Farm-scale variations in soil color as influenced by organic matter and iron oxides in Japanese paddy fields

Naoki Moritsuka\textsuperscript{a}, Kaori Matsuoka\textsuperscript{b}, Keisuke Katsura\textsuperscript{b} and Junta Yanai\textsuperscript{a}

\textsuperscript{a}Graduate School of Agriculture, Kyoto University, Kyoto, Japan; \textsuperscript{b}Graduate School of Agriculture, Tokyo University of Agriculture and Technology, Fuchu, Japan; \textsuperscript{c}Graduate School of Life and Environmental Sciences, Kyoto Prefectural University, Kyoto, Japan

ABSTRACT
To understand how soil color is influenced by soil components at the farm scale, we evaluated spatial variation in soil color and related soil properties in Japanese paddy fields. After harvest of rice, 246 surface soil samples were collected in 10-m grids from five contiguous irrigated paddy fields, each with an area of about 0.5 ha. The samples were analyzed to determine color parameters (L*, a*, and b*), and contents of total C, total N, Fe oxides, sand, and loss-on-ignition. The results obtained were modeled and mapped geostatistically. All color parameters indicated strong spatial dependence with long ranges (>85 m). In contrast, total C and N showed short ranges (about 40 m). The contents of Fe oxides, sand, and loss-on-ignition showed intermediate ranges (50–85 m). The ranges of these properties and their distribution patterns suggested that the contents of total C and N were influenced by long-term application of manure and that sand content was influenced by topography and past land consolidation. Further soil color analysis after removal of organic matter or silt plus clay particles revealed that soil organic matter, texture, and Fe oxides affected soil color parameters in a complex manner. Prediction of total C from soil darkness was hindered by the presence of silt plus clay particles containing Fe oxides. On the other hand, citrate-dithionite extractable Fe was estimated accurately from the b* value (yellowness), which can be useful for predicting the occurrence of akiochi (autumn decline) disease of rice at the farm scale.

1. Introduction
Rice (\textit{Oryza sativa} L.) is the most popular staple crop in Japan, where 54% (2017) of the agricultural land is classified as paddy fields. In recent decades, socioeconomic changes have strongly influenced the rice production system. From 2005 to 2015, the number of producers growing rice commercially has decreased by 35% (MAFF 2017). To produce rice cost-effectively with fewer producers, small fields with irregular shape have been consolidated into larger fields with rectangular shape (Katayama \textit{et al.} 2015). In 2016, 65% of the paddy fields have an area of 0.3 ha (the standard size in Japan) or larger (MAFF 2018).

At the farm scale, the primary cost (total cost of production of rice minus by-products) per unit field area is expected to decrease as the total area of paddy fields in a farm increases up to 5 ha (Fujiki 1999). From 2005 to 2015, the number of agricultural corporations involved in rice production increased 3.19 times, and the percentage of the number of farms managing more than 5 ha of paddy fields increased from 2.8% to 4.9% (MAFF 2017). Under these circumstances, more attention is being paid to spatial variation in soil fertility within a large consolidated field (>0.5 ha) or across a group of fields belonging to the same farm household or agricultural corporation, as a basis for site-specific field management practices at the farm scale (Toriyama \textit{et al.} 2003; Nishida \textit{et al.} 2018).

Soil color can be used to estimate the contents of soil pigments such as organic matter and iron (Fe) oxides. It can be measured easily and rapidly with a Munsell color chart or by colorimeter. Aitkenhead \textit{et al.} (2018) have reviewed the past studies on color-based soil assessment.

At the regional scale, Aitkenhead \textit{et al.} (2013) explored the relationships between field observations of soil color and laboratory measurements of soil physicochemical properties by using various soils across Scotland. They converted soil color data from Munsell system to RGB and CIELAB systems (Viscarra Rossel \textit{et al.} 2006), and found that several properties including organic matter (measured by loss on ignition), total N, soil texture, and contents of several elements could be estimated from soil color parameters. Liles \textit{et al.} (2013) estimated the content of total C in forest soils in Northern California from soil L* value (lightness). They found that the accuracy of estimation varied significantly with soil parent material. The best regression model was obtained from soils with felsic parent material (granodiorite). Baumann \textit{et al.} (2016) evaluated the relationships between soil components and color parameters using paired forest and grassland soil samples collected from three regions in Germany. For all regions and land uses, the content of organic C was negatively correlated with the L* value. However, the contents of acid oxalate extractable Fe (Fe\textsubscript{o}) and citrate-dithionite-bicarbonate extractable Fe could not be estimated with sufficient accuracy from the b* value (yellowness). In contrast, we reported that the
content of Fe in Japanese paddy soils (Lowland Paddy soils, Gley Lowland soils, and Gray Lowland soils) was positively correlated with the b* value at the nationwide scale (Moritsuka et al. 2014).

