ORIGINAL ARTICLE

Decadal sustainability of spatial distribution of soil properties in a paddy field as a fingerprint reflecting soil-forming factors and field management

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Abstract

Spatiotemporal variations of soil properties were measured in a Japanese paddy field in order to evaluate how they were created and sustained through various field managements. The field was subjected to land consolidation during 1960s, heterogeneous application of manure in the late 1970s and land leveling in 1986, 1987 and 2003. Surface soils were collected from throughout the field in 2002 and 2012, and the physicochemical properties were analyzed. Additional analyses were carried out for relative altitude in 1986, 1999 and 2012, and soil hardness in 2012. In the field examined, the distribution of field attributes reflected past field managements. The heterogeneous distribution of relative altitude was partly explained by the passage of agricultural machinery, whereas the heterogeneous distribution of soil organic matter was partly explained by both past and recent applications of animal dung manure. In general, the measured soil properties were maintained from 2002 to 2012, and the pattern of spatial distribution did not change significantly for many of the properties. The correlation coefficient of the distribution patterns between 2002 and 2012 was highest for yellowness (0.95), followed by sand (0.90), acid-oxalate extractable iron (Fe; 0.88), available phosphorus (P; 0.87), redness (0.82), lightness (0.77), sand-size organic matter (0.74) and total nitrogen (N; 0.72). Land leveling carried out in 2003 barely influenced the distribution of these properties. Among these properties, soil color parameters and sand content can be measured rapidly without reagents and will be useful for characterizing paddy fields according to the distribution of stable soil properties. The analysis of the natural abundance of ¹⁵N in soil was also effective to suggest the contribution of the application of animal dung manure to the accumulation of soil organic matter at a within-field scale. It can be concluded, as a general rule, that each paddy field has its own fingerprint which is unveiled by precise soil sampling and analyses of stable properties.

Key words: field management history, land leveling, manure, paddy soil, spatial distribution.

INTRODUCTION

Crop production requires a continuous effort to manage land surface topography and soil fertility. Rice cultivation has been carried out in Monsoon Asia, which is characterized by a very high population density, intensive use of the land for food production and the dominance of paddy rice cultivation in its agricultural systems (Kyuma 2004). In irrigated paddy fields, water is supplied through consecutive fields from top to bottom, and it is ponded in each field with a flat surface surrounded with embankments.

In Japan, the government has promoted the joining of small paddy fields into a large one during these several decades to cope with the decreasing number of producers (Toriyama 2001). Statistics in 2012 indicated that 63.2% of the paddy fields have an area of about 0.3 ha and 8.8% of them have an area greater than 1.0 ha (MAFF 2014). This land consolidation has contributed to labor-saving and cost-effective production. However, when small fields with different relative altitudes are
joined together, surface soil in each field must be moved heavily after removal of embankments. In such cases, the depth of the original topsoil and the yield of rice may vary within a field for more than a generation (Ohnishi et al. 2001). Furthermore, when the area of a field is enlarged, it becomes difficult to maintain a flat surface in the field, although it is important for the homogenization of water supply, seedling establishment and initial rice growth (Yamaguchi et al. 1967; Kimura et al. 1999; Sasaki et al. 2002) and also to control weed proliferation (Shoji et al. 2013).

Accordingly, precision agriculture has been adopted in consolidated paddy fields. Precision agriculture is generally defined as the application of technologies and principles to manage spatial and temporal variability associated with all aspects of agricultural production, for the purpose of improving crop performance and environmental quality (Pierce and Nowak 1999). For example, land leveling with a laser leveler has become a popular method for land management in consolidated paddy fields (Kimura et al. 1999). Based on this background, researchers in Kyoto University carried out joint research in the late 1990s for the application of precision agriculture to a consolidated paddy field located in Experimental Farm, Kyoto University.

Yanai et al. (2000) applied geostatistical analysis to the field. Soil chemical properties were found to vary significantly in the flat and apparently homogeneous field. Yanai et al. (2001) tried to extract the factors affecting rice yield in the field. The spatial variation of the yield was measured in 1999 with a yield-sensing combine developed by Lee et al. (2000). The authors proposed that spatially independent variation of rice yield, however large it may be as detected, cannot be controlled by site-specific field management. This is because site-specific field management becomes possible only when the within-field variation of the field attribute is spatially dependent at the scale of field management. The multivariate analysis combined with geostatistics revealed that the soil chemical properties affected rice yield significantly. As much as 65% of the spatially dependent variation of the yield was explained by chemical properties of the surface soil.

