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# Simultaneous Application of Controlled Availability Fertilizers to Seeding Furrows with Seeding Increases Grain Yield and Quality of No-Till Cultivated Common Wheat in Japan

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## Abstract

**In Japan, common wheat is cultivated in upland fields converted from paddy fields, where poor drainage and high precipitation cause delay of sowing, lodging at the jointing stage, difficulty in topdressing at the ripening stage, and low yield. No-till cultivation has been promoted to overcome these problems but the yield is still low due to the lack of proper fertilizer application protocols. In this study, we determined whether an additional application of two kinds of Sigmoid coated urea as controlled availability fertilizers (CAFs) to the standard fertilization protocol for tillage cultivation can increase the yield and lodging resistance in no-till cultivated common wheat. Also, additional fertilization was applied to the seeding furrow simultaneously with seeding using a V-furrow no-till direct sowing (VFDS) machine. No-till cultivated plants had more tillers than tillage cultivated ones and consequently higher number of panicles and yield, caused by increased fertilizer application. The point-injected CAFs to the seeding furrow, which eluted at the jointing and ripening stages greatly increased the grain yield and protein content, respectively, compared to broadcast topdressing of ammonium sulfate at each stage. The simultaneous sowing and fertilization of additional CAFs using VFDS method in multi-year tests in farmers' fields significantly**

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**increased the yield of no-till cultivated common wheat, and can be adopted by Japanese local farmers.**

## Keywords

**Controlled Availability Fertilizer, No-Till Cultivation, *Triticum aestivum*, V-Furrow No-Till Direct Sowing Method**

## 1. Introduction

In Japan, common wheat is cultivated as a diversification crop in upland fields converted from paddy fields (hereafter referred to as "converted upland fields") as a component of large-scale paddy-upland rotation farming. However, the yields (4.1 t·ha$^{-1}$ in 2012) [1] are relatively lower in converted upland fields in Japan compared with other major wheat producing countries. One of the reasons for such low yield is the high rainfall in November (late autumn), which coincides with the wheat sowing period and the subsequent germination is exposed to waterlogging, which is stressful to wheat [2]. Given that the crop is cultivated in converted paddy fields where drainage is poor, the soil moisture content remains high and the plowed paddy fields are too soft for sowing using the seeding machines [3]. This means that sowing cannot be performed at the appropriate timing and may possibly be delayed. Therefore, in some of the areas including Aichi prefecture in Japan, the no-till technique has been developed for wheat cultivation as a countermeasure to avoid the delay of sowing because sowing is not greatly affected by soil moisture levels under no tillage.

Conservation tillage including no-tillage has been developed originally in the sub-humid to semi-arid climates to conserve soil moisture and reduce soil erosion [4]. In addition, the no-tillage technique saves use of labor as well as fuel for machinery [5] [6] and thus, can be used as an alternative to a conventional tillage practice for wheat cultivation. Therefore, it is expected that this technique can be applied also for large-scale paddy field farming. However, no-tillage often adversely affects root development due to the higher soil mechanical impedance to root elongation, resulting in a shallow root system and yield reduction under unfavorable rainfall pattern which causes drought incidences [7]. Moreover, no-tillage increases the risk of competition between crop and weeds that are controlled with herbicides instead of tillage.

Fertilizer application method is one of the factors that can maximize the yield in no-till cultivated wheat. Band-application of ammonium sulfate (AS) in the fall or polymer-coated urea in the seed row at the time of direct seeding as a method of spring broadcasting N produced a comparable or even slightly greater yield compared with the conventional one and also reduced the operation cost [8] [9]. However, the positive and significant effect of the fertilization method for no-till wheat is environment dependent; e.g. spring broadcast AS is more effective than fall N application due to the greater risk of over-winter N loss in more humid regions [10]-[14].

In Japan, no-till cultivation is widely studied in wetland rice production. On the other hand, little research has been done in wheat production under no-till cultivation. Thus, the effective cultivation method still needs to be studied. Hamada *et al.* [3] studied no-till cultivation of wheat using the V-furrow direct seeding (VFDS) method. The VFDS machine is an attached implement to a tractor, with disk that can make seeding furrow where simultaneous seeding and fertilization can also be done [3]. In rice, by applying all the fertilizers as basal dressing, the VFDS method requires 30% less labor compared to the conventional transplanting method [15] and showed no decrease in grain yield and quality [16]. It is also known that wheat seeds can be sown approximately 10 days earlier under no tillage than under tillage cultivation. Owing to these advantages, no-till cultivation started to be used in some large-scale farms with VFDS machine in Aichi Prefecture. However, farmers observed lower yield in this type of wheat cultivation compared to the traditional tillage cultivation technique, and so this technique was not widely adopted by wheat farmers [17]. Therefore, it is important to develop an effective cultivation method such as fertilization that can increase the yield in no-till cultivated common wheat grown under converted paddy fields.

