Path Analysis of Tiller Density of Winter Wheat Demonstrates the Importance of Practices that Manipulate Clod Size Based on Soil Moisture at Seeding in the Rice–Wheat Cropping System

Tatsuya Inamura, Akane Yoshikawa, Sachiko Ikenaga and Michihisa Iida

(Graduate School of Agriculture, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan)

Abstract: The moisture of paddy soil after rice cropping is a major impediment to the establishment, tillering and yield of winter wheat in the rice–wheat (R–W) cropping system. We examined the seedling establishment ratio, based on soil moisture at seeding by path analysis of nine soil/plant traits in the farmer’s fields in Western Japan where the R–W cropping system was being used, to establish a strategy for improving tiller density by optimizing the seedling establishment ratio. The clod size of surface soil, which showed a significant positive correlation with soil moisture at seeding, had a significant negative direct effect on the seedling establishment ratio. The reduction in seedling establishment ratio, together with fewer tillers per plant, resulted in a significant decrease in tiller density. The sum total of contribution of soil moisture contents to tiller density via clod size was smaller than that of seeding rate, and similar to that of the amount of nitrogen (N) basal dressing. This indicates that manipulating clod size based on soil moisture at seeding provides an opportunity for maintaining tiller density, as well as changing the amount of N basal dressing with the soil moisture conditions after rice cropping.

Key words: Emergence depth, Seeding rate, Seedling establishment ratio, Site-specific management, Tiller.

Rice (Oryza sativa L.) and wheat (Triticum aestivum L.) are now grown in sequence on the same land in the same year over 26 Mha of South and East Asia to meet the food demand of a rapidly expanding human population (Timsina and Connor, 2001). The moisture of paddy soil after rice cropping is a major impediment to the establishment, tillering and yield of winter wheat in the rice–wheat (R–W) cropping system (Timsina and Connor, 2001). In Western Japan, winter wheat is grown in the paddy field, the moisture of paddy soil is a major impediment in the cultivation of winter wheat (Taya, 1993; Inamura et al., 2007). Clod size and soil moisture content in the plowed layer are important factors for rapid, uniform seedling emergence and establishment under both dry and wet conditions (Brown et al., 1996; Dürr and Aubertot, 2000; Guérif et al., 2001; Håkansson et al., 2002). Rapid and uniform establishment improves tiller production, which is an essential developmental process in the growth of cereals, and has a direct effect on all subsequent yield-related traits (García et al., 1991; García et al., 2003). The number of seedlings established is a product of seeding rate and seedling establishment ratio. Tiller production, adjustment of seeding rate, seedling establishment ratio and the number of tillers per plant are critical issues in crop management practices. Inamura et al., (2007) indicated the importance of altering the seeding rate based on soil moisture content at seeding for maintaining tiller and panicle density and crop yield of winter wheat after paddy rice cropping in the southwestern region of Japan. Tiller density and seeding rate may be improved by controlling the seedling establishment ratio based on soil characteristics at seeding. For this purpose, it is important to elucidate the hierarchical causal-relationship between the seedling establishment ratio and seedling establishment ratio-related soil characteristics, and between tiller density and seedling establishment ratio. Furthermore, the contribution of the variation of the related soil characteristics to the variation of tiller density via seedling establishment ratio must be investigated. Path analysis is an effective technique for organizing and presenting significant causal-relationships between component variables and response variables through a path diagram based on experimental results or on priori grounds (Samonte et al., 1998; Ball et al., 2001).
To date, very few studies have focused on the potential of altering the seedling establishment ratio based on soil moisture contents at seeding for improving the tiller density of winter wheat in R−W cropping system. A field study with winter wheat after paddy rice cropping in the southwestern region of Japan was undertaken to organize the significant causal-relationships required to determine the contribution ratio of seedling establishment ratio-related soil characteristics to tiller density via seedling establishment ratio and to examine the potential of altering seedling establishment ratio based on soil conditions at seeding.