After this study, Ryu et al. (2004) evaluated the effectiveness of site-specific management for the yield and quality of rice in 2002. The site-specific topdressing of nitrogen (N) fertilizer according to heterogeneous rice growth could save the amount of fertilizer by 15% without a decrease of the yield. Moritsuka et al. (2004) also demonstrated that soil properties in this field were grouped into two types, being influenced by organic matter or clay. The shoot biomass of rice grown in pots filled with different soils in the field was influenced significantly by the soil properties related to organic matter.

In the spring of 2003, land leveling with a laser leveler was introduced in this field, and intensive research activities ceased thereafter. Within-field heterogeneities of soil properties and the effectiveness of site-specific fertilizer management have been well documented from this field. However, limited information is available on how much these soil heterogeneities have been created and sustained through a long history of field managements such as land consolidation, land leveling and fertilizer application. To evaluate this, we need to know how stable the properties analyzed are in terms of time and space, and also how much they will be influenced by field management.

On the latter point, Ruth and Lennartz (2008) mentioned that the soil properties can be interpreted by the extent to which they have been influenced by intrinsic (soil formation) or extrinsic (field management) factors. They evaluated the spatial variability of soil properties in continuous paddy fields along two toposequences in southeast China, and found that soil texture, total carbon (C) and total N had strong spatial dependence with the limit of dependence (range) of more than 100 m. The range values exceeded the scale of management at each field. These properties were considered to be controlled mainly by intrinsic factors at their study sites as well as at their sampling scale.

At a larger sampling scale, Darmawan et al. (2006) reported that the contents of total C and total N in paddy soils in Java, Indonesia, have been influenced by extrinsic factors. They analyzed paddy soil samples collected from 40 sites of the island of Java in both 1970 and 2003. During this period, the contents of total C and total N in the surface soil were increased by about 30%. These results suggest that the contents of total C and total N in the surface soil were increased by so-called Green Revolution technologies, such as the introduction of a high-yielding rice variety and the extensive use of chemical fertilizers, irrigation and pesticides.

It is considered in general that soil texture and mineralogy are barely influenced by recent field management and are more stable than many of the soil chemical properties. In the case of a field scale, however, it is unknown whether the analysis of spatial dependence of soil properties can be a suitable tool for suggesting the influencing factors. Such information will allow us to understand how paddy surface soils sustain their properties and functions within a field.

In this study, therefore, we collected soil samples from throughout this field in 2012 in the same way as we did 10 years ago, and analyzed the decadal changes of soil properties. Besides the soil properties analyzed routinely, we measured the properties that will reflect soil texture and mineralogy. Based on this precise soil sampling and these analyses, we discuss how much the present soil properties have been created and sustained through field management from past to present.
MATERIALS AND METHODS

Experimental field
The sampling was carried out at one of the paddy fields in Experimental Farm, Kyoto University, located at Takatsuki City, Osaka Prefecture in Japan. The area of the field was 0.5 ha (Fig. 1). The soil in this field was classified as Typic Fluvaquent (Soil Survey Staff 2010). The field has been used as a paddy field for more than 80 years. In 1928, the field was equipped with underground drainage systems and became an experimental field of the university. From 1962 to 1967, five fields with an area of 0.1 ha were joined together (Fig. 2). After this consolidation, research was focused on sowing rice seeds directly on a drained field. This is probably because the area of direct-seeded paddy fields reached a peak in 1974, amounting to about 2% of the total area of paddy fields in Japan. From 1978 to 1980, cow dung manure was applied at different rates (0, 20, 40 Mg ha⁻¹) in the direct-seeded field every year (Yabuki et al. 1981). Field-scale land leveling was carried out at least in the autumn of 1986 and 1987 and in the spring of 2003, besides a small-scale land leveling after puddling in each year. In 1986 and 1988, cow dung manure was applied after harvest of rice at the uniform rate of approximately 20 Mg ha⁻¹. From 1989 to 1996, it is unknown whether manure was applied to this field. From 1997 to 2007, manure application was not carried out. From 2008 to 2012, horse dung manure was applied every year after harvest of rice at the uniform rate of approximately 20 Mg ha⁻¹. Rice straw was returned to the field at harvest. During the period between 1986 and 2011, the

Figure 1  Map of the experimental field. The field, with a size of 50 × 100 m, was divided into 100 plots from which soil samples were collected (open circles). At the points marked with an asterisk, the δ¹⁵N value of the samples was also analyzed.