In Aichi Prefecture, Japan, common wheat sown in November grows slowly in the following low-temperature months of December to February, and then growth becomes vigorous in March in conjunction with rising temperatures. Conventional fertilizer application in common wheat cultivation is done two to three times using quick acting fertilizers in these areas. First, fertilization is done as basal dressing. Then, to ensure maximum tillering before the jointing stage, fertilizer is applied in late January during the tillering stage. Extra N fertilizer is also topdressed at the beginning of March, during the jointing stage. However, the jointing stage in March often suffered from excess-moisture damage, which may negatively affect wheat growth and reduce yield and grain quality. Thus, the second topdressing usually done in March is not done to common wheat cultivars that are susceptible to lodging such as Norin 61, one of the most popular cultivars, which is suited for making noodle flour. These fertilization protocols are commonly used for both tillage and no-till wheat cultivation in Japan. However, the application of the conventional fertilization method in no-till cultivation of common wheat in March and onwards also results in inferior growth and lower yields compared with tillage-cultivation, though the reasons remain unclear.

In addition to grain yield, grain protein content is another important factor for high quality milling and noodle production. If the desired protein content is not maintained, demand for wheat is expected to decline. N fertilization at late season by foliar application of a urea solution or topdressing to soil increases grain protein content [18]-[24], but has no effect on yield unless N is severely deficient. Also, since the late season for common wheat cultivation overlapped with rice transplanting season in Japan, late season N fertilization is difficult to employ. Therefore, broadcast application of controlled availability fertilizers (CAFs) to soil has been investigated for tillage cultivation and validated as labor-saving technique that reduces top dressing usage [25] [26] but increases grain protein in common wheat [27]. Although the usage of CAFs increased the quality of wheat grain throughout the production areas, the root growth is often inhibited by excess moisture in converted paddy fields, which limits the absorption of the broadcasted CAF and the resulting yield.

In this study, since the VFDS method can point-inject fertilizer in the rhizosphere, we hypothesized that N fertilizer applied to the seeding furrow through this method can be efficiently absorbed by roots even if the root growth is limited by either excess moisture by waterlogging or soil hardness caused by no-tillage in converted paddy fields. Furthermore, we also hypothesized that application of suitable CAFs during fall, which will be eluted and efficiently absorbed by roots at the proper stages can increase both the grain yield and protein content of common wheat. Therefore, we evaluated the effects of simultaneous sowing and additional application of CAFs to the seeding furrow using the VFDS method on the growth, yield and grain quality of no-till cultivated common wheat in converted paddy fields in Aichi Prefecture, Japan. We also evaluated the advantage of using an improved fertilization protocol for no-till cultivation of common wheat over the conventional cultivation in improving both grain yield and quality.

## 2. Materials and Methods

### 2.1. Experimental Design in Experiments 1 and 2

We conducted two experiments to determine the adequate fertilizer application method and compared the yield and growth of fertilized common wheat established through no-till or tillage-cultivation. The common wheat cv. Iwainodaichi, a winter wheat developed by the National Agricultural Research Center for Kyushu Okinawa regions in Japan [28], was used for both experiments. The trials were performed at the experimental field of Aichi Agricultural Research Center in Aichi, Japan (35˚16'N, 137˚07'E) for two years (2004 to 2006). Field soil type was aeric, typic epiaquults. The climate data during the conduct of the two experiments are summarized in **Table 1**. The data for daily mean temperature, precipitation and total radiation were obtained from Nagoya Meteorological Station, which is about 9.6 km from the experimental site. The size of the fields used for both the no-till and tillage cultivation experiments was 100 m in length × 10 m in width.

Experiment 1: Effect of additional fertilizer application to no-till cultivation of common wheat

The fields were prepared on November 4, 2004 by tilling a shallow layer of soil and compacting to level the surface. The wheat seeds were first disinfected with 0.5% (w/w) of thiram + benomyl (1:1) water-dispersible powder and then sown on November 4, 2004 using the VFDS machine. The VFDS machine has a disk attached to the tractor, which made seeding furrow (2 cm width, 5 cm depth and 20 cm distance between rows) as driven through the field [3]. The sowing rate was 8 $g/m^2$. To avoid waterlogging during sowing, open ditch drainage was dug to a depth of approximately 15 cm orthogonally to the rows. The 5 ditches were made at 25 m apart.

The pattern of fertilization and additional fertilizer application are shown in **Table 2**. Basal dressing was applied at the time of land grading using an inorganic fertilizer (BB230, JA-Aichi Economic Federation of Agri-

**Table 1.** Monthly means for mean air temperature, daily solar radiation and total precipitation at Aichi Agricultural Research Center during wheat cropping (October-June) from 2004-2005 and 2006-2007.

| | Mean temperature (˚C) | | Solar radiation ($MJ/m^2/d$) | | Precipitation (mm) | |
|---|---|---|---|---|---|---|
| | 2004-2005 | 2006-2007 | 2004-2005 | 2006-2007 | 2004-2005 | 2006-2007 |
| October | 18.3 | 19.5 | 10.7 | 12.8 | 490 | 89 |
| November | 14.1 | 13.2 | 10.1 | 9.4 | 95 | 59 |
| December | 8.6 | 7.6 | 8.6 | 7.7 | 102 | 111 |
| January | 4.6 | 6.1 | 10.0 | 9.6 | 11 | 37 |
| February | 4.8 | 7.7 | 11.7 | 13.1 | 68 | 62 |
| March | 7.8 | 9.0 | 14.4 | 15.5 | 132 | 87 |
| April | 15.0 | 14.0 | 18.9 | 18.3 | 57 | 30 |
| May | 18.3 | 19.0 | 20.4 | 20.6 | 112 | 128 |
| June | 24.0 | 23.1 | 17.4 | 19.1 | 58 | 210 |

**Table 2.** The pattern of fertilization and additional fertilizer application in Experiments 1 and 2. (a) Experiment 1; (b) Experiment 2.

