Effects of Tillage on Along-Row Variability of Wheat and Maize Biomass

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Abstract: Spatial variability of wheat and maize biomass was studied under two tillage systems, minimum tillage (MT) and conventional moldboard plowing (CT). The above-ground biomass data were collected from 10 locations separated at 5 m intervals along the crop rows. The range of semivariogram, estimated by fitting a linear model to observed semivariances, was used to investigate spatial dependence. A range of >5 m was regarded as the existence of spatial dependence and that of <5 m as the non-existence of spatial dependence. The frequencies of existence of spatial dependence were 46% and 63% under MT and CT, respectively, in wheat and 13% and 42%, respectively, in maize. Spatial dependence appeared more frequently under CT than under MT. Wheat showed spatial dependence more frequently and had a longer range than maize. Spatial dependence was unstable and variable with the year even on the same sampling lines. The origin of tillage-induced spatial dependence and its possible role in precision farming are discussed.

Key words: Minimum tillage, Precision farming, Semivariogram, Spatial dependence.

Materials and Methods

1. Site and treatments

Data were collected from the field at the University Farm of the University of Tokyo (Nishi-Tokyo, Tokyo, Japan), where we conducted a previous study (Yamagishi et al., 2003). The soil was a volcanic ash of the

Abbreviations: CT, conventional tillage; MT, minimum tillage.
Kanto loam type (Humic Andosol, Loam). The field, 50 m × 50 m, had been uniformly managed for growing poplar seedlings until 1995 and for conventional cultivation of barley and sorghum in 1996-1997. From the autumn of 1997, winter wheat and maize were grown in a one-year rotation for three years (1998-2000) and winter wheat with summer fallow in subsequent two years (2001-2002).

Two contrasting tillage practices were applied to the field before seeding. Minimum tillage (MT) was conducted with a rotary tiller (working width = 1.7 m), which was adjusted to disturb only the top 3 cm to enable our seeding machine to sow, leaving previous crop residues on the surface. Conventional tillage (CT) was conducted with a moldboard plow (36 cm double-furrow) to 20 cm depth and disc-harrowed (working width = 2.3 m) twice.

Dates of seeding and harvesting and the climatic data during the growth periods are summarized in Table 1. Wheat (cv. Bandowase or Gunma W6 in 2002) was sown with a corn planter (four rows with 71-cm spacing) in June or early July with side-dress fertilization. Dates of seeding and harvesting (Table 1) were 89°C, 1004°C, 1004°C, 784°C, 784°C, and 202°C for NH4-N, P2O5, and K2O, respectively.

### Table 1. The dates of seeding and harvesting wheat and maize, mean air temperature, total rainfall, and total solar radiation during growth period of 1998-2002.

| Year | Crop | Seeding | Harvesting (Sampling) | Duration (days) | Mean air temperature (°C) | Total rainfall (mm) | Total solar radiation (MJ m−2) |
|------|------|---------|-----------------------|----------------|--------------------------|-------------------|-------------------------------|
| 1998 | Wheat | 16 Nov. (1997) | 8 Jun. | 214 | 10.8 | 1026 | 1951 |
|      | Maize | 29 Jul. | 23 Oct. | 89 | 23.9 | 820 | 801 |
| 1999 | Wheat | 12 Nov. (1998) | 16 Jun. | 226 | 10.7 | 784 | 2186 |
|      | Maize | 1 Jul. | 12 Oct. | 103 | 26.7 | 1004 | 1323 |
| 2000 | Wheat | 15 Nov. (1999) | 16 Jun. | 223 | 10.9 | 505 | 2338 |
|      | Maize | 30 Jun. | 28 Sep. | 89 | 26.4 | 701 | 1149 |
| 2001 | Wheat | 16 Nov. (2000) | 8 Jun. | 214 | 9.7 | 609 | 2123 |
| 2002 | Wheat | 5 Nov. (2001) | 5 Jun. | 222 | 10.2 | 559 | 2102 |

Data of biomass were obtained from 10 locations at intervals of 5 m along the sampling lines. The minimum sampling interval in this study was 5 m. This was partly because farmers can manage this size site-specifically with their ordinary equipment and partly because sampling size in this experiment should not be too large.

On the day of harvest, above-ground parts of wheat were collected from an area of 1 m × 1 m (1 m each of four neighboring rows; 120-140 plants); those of maize were collected from 10 plants (equivalent to 1.7 m²) nearest to each sampling location. They were oven-dried at 80°C and weighed.