Figure 2  Map of field management (modified from Lee et al. 2001). The shaded areas indicate the areas to which cow dung manure was applied at two different rates in the late 1970s. Broken lines in the field indicate the original borders of the fields before land consolidation in the 1960s. The arrows in the field indicate the direction of passage of agricultural machinery.
yield of hulled rice ranged from 4.4 to 6.7 Mg ha\(^{-1}\) according to the Bulletin of Experimental Farm, Kyoto University, from volume 1 (1988) to volume 21 (2012). Cultivation of rice in this field came to an end in 2013, and the field will become a park of Takatsuki City in the near future.

**Soil sampling and analysis**

On April 30, 2002, and May 1 and 2, 2012, soil samples were collected from the surface layer (< 15 cm) before puddling and transplanting of seedlings of rice (*Oryza sativa* L. var. Hinohikari). Soil sampling in 2012 was carried out in the same way as we did in 2002, which is described by Moritsuka et al. (2004). Briefly, the field was divided into 100 plots with an area of 5 x 10 m (Fig. 1). At each plot, a soil sample consisting of five subsamples was collected from the center and the surrounding four points. After air-drying and 2-mm sieving of the samples, the following properties were measured by the methods described by Yanai et al. (2000) and Moritsuka et al. (2004); inorganic N, available N, total N, available phosphorus (P), exchangeable potassium (K), pH, electrical conductivity (EC) and total C. The analyses of these properties were carried out separately for soil samples collected in 2002 and 2012, and the data of 2002 were cited from our previous paper (Moritsuka et al. 2004).

In addition to these properties, soil color parameters (L*, a* and b*), acid oxalate extractable iron (Fe\(_{a}\)) and sand content were measured by the methods described by Moritsuka et al. (2014) and Moritsuka et al. (submitted). Briefly, soil color parameters were analyzed with a soil color reader (SPAD-503, Konica Minolta Optics, Inc.) according to the CIELAB color space. The positive values of L*, a* and b* indicate lightness, redness and yellowness, respectively. Sand content was measured by a simplified wet-sieving method using a 20-µm-opening nylon mesh cloth.

Furthermore, since the sand fraction collected by this method contains organic matter, the content of sand-size organic matter was measured by the weight loss on ignition at 550°C for 3 h after oven-drying at 105°C overnight. The content of this organic matter fraction was calculated based on the percentage of the weight loss on ignition to the weight of the original 2-mm sieved soil. It would be almost identical to particulate organic matter (POM), although POM is usually collected with a coarser 53-µm sieve after soil dispersion treatment (Cambardella and Elliott 1992). In this paper, the content of sand-size organic matter is referred to as POM\(_{sand}\). In our case, POM\(_{sand}\) was considered to include fragmented rice straw and horse dung manure at the early stage of decomposition. The natural abundance of \(^{15}\text{N} (\delta^{15}\text{N})\) was also measured for selected soil samples, i.e., every 16 samples for 2002 and 2012 samples (Fig. 1), with a continuous-flow stable isotope ratio mass spectrometer (DELTA V advantage, Thermo Fisher Scientific Inc., Massachusetts). The analyses of these additional properties were carried out together for soil samples collected in 2002 and 2012.

**Measurement of relative altitude**

On November 7, 2012, the relative altitude at the center of the 100 plots was measured after harvest with a total station (SET6ES, Topcon Corporation, Tokyo). The error of measurement by the total station was ± 10 mm at most. When the surface at the sampling points was disrupted by the prints of the harvester, a point for measurement was moved to a nearest place which was not influenced by the prints of the harvester. On October 27, 2013, the relative altitude of the experimental field and the surrounding paddy fields was also measured after harvest with the total station.