(a)

| Fertilization pattern | Added fertilizer | Basal dressing | First topdressing | Second topdressing |
|---|---|---|---|---|
| Standard | 40 kg N of S30 in basal dressing | 60 kg N + 40 kg N (S30) | 40 kg N | 40 kg N |
| | 40 kg N of S30-40 in basal dressing | 60 kg N + 40 kg N (S30-40) | 40 kg N | 40 kg N |
| | 40 kg N of AS in 2nd top dressing | 60 kg N | 40 kg N | 40 kg N + 40 kg N (AS) |
| Single reduced topdressing | 40 kg N of S30 in basal dressing | 60 kg N + 40 kg N (S30) | 40 kg N | |
| | 40 kg N of S30-40 in basal dressing | 60 kg N + 40 kg N (S30-40) | 40 kg N | |
| Standard | | 60 kg N | 40 kg N | 40 kg N |

(b)

| Tillage | Added fertilizer | Basal dressing | First topdressing | Second topdressing | Third topdressing |
|---|---|---|---|---|---|
| No-tillage | 40 kg N of S30-40 in basal dressing | 60 kg N + 40 kg N (S30-40) | 20 kg N | 20 kg N | |
| | 20 kg N of AS twice in 2nd and 3rd top dressing | 60 kg N | 20 kg N | 20 kg N + 20 kg N (AS) | 20 kg N (AS) |
| Tillage | 20 kg N of AS twice in 2nd and 3rd top dressing | 60 kg N | 20 kg N | 20 kg N + 20 kg N (AS) | 20 kg N (AS) |

For additional fertilizer treatment, controlled availability fertilizers [S30 or mixed S30 and S40 (S30-40)] or ammonium sulfate (AS) were added to basal or topdressing. The amount of N fertilizer presented is in per ha basis.

cultural Cooperatives, Aichi, Japan) ($N:P_2O_5:K_2O$ = 12:13:10) at 60 kg N per ha. Topdressing was applied on February 4 and March 3, 2005, using another inorganic fertilizer (NK2, JA-Aichi Economic Federation of Agricultural Cooperatives, Aichi, Japan) ($N:K_2O$ = 16:16) at a rate of 40 kg N per ha, which is the standard fertilization rate for Iwainodaichi cultivation in Aichi Prefecture. In addition to the standard fertilization protocol with double topdressing, we tested a single reduced topdressing protocol with second topdressing skipped.

The CAFs used were a Sigmoid 30-day coated urea (S30), and a 1:1 mix of S30 and Sigmoid 40-day coated urea (S40) (S30-40). In addition to the above basal dressing and topdressing, two sets of CAFs (S30 and S30-40) were applied to the seeding furrow simultaneously with seeding at the rate of 40 kg N per ha. For comparison, AS at 40 kg N per ha was applied on March 3 together with the second topdressing.

To determine the elution pattern of S30 and S40 fertilizers, net bags containing each fertilizer were buried underground at a depth of 5 cm on October 25, 2004. At approximately 2-week intervals, the bags were dug up

(15 times in total) and washed by water. The remaining granules were used for the measurement of N concentration with the Kjeldahl method.

Experiment 2: Comparative investigation between no-till with improved fertilization protocol, and conventional tillage and fertilizer application.

The experiments were conducted from 2005 to 2006, using the wheat cultivar Iwainodaichi. The sowing protocol was the same as that in Experiment 1. In no-till cultivation, 60 kg N per ha of BB230 as basal dressing and 20 kg N NK2 per ha as topdressing were applied twice on February 3 and March 3. For CAFs treatment, 40 kg N per ha of cocktailed S30-40 was applied to the seeding furrow. For comparison, additional topdressing of AS at the rate of 20 kg N per ha was applied on March 3 and April 21. Under tillage cultivation, the amount of fertilizer was the same as in no-till cultivation but without S30-40, and the application dates for topdressing were February 3, March 9 and April 26. The total amount of applied N was 140 kg N per ha, which was similar to the conventional method used by local farmers. The pattern of fertilization and additional fertilizer application are shown in **Table 2**.

The dates of sowing, heading and maturation stage were October 25, April 15 and June 7 in no-till cultivation, and November 4, April 22, and June 11 in tillage cultivation treatments, respectively.