Materials and Methods

1. Experimental design

A field study was conducted on paddy fields (135°49’E, 34°32’N, 65 m above sea level) located in Ohnishi, Sakurai, Nara, Japan (Fig. 1) during two crop seasons of winter wheat. All the paddy fields in Ohnishi were divided into three groups empirically; group A (19 ha), group B (11 ha) and group C (7 ha) (Fig. 1). The land use system of these fields was three croppings in the two years (Paddy rice–Winter Wheat–Soybean) (Inamura et al., 2004). The
crop rotations for groups A, B and C are given in Table 1. Winter wheat was grown from December to the following June. The previous crop of winter wheat was irrigated paddy rice, which was grown from June to October. Soybean was grown from late June to December. In this study region, high moisture content of paddy soil after rice cropping was one of the major impediments to the growth and yield of winter wheat (Inamura et al., 2007). As shown in Fig. 1, the study areas A and B were in the center of groups A and B, respectively. One study area was composed of 14 paddy fields. The size of each paddy field was 10−20 m × 100 m. The soil was Gray lowland soil. The physical properties of this soil in the study areas are shown in Table 2. There was observed no significant difference (P > or =0.05) in the soil properties between the areas. Fields were managed by local farmers using their conventional practices for winter wheat (Table 3). For all studies, winter wheat (Triticum aestivum L.), cultivar Kinuiroha was utilized. The seed of Kinuiroha was supplied from Nara Agricultural Cooperative Association. The germination rate of seed in 2002−03 and 2003−04 crop season was 91% and 84%, respectively. Seed weight in 2002−03 and 2003−04 was 35.0 mg and 29.7 mg, respectively. A rotary tiller was used to disturb the stubble of the preceding rice crop down to a depth of 0.15 m. On the day of the first tillage, winter wheat seeds were broadcast on the soil surface together with basal fertilizer. Immediately thereafter, the fields were tilled to a depth of 0.06 m with a rotary tiller to incorporate the seeds and chemical fertilizer. We used a 30-blade rotary tiller with a working width of 1.2 m. The blade rotation speed was 122 rpm with the rear shield fully lowered. A rotary tiller was attached to a 15.4 KW four-wheel-drive tractor. Small-scale farmers in Japan most commonly use this rotary tiller system. The fertilizer used for this basal application contained 14.0% N, 10.0% P₂O₅, and 15.0% K₂O. Ammonium sulfate fertilizer (21.0% N) was used for top dressing (20 Feb. 2003 and 15 Feb. 2004).

### 2. Data collection and measurements

The seeding, heading and maturity date, seeding rate, and the amount of N for basal and top dressing on the 14 paddy fields were recorded (Table 3). There was no significant difference (P > or =0.05) in the farmer’s practices between the two study areas. All samples for analyzing the soil properties were collected on the day before the first tillage. Study area A was equally divided into three subplots and study area B into five subplots. Soil samples were collected from the plowed layer (0 to 0.15 m deep) in each subplot with three subsamples. Samples were then air-dried and ground until they were fine enough to pass through a 2 mm sieve before the analysis. Soil hardness, at a depth of 0.15 m, was measured with a soil hardness gauge before the first tillage at each place of soil sampling. Moisture contents of the soil surface (0 to 0.15 m deep, W/W) was measured using a soil moisture meter (HH2 Delta-T, Devices Ltd.) just before the first tillage near the place of soil sampling. Soil total carbon (TC) contents were measured using the trace mass spectrophotometer (Tracer MAT, Thermo Quest Co. Ltd., Tokyo) just before the first tillage near the place of soil sampling. Soil total carbon (TC) contents were measured using the trace mass spectrophotometer (Tracer MAT, Thermo Quest Co. Ltd., Tokyo) in the experiment in study area B. Clod size of the surface soil was determined using images taken with a digital camera near the place of soil sampling on the day after seeding. The original digital image was 0.36 m × 0.54 m on the soil surface. A further digital image of 0.18 m × 0.27 m on the soil surface was extracted from the