We expect that such relationships can be used to estimate the variation in soil properties at smaller scales. Schulze et al. (1993) tested the hypothesis that soil darkness and organic matter content are more closely related for soils occurring together within a landscape than for soils over a wide geographic region. However, they found that the relationship between Munsell value and the content of organic matter was strongly influenced by soil texture. The relationship was unpredictable if the soil texture varied widely within the landscape.

Similar results have been reported from paddy fields. In a relatively large paddy field in Japan, we reported that the content of Fe in was positively correlated with soil b* value ($R^2 = 0.59$) (Moritsuka et al. 2014). The contents of total C and N were also negatively correlated with the L* value, but their correlations were not sufficient for prediction ($R^2 < 0.30$). In two small paddy fields in China with different lengths (50 and 300 years) of rice cultivation, Kölbl et al. (2015) evaluated the within-field variation in soil organic C and soil L* value. In both fields, the content of organic C was negatively correlated with the L* value. Their relationships were statistically significant but not sufficient for prediction ($R^2 < 0.35$ for both fields). The authors suggested that the low $R^2$ values were due to relatively small within-field variation in soil organic C and L* value (the coefficients of variation were 9.2-14.1% and 1.1-1.7%, respectively), incorporation of dark-colored burnt straw residues into soil, and possible variations of soil texture within the field.

We aimed to better understand how soil color is influenced by soil components, especially organic matter, Fe oxides, and soil texture, at the farm scale. For this purpose, we attempted to measure soil color after selective removal of various soil components, with the idea that such an experimental approach will provide insight into how each component affects soil color and help to develop a color-based method for estimating paddy soil properties at the farm scale.

2. Materials and methods

2.1. Experimental field

Soil sampling was carried out at five contiguous irrigated paddy fields (34°51’N, 135°37’E, about 7 m a.s.l.) at Kyoto University Farm in Takatsuki City, Osaka Prefecture, Japan (Fig. 1). For irrigation, each field was leveled and surrounded with embankments. One of these fields (Field E, Fig. 1) was used as an experimental site in our previous studies (e.g., Yanai et al. 2000; Moritsuka et al. 2014). The fields were located on a very gentle slope from northwest to southeast (Fig. 1). The soil in these fields was classified as Typic Fluvaquent (Soil Survey Staff 2014) with Quaternary unconsolidated sediments as the parent material. Soil pH(H2O) was slightly acidic, ranging from 5.9 to 6.6. The fields were used as experimental paddy fields from 1928 to 2014. From 1962 to 1967, five groups of five fields, each with an area of 0.1 ha (20 × 50 m), were consolidated, resulting Fields A–E, each about 0.5 ha (100 × 50 m) (Moritsuka et al. 2015a). Cow dung manure had been applied to the fields until 1999. Since 2000, horse dung manure had been applied to the fields 5-10 times at about 10 Mg ha⁻¹ per dosage.

2.2. Soil sampling

From November 21 to 25, 2013, soil samples were collected from the surface layer (<10 cm) of the fields after harvest of rice (var. ‘Hinohikari’). The fields were divided into 246 plots, each with an area of 10 × 10 m (Fig. S1). In each plot, a soil sample consisting of five sub-samples was collected from the center and four surrounding points with about 2 m apart from the center. The samples were air-dried and 2-mm sieved before analyses.

2.3. Sample pretreatment and color analysis

A part of the original air-dried samples was pretreated before analysis. Firstly, the samples were treated with about 3% hydrogen peroxide solution (H2O2) at the ratio of 1:20 (w/v) overnight, boiled for about 1 h on a hotplate, and the residues were collected after drying at 60°C. This pretreatment was carried out to remove organic matter as selectively as possible without leaving the extractant in the residual samples. Secondly, sand samples free from silt plus clay particles were obtained by wet-sieving of the original air-dried samples using a 20-μm-opening nylon mesh cloth (Moritsuka et al. 2015b).