The data of the relative altitude measured in 1986 and 1999 were also used for comparison. The data of 1986 were cited from the Bulletin of Experimental Farm, Kyoto University (volume 1, 1988), in which the method for measurement was not described in detail. The data of 1999 were cited from Lee et al. (2001). On November 10, 1999, the relative altitude at the soil sampling points was measured with a total station (SET4100S, Topcon Corporation, Tokyo).

**Measurement of soil hardness**

On November 25, 2012, soil hardness was measured with a Hasegawa-type penetrometer (a portable H-100 type) at the center of the 100 plots. A 2-kg weight was dropped through a pole of the penetrometer over a distance of 25 cm (the falling distance was halved due to soft surface layer). The position of a cone moved downward in soil was recorded every drop until the cone reached below 30 cm from the surface. The number of drops required for the cone to pass through 15 cm and 30 cm soil depth was counted and the hardness of surface and subsurface soils was calculated by summing up the number of drops.

**Statistical analysis**

The above data were analyzed geostatistically using GS' Version 9 for Windows (Robertson 2008). For drawing a semivariogram, the active lag distance, i.e., the range over which semivariance is calculated, was set at 60 m, and the lag class distance interval, i.e., a step size of the semivariogram determined by the minimum distance of
the adjacent sampling points, was set at 5 m. The semi-
variance data for each lag interval, i.e., a semivariogram,
were fitted to linear, spherical, exponential or Gaussian
models, depending on the smallest residual sum of
squares. Based on the best-fit model, semivariogram
parameters such as the Q value and range were calcu-
lated. The Q value is the degree of spatial dependence of
a measured property, whereas the range value is the
maximum distance within which the properties correlate
spatially. Then, the spatial distributions of the data were
visualized by block kriging. Detail procedures for mapping
are described in a previous paper (Moritsuka et al.
2004), although we used the latest version of the
GS+ software to which a Gaussian model was added.
Besides the geostatistical analysis, descriptive statistics
of the above data and correlation analysis among them
were carried out using Microsoft Office Excel 2010.

RESULTS AND DISCUSSION

Spatiotemporal changes of relative altitude
The field examined was located on a relatively flat area.
The difference of the altitude of the field compared to the
fields on the west or east side was only about 14 cm.

Figure 3 shows the spatial distributions of the relative
altitude measured in 1986, 1999 and 2012. In 1986 and
1987, surface soil located in the middle of the field was
moved to the southeast corner. Probably due to this
movement, the range of relative altitude became smaller
in 1999 and the point with the highest altitude was
moved to the northwestern part of the field. In 2003,
the surface soil in the whole field was leveled with a laser
leveler. The range of relative altitude must have been
reduced by this leveling, although the data is not avail-
able. After 9 years, however, the range of relative alti-
tude in 2012 became almost the same as that in 1999.
The standard deviation of the relative altitude in 1999
and 2012 (< 1.5 cm) was smaller than the maximum
acceptable level of 1.8 cm (Osari 2001). The patterns of
spatial distributions of relative altitude were similar
between 1986 and 2012 (r = 0.48, p < 0.01), and the
lowest site was located at the southeast corner.

These results suggest that the five small fields present
in this field had similar relative altitudes (Fig. 2), and the
pattern of distribution of relative altitude emerged after
several years of rice cultivation was ascribed to the recent
field management rather than the land consolidation in
the 1960s. Since the southeast corner has been used for
the entrance and exit of agricultural machinery, the low-
est altitude at this corner may be due to their frequent
passage.