| Variable          | Unit | Mean    | Maximum | Minimum | C.V.(%) |
|-------------------|------|---------|---------|---------|---------|
| Study area A      |      |         |         |         |         |
| Seeding date      |      | 16 Nov. | 17 Nov. | 15 Nov. | 3.4     |
| Heading date      |      | 15 Apr. | 15 Apr. | 15 Apr. | 0.0     |
| Maturity date     |      | 4 Jun.  | 4 Jun.  | 4 Jun.  | 0.0     |
| Seeding rate      | g m⁻³| 10.0    | 15.0    | 7.5     | 24.7    |
| N basal dressing  | g m⁻³| 7.0     | 10.4    | 5.6     | 20.2    |
| N top dressing    | g m⁻³| 4.0     | 5.2     | 2.8     | 16.6    |
| Study area B      |      |         |         |         |         |
| Seeding date      |      | 17 Nov. | 23 Nov. | 15 Nov. | 15.6    |
| Heading date      |      | 15 Apr. | 15 Apr. | 15 Apr. | 0.0     |
| Maturity date     |      | 2 Jun.  | 2 Jun.  | 2 Jun.  | 0.0     |
| Seeding rate      | g m⁻³| 11.1    | 15.0    | 7.5     | 20.1    |
| N basal dressing  | g m⁻³| 6.1     | 8.4     | 2.8     | 29.3    |
| N top dressing    | g m⁻³| 2.6     | 4.2     | 0.0     | 52.3    |
Neat the place of soil sampling, the number of established seedlings per square meter, and number of tillers per 20 hills were counted (14 Feb. 2003 and 10 Feb. 2004). The seedling establishment ratio was calculated by dividing the number of established seedlings by the product of seeding density and seed germination ratio (0.91 and 0.84 in study areas A and B, respectively). Seeding density was calculated by dividing the seeding rate by seed weight (35.0 mg and 29.7 mg in study areas A and B, respectively). Tiller density was calculated by multiplying the number of established seedlings and the number of tillers per plant. The emergence depth of ten plants of winter wheat was measured near the place of soil sampling (14 Feb. 2003 and 10 Feb. 2004). The emergence depth was defined as the perpendicular distance from the soil surface to the seed that had established.

Winter wheat plants were sampled from a 2 m² area near the place of soil sampling at maturity (4 Jun. 2003 and 2 Jun. 2004). Wheat plants were divided into grains and straw. Subsamples of grain were oven-dried at 70°C for 3 d to calculate the moisture contents and dry matter. Winter wheat yield was calculated at 13.0% moisture content.

The data set from fields with soil properties and crop growth properties for path analysis are displayed in Table 4. No significant difference (P ≥ 0.05) was observed in these properties between the study areas.

3. Meteorological Observation
Daily mean air temperature was measured using a temperature probe (HMP45C, Campbell Scientific, Inc., UK), and daily rainfall was measured using a tipping bucket rain gauge (TE525MM, Campbell Scientific, Inc., UK). A data logger (CR10X, Campbell Scientific, Inc., UK), which was driven by solar battery (SP-10, Campbell Scientific, Inc., UK), provided a central location to electronically store the data collected by HMP45C and TE525MM.

4. Statistical analyses
Path analyses have been used to estimate the magnitude and significance of causal-relationships among response and component variables using path coefficients (standardized partial regression coefficients) and to
identify important component variables for improving a response variable (Dewey and Lu, 1959; Ball et al., 2001). 
Path analysis is a straightforward extension of multiple linear regressions. Multiple regression analysis was performed to obtain the optimum model for predicting the causal-relationship based on hypothesized causal-relationships among the response variables and component variables in the path analysis study.
We used path analysis to clarify how seedling establishment ratio-related soil characteristics affect tiller density via seedling establishment ratio. Fig. 2 shows a path diagram of the hypothesized causal-relationships of
the response and component variables. For example, clod size was used as the response variable (X₄), with soil moisture content (X₁), soil hardness (X₂), and TC (X₃) as the component variables:

\[ X₄ = P₁,4 \times X₁ + P₂,4 \times X₂ + P₃,4 \times X₃ + \text{Residual} \]  

Where \( P₁,4, P₂,4, \) and \( P₃,4 \) represent path coefficients (standardized partial regression coefficient) to the clod size from soil moisture content, soil hardness, and TC, respectively. The path coefficient represents the direct effect of a component variable on a response variable in multiple regression analysis, while the other component variables held constant. \( R²(1,2,3) \) (Fig. 2) represents the adjusted coefficient used to determine the relationship between clod size (X₄) and the three component variables (X₁, X₂, and X₃), and the proportion of the variation explained by the model in equation (1) to the total variation of clod size.

