|
| No. of rice seedlings per m²  | -0.095| -0.127| 0.033 | 0.947 | 0.131 |
| Crop management and Npf      |       |       |       |       |       |
| Plowing frequency             | -0.048| 0.221 | 0.103 | -0.197| 0.782 |
| Planting density              | -0.074| -0.322| -0.469| 0.158 | 0.657 |
| N basal-dressing              | 0.197 | 0.001 | 0.916 | 0.153 | -0.144|
| N top-dressing                | 0.047 | 0.047 | 0.829 | -0.376| -0.254|
| Amount of N in rice           |       |       |       |       |       |
| Npf                           | 0.479 | -0.273| 0.756 | 0.089 | 0.045 |
| Nh                            | 0.317 | -0.259| 0.667 | 0.299 | 0.166 |
| Eigenvalue                    | 3.759 | 3.713 | 3.033 | 2.222 | 1.763 |
| Ratio of cumulative contribution| 0.221 | 0.439 | 0.618 | 0.749 | 0.852 |
4. Principal component analysis

Significant correlations were observed between physicochemical properties of soil, properties of rice seedling, properties of crop management practices, and amounts of Npf and Nh. For example, there were the significant correlations between the depth of plow layer and the amount of T-N, the amount of T-N and the amount of T-C, and the amount of N in seedling and the leaf area of seedling. The variables with the significant correlation to each other cannot be used for the independent variables of the multiple regression analysis. By the principal component analysis, the soil physicochemical properties, rice seedling properties, farmer's crop management practices and amount of N in rice were integrated into the several principal components that were independent to each other. As a result of principal component analysis with varimax rotation, the first five principal components (PC1 to PC5) were extracted as components with eigenvalues higher than 1.0, and they accounted for about 85% of the total variance (Table 3). The first component (PC1) showed high loading with the amount of T-N, amount of T-C, amount of Nm and depth of plow layer. These properties were related to the soil fertility status, so the first component was referred to as "soil fertility factor". The second component (PC2) showed high loading with the four properties of rice seedling (plant length, aboveground of biomass, leaf area and amount of N in seedling). This component was related with the early growth of rice, so this component was designated as "early growth factor". The rice plant with a high PC2 can easily absorb the applied chemical N and soil N and its early growth becomes vigorous. At later growth stages, the rice plant may become more vigorous in paddy fields with more N top-dressing or suffer N shortage because a considerable portion of the applied N has already been absorbed by the plant in the paddy fields with a low cation exchange capacity. In this way, PC2 may also influence the rice plant growth at later growth stages. The third component (PC3) showed high to moderate loading with the N basal-dressing, N top-dressing, Npf and Nh, therefore, this component was designated as "N dressing and uptake factor". The fourth component (PC4) showed high loading with the number of rice seedlings per hill and the number of rice seedlings per square meter. This component was related with "N uptake in early growth stage of rice". Since the fifth component (PC5) showed high to moderate loading with the soil pH and plowing frequency, this component was designated as "soil management factor" related with rice plant growth. In this way, the variation of five physicochemical properties of soil, six properties of rice seedling, four properties of crop management practices, Npf and Nh, was summarized into five agronomical factors, which were independent of each other.

5. Multiple regression analysis for predicting yield components

Stepwise multiple regression analysis was subsequently performed to obtain the optimum models for predicting yield component performance. In the analysis, each yield component was used as a dependent variable and standardized scores of the five principal components of 17 paddy fields were used as independent variables. The standardized score of a principal component of a paddy field was the total sum of product of each measured value of 17 variables on the field and each component loading of the principal component of the 17 variables.

The following equations showed the most appropriate models for the performance of each yield component.

- The number of spikelets per square meter
  \[ \text{Number of spikelets} = 34990 \times PC1 + 3204 \times PC3 \]
- The filled-spikelet percentage
  \[ \text{Filled-spikelet percentage} = 73.6 - 2.50 \times PC1 - 4.19 \times PC3 \]
- The 1000-grain weight
  \[ \text{1000-grain weight} = 21.45 - 0.28 \times PC1 - 0.31 \times PC2 \]

The regression coefficients in the equations indicate the magnitude of each standardized score of principal component in its contribution to the performance of yield components (Table 4). \( R^2 \) shows the proportion of the variation explained by each model for the total variation of yield components (Table 4).

The model using PC1 and PC3 explains 79.7% of the total variance of the number of spikelets per square meter. Since PC3 contributed to the number of spikelets per square meter with a larger magnitude than PC1, N application increased the number of spikelets per square meter to a larger extent than improvement in soil fertility. The model using PC1 and PC3 explained 52.1% of the total variance of the filled-spikelet percentage. PC1 and PC3 showed negative contributions to the filled-spikelet percentage. The model using PC1 and PC2 explained 41.8% of the total variance of the 1000-grain weight. PC1 and PC2 showed negative contributions to the 1000-grain weight. N absorption by the paddy rice in the paddy-upland rotational paddy fields is vigorous, but the amount of N applied by farmers is not reduced in

Table 4. Contribution of each principal component to each yield component.

| Yield component         | PC1 | PC2 | PC3 | PC4 | PC5 | \( R^2 \) |
|-------------------------|-----|-----|-----|-----|-----|---------|
| Number of spikelets     | 0.242 | -   | 0.758 | -   | -   | 0.797   |
| Filled-spikelet percentage | 0.373 | 0.627 | -   | -   | -   | 0.521   |
| 1000-grain weight       | 0.473 | 0.527 | -   | -   | -   | 0.418   |
component factors. The agronomic factors (soil fertility factor, early growth factor, N dressing and uptake factor) as yield-limiting factors (soil fertility factor, early growth factor, N dressing and uptake factor) demonstrated the high contribution of the agronomic factors. Cassman, K. G. 1999. Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. Proc. Natl. Acad. Sci. USA. 96 : 5952-5959.

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Inamura, T., Hamada, H., Iida, K. and Umeda, M. 2003. Correlation of the amount of nitrogen accumulated in the aboveground biomass at panicle initiation and nitrogen fertility factor, early growth factor, N dressing and uptake factor) could control about 77.1% of the spatially structured variation of the brown rice yield. The spatial structure of depth of plow layer, amount of T-N and Npf was developed, and existence of the stable management unit within the ranges was confirmed. The depth of plow layer, amount of T-N and Npf could be the most effective objectives for site-specific crop management practice in the paddy field.

These results suggest the possible benefit of rational site-specific crop management practices in the 17 paddy fields in an area of 2.0 ha and may provide basic information of a criterion for such management in large-scale farm management in general, although only one case study was conducted.

Geostatistical characterization of the spatial variability using semivariograms can digitize and visualize the stable management units within the range in the kriged map. Kriged map of yield is easy to understand and will allow the farmer to make better choice of crop managements in the next year, by taking variability into account. Any spatially and temporally distributed information of rice yield in large-scale farm management is incomplete if the observation of spatial variability using a yield-monitoring combine is not taken into account. Yield-monitoring technique and geostatistical analysis can provide practical information, that is, the stable management unit in consideration of the crop growth and the controllable proportion of the spatial variability of rice yield. Such practical information will be a criterion for the prevalence of site-specific crop management in large-scale farm management in Japan.

Acknowledgement

The authors are grateful to K. Fukuda and Y. Nakano for providing valuable information on the cropping system and farmer’s cropping management practices, and Dr. T. Kosaki, Kyoto University, for valuable discussion on the multivariate approach.

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