## 2.2. Field Trials of No-Till Cultivation with Improved Fertilizer Application Methods in Farmer's Wheat Fields

To examine the practicality of the simultaneous and additional application of CAFs to seeding furrow during seeding in no-till cultivation of common wheat, we conducted local field trials in two different common wheat production areas in Mikawa region in Aichi Prefecture for several years using two common wheat cultivars. The climate data in two areas in Mikawa region, namely Anjo and Toyokawa are presented in **Table 3**.

**Table 3.** Monthly means for mean air temperature and total precipitation at the farmers' fields in Anjo (a) and Toyokawa (b) during wheat cropping (October-June) from 2007-2008 to 2010-2011. (a) Anjo; (b) Toyokawa.

(a)

| | Mean temperature (˚C) | | Precipitation (mm) | |
|---|---|---|---|---|
| | 2009-2010 | 2010-2011 | 2009-2010 | 2010-2011 |
| October | 18.8 | 19.7 | 264 | 234 |
| November | 13.4 | 12.7 | 219 | 44 |
| December | 8.2 | 8.2 | 66 | 65 |
| January | 5.3 | 3.6 | 8 | 7 |
| February | 7.4 | 6.7 | 128 | 125 |
| March | 9.6 | 7.8 | 196 | 49 |
| April | 13.5 | 13.5 | 175 | 89 |
| May | 18.8 | 19.0 | 144 | 308 |
| June | 24.0 | 23.8 | 213 | 193 |

(b)

| | Mean temperature (˚C) | | | | Precipitation (mm) | | | |
|---|---|---|---|---|---|---|---|---|
| | 2007-2008 | 2008-2009 | 2009-2010 | 2010-2011 | 2007-2008 | 2008-2009 | 2009-2010 | 2010-2011 |
| October | 18.0 | 17.5 | 16.8 | 18.2 | 107 | 94 | 201 | 246 |
| November | 12.0 | 11.0 | 12.2 | 10.9 | 22 | 59 | 197 | 107 |
| December | 7.2 | 7.0 | 6.9 | 7.4 | 76 | 47 | 49 | 96 |
| January | 4.5 | 4.6 | 4.1 | 2.3 | 50 | 113 | 25 | 11 |
| February | 3.8 | 7.4 | 6.6 | 6.3 | 60 | 106 | 234 | 137 |
| March | 9.3 | 8.8 | 9.3 | 6.6 | 194 | 207 | 310 | 61 |
| April | 14.2 | 13.8 | 12.6 | 12.2 | 235 | 152 | 181 | 221 |
| May | 18.0 | 18.2 | 17.2 | 17.9 | 305 | 334 | 213 | 350 |
| June | 20.9 | 21.4 | 22.4 | 22.2 | 266 | 339 | 322 | 297 |

In Anjo (34˚94'N, 137˚01'E), local farm field trials of no-till cultivation in farm fields using cv. Iwainodaichi were conducted for two years. In the first year (2009-2010), the fertilization protocol for no-till cultivation involved simultaneous application of S30-40 to seeding furrow at sowing at the rate of 40 kg N per ha, basal fertilization of BB230 at the rate of 60 kg N per ha, and two additional topdressings of NK2 at the rate of 20 kg N per ha on January 29 and March 8. The fertilization protocol for tillage cultivation involved basal fertilization (60 kg N per ha) and two topdressings (32 kg N per ha) on January 25 and March 5, which is the standard procedure used by local farmers. The sowing date in no-till and tillage cultivations was October 29 and November 6, respectively.

In the second year (2010-2011), the fertilization protocol for no-till cultivation was the same as that in the first year but with additional topdressings on January 27 and March 3. The fertilization protocol for tillage cultivation involved basal dressing at a rate of 120 kg N per ha [72 kg N of quick acting fertilizer + 48 kg N of linear-type coated urea as a CAF (LP30) (Mugi Ace One-Touch, JA-Aichi Economic Federation of Agricultural Cooperatives, Aichi, Japan)] ($N:P_2O_5:K_2O$ = 20:12:14) and single topdressing (24 kg N per ha) on March 12. The sowing date in no-till and tillage cultivations was November 9 and November 11, respectively.

In Toyokawa (34˚87'N, 137˚45'E), an area where wheat yields are often low because of excess-moisture damages, the local farmer field cultivation trials using cv. Norin 61 were conducted for four years (2007-2011). The fertilization protocol for no-till cultivation involved simultaneous application of S30-40 to seeding furrow at sowing at the rate of 40 kg N per ha, basal fertilization of BB230 at the rate of 60 kg N per ha, and one additional topdressing of NK2 at the rate of 20 kg N per ha. However, in 2009-2010 cultivation period, basal application of BB230 was reduced to a rate of 30 kg N per ha. The fertilization protocol for tillage cultivation involved basal dressing at a rate of 80 kg N per ha ($NH_4$-N:LP30:S30, 1:1:1) using Mugi Ace One-Touch, which is the standard application rate for Norin 61 cultivation by local farmers. No additional topdressing was applied for tillage cultivation of Norin 61 because the soil in the experimental fields was already fertile and lodging was evident when topdressing was applied. The sowing days for both no-till and tillage cultivation were as follows: November 16 in 2007-2008; November 20 in 2008-2009; December 9 in 2009-2010 and November 9 in 2010-2011 cultivation periods.