Tiller density (X₁₀) is expressed as the product of the seedling establishment ratio (X₇), the number of tillers per plant (X₈), and the seeding rate (X₉) (Eq. (2)).

\[ X₁₀ = X₇ \times X₈ \times X₉ \]  

An additive model, required for path analysis, is derived from equation (2) by a natural logarithm transformation, as follows:

\[ \ln(X₁₀) = P₇,1₀ \times \ln(X₇) + P₈,1₀ \times \ln(X₈) + P₉,1₀ \times \ln(X₉) \]  

Where \( P₇,1₀, P₈,1₀, \) and \( P₉,1₀ \) represent the direct effect of each component variable on the log-transformed tiller density (X₁₀). The direct contribution of soil moisture content (X₁) to the total variation of clod size (X₄) is as follows:

\[ \text{The direct contribution} = A \times B \]

where A is the proportion of variation explained by the model for total variation in clod size. A is represented by \( R²(1,2,3) \). B is the relative contribution of soil moisture to the clod size variation. B is:

\[ B = C / (C + D + E) \]

where C is the direct effect (P₁,4; the partial regression coefficient) of soil moisture on clod size, D is the direct effect (P₂,4) of soil hardness (X₂) on clod size, and E is the direct effect (P₃,4) of TC (X₃) on clod size.

**Results**

1. **Weather conditions and path analysis**

Fig. 3 shows the meteorological conditions during the two-year experimental period at the study areas. The weather conditions in study area A were characterized by low air temperature and plentiful rainfall during the

---

**Table 5.** Correlation coefficients between the component and response variable in each multiple regression in study area A. Four multiple regressions (causal-relationships) are shown in Fig. 2. n = 14.

| Response variable of multiple regression | Component variable | Correlation coefficient |
|-----------------------------------------|--------------------|------------------------|
| Clod size                               | Soil moisture contents | 0.828 ***               |
|                                        | Soil hardness       | -0.801 ***             |
|                                        |                      | -0.690 **              |
|                                        | Clod size            | Soil moisture          |
|                                        |                      | Soil hardness          |
| Seedling establishment ratio            | Clod size            | -0.732 **              |
|                                        | Seedling emergence depth | 0.747 **             |
|                                        |                      | 0.717 **               |
|                                        | Soil moisture contents | -0.654 *               |
|                                        |                      | 0.828 ***              |
|                                        | Amount of N basal dressing | 0.119 ***           |
|                                        |                      | -0.210 **              |
|                                        |                      | -0.142 **              |
|                                        |                      | -0.093 **              |
| No. of tillers per plant                | Seedling emergence depth | -0.597 *              |
|                                        | Amount of N basal dressing | 0.563 *              |
|                                        |                      | -0.142 **              |
| Tiller density                         | Tiller density       |
|                                        | Establishment ratio  |
|                                        |                     |
|                                        | Seedling establishment ratio | 0.819 ***          |
|                                        | Seeding rate        | 0.717 **               |
|                                        | No. of tillers per plant | 0.741 **             |
|                                        |                      | 0.572 **               |

* *, **, *** and ns indicate the significance levels of P<0.05, P<0.01, P<0.001 and not significant, respectively.
Inamura et al. — Path Analysis of Tiller Density of Winter Wheat

2. Causal relationship for clod size

Correlation coefficients (Tables 5 and 6) revealed that clod size had significant and positive correlation with soil moisture contents, while it had significant and negative correlation with soil hardness in the two study areas. A negative and significant relationship was confirmed between soil moisture contents and soil hardness in the two study areas. Soil moisture contents had significant and positive correlation with TC in study area A. The multiple regression models (Figs. 4, 5) for two components (soil moisture contents and soil hardness) accounted for more than half of the noted variations in clod size with adjusted R² values (0.748 and 0.678 in study areas A and B, respectively). The direct effect of soil moisture contents on clod size was significant and positive, and that of soil hardness was significant and negative in the two study areas. The direct contribution (Table 7) of soil moisture contents to clod size (0.408 and 0.298 in study areas A and B, respectively) was similar to that of soil hardness to clod size (0.340 and 0.389 in study areas A and B, respectively). That of soil moisture contents to clod size in study area A (0.408) was greater than that in study area B (0.298).