Spatiotemporal changes of soil properties
Figure 4 shows the spatial distributions of the surface
soil properties collected in 2002 and 2012. In general,
the measured soil properties were maintained during
the period between 2002 and 2012, although the aver-
age contents of total N, available P, exchangeable K,
total C and POMsand in 2012 were slightly lower than
those in 2002. Furthermore, the pattern of spatial
distribution did not change significantly for many of
the properties. The correlation coefficient of the
Figure 4  Spatial distributions of the surface soil properties measured in 2002 and 2012. Values above each figure indicate an average and a CV value. Values between figures of 2002 and 2012 indicate a correlation coefficient between 2002 and 2012 ($r = 0.26$ at a 0.01 probability level). The values of the contour lines, which are not shown in the figure, are not identical between a pair of the same property.
Figure 4 Continued.
distribution patterns between 2002 and 2012 was higher than 0.70 for the following properties; b* value (0.95), sand (0.90), Fe_{o} (0.88), available P (0.87), a* value (0.82), L* value (0.77), POM_{sand} (0.74) and total N (0.72). This indicates that these properties were stable in time and space and that land leveling carried out in 2003 barely influenced the distribution of such stable properties. On the other hand, the distribution of inorganic N and exchangeable K was highly variable in time and space. The contour maps in Fig. 4 were drawn geostatistically. For mapping, the degree and the limit of spatial dependence, i.e., the Q value and range, of each property were obtained by drawing a semivariogram and fitting a suitable model to it. The semivariogram models showed that the Q values of all soil properties were higher than 0.60. Accordingly, more than 60% of the variation was spatially dependent. On the other hand, as can be seen from the different density of contour lines in Fig. 4, the limit of spatial dependence (range) varied among the soil properties (Fig. 5). The range was more than 100 m for all color parameters, around 50–100 m for exchangeable K, Fe_{o} and sand, and less than 50 m for six chemical properties showing similar distribution patterns (Fig. 4). The ranges of these properties were similar between 2002 and 2012, whereas the ranges of inorganic N and pH were different between these periods. It should be noted here that the active lag distance was set at 60 m for calculation of semivariance and that the range values exceeding 60 m were extrapolated estimates obtained from the best-fit model.

Some of these results agreed with previous findings by Moritsuka et al. (2004) and Yanai et al. (2008) and reconfirmed that site-specific management of inorganic N level in soil is not practical in this field. Our new finding was that soil color parameters and sand content were very stable in time and space. Among the properties measured, the b* value (yellowness) was most stable, and showed a significantly positive correlation with Fe_{o} (r = 0.79 and 0.77 in 2002 and 2012, respectively). This is consistent with a previous finding that active Fe in paddy soils is one of the main sources of the yellowness (Moritsuka et al. 2014). The range of soil color parameters exceeding the size of the field suggested that soil color variations were spatially dependent not only within the field but also across the surrounding fields, and that they were influenced by intrinsic factors more than by field management. To reveal this, soil sampling and analyses at an inter-field scale is necessary.

Relationship between relative altitude and soil properties

What was the main factor affecting the spatial distribution of soil properties? In this section, the influences of the relative altitude and land leveling are discussed. Table 1 shows the correlation coefficients between relative altitude and soil properties measured in 2012. The correlation coefficients among the soil properties are also presented for comparison. The relative altitude was significantly correlated with the a* value, the b* value and Fe_{o}, whose correlation coefficients with the altitude were 0.55, 0.37 and 0.34, respectively. These positive correlations were lower than those observed among soil properties. A high negative correlation between Fe_{o} and sand (-0.74) suggested that both properties were

Figure 5  Comparison of limit of spatial dependence (range) for soil properties in 2002 and 2012. A line in the figure shows a 1:1 line. An enlarged figure is also shown for the properties with a range of less than 50 m (open circles).
Table 1 Correlation matrix of field attributes measured in 2012