### 2.3. Measurement

The traits measured were growth (*i.e*. plant length, stem number, leaf color, culm length, ear length and ear number), pearled wheat grain yield and quality (*i.e*. grain protein content, bulk density, and exterior appearance). Exterior appearance of grains was evaluated by visual inspection using a scale from 1 to 5 going up in 0.5 increments, where 1 was the highest grade and 5 was the lowest grade.

Leaf color was measured with a Minolta SPAD502 chlorophyll meter while the protein content of grain was measured using near-infrared spectrum photometer (HON6400, Nireco). The values are presented on a dry weight basis.

### 2.4. Statistical Analysis

The two-way analysis of variance (ANOVA) was done using cultivation methods and years as independent factors. Means were compared using Tukey's HSD at 1% level of significance.

## 3. Results and Discussion

### 3.1. Improved Fertilization Protocol for No-Till Cultivated Common Wheat in Paddy Fields

To develop an adequate fertilization protocol for no-till cultivation of common wheat in Japan, we determined the effect of additional application of two kinds of CAFs (S30 or S30-40) into the seeding furrow simultaneously with seeding or alternative additional topdressing using AS at the jointing stage on the yield and grain quality of common wheat compared to the standard fertilization protocol for Iwainodaichi (**Table 4**). Also, single reduced topdressing protocol was conducted instead of the regular fertilization.

To perform simultaneous sowing and fertilization, we selected Sigmoidal CAFs, S30 and S40, which had no negative effect on germination (data not shown). The release patterns showed that S30 reached its peak release rate in March, the jointing stage, and S40 began to show release in mid-March, with an elution peak in April

**Table 4.** Effect of additional N fertilizer on the yield and yield components of no-tilled common wheat.

| Fertilization pattern | Added fertilizer | Yield ($g/m^2$) | Protein content (%) | Bulk density (g/l) | Kernel weight per 1000 (g) | Culm length (cm) | Panicle length (cm) |
|---|---|---|---|---|---|---|---|
| Standard | 40 kg N of S30 as basal dressing | 573 b | 9.0 abc | 837 ab | 43.0 a | 91 a | 8.6 ab |
| Standard | 40 kg N of S30-40 in basal dressing | 539 b | 9.4 c | 843 b | 42.9 a | 91 a | 8.7 b |
| Standard | 40 kg N of AS in 2nd top dressing | 434 ab | 9.1 bc | 835 ab | 42.4 a | 88 a | 8.7 b |
| Single reduced topdressing | 40 kg N of S30 in basal dressing | 433 ab | 8.2 ab | 825 a | 41.8 a | 85 a | 8.1 a |
| Single reduced topdressing | 40 kg N of S30-40 in basal dressing | 401 ab | 8.6 abc | 831 ab | 41.0 a | 84 a | 8.2 ab |
| Standard | | 332 a | 8.1 a | 826 a | 42.2 a | 84 a | 8.3 ab |

The standard fertilization pattern was 60 kg N per ha of basal dressing and 40 kg N per ha of topdressing for two times (February and March). A single reduced topdressing pattern was 60 kg N per ha of basal dressing and single 40 kg N per ha of topdressing. Forty kg N per ha of controlled availability fertilizers (S30 or mixed S30 and S40) or ammonium sulfate (AS) was added to basal or second topdressings, respectively. Means followed by same letters are not significantly different by the Tukey's test at $P < 0.01$. The amount of N fertilizer presented is in per ha basis.

during the heading stage (**Figure 1**). This result indicates that S30 supplies fertilizer at the jointing stage, which is important for yield increase and that S40 plays a role in protein content increase and so are useful for additional fertilization during heading stage. The results also confirmed that S30 and S40 provide an effective release pattern for no-till wheat cultivation.

Compared to the standard fertilization (the bottom row in **Table 4**), the additional application of both CAFs to the seeding furrow significantly increased the yield (**Table 4**) without causing lodging. On average, a trend was observed that the S30-applied treatment had the highest yield, followed by the S30-40 treatment while the AS treatment had the lowest. When comparing the effect of S30 and AS, although the same amount of N was additionally applied using AS at the jointing stage based on the elution timing of S30 fertilizer, the simultaneous application of either S30 or S30-40 fertilizers to seeding furrow with seeding increased the yield at a greater extent than the topdressing of AS. This indicates that the applied S30 fertilizer to the seeding furrow might elute in a relatively limited part around the roots so that the concentration of available N in the rhizosphere was higher compared to when AS was topdressed to the soil. In addition, the point injection of N fertilizers using the VFDS method used in this study, may be effective to reduce weed density and biomass relative to when the fertilizers are broadcasted [29]. This can compensate for the disadvantage of no-tillage system, which generally causes greater expenditures for herbicides [30].