3. Causal relationship for seedling establishment ratio

The seedling establishment ratio had a significant negative correlation with clod size, seedling emergence depth, and soil moisture contents, except the soil moisture contents in study area B (Tables 5 and 6). The interrelationships between clod size and seedling emergence depth, and between clod size and soil moisture contents were positive and significant in the two study areas. The multiple regression models (Figs. 4, 5) for two components (clod size and seedling emergence depth) accounted for more than half of the variation noted in the seedling establishment ratio (adjusted R² values were 0.573 and 0.735, in study areas A and B, respectively). The direct effects of clod size and seedling emergence depth on the seedling establishment ratio were significant and negative in the two study areas. The direct contribution (Table 7) of clod size to seedling establishment ratio (0.269 and 0.356...
in study areas A and B, respectively) was smaller than that of seedling emergence depth to seedling establishment ratio (0.304 and 0.377 in study areas A and B, respectively).

4. Causal relationship for the number of tillers per plant

The number of tillers per plant had a significant negative correlation with seedling emergence depth, and had a significant positive correlation with the amount of N basal dressing in the two study areas (Tables 5 and 6). The adjusted R² values of multiple regression models (Figs. 4, 5) for the two components (seedling emergence depth and amount of N basal dressing) were 0.516 and 0.765 in study areas A and B, respectively. The direct effect of seedling emergence depth on the number of tillers per plant was significant and negative, and that of the amount of N basal dressing was significant and positive in the two years. The direct contribution (Table 7) of seedling emergence depth to number of tillers per plant (0.248 and 0.383 in study areas A and B, respectively) was similar to that of the amount of N basal dressing to the number of tillers per plant (0.516 and 0.766 in study areas A and B, respectively). That of seedling emergence depth to the number of tillers per plant in study area A was smaller than that in study area B. Moreover, that of the amount of N basal dressing to the number of tillers per plant in study area A was smaller than that in study area B.

5. Causal relationship for tiller density

Tiller density had a significant and positive correlation with seedling establishment ratio, seeding rate, and the number of tillers per plant (Tables 5 and 6). The interrelationship between seedling establishment ratio and the number of tillers per plant was significant and positive in the two study areas. The three-components (seedling establishment ratio, seeding rate, and the number of tillers per plant) in multiple regression models (Figs. 4, 5, Tables 5 and 6) accounted for most of the variation in tiller density with adjusted R² values (0.810 and 0.875 in study areas A and B, respectively). The direct effects of seedling establishment ratio, the number of tillers per plant and seeding rate on tiller density were significant and positive in the two study areas. The direct contribution (Table 7) of seedling establishment ratio to tiller density (0.310 and 0.252 in study areas A and B, respectively) was larger than that of
Table 7. Hierarchical direct contribution of each component variable to each response variable.

| Component variable | Study area A | Study area B |
|--------------------|--------------|--------------|
|                    | Clod size    | Seeding establishment ratio | No. of tillers per plant | Tiller density |
| Soil moisture contents | 0.408         | 0.110         | –                      | 0.034          |
| Soil hardness      | 0.540         | 0.091         | –                      | 0.028          |
| Clod size          | 0.269         | –             | 0.083                  |                |
| Seeding emergence depth | 0.304       | 0.268         | 0.164                  |                |
| Amount of N basal dressing | 0.248 | 0.065         |                         |                |
| Seeding establishment ratio | 0.316 |                  |                         |                |
| Seeding rate       | 0.258         |              |                         |                |
| No. of tillers per plant | 0.262       |              |                         |                |

Fig. 5. Path coefficient diagram showing the hierarchical relation of four significant (P<0.001) multiple regressions of the components variables on the response variables in study area B. The response variables were clod size, seedling establishment ratio, number of tillers per plant, and tiller density. The single-headed arrows indicate the significant (P<0.05) path coefficients, the single-headed arrows with a broken line indicate non-significant path coefficient. Double-headed arrows indicate simple linear correlation coefficients. NS, and *, **, ***: Not significant, and significant at P<0.05, 0.01, and 0.001, respectively.
seeding rate to tiller density (0.238 and 0.218 in study areas A and B, respectively).