### 3. Geostatistics for evaluation of spatial dependence

Spatial variability was investigated by variography. It is based on the concept that the values of data close to each other are similar whereas the values far apart from each other are dissimilar. The semivariogram γ(h) is defined as

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

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 semivariogram γ(h) is a function only of h. In this study, Z was above-ground biomass [g m⁻²] and γ [g² m⁻⁴] for h=5, 10, 15, 20, 25, 30 [m] were calculated. Theoretically, γ(h) increases with increase in h and reaches an asymptotic maximum called the sill (Fig. 1). The distance h where γ reaches the sill is called the range, which shows the distance within which the sample pairs are correlated but over which they are independent. In some cases, γ(h) will remain nonzero as h approaches zero (Fig. 1a) and this limit value is called the nugget.

There are several common semivariogram models, such as the linear, spherical, and exponential ones,
satisfying the theoretical properties of a semivariogram. Values for the sill, range, and nugget are obtained by fitting the model to a semivariogram produced from observed data. Selecting a reasonable model depends on the objective of a study and may be more or less arbitrary. In this study, each semivariogram consisted of only six points and, therefore, a simple linear model with the least number of parameters was used. The model was,

\[ y = c(h/a), \quad h < a \]

\[ = c, \quad h \geq a \]

where \( c \) and \( a \) are the sill and range, respectively, and the nugget effect was not included. Model fitting was done by the least squares method. There were three cases of fitting:
1) Both \( c \) and \( a \) were definite (Fig. 2A).
2) \( c \) was definite and \( a \) (<5 m) was indefinite (Fig. 2B).
3) Only the value of \( c/a \) could be determined and \( a \) (>50 m) was indefinite (Fig. 2C). If the model fit a semivariogram with the type 1) but only poorly with an \( r^2 \) of the regression of less than 0.25, which means that the semivariogram showed no distinct trend, fitting with the type 2) was preferred.

There have been several approaches for evaluating spatial dependence. For example, the ratio of nugget to total semivariance was used to classify spatial dependence (Cambardella et al., 1994). In this study, the minimum sampling distance, the resolution of the range, was 5 m. Hence, the range larger than 5 m was tactically defined as the existence of a spatial dependence structure. If the range was smaller than 5 m, it was regarded as indicating the non-existence of spatial dependence.

The value of \( c \), the sill, indicated the semivariance between two independent points. When \( c \) could not be determined as in case 3), mentioned above, \( c \) was set to the semivariance value at \( a = 30 \) m, although it underestimated the sill.

4. Statistical analysis

The effects of tillage and crop on the range, estimated by the value of \( a \) through the above-mentioned procedures, were analyzed. The distribution of the range was continuous only between 5 and 30 m. Furthermore, it was so biased (Fig. 3) that any simple transformation could not attain normality required for ANOVA. Therefore, the range values were classified into three distinct groups (\( a > 5 \) m, \( 5 \) m \( < a < 30 \) m, \( a > 30 \) m) and chi-square test in a 2 \( \times \) 3 contingency table was conducted for analysis of frequencies (Snedecor and Cochran, 1989). The effect of tillage and that of crop on the range during 1998-2000 were separately tested by regarding both sampling lines and years as replications (Table 3, Table 4). The effect of tillage conversion on the range for wheat biomass was inspected only visually (Fig. 4).

Furthermore, we investigated if the existence or non-existence of spatial dependence persists in the same sampling lines over years. Eight sampling lines for each combination of tillage and crop were classified by the number of times spatial dependence existed \( (k) \) in three years (1998-2000). The binomial distribution was fitted to the frequency distribution of \( k \). If spatial dependence occurs randomly, the frequency distribution of \( k \) will not be different from the binomial distribution. If some sampling lines tend to show more spatial dependence than others, the frequency distribution of \( k \) will be different. In making the chi-square test of goodness of fit, some classes were combined to give a minimum expectation of at least 1 (Snedecor and Cochran, 1989, p. 132), whenever possible.

The frequency distribution of \( c \) was also tested using a contingency table to know if the sill values were different between tillage treatments.

![Fig. 2. Fitting the linear model \( y = c(h/a), h < a \) to semivariograms for wheat above-ground biomass (line no. 6, 3, and 7 under MT in 1998). A: Both range \( (a) \) and sill \( (c) \) were estimated. B: \( a \) (<5 m) was indefinite. C: \( a \) (>30 m) was indefinite.](image-url)
Results

The mean above-ground biomass and coefficient of variation (CV) within sampling line are summarized in Table 2. Although the mean values varied greatly with the year, CVs were fairly constant (0.06-0.17), except for wheat under CT in the first year (0.28). Differences in above-ground biomass between tillage practices were usually small, although they were statistically significant in some years. Smaller wheat biomass in 2001 was considered to be due to the low temperature in early spring.