Figure 1. Aerial view of the experimental fields on 24 July 2007. The size of each field (A–E) is approximately 100 m × 50 m. The figures indicate the relative altitude of the fields measured on 27 October 2013. Filled and open circles indicate the inlet and outlet of irrigation water, respectively. Photo source: No. CKK20071-C9-34 provided by Geospatial Information Authority of Japan.
The three types of soil samples are abbreviated as ‘original,’ ‘H$_2$O$_2$,’ and ‘sand’ hereafter.

Soil color was measured by the method of Moritsuka et al. (2014). In brief, 2 g of the air-dried, 2-mm-sieved samples were ground by hand for 3 min, packed firmly in a plastic cell, and their colors as they appeared on windows in both sides of the cell were measured by a soil color reader (SPAD-503, Konica Minolta Optics, Inc.). A CIE 1976 (L*, a*, b*) color space was used for color description. Positive values of L*, a* and b* indicate lightness, redness, and yellowness, respectively (Viscarra Rossel et al. 2006).

It should be noted here that the H$_2$O$_2$ treatment cannot remove soil organic matter completely and that it may also cause the transformation of some acid oxalate-extractable Fe into more crystalline Fe (Mikutta et al. 2005). However, we considered this method to be the best choice for our research purpose. Similarly, Matsunaga and Uwasawa (1992) applied the H$_2$O$_2$ treatment to surface upland soils to identify the wavelength in the near infrared range that can be ascribed to the presence of soil organic matter. Besides this, the 3-min grinding treatment prior to the color measurement effectively decreased soil micro-aggregates and coarse sand particles without increasing the content of silt plus clay particles (Moritsuka et al. 2014).

### 2.4. Analysis of soil properties that may affect soil color

Total C, total N, Bray Fe (Fe$_b$), Fe$_d$, citrate-dithionite extractable Fe (Fe$_d$), sand content, and loss-on-ignition (LOI) were analyzed. Total C and N were measured by the dry combustion method (Sumigraph NC-95A, Sumika Chem. Anal. Service, Osaka, Japan) using the finely ground samples. Fe$_b$ was extracted with a mixture of 0.1 mol L$^{-1}$ HCl and 0.03 mol L$^{-1}$ NH$_4$F at a ratio of 1:20 (w/v) according to the Bray no. 2 method (Bray and Kurtz 1945). Fe$_d$ was extracted with 0.2 mol L$^{-1}$ ammonium oxalate solution at pH 3.0 (Loeppert and Inskeep 1996). Fe$_d$ was extracted from the finely ground samples with a mixture of sodium dithionite and sodium citrate (Loeppert and Inskeep 1996). The concentration of Fe in the extracts were determined colorimetrically by the 1,10-phenanthroline method (Loeppert and Inskeep 1996). Fe$_b$ was quantitatively comparable to soil Fe extractable with 1 mol L$^{-1}$ sodium acetate at pH 3.0 for paddy soils derived from volcanic ash (Saito et al. 2007), although the Bray no. 2 method was originally designed for extracting soil available phosphorus (Bray and Kurtz 1945) and it may be uncommon worldwide.

The sand content was measured gravimetrically after the above 20-µm wet-sieving of the original 2-mm sieved samples. The LOI content in the original and sand samples was also measured by the weight loss on ignition at 550°C for 3 h after oven-drying at 105°C overnight (Moritsuka et al. 2015a), and the data obtained were regarded as estimates of organic matter content in each type of the samples.