6. Influence of seedling establishment ratio-related soil characteristics on tiller density

The causal relation analysis clearly showed significant contributions of seedling establishment ratio-related soil characteristics to tiller density in the two study areas. Clod size of surface soil, which showed significant correlation with soil moisture contents and soil hardness at seeding, had a significant negative effect on tiller density via seedling establishment ratio. Soil moisture contents at seeding showed significant correlation with soil hardness at seeding. Seedling emergence depth, which showed significant positive correlation with clod size, had significant negative effects on tiller density via seedling establishment ratio and via number of tillers per plant. The amount of basal dressing had a significant positive effect on tiller density via number of tillers per plant. Seeding rate had a significant positive effect on tiller density.

7. Hierarchical direct contribution

The hierarchical direct contribution of a component variable to the variation of response variable via other component variables can be estimated using standardized partial regression coefficients in hierarchical causal-relationships (Inamura et al., 2004). Table 7 summarized the hierarchical direct contribution of nine component variables to each response variable. The hierarchical direct contribution of soil moisture contents to tiller density (0.094 and 0.027 in study areas A and B, respectively) was similar to that of soil hardness to tiller density (0.028 and 0.034 in study areas A and B, respectively). The hierarchical direct contribution of seedling emergence depth to tiller density (0.164 and 0.250 in study areas A and B, respectively) was greater than that of clod size (0.083 and 0.089 in study areas A and B, respectively), and that of the amount of N basal dressing (0.065 and 0.155 in study areas A and B, respectively), and of that of the number of tillers per plant (0.262 and 0.405 in study areas A and B, respectively) was greater than that of seeding rate (0.238 and 218 in study areas A and B, respectively). That of clod size to tiller density via seedling establishment ratio (0.310 and 0.252 in study areas A and B, respectively) was greater than that of soil moisture contents at seeding (0.238 × 0.717 and 0.250 × 0.752 in study areas A and B, respectively). The sum total of contribution of soil moisture contents to clod size and that via seedling emergence depth was 0.118 (0.164 × 0.717) and 0.188 (0.250 × 0.752) in study areas A and B, respectively. The sum total of contribution of soil moisture contents to tiller density via seedling emergence depth was 0.201 (0.083 + 0.118) and 0.277 (0.089 + 0.188) in study areas A and B, respectively. Furthermore, the sum total of contribution of soil moisture contents to clod size and that to tiller density via soil hardness was 0.645 (0.048 + 0.340 × 0.690) and 0.505 (0.298 + 0.380 × 0.545) in study areas A and B, respectively, because soil moisture contents related with soil hardness at seeding (r = 0.690 and 0.545 in study areas A and B, respectively). According to the management strategy of clod size improvement based on the difference in soil moisture contents for improving tiller density, the sum total of contribution of soil moisture contents to tiller density via clod size improvement was 0.129 (0.201 × 0.645) and 0.140 (0.277 × 0.505) in study areas A and B, respectively. This contribution ratio was smaller than that of seeding rate to tiller density (0.238 and 0.250 in study areas A and B, respectively). However, this contribution ratio in study area A was larger than that of the amount of N basal dressing via the number of tillers per plant (0.065), and, in study

8. Influence of tiller density on yield

Correlation coefficients (0.720 (P<0.01) and 0.680 (P<0.05) in study areas A and B, respectively) revealed that winter wheat yield had a significant and positive correlation with tiller density in the two study areas.