On average, a trend was observed that the S30-40-applied treatment had the highest protein content and bulk density of grain among fertilizer treatments (**Table 4**). The S30 and AS treatment had comparable protein content and bulk density of grain. Since the S40 fertilizer was eluted mainly at the heading and ripening stages (**Figure 1**), the result corresponds to the fact that the increased application of N fertilizers at the reproductive stage increases grain protein content [20] [21]. Turley *et al.* [31] suggested that foliar spray of a urea solution is more appropriate to increase N uptake during and after anthesis than direct application of granules to the soil. Although the foliar spraying of N fertilizers at the later stage was not done in this study, we suggest that the simultaneous application of S40 fertilizers to the seeding furrow is already enough and thus, an effective fertilization protocol for no-till cultivation of common wheat to increase grain protein content. Also, this protocol is more advantageous for farmers using rice-wheat double cropping in Japan compared with topdressing at ripening stage, because the wheat ripening time overlaps with seedling preparation time for rice cultivation so that the topdressing at this time could not be done by the farmers. Based on these results, applying the S30 fertilizer is appropriate to achieve high yield. However, in low grain protein varieties such as Iwainodaichi, S40, which raises protein content effectively, is more preferable. It may be concluded that cocktailed combination of S30 and S40 fertilizers should be used in the cultivation practice.

We also made an additional CAF application with the single reduced topdressing protocol (**Table 4**). The S30 and S30-40-applied treatments in the single reduced topdressing showed relatively higher yield compared to the standard fertilization (the bottom row in **Table 4**). These results also emphasized that the simultaneous application of the CAFs with seeding maybe effective for yield increase.

The weight per 1000 grains was comparable among fertilizer treatments. Also, there was no difference in

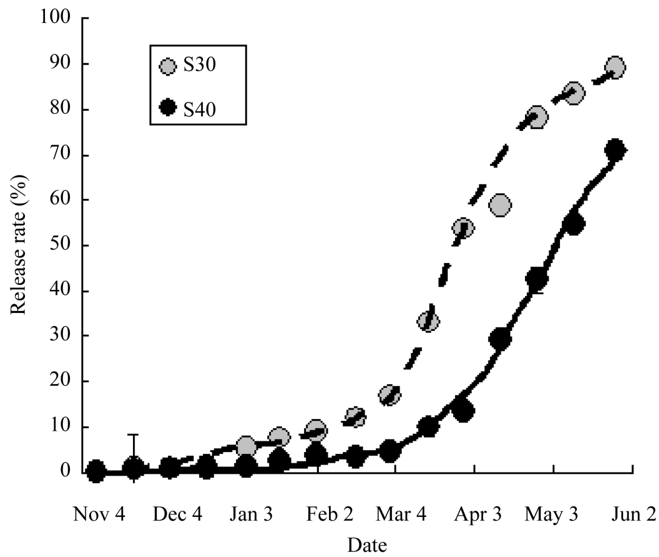


**Figure 1.** Release patterns of two kinds of Sigmoidal controlled availability fertilizers used in this study. S30, Sigmoid 30-day coated urea; S40, Sigmoid 40-day coated urea. To determine the elution pattern of S30 and S40 fertilizers, net bags containing those fertilizers were buried underground at a depth of 5 cm on October 25, 2004. At approximately 2-week intervals, the bags were dug up and washed by water. The remaining granules were used for the measurement of N concentration by the Kjeldahl method.

exterior appearance of grains between treatments, with all plants showing more than 75% of whole grain percentage (data not shown).

### 3.2. Comparison of Grain Yield between No-Till Cultivation Applied with CAFs Simultaneously to Seeding Furrow and Tillage Cultivation with AS Applied as Topdressing

Next, we determined whether the application of cocktailed S30-40 fertilizers (40 kg N per ha) simultaneously to seeding furrow in no-till common wheat cultivation produced greater yield and better grain quality than either the no-tillage or tillage cultivation with topdressing (**Table 5**). For comparison, the same amount of N fertilizers was applied to both tillage and no-tillage treatments as AS in March and April based on the elution pattern of S30 and S40, instead of simultaneous application to the seeding furrow (**Figure 1**). Yields were significantly higher in the no-tillage treatment supplied with S30-40 cocktails than in the tillage treatment with same amount of N fertilizer applied as topdressing (**Table 5**). The protein content, bulk density, weight per 1000 grains and grain exterior appearance in the S30-40 applied no-till treatment were comparable to those in the tillage treatment. The no-till treatment without CAFs did not show significant differences in all the parameters measured compared with the tillage treatment (**Table 5**).

The number of tillers per plant during tillering and the jointing stages was highest in the S30-40 no-till treatment, followed by no-till treatment without application of S30-40, though the difference was not significant, while the tillage treatment showed the lowest number of tillers (**Table 6**). On the other hand, the number of panicles per plant was highest in S30-40 applied no-till treatment while it was comparable between no-till treatment without S30-40 applied and tillage treatment (**Table 6**). These results indicate that no-till cultivation contributed to the increase in the number of tillers relative to the tillage one. However, the increase in the number of panicles (reproductive tiller) may be contributed by the simultaneous sowing and fertilizations with CAF. This is coincidental to the fact that the difference among wheat cultivars in the number of spikelets per plant is due to their differences in survival rate of emerged tillers but not to the rate of tiller emergence [32] [33].