The ranges for wheat and maize biomass under MT and CT were calculated by fitting the linear model to 24 semivariograms, from eight sampling lines for three years, and they were grouped into 5-m classes to show the frequency distribution (Fig. 3). The frequencies of the existence of spatial dependence, defined by the range larger than 5 m in this study, were 45.8% (MT) and 62.5% (CT) for wheat and 12.5% (MT) and 41.7% (CT) for maize. The difference in the frequency distribution of the range between MT and CT was statistically significant in maize cropping (p = 0.017) but not in wheat cropping (Table 3). Spatial dependence of maize biomass was observed more frequently and the range tended to be longer under CT than under MT. The difference in spatial dependence between wheat and maize biomass was also tested (Table 4). Wheat biomass showed more frequent spatial dependence and longer ranges than maize biomass under both MT (p = 0.030) and CT (p = 0.059).

Eight sampling lines for each tillage treatment were classified by the number of times spatial dependence existed in three years (Table 5), and the frequency distribution was compared with the binomial distribution.
The mean above-ground biomass (g m⁻²) at 10 locations along sampling lines of wheat and maize under minimum tillage (MT) and conventional tillage (CT) in 1998-2002. The tillage method was converted at the end of 2000 in several sampling lines. Means from eight (1998-2000) or two (2001-2002) sampling lines. Numbers in parentheses are standard deviations. Values followed by different letters differ significantly between tillage treatments at \( p = 0.05 \).

| Tillage | 1998  | 1999  | 2000  | Tillage | 2001  | 2002  |
|---------|-------|-------|-------|---------|-------|-------|
|         | Wheat | Maize | Wheat | Maize   |       |       |
| MT      | 739 a | 1096 a| 1219 a| 1426 a  | 1184 a| 1010 a|
|         | (0.10)| (0.11)| (0.15)| (0.09)  | (0.17)|       |
| CT      | 605 b | 947 b | 1049 b| 1388 a  | 1115 a| 968 b |
|         | (0.28)| (0.13)| (0.12)| (0.12)  | (0.14)|       |

Table 3. The effect of tillage on the range for above-ground biomass and the results of chi-square test using contingency tables. Sampling lines were classified according to the tillage method and range under wheat and maize cropping in 1998-2000.

| Crop | Tillage | Range (m) | Total |
|------|---------|-----------|-------|
|      |         | <5 5-30 >30 |       |
| Wheat | MT      | 13 7 4 | 24 |
|       | CT      | 9 8 7 | 24 |
| Total |         | 22 15 11 | 48 |
| \( \chi^2 = 1.61 \) | \( df = 2 \) | \( p = 0.447 \) |
| Maize | MT      | 21 1 2 | 24 |
|       | CT      | 14 9 1 | 24 |
| Total |         | 35 10 3 | 48 |
| \( \chi^2 = 8.13 \) | \( df = 2 \) | \( p = 0.017 \) |

| Crop | Tillage | Range (m) | Total |
|------|---------|-----------|-------|
|      |         | <5 5-30 >30 |       |
| Wheat | MT      | 13 7 4 | 24 |
|       | CT      | 34 8 6 | 48 |
| \( \chi^2 = 7.04 \) | \( df = 2 \) | \( p = 0.030 \) |
| Maize | MT      | 9 8 7 | 24 |
|       | CT      | 14 9 1 | 24 |
| Total |         | 33 17 8 | 48 |
| \( \chi^2 = 5.65 \) | \( df = 2 \) | \( p = 0.059 \) |

Table 5. Number of years in which spatial dependence was observed (\( k \)) in three years (1998-2000) on sampling lines (\( n = 8 \)), with fitted binomial distribution.

| Crop (Tillage) | Number of years with spatial dependence (\( k \)) | Observed Frequency | Expected Frequency |
|----------------|-----------------------------------------------|-------------------|-------------------|
| Wheat (MT)     | 0                                             | 1.27              |
|                 | 1                                             | 3.23              |
|                 | 2                                             | 2.73              |
|                 | 3                                             | 0.77              |
| Total           | 8                                             | 8.00              |
| \( \chi^2 = 4.30 \) | \( df = 1 \) | \( p = 0.038 \) |

| Wheat (CT)     | 0                                             | 5.36              |
|                 | 1                                             | 2.30              |
|                 | 2                                             | 0.33              |
|                 | 3                                             | 0.02              |
| Total           | 8                                             | 8.00              |
| \( \chi^2 = 0.58 \) | \( df = 1 \) | \( p = 0.466 \) |

| Maize (MT)     | 0                                             | 0.42              |
|                 | 1                                             | 2.11              |
|                 | 2                                             | 3.52              |
|                 | 3                                             | 1.95              |
| Total           | 8                                             | 8.00              |
| \( \chi^2 = 1.20 \) | \( df = 1 \) | \( p = 0.273 \) |