### 2.5. Statistical analysis

For mapping soil properties based on the possible spatial dependence existing between the sampling plots, the data were analyzed geostatically by using GS$^2$ Version 10 for Windows (Gamma Design Software 2011). For drawing the semivariogram, the active lag distance was set at 150 m (about 50% of the maximum sampling interval), and the lag class distance interval was set at 10 m. The semivariance data for each lag interval 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 Q value (the ratio of sill minus nugget to sill) and range were calculated. The Q value represents the degree of spatial dependence of a measured property and ranges from 0 (spatially independent) to 1 (spatially dependent), whereas the range is the maximum distance within which the properties correlate spatially (Yanai et al. 2000). Then, the spatial distribution of the data was mapped by block kriging. The accuracy of prediction by the kriging was also evaluated by the leave-one-out cross-validation analysis (Gamma Design Software 2011). The determination coefficients between measured and predicted values (cross-validation $R^2$) were calculated. In addition to the geostatistical analysis, other statistical analyses including the Student’s t-test, the correlation analysis and one-way ANOVA with Tukey-Kramer multiple comparison test were carried out using Microsoft Office Excel 2010 and Ekuseru-Toukei 2012 (Social Survey Research Information Co., Ltd., Tokyo, Japan).

### 3. Results

#### 3.1. Descriptive statistics and semivariogram parameters

Table 1 shows the descriptive statistics, semivariogram parameters, and cross-validation $R^2$ for the soil properties. Compared to average paddy soils in Japan, the soils in our fields were average to slightly high in total C and N (MAFF Agricultural Production Bureau 2008) and low in Fe$_b$ (Moritsuka et al. 2014), and exhibited relatively large variation at the farm scale. Soil color parameters were significantly changed by both pretreatments. The L* and b* values increased following the H$_2$O$_2$ treatment, whereas they decreased following the sieving treatment. The a* value showed the opposite pattern to the L* and b* values. These color parameters also varied at the farm scale, although the variation quantified by the colorimetric method were too slight to distinguish with the naked eye (Fig. S1).

Fig. 2 shows the shape of the semivariograms for the soil properties. All properties showed very high spatial dependency (Q value >0.85) based on model fitting (Table 1). The ranges were shorter than 50 m for total C and N, longer than 150 m for the a* and b* values (original and H$_2$O$_2$) and the b* value (sand), and 50-150 m for many other properties (Table 1). The short ranges calculated for total C and N suggest that the farm-scale variation was derived mainly from within-field variation (Fig. 2). On the other hand, the long ranges calculated for the a* and b* values, exceeding the field size, suggest that the variation was derived mainly from inter-field variation (Fig. 2). Interestingly, the ranges of the L* and a* values decreased considerably by the H$_2$O$_2$ treatment.

According to the cross-validation $R^2$, the properties with longer ranges showed higher accuracy of prediction (Table 1). For all properties except total C, more than 70% of the variation of the measured values could be estimated by the kriging-based interpolation.
Table 1. Descriptive statistics, semivariogram parameters and cross-validation $R^2$ of soil properties and soil color parameters.

| Pretreatment | Soil properties | Average | Coefficient of variation (%) | Model type | $R^2$ | Q value | Range (m) | Cross-validation $R^2$ | Paddy soil average (nationwide) |
|--------------|-----------------|---------|------------------------------|------------|-------|---------|-----------|------------------------|-------------------------------|
|              | Total C (g kg$^{-1}$) | 28.3    | 13.7                         | Spherical  | 0.95  | 0.96    | 40        | 0.69                   | 26.8                          |
|              | Total N (g kg$^{-1}$) | 2.55    | 13.2                         | Spherical  | 0.95  | 1.00    | 39        | 0.75                   | 2.39                          |
|              | Fe$_x$ (mg kg$^{-1}$) | 2366    | 26.1                         | Gaussian   | 0.86  | 0.96    | 57        | 0.93                   | n.d.                          |
|              | Fe$_y$ (mg kg$^{-1}$) | 4666    | 26.6                         | Gaussian   | 0.80  | 0.94    | 59        | 0.85                   | 7766                          |
|              | Fe$_z$ (mg kg$^{-1}$) | 6434    | 26.7                         | Spherical  | 0.94  | 1.00    | 78        | 0.69                   | n.d.                          |
|              | Sand (g kg$^{-1}$) | 564     | 12.6                         | Gaussian   | 0.97  | 0.94    | 81        | 0.92                   | n.d.                          |
|              | LOI (g kg$^{-1}$)  | 72.5    | 11.0                         | Exponential| 0.96  | 1.00    | 82        | 0.78                   | n.d.                          |
|              | LOI (g kg$^{-1}$)  | 54.4**  | 20.3                         | Spherical  | 0.94  | 0.89    | 84        | 0.78                   | n.d.                          |
|              | L*               | 55.3    | 3.4                          | Gaussian   | 0.98  | 0.91    | 87        | 0.96                   | 58.5**                        |
|              | a*               | 3.64    | 12.4                         | Spherical  | 1.00  | 0.99    | > 150      | 0.96                   | 4.7**                         |
|              | b*               | 11.5    | 12.5                         | Exponential| 0.97  | 1.00    | > 150      | 0.96                   | 15.6**                        |
|              | H$_2$O$_2$       | 70.2**  | 1.5                          | Spherical  | 0.98  | 0.94    | 92        | 0.85                   | n.d.                          |
|              | L*               | 12.5**  | 19.5                         | Exponential| 0.92  | 0.99    | > 150      | 0.96                   | n.d.                          |
|              | a*               | 52.9**  | 2.7                          | Spherical  | 0.97  | 1.00    | 54        | 0.76                   | n.d.                          |
|              | b*               | 4.01    | 8.2                          | Spherical  | 0.86  | 1.00    | 68        | 0.84                   | n.d.                          |
|              | LOI (g kg$^{-1}$) | 10.5**  | 9.6                          | Exponential| 0.98  | 1.00    | > 150      | 0.94                   | n.d.                          |