The culm length of the longest tiller at the heading stage was greatest in no-tillage treatment supplied with S30-40, while the lowest was in tillage treatment. The panicle length and the SPAD value in the flag leaves at

**Table 5.** Effect of additional fertilizer on the yield and yield components of no-tilled common wheat.

| Tillage | Added fertilizer | Yield ($g/m^2$) | Protein content (%) | Bulk density (g/l) | Kernel weight per 1000 (g) | Exterior appearance |
|---|---|---|---|---|---|---|
| No-tillage | 40 kg N of S30-40 in basal dressing | 723 b | 9.4 a | 830 a | 41.5 a | 2.4 a |
| No-tillage | 20 kg N of AS twice in second and third topdressings | 537 a | 8.5 a | 825 a | 40.9 a | 2.3 a |
| Tillage | 20 kg N of AS twice in second and third topdressings | 589 a | 9.5 a | 831 a | 41.6 a | 2.5 a |

The standard fertilization pattern in Experiment 2 was 60 kg N per ha of basal dressing, 20 kg N per ha of topdressing for two times (February and March). Additional N fertilization applied was up to 140 kg per ha in total. In no-till cultivation, 40 kg N per ha of CAFs (cocktailed S30 and S40) was added to the seeding furrow simultaneously with the seeding. For comparison, 20 kg N per ha of ammonium sulfate (AS) was applied twice to second and third topdressings (March and April, respectively) in no-till and tillage cultivation. Means followed by same letters are not significantly different by the Tukey's test at $P < 0.01$. The amount of N fertilizer presented is in per ha basis.

**Table 6.** Effect of additional fertilization on the growth of no-tilled common wheat.

| Tillage | Added fertilizer | Tiller number | | Culm length (cm) | Panicle length (cm) | Panicle number | SPAD value of flag leaves |
|---|---|---|---|---|---|---|---|
| | | Tillering stage | Jointing stage | | | | |
| No-tillage | 40 kg N of S30-40 in basal dressing | 1165 b | 1145 b | 93 c | 9.5 ab | 763 b | 39.6 b |
| No-tillage | 20 kg N of AS twice in second and third topdressings | 1004 b | 1031 b | 88 b | 9.1 a | 565 a | 37.1 a |
| Tillage | 20 kg N of AS twice in second and third topdressings | 517 a | 819 a | 84 a | 10.0 b | 531 a | 40.4 b |

The standard fertilization pattern in Experiment 2 was 60 kg N per ha of basal dressing, 20 kg N per ha of topdressing for two times (February and March). Additional N fertilization was up to 140 kg per ha in total. In no-till cultivation, 40 kg N per ha of CAFs (cocktailed S30 and S40) was added to the seeding furrow simultaneously with seeding. For comparison, 20 kg N per ha of ammonium sulfate (AS) was applied twice to second and third topdressings (March and April, respectively) in no-till and tillage cultivation. Tiller number was measured on February 14 (tillering stage) and March 3 (jointing stage). Means followed by the same letters are not significantly different by Tukey's test at $P < 0.01$. The amount of N fertilizer presented is in per ha basis.

the heading stage were greatest for the tillage treatment, followed by no-till treatment with S30-40, and lowest in the no-till treatment without S30-40, indicating that these factors might not be related to the increment in yield by the application of CAFs in no-till cultivated common wheat (**Table 5**).

### 3.3. Yield Comparison between No-Till with Improved Fertilization Methods and Conventional Tillage Cultivation in Farmers' Fields

We investigated whether the improved fertilization protocol with simultaneous sowing and fertilization using CAFs for no-till cultivation of common wheat can improve the yield in local farms. We compared no-till cultivation with the improved fertilization protocol using CAFs and conventional tillage cultivation used by local farmers. **Table 7** shows the grain yield and quality of Iwainodaichi grown in no-till and tillage cultivation in farm fields in the central region of Aichi Prefecture (Anjo). Generally, the 2009-2010 season had lower yields owing to the observed excess moisture damage caused by heavy rain after sowing. The 2010-2011 season experienced better weather, and good crop growth conditions. In both years, yields were consistently higher in no-tillage treatment with improved fertilization method than in conventional tillage treatment (**Table 7**). Protein content, bulk density, and panicle length showed no significant differences between no-till and tillage cultivations. Although no-till cultivation treatment showed significantly higher weight per 1000 grains and culm length compared to the conventional tillage cultivation, a significant interaction between cultivation and years on these traits was observed.