Discussion

High tiller density occurred in the farmer’s fields with high seedling establishment ratio, large tiller number per plant, and high seeding rate. Seedling establishment ratio is one of the major constraints for wheat production (Timsina and Connor, 2001). Large tiller number per plant occurred in the fields with small clod, shallow-emergence seedlings and high application rate of N basal dressing in this study. Clod size and soil moisture contents in the plowed layer are important factors for rapid, and uniform seedling emergence and establishment (Dürr and Aubertot, 2000; Guérif et al., 2001; Håkansson et al., 2002). Richard et al. (1997) reported that large clods are mainly caused by a reduction in the fragmentation of soil aggregates by tillage under wet and dry soil conditions. Larger clods increased the number of deep-sown seeds, and induced deep seedling emergence (Inamura et al., 2007). This was considered to result in the positive and significant correlations between clod size and seedling emergence depth. The negative effect of clod size on seedling emergence, as demonstrated in our study, has been previously reported (Dürr and Aubertot, 2000; Guérif et al., 2001; Håkansson et al., 2002).

Tillering may therefore be increased, via seedling establishment ratio, seedling emergence depth and number of tillers per plant, by manipulating the clod size based on soil condition of moisture and hardness. Because clod size affected seedling emergence depth (r = 0.717 and 0.752 in study areas A and B, respectively), the contribution of clod size to tiller density via seedling emergence depth was 0.118 (0.164 × 0.717) and 0.188 (0.250 × 0.752) in study areas A and B, respectively. The sum total of contribution of clod size to tiller density via seedling establishment ratio and that via seedling emergence depth was 0.201 (0.083 + 0.118) and 0.277 (0.089 + 0.188) in study areas A and B, respectively. Furthermore, the sum total of contribution of soil moisture contents to clod size and that to tiller density via soil hardness was 0.645 (0.408 + 0.340 × 0.690) and 0.505 (0.298 + 0.380 × 0.545) in study areas A and B, respectively, because soil moisture contents related with soil hardness at seeding (r = 0.690 and 0.545 in study areas A and B, respectively). According to the management strategy of clod size improvement based on the difference in soil moisture contents for improving tiller density, the sum total of contribution of soil moisture contents to tiller density via clod size improvement was 0.129 (0.201 × 0.645) and 0.140 (0.277 × 0.505) in study areas A and B, respectively. This contribution ratio was smaller than that of seeding rate to tiller density (0.238 and 0.250 in study areas A and B, respectively). However, this contribution ratio in study area A was larger than that of the amount of N basal dressing via the number of tillers per plant (0.065), and, in study
The difference in the contribution of the amount of N basal dressing between the two study areas was caused by the difference in the contribution of number of tillers per plant to the tiller density between the two study areas. The difference in the contribution of number of tillers per plant seemed to be affected by the difference in weather conditions during tillering stage between years.

These data indicate that controlling clod size in the plowed layer depending on the soil condition of moisture is an effective method for improving tiller density, as well as the changing of the amount of N basal dressing. Thus, it is considered that control of the clod size will result in high yield of winter wheat via improvement of tiller density. However, under the climate conditions suitable for tillering, control of the clod size may not always surpass the change of the amount of N basal dressing for tiller density improvement.

The breakdown of soil clods to different clod sizes is influenced by a number of factors, including intrinsic soil properties, climatic conditions, and the types of tillage implements (Barzegar et al., 2004). To improve clod size, tillage intensity should be varied according to soil moisture contents at the time of tillage operations (Tapela and Colvin, 2002; Barzegar et al., 2004). Tillage intensity can be adjusted for proper clod size, based on the knowledge of the optimum relation among tillage system, its intensity and soil moisture contents, which significantly correlated with soil hardness.

Acknowledgments

Special thanks go to our cooperating farmers in this research. Without their cooperation, this research would not have been possible.