The asterisks (**) indicate significant differences from the corresponding values without pretreatment (original) at $p < 0.01$ (t-test).

a) Nationwide averages reported by MAFF Agricultural Production Bureau (2008)

b) Nationwide averages reported by Moritsuka et al. (2014)

Fe$_x$: Bray no. 2-extractable Fe; Fe$_y$: acid oxalate-extractable Fe; Fe$_z$: dithionite-citrate-extractable Fe; LOI: loss-on-ignition; n.d.; no data.

3.2. Spatial distribution at the farm scale

In general, the spatial distributions of surface soil properties in paddy fields are influenced by intrinsic soil formation factors such as climate, topography, parent material, vegetation, and soil formation time and by extrinsic field management factors such as land consolidation, land leveling, fertilization, and puddling. In our fields, all the properties showed strong spatial dependence ($Q > 0.85$ with various ranges (Table 1, Fig. 2).

4.1. Spatial distributions of soil properties at the farm scale

The relationship between the $b^*$ value (original) and Fe$_y$ was also significantly positive at both field and farm scales with the range ranging from 0.41 to 0.50 at the farm scale (all fields).
showed relatively similar distribution patterns among the fields (Fig. 3). Accumulation of total C near the center of the fields (Fig. 5) may be explained by the long-term application of animal dung manure with a manure spreader having an effective width of about 6.5 m (DH1500, Takakita Co., Ltd., Mie, Japan) with special care not to spread the manure on narrow farm roads surrounding the fields (Fig. 1).

The large inter-field variation in the sand content may be attributed to both intrinsic and extrinsic factors, i.e., the original topography and the field consolidation during the 1960s, respectively. Based on the relative altitude of the fields measured in 2013 (Fig. 1), the disturbance of surface soil during consolidation must have occurred most intensively near the boundary between Fields A and B. The sandy soil with low Fe oxides in the western part of Field A (Fig. 3) might be due to the loss of surface soil caused by the past land consolidation.

Previous studies postulated that strong spatial dependence of soil properties can be attributed to intrinsic factors, whereas weak spatial dependence can be attributed to extrinsic factors (Cambardella et al. 1994; Rüth and Lennartz 2008). In our case, however, all properties showed strong spatial dependence (Table 1), although total C and N appeared to be influenced by extrinsic fertilization (Fig. 5). It would be more plausible to consider that the intrinsic factors expand the range beyond the size of the field, whereas the extrinsic factors limit the range to the scale of field management (Moritsuka et al. 2015a). Thus, we suggest that the range can be more informative than the Q value when examining the factors affecting soil variation at the farm scale.

It should be emphasized that both the Q value and range will help to estimate whether some soil property can be mapped and predicted from another property. High Q value is required for good mapping, whereas similar ranges are required for good prediction. The ranges of our data suggest that soil total C and N cannot be predicted from original soil color. We will discuss the reason for this in Section 4.2.