|                 | Relative altitude | Inorganic N | Available N | Total N | Available P | Exchangeable K | pH | EC | C | L* value | a* value | b* value | Fe<sub>o</sub> | Sand | POM<sub>sand</sub> |
|-----------------|-------------------|-------------|-------------|---------|-------------|----------------|-----|----|---|----------|----------|----------|-----------|-------|------------------|
| Relative altitude | 1.00              |             |             |         |             |                |     |    |   |         |          |          |            |       |                  |
| Inorganic N     | -0.21             | 1.00        |             |         |             |                |     |    |   |         |          |          |            |       |                  |
| Available N     | 0.30              | -0.09       | 1.00        |         |             |                |     |    |   |         |          |          |            |       |                  |
| Total N         | 0.05              | 0.35        | 0.47        | 1.00    |             |                |     |    |   |         |          |          |            |       |                  |
| Available P     | 0.01              | 0.36        | 0.61        | 0.70    | 1.00        |                |     |    |   |         |          |          |            |       |                  |
| Exchangeable K  | -0.09             | 0.46        | 0.17        | 0.56    | 0.59        | 1.00          |     |    |   |         |          |          |            |       |                  |
| pH              | -0.05             | -0.12       | -0.49       | -0.46   | -0.41       | -0.27         | 1.00|    |   |         |          |          |            |       |                  |
| EC              | 0.15              | 0.19        | 0.66        | 0.52    | 0.56        | 0.18          | -0.31| 1.00|   |         |          |          |            |       |                  |
| Total C         | 0.03              | 0.26        | 0.44        | 0.93    | 0.62        | 0.55          | -0.37| 0.50| 1.00|         |          |          |            |       |                  |
| L* value        | 0.02              | -0.51       | -0.30       | -0.51   | -0.48       | -0.45         | 0.62 | -0.26| -0.43| 1.00    |          |          |            |       |                  |
| a* value        | 0.55              | -0.18       | 0.37        | 0.07    | 0.00        | -0.22         | -0.02| 0.34| 0.12| 0.10    | 1.00     |          |            |       |                  |
| b* value        | 0.37              | -0.43       | -0.02       | -0.38   | -0.40       | -0.52         | 0.53 | 0.04| -0.28| 0.70    | 0.70     | 1.00     |            |       |                  |
| Fe<sub>o</sub>  | 0.34              | -0.35       | 0.23        | -0.02   | -0.04       | -0.23         | 0.35 | 0.34| 0.04| 0.51    | 0.56     | 0.77     | 1.00     |       |                  |
| Sand            | -0.14             | 0.29        | -0.03       | 0.03    | 0.13        | 0.06          | -0.49| -0.13| 0.00| -0.54   | -0.50    | -0.74   | 1.00     |       |                  |
| POM<sub>sand</sub> | 0.18             | 0.16        | 0.72        | 0.69    | 0.71        | 0.45          | -0.42| 0.77| 0.66| -0.33   | 0.33     | -0.05   | 0.30     | -0.15| 1.00               |

Shaded values indicate significant correlation at 1% level. Values significant at 1% and 5% levels are 0.26 and 0.20, respectively.
determined mainly by intrinsic factors. Besides this, it can be postulated that soils at higher relative altitudes were kept under more aerobic conditions favoring the oxidation of Fe$^{2+}$ to Fe minerals such as ferrihydrite, with reddish and yellowish colors. Further research is needed to evaluate whether and to what extent soil Fe-related properties are affected by extrinsic management factors.

Except for these Fe-related properties, weak and unexplainable relationships were observed between the relative altitude and soil properties (Table 1). This may be partly due to limited movement of soil by the land leveling. The maximum relative altitude in this field observed in 1999 and 2012 was about 7 cm (Fig. 3). So the depth of soil which was removed or added by the land leveling in 2003 must have been only a few centimeters. This is much smaller than the maximum depth of soil which we collected from the surface layer (about 15 cm).

In addition to the properties of surface soils presented in Fig. 4, there was a large variation of hardness in surface and subsurface soils (Fig. S1). Surface and subsurface soils tended to be harder in the eastern part of the field. The higher hardness of subsurface soil at the eastern corner of the field may be due to the frequent passage of agricultural machinery (Fig. 2). On the other hand, the lower hardness of the surface soil located in the north-western part of the field was apparently due to a close distance from an inlet of irrigation water, resulting in a high moisture content of the soil. Similar to the results from the relative altitude, however, only weak relationships were observed between hardness and chemical properties of the surface soil (data not shown).

These results indicate that most of the soil chemical properties in this field were independent of the relative altitude and hardness. A combination of these factors may have influenced the yield of rice, as suggested by Yanai et al. (2001). It is plausible to consider that the spatial distribution of many chemical properties in the surface layer was affected by fertilizer management rather than the relative altitude and land leveling, at least during the period between 2002 and 2012.