References

Ball, R.A., Mencik, R.W., Vories, E.D., Keising, T.C. and Purcell, L.C. 2001. Path analyses of population density effects on short-season soybean yield. Agron. J. 93: 187-195.
Barzegar, A.R., Hashemi, A.M., Herbert, S.J. and Assoolar, M.A. 2004. Interactive effects of tillage system and soil water content on aggregate size distribution for seedbed preparation in Fluvioels in southwest Iran. Soil Till. Res. 78: 45-52.
Brown, A.D., Dexter, A.R., Chamen, W.C.T. andSpoor, G. 1996. Effect of macroporosity and aggregate size on seed-soil contact. Soil Till. Res. 38: 203-216.
Dewey, D.R. and Lu, K.H. 1959. A correlation and path-coefficient analysis of components of crested wheatgrass seed production. Agron. J. 51: 515-518.
Dürr, C. and Aubertot, J. 2000. Emergence of seedlings of sugar beet (Beta vulgaris L.) as affected by size, roughness and position of aggregates in the seedbed. Plant Soil 219: 211-220.
García del Moral, L.F., Ramos, J.M., García Del Moral, M.B. and Jimenez-Tejada, P. 1991. Ontogenetic approach to kernel production in spring barley based on path-coefficient analysis. Crop Sci. 31: 1179-1185.
García del Moral, L.F., Kharrabi, Y., Vilegas, D. and Royo, C. 2003. Evaluation of grain yield and its components in durum wheat under Mediterranean conditions: An ontogenetic approach. Agron. J. 95: 266-274.
Guérif, J., Richards, G., Dürr, C., Machet, J.M., Recous, S. and Roger-Estrade, J. 2001. A review of tillage effects on crop residue management, seedbed conditions and seedling establishment. Soil Till. Res. 61: 153-162.
Håkansson, I., Myrbeck, A. and Estrade, J. 2001. Path analyses of population density effects on short-season soybean yield. Agron. J. 93: 187-195.
Inamura et al.—Path Analysis of Tiller Density of Winter Wheat

Conclusions

This project demonstrated that soil moisture content at the time of seeding of winter wheat in R−W cropping system influences its tiller density via clod size, seedling emergence depth, the number of tillers per plant and the seedling establishment ratio. The reduction in the seedling establishment ratio, together with that in the number of tillers per plant, resulted in significant reductions in tiller density. An increase in soil moisture contents was associated with a significant reduction in the seedling establishment ratio via clod size. Responses to soil moisture content extended the influence of clod size on the reproductive growth through the seedling establishment ratio. Path analysis of causal-relationships and analysis of hierarchical direct contributions were very useful in clarifying the effects of soil moisture contents on tiller density through these variables. The direct effect can represent the nature of relationship between a targeted component variable and a response variable with other component variables kept constant, analogous to an experiment under controlled conditions. Analysis of hierarchical direct contributions provided useful information for improving crop management, e.g., site-specific variable rate seeding and changing tillage intensity based on soil moisture conditions at seeding. Controlling clod size in the plowed layer, based on soil moisture content at seeding, was suggested to be a useful method of maintaining tiller density, as well as changing the amount of N basal dressing, depending on weather conditions during the tillering stage.

The research was conducted on paddy soil. Intrinsic soil properties, such as clay content and permeability, influence the causal-relationships of soil moisture content at seeding with the seedling establishment ratio via clod size and seedling emergence depth. Our observations may be valid when applied to paddy soils with similar intrinsic soil properties.
and Yamasue, Y. 2007. Analysis of the sources of variations of wheat yield in the field, and possibility of the variable rate management. Jpn. J. Crop Sci. 76: 189-197*.

Richard, G., Boizard, H. and Guérif, J. 1997. Soil compaction and fragmentation at seed bed preparation as a function of soil moisture and tyre inflation pressure in loess and chalky soil. In: Fotyma M (eds) Proceedings of the 14th ISTRO Conference. Poland, pp 563-566.

Samonte, S.O.P.B., Wilson, L.T. and McClung, A.M. 1998. Path analyses of yield and yield-related traits of fifteen diverse rice genotypes. Crop Sci. 38: 1130-1136.

Tapela, M., and Colvin, T.S. 2002. Quantifying seedbed condition using soil physical properties. Soil Till. Res. 64: 203-210.

Taya, S. 1993. Breeding of early maturing wheat varieties with higher grain yield in southwestern regions of Japan. Bull. Kyushu Natl. Agric. Exp. Sta. 27: 333-398.

Timsina, J. and Connor, D.J. 2001. Productivity and management of rice-wheat cropping systems: issue and challenges. Field Crops Res. 69: 93-132.

Yang, R.P.J., Noels, K.A. and Saumure, K.D. 2006. Multiple routes to cross-cultural adaptation for international students: Mapping the paths between self-construals, English language confidence, and adjustment. International Journal of Intercultural Relations 30: 487-506.

* In Japanese with English abstract.