4.2. Relationship between soil organic matter and soil color parameters

Linked with the content of organic matter, soil darkness usually diminishes with increasing depth (Japanese Society of Pedology 1997). As mentioned in Introduction, however, this empirical rule at the profile scale cannot be necessarily extrapolated to the field and farm scales.

In our fields, the correlation between the \( L^* \) value (original) and total C was significant (\( r = -0.42 \), Table 3) but not sufficient.
for prediction ($R^2 = 0.18$). The $L^*$ value (original) was more closely associated with all Fe forms and sand content (Table 3). These results indicate that the $L^*$ value (original) was more strongly influenced by fine particles containing Fe oxides than by organic matter. After removal of silt and clay fractions, the $L^*$ value (sand) was significantly correlated with total C and N ($r = -0.77$, Table 3).

Our observations agree with the previous findings that the relationship between soil darkness and organic matter content within a landscape is strongly influenced by soil texture (Schulze et al. 1993). Schulze et al. (1993) showed that sandy soil was darker than clayey soil at the same level of organic matter. The darker color of the sandy soil can be explained by the presence of dark sand particles originated from mafic parent materials or by the presence of transparent particles, such as quartz, with low scattering of visible light and an apparent dark color (low $L^*$ value). Schulze et al. (1993) speculated that the latter was responsible for the darkness of their soil samples.

In our case, the $L^*$ value was increased significantly by removing organic matter ($H_2O_2$ treatment), indicating that the mineral particles of our samples was not darker than organic matter in the samples. On the other hand, the $L^*$ value was decreased slightly but significantly by removing fine particles (sieving treatment) (Table 1). The average content of LOI (sand)
Fe and sand indicate the type of sample pretreatments before analysis of LOI. The content of LOI (sand) was negatively correlated with the L* value (sand) \((r = -0.65)\) and positively correlated with total C \((r = 0.70)\) (Table 2–3). These relationships could explain the significant negative correlation between the L* value (sand) and total C at both field and farm scales (Table 3, Fig. 6).

The significant increase in the L* value following the \(\text{H}_2\text{O}_2\) treatment is considered to be caused by the removal of organic matter (Table 1). However, the increase of the L* value brought by the \(\text{H}_2\text{O}_2\) treatment did not bring a high correlation with total C \((r = -0.63)\). These results further suggest that removal of organic matter by the \(\text{H}_2\text{O}_2\) treatment caused exposure of soil mineral surfaces that had been masked by organic matter, and that the influence of such minerals, especially Fe oxides, on soil color parameters was stronger than that of organic matter due to the larger variation in Fe contents (Table 1). Katsura et al. (2018) observed significant negative correlations between total C and the \(a^*\) and \(b^*\) values in floodplain soils in Ghana, and suggested that they were due to the exposure of reddish or yellowish surface of Fe oxides in accordance with the decrease of soil organic matter. A similar explanation may apply to the significant negative correlations observed between total C and the \(a^*\) and \(b^*\) values (original) in our samples (Table 3). In other words, soil total C could be estimated only indirectly from the original soil color parameters, as far as our samples are concerned.

We confirmed the observations made by Schulze et al. (1993), although we could not find relationships that are useful for estimating organic matter content from soil color. These findings can be summarized as follows: the accuracy of farm-scale prediction of organic matter from soil darkness depends on the variation in organic matter relative to that of other sources of soil darkness, such as soil texture and Fe oxides.

### 4.3. Relationship between Fe forms and soil color parameters

Iron oxides significantly influence soil color (Schwertmann 1993). Compared to estimation of soil organic matter from soil darkness, however, much less attention has been paid to the relationship between Fe oxides and soil color at all scales except the profile scale (Japanese Society of Pedology 1997; Kirillova et al. 2015). This may be because research has often been conducted in aerobic fields, where predicting the level of soil organic matter is more important from agronomic and environmental viewpoints. In the case of paddy fields, however, it is also important to estimate the level of Fe oxides in soil, because insufficient Fe oxides in paddy soil can cause physiological disorders of rice due to production of toxic hydrogen sulfide under anaerobic conditions. Such disorders are called ‘akiochi’ (autumn decline) in Japanese. The symptom of the akiochi-induced brown spot disease in rice has increased rapidly in Japan, and the percentage of the suffered paddy fields in 2017 reached 40% and 24% in Chubu and Kyushu regions, respectively (Sumida 2018).