**Effect of manure application on accumulation of soil organic matter**

So, how much did past fertilizer management affect the distribution of soil properties in this field? From 1978 to 1980, cow dung manure was applied heterogeneously to this field (Fig. 2). We considered that the distribution of total C in soil collected in 1999 was affected significantly by this fertilizer management (Yanai et al. 2001), because the area of heavy application coincided well with the area of high total C content in soil (Fig. 2 and 4). Indeed, the content of total C in the surface soil increased from 1.65% to 2.31% (20 Mg ha$^{-1}$ treatment) and 2.58% (40 Mg ha$^{-1}$ treatment) after the 3-year application (Yabuki et al. 1981). But the average content of total C in soil further increased since then; 2.6% in 1986 (cited from the Bulletin of Experimental Farm, Kyoto University, volume 1), 3.5% in 2002 and 3.1% in 2012 (Fig. 4). This suggests that uniform application of cow dung manure in 1986 and 1988, and of horse dung manure during 2008 and 2012, also contributed to the accumulation and maintenance of the content of organic matter in soil.

It is well known that animal dung manure shows a high value of $\delta^{15}$N and that its application can increase the $\delta^{15}$N value of soil gradually (Nishida et al. 2007). It should be noted that the $\delta^{15}$N value in soil is influenced by many other factors, i.e., the type of plant species, chemical fertilizer and manure, the rates of input and decomposition of plant residues and manure (Peukert et al. 2012), and the rate of natural input through irrigation water, rainfall and biological fixation (Nishida et al. 2007).

The $\delta^{15}$N value of the horse dung manure sampled in 2013 was 13.6‰. Due to a mixture of wood chips, the content of N in the manure was relatively low (1.05%) compared to the content of C (47.1%), resulting in a high C/N ratio (44.7). Figure 6 shows the relationship between the $\delta^{15}$N value and total C for selected samples collected in 2002 and 2012. A significantly positive relationship was observed between these two properties. The $R^2$ value of the regression equation indicated that the $\delta^{15}$N value could explain 48% of the variation of total C in soil. The patterns of spatial distribution of the $\delta^{15}$N value were similar between 2002 and 2012 ($r = 0.73$, $p < 0.01$; Fig. S2), suggesting that the $\delta^{15}$N value was spatially stable. These results suggest strongly that application of manure influenced the spatiotemporal changes of total C and the $\delta^{15}$N value in soil of this field. The influence of manure application on the accumulation of total C in soil may continue for more than a decade through a higher input of rice straw to soil, as was suggested by the heterogeneous distribution of POM$_{sand}$ according to the input of cow dung manure in the late 1970s (Fig. 4).

As shown in a previous paper (Moritsuka et al. 2004) and Table 1 for the data of 2002 and 2012, respectively, total C was significantly correlated with available N, total N, available P and exchangeable K in both 2002 and 2012. POM$_{sand}$ was also positively correlated with available N with correlation coefficients of 0.55 and 0.72 in 2002 and 2012, respectively. So POM$_{sand}$ must have contained organic matter at the early stage of
decomposition, acting as an important source of readily mineralizable N. These results emphasize the importance of continuous application of manure for improving and sustaining the availability of N, P and K in a paddy soil.

CONCLUSIONS

Our results revealed that many of the soil properties were spatially stable even after land leveling of the paddy field. Among the soil properties measured, soil color parameters and sand content were very stable in time and space. In routine soil analyses in the laboratory, soil color parameters and sand content are often regarded as less important and/or more laborious than soil chemical properties. By the methods applied in this study, however, they can be measured rapidly, without reagents. Given their intrinsic nature and persistence over time, these properties will be useful for characterizing paddy fields according to the distribution of soil stable properties. The analysis of the $\delta^{15}$N value of soil was also useful to suggest the contribution of animal dung manure to the accumulation of soil organic matter at a within-field scale. It can be concluded, as a general rule, that each paddy field has its own fingerprint which is unveiled by precise soil sampling and analyses of stable properties. The evaluation of such field-specific fingerprints will provide information on paddy soil formation at a field scale and the possibility of site-specific soil management when deemed necessary.

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SUPPLEMENTARY MATERIAL

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Figure 6 Relationship between $\delta^{15}$N value and total C content for selected samples collected in 2002 (open circles) and 2012 (filled circles).