| Maize (CT)     | 0                                             | 1.59              |
|                 | 1                                             | 3.40              |
|                 | 2                                             | 2.43              |
|                 | 3                                             | 0.58              |
| Total           | 8                                             | 8.00              |
| \( \chi^2 = 0.27 \) | \( df = 1 \) | \( p = 0.606 \) |

with the probability of the existence of spatial dependence mentioned above (\( p = 0.458, 0.625, 0.125, \) and 0.417 for MT-wheat, CT-wheat, MT-maize, and CT-maize, respectively). If the frequencies of middle classes are lower and those of extreme classes are higher than the expected values, the existence (or non-existence) of spatial dependence is considered to be persistent on the same sampling line. The observed and expected frequency distributions were significantly different only in sampling lines with wheat cultivated under MT (\( p = 0.038 \)). However, a higher value in the middle class (\( k = 1 \)) and lower values in outer classes (\( k = 0, 2-3 \)) than the expected frequency did not support the persistency of spatial dependence in the same sampling lines. It rather suggested that spatial dependence was quite unsettled even in the same sampling lines. It is concluded, therefore, that spatial dependence in a given sampling line was unstable and easily varied with the year.
The conversion of tillage methods at the end of 2000 caused a change in frequency distribution of the range for wheat above-ground biomass (Fig. 4). Although the number of studied sampling lines was small (two for each treatment), it was recognized that there was more frequent spatial dependence under CT than under MT after the conversion of tillage methods irrespective of previous tillage history. This was in good agreement with the results of 1998-2000 that spatial dependence existed more frequently under CT than under MT and it varied easily with the year.

The frequency distribution of the sill significantly differed between MT and CT under wheat cropping ($p = 0.023$, Table 6). It apparently showed that the variance of wheat biomass was larger under CT. The sill for maize biomass was not affected by the tillage method.

**Discussion**

If soil properties and crop productivity were uniform in a whole field, there would be no need for precision farming. However, they usually have variability and a potential for adoption of precision farming exists in most fields. For the efficient application of precision farming the variability should have spatial dependence, expressed as the manageable range of spatial correlation. Although many researches investigated the spatial variability of soil properties, the effect of tillage has scarcely been studied (Tegaye and Hill, 1998). The result of this study showed that spatial dependence of crop biomass tends to be more prominent if the field is tilled conventionally (Fig. 3, Fig. 4). If the sampling interval of 5 m in this study is regarded as a minimum distance, with which farmers can treat their field variably with ordinary equipment, the feasibility of precision farming seems to be higher in conventionally tilled fields. Higher variability in wheat cropping under plowing, shown by larger sill values (Table 6), also suggested that precision farming was more needed there. For future practical application, it is necessary to identify soil factors that affect crop growth, although low stability of spatial dependence suggested that factors determining crop growth may vary with the year (Yamagishi et al., 2003).

Spatial variability of a few soil properties is known to be affected by tillage. Spatial dependence of soil nitrate concentration (Mohanty and Kanwar, 1994) and hydraulic conductivity (Diiwu et al., 1998) tends to be more prominent under conventional tillage than under no tillage. It is considered that intensive tillage reduces local spatial variability mainly by mixing soil but it does not affect spatial variability in a large-scale, which then becomes more easily recognized. However, it is doubtful whether tillage can always cause spatial dependence. The degree of spatial dependence varies with the soil properties (Cambardella et al., 1994) and possibly with the tillage methods. Furthermore, in the field with serious soil degradation and erosion, soil spatial variability pattern itself may be greatly modified by tillage. If precision farming is to be applied to various fields widely and flexibly, tillage effects on soil variability should be investigated more in detail.

An interesting finding for us, crop scientists, is that spatial dependence varied with crop species. Irrespective of the tillage method, above-ground biomass of wheat tended to show spatial dependence more frequently than that of maize (Fig. 3). There is a possibility that the growth of both species is restricted by different soil factors, such as available phosphate, nitrate and organic matters, which are differently distributed in the field. However, it is more probable that maize growth is more dependent on subsoil conditions. The soil of this experiment site, the typical soil in Kanto Plain in Japan, consists of distinct two layers. The dark-colored topsoil of about 30 cm in depth greatly differs from the dense red-brown subsoil in chemical and physical properties. Studies on root distribution in this type of soil showed that maize has a deeper root system extending into subsoil (Nakamoto et al., 1992) while most of the wheat roots are restricted in topsoil (Oyanagi et al., 1993). If maize is affected by the heterogeneity of subsoil properties, which are not reduced by ordinary field operations, it will show higher variability (and no or weak spatial dependence) compared with wheat, whose growth is subject to topsoil conditions, more heterogeneous and more influenced by tillage operations.

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