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**Table 2. Correlation matrix among the soil properties that may affect soil color.**

|          | Total C | Total N | Fe\(_b\) | Fe\(_d\) | LOI (original) | LOI (sand) |
|----------|---------|---------|----------|----------|---------------|------------|
| Total C  | 1.00    |         |          |          |               |            |
| Total N  | 0.96    | 1.00    |          |          |               |            |
| Fe\(_b\) | -0.27   | -0.23   | 1.00     |          |               |            |
| Fe\(_d\) | -0.10   | -0.07   | 0.89     | 1.00     |               |            |
| LOI (original) | 0.89 | 0.91 | -0.10 | 0.08 | -0.18 | -0.30 | 1.00 |
| LOI (sand) | 0.76 | 0.76 | 0.20 | 0.36 | 0.10 | -0.58 | 0.86 | 1.00 |

Values significant at 0.1%, 1%, and 5% levels are 0.21, 0.17, and 0.13, respectively \(n = 246\).

Fe\(_b\): Bray no. 2-extractable Fe; Fe\(_d\): dithionite-citrate-extractable Fe; LOI: loss-on-ignition.

Original and sand in the parenthesis after LOI indicate the type of sample pretreatments before analysis of LOI.

**Table 3. Correlation matrix between soil properties and soil color parameters.**

|          | Total C | Total N | Fe\(_b\) | Fe\(_d\) | LOI (original) | LOI (sand) |
|----------|---------|---------|----------|----------|---------------|------------|
| Original L* | -0.42  | -0.31  | 0.81  | 0.69  | -0.63 | -0.77 | -0.26 | 0.11 |
| a*       | -0.48  | -0.53  | 0.35  | 0.68  | -0.02 | -0.55 | -0.36 |
| b*       | -0.50  | -0.49  | 0.63  | 0.63  | 0.85  | -0.44 | -0.45 | -0.14 |
| H\(_2\)O\(_2\) L* | 0.40  | 0.44  | 0.31  | 0.24  | -0.11 | -0.45 | 0.50  | 0.49 |
| a*       | -0.56  | -0.58  | 0.56  | 0.69  | 0.88  | -0.42 | -0.49 | -0.19 |
| b*       | -0.56  | -0.56  | 0.69  | 0.69  | 0.88  | -0.42 | -0.49 | -0.19 |
| Sand L*  | -0.77  | -0.77  | 0.37  | 0.17  | 0.30  | -0.04 | -0.79 | -0.65 |
| a*       | -0.30  | -0.30  | 0.67  | 0.72  | 0.80  | -0.44 | -0.23 | -0.02 |
| b*       | -0.57  | -0.53  | 0.61  | 0.60  | 0.79  | -0.43 | -0.53 | -0.22 |

Values significant at 0.1%, 1%, and 5% levels are 0.21, 0.17, and 0.13, respectively \(n = 246\).

Underlined values indicate those with the absolute values higher than 0.70.

Fe\(_b\): Bray no. 2-extractable Fe; Fe\(_d\): acid oxalate-extractable Fe; Fe\(_d\): dithionite-citrate-extractable Fe; LOI: loss-on-ignition.

Original, \(\text{H}_2\text{O}_2\), and sand indicate the type of sample pretreatments before analysis of LOI and color.

\((54 \text{ g kg}^{-1})\) was significantly lower than that of LOI (original) \((73 \text{ g kg}^{-1})\) (Table 1). These results indicate collectively that the removal of silt plus clay particles significantly decreased the content of organic matter in the samples but increased the sample darkness. These results strongly suggest the presence of transparent minerals, probably quartz, in the sand fraction. The content of LOI (sand) was negatively correlated with the L* value (sand) \((r = -0.65)\) and positively correlated with total C \((r = 0.70)\) (Table 2–3). These relationships could explain the significant negative correlation between the L* value (sand) and total C at both field and farm scales (Table 3, Fig. 6).

Figure 5. Box plot of the content of total C in soil at different field locations. As shown in the diagram, Outer, Middle and Inner indicate the positions of the central sampling points located at 5, 15, and 25 m, respectively, from the nearest border of the field. Plots marked with different letters are significantly different at \(p < 0.01\) (Tukey-Kramer test). The horizontal line in each box represents the median. The lower and upper limits of each box are the 25th and 75th percentiles, and the lower and upper whiskers represent the 10th and 90th percentiles.