Another comparison between no-till cultivation using the CAFs and conventional tillage cultivation was also conducted in local farmers' fields using another common wheat cultivar (Norin 61) in the eastern region of Aichi Prefecture (Toyokawa), where Iwainodaichi is not cultivated for 4 years. In this area, farmers do not practice topdressing of N fertilizer to avoid lodging since Norin 61 is more susceptible to waterlogging than Iwainodaichi [34] where its root growth is greatly inhibited [35]. Under no-till cultivation, additional application of CAF to seeding furrow was also used to reduce lodging in this study (data not shown). In all years, the grain yield for the no-till cultivation was greater than that for the tillage cultivation by at least 20% (**Table 8**). Bulk density was also greater for no-till cultivation than for tillage cultivation. Protein content was greater under no-till cultivation than under tillage cultivation in all years except in 2010-2011. Overall, local field trials in two different areas using two different common wheat cultivars consistently showed that no-till cultivation with the improved fertilization protocol increased grain yield and quality relative to the conventional cultivation techniques in converted paddy fields.

## 4. Conclusion

In Japan, no-till cultivation of common wheat in converted paddy fields has been introduced to improve the delay of sowing and lessen the incidence of lodging. However, the compacted soil causes the limited growth of the roots, and the yield is low when the conventional fertilization protocol for tillage cultivation is used. In this

**Table 7.** Yield and yield components of tillage- and no-till cultivated common wheat in local farms of Anjo.

| Experimental year | Treatment | Yield ($g/m^2$) | Protein content (%) | Bulk density (g/l) | Kernel weight per 1000 (g) | Culm length (cm) | Panicle length (cm) | Panicle number ($/m^2$) |
|---|---|---|---|---|---|---|---|---|
| 2009-2010 | No-tillage | 522 | 8.0 | 840 | 41.9 | 85 | 9.0 | 715 |
| | Tillage | 323 | 7.3 | 836 | 37.8 | 61 | 9.0 | 310 |
| 2010-2011 | No-tillage | 589 | 10.9 | 810 | 38.6 | 87 | 8.6 | 619 |
| | Tillage | 524 | 11.1 | 823 | 36.5 | 86 | 9.2 | 639 |
| Average | No-tillage | 556 | 10.9 | 825 | 40.3 | 86 | 8.8 | 667 |
| | Tillage | 423 | 9.2 | 830 | 37.2 | 74 | 9.1 | 475 |
| ANOVA | Treatment | * | ns | ns | ** | * | ns | * |
| | Year | * | * | * | ** | * | ns | ** |
| | Interaction | ns | ns | ns | ** | * | ns | * |

The common wheat cv. Iwainodaichi was used in the field trials. We compared no-till cultivation with the improved fertilization protocol using CAFs and conventional tillage cultivation used by local farmers. * and ** indicate significant difference at $P < 0.05$, $P < 0.01$, respectively, and ns indicates not significant.

**Table 8.** Yield and yield components of tillage- and no-till cultivated common wheat in local farms of Toyokawa.

| Experimental year | Treatment | Yield ($g/m^2$) | Protein content (%) | Bulk density (g/l) | Exterior appearance |
|---|---|---|---|---|---|
| 2007-2008 | No-tillage | 602 | 9.7 | 820 | 2.8 |
| | Tillage | 486 | 8.3 | 809 | 2.5 |
| 2008-2009 | No-tillage | 489 | 8.5 | 826 | - |
| | Tillage | 323 | 7.9 | 798 | - |
| 2009-2010 | No-tillage | 376 | 8.4 | 831 | 2.8 |
| | Tillage | 311 | 7.3 | 823 | 3.3 |
| 2010-2011 | No-tillage | 423 | 10.7 | 832 | 3.5 |
| | Tillage | 345 | 11.2 | 821 | 5.0 |
| Average | No-tillage | 472 | 9.3 | 827 | 3.0 |
| | Tillage | 366 | 8.7 | 813 | 3.6 |
| ANOVA | Treatment | ** | * | ** | ** |
| | Year | ** | ** | * | ** |
| | Interaction | ns | * | ns | ** |

The common wheat cv. Norin 61 was used in the field trials. We compared no-till cultivation with the improved fertilization protocol using CAFs and conventional tillage cultivation used by local farmers. * and ** indicate significant difference at $P < 0.05$, $P < 0.01$, respectively, and ns indicates not significant.

study, we found that the application of cocktailed CAFs that elute at the jointing and heading stages of wheat plant to seeding furrow simultaneously with seeding through point-injection of N fertilizer increased the number of reproductive tillers, grain yield and protein content of common wheat grown in converted paddy fields, compared with the conventional tillage cultivation. If the simultaneous fertilization with seeding can be done using the VFDS method [3], this no-till cultivation system with improved fertilization protocol saves labor and has potential for wider acceptance by local wheat farmers. In addition, when common wheat plants suffer from waterlogging at the jointing stage, the root growth is greatly affected [34] and early leaf senescence is induced at the ripening stage [36], which decreases the yield and protein content of the grain. Therefore, the results also suggest that the improved fertilization protocol is effective for ameliorating yield losses due to waterlogging by compensating the decreased N uptake at the jointing stage. Selection of appropriate CAFs that elute during proper growth stages (jointing stage for yield increase and heading stage for increasing protein content for common wheat) is important and that the broadcast application of the CAFs does not affect the yield of common wheat in converted paddy fields.

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