![Box plot of the content of total C in soil at different field locations. As shown in the diagram, Outer, Middle and Inner indicate the positions of the central sampling points located at 5, 15, and 25 m, respectively, from the nearest border of the field. Plots marked with different letters are significantly different at \(p < 0.01\) (Tukey-Kramer test).](image)
In our fields, the correlation between the b* value (original) and Fe_d was very high ($r = 0.85$, Table 3). The correlation between the L* value (original) and the other two forms was also relatively high. Both Fe_o and Fe_d could be estimated from the original soil color with acceptable accuracy. The strong relationships between soil color and Fe oxides are partly due to the higher variation in Fe oxides than in total C. The light-colored (felsic) parent material in our soils may have strengthened the correlation coefficients between soil color and Fe oxides.

Removal of organic matter (H$_2$O$_2$ treatment) increased the correlation between the b* value and Fe_d slightly by 0.03, whereas it decreased the correlations between the L* value and the other two forms of Fe by more than 0.4 (Table 3). The determination coefficients between the b* value (H$_2$O$_2$) and Fe_d were higher than 0.4 for all individual fields (Fig. 6). At the farm scale including all fields, the regression equation between the b* value (H$_2$O$_2$) and Fe_d was $y = 624x - 1359$ ($R^2 = 0.78$), where x and y represent the b* value (H$_2$O$_2$) and Fe_d, respectively. The b* value (H$_2$O$_2$) became very small (2.2) when Fe_d was zero. These results suggest that the color of Fe_d affected soil yellowness directly and significantly, whereas the colors of Fe_o and Fe_d did not directly influence soil darkness (L* value).

The type of Fe oxides in our samples is uncertain, but Fe_o and Fe_d are operationally defined as active and free Fe oxides, respectively (Loeppert and Inskeep 1996). Suzuki and Shiga (1956) proposed a threshold of the level of free Fe oxides at about 5 gFe kg$^{-1}$ below which hydrogen sulfide starts to evolve from soil by using the 21-d anaerobic incubation of various paddy soils following application of ammonium sulfate at 300 mgS kg$^{-1}$ and determining the free Fe oxides by the method of Drosdoff and Truog (1935). Furthermore, Asami and Kumada (1960) demonstrated that the ability of Drosdoff and Truog’s method to extract free Fe oxides was similar to that of the method of Aguilera and Jackson (1953) developed for removing soil Fe_d with a mixture of sodium dithionite and citrate. A part of our samples (18%) contained Fe_d at less than 5 g kg$^{-1}$ (Fig. 6) and was regarded as low in free Fe oxides. The regression analysis suggested that, as far as our samples are concerned, the threshold of the b* value below which the samples are regarded as low in Fe_d was about 10 for both original and H$_2$O$_2$ samples (Fig. 6).

Taken together, our results suggest that the b* value can be useful for estimating the content of soil Fe_d and thereby predicting the occurrence of akiochi disease at the farm scale. As few comparable results are available, it remains to be explored how much our findings can be applied to other types of soils and paddy fields.

### 5. Conclusions

Spatial variation in soil color and related properties were evaluated in five contiguous paddy fields in Japan. For all
properties, more than 85% of the variation was spatially
dependent with different ranges; about 40 m for total C and
N, 50–85 m for Fe oxides (Feox, Fe3o4, and Fe2o3), sand and LOI, and
longer than 85 m for the color parameters (L*, a*, and b*) of
untreated soil. The ranges of these properties and their dis-
tribution patterns suggested that the contents of total C and
N were influenced by an extrinsic factor (fertilization) and that
sand content was influenced by both intrinsic and extrinsic
factors (topography and land consolidation). Soil color analysis
after removal of organic matter or fine particles further
revealed that soil color parameters were influenced by soil
organic matter, texture and Fe oxides in a complex manner.
In our case, the b* value (yellowness) was helpful for estimat-
ing the content of Fe2o3. To extend our findings with the aim
of developing methods for rapid soil assessment, it may be
worth trying to measure soil color on-site to determine the
compatibility with the laboratory measurements and, if neces-
sary, to improve the reproducibility of field measurements.

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