High-Yielding Intensive Production System in Early-Sown Winter Wheat

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It is important to increase the yield of wheat (Triticum aestivum L.) in Japan. To develop a high-yielding wheat production system in the warm Tokai region, we analyzed the effects of rolling, the plant growth regulator ethephon, and the foliar fungicide metconazole under a high nitrogen condition on the agronomic characteristics and grain quality of early-sown ‘Satonosora’ winter wheat in 2016–17 and 2017–18. Early sowing of winter wheat avoided both frost injury in early spring and preharvest sprouting in the rainy season. Rolling at the spikelet differentiation stage reduced lodging without shortening culm length, and ethephon at the start of heading reduced lodging by shortening culm length; rolling plus ethephon reduced lodging the most. Metconazole at both the third-leaf-below-flag-leaf and flag-leaf stages reduced foliar disease. The effect of rolling on yield varied with the year (probably with soil moisture condition). Ethephon and metconazole did not affect yield, probably because lodging and disease were mild. The combination of rolling, ethephon, and metconazole produced 750 g m\(^{-2}\) in 2016–17 and 676 g m\(^{-2}\) in 2017–18, and the grain satisfied most standard values for noodle quality. Large-plot experiments confirmed the high yield and quality. The results show that this system for the intensive production of early-sown winter wheat achieves high productivity and quality in the warm Tokai region of Japan.

Key words: ethephon, metconazole, rolling, wheat, yield

1. Introduction

The world’s population is projected to grow from 7.5 billion (10\(^9\)) in 2017 to 10 billion in 2050, so to feed the 800 million people currently suffering from hunger as well as the extra population, it is essential to increase the yields of cereals such as wheat in sustainable ways (FAO 2017). In Japan, it is necessary to increase the yield of wheat and improve its self-sufficiency rate above the current 15% (MAFF 2015). The yields in north–west Europe are higher than that in Japan: 794 g m\(^{-2}\) in the UK, 775 g m\(^{-2}\) in Germany, and 699 g m\(^{-2}\) in France versus 384 g m\(^{-2}\) in Japan (average of 2008–2017; FAO 2019). By region in Japan, yields are 442 g m\(^{-2}\) in the northern cool Hokkaido region, and 348 g m\(^{-2}\) in Kanto–Tosan, 319 g m\(^{-2}\) in Kyushu, and 303 g m\(^{-2}\) in Tokai, three southern warm regions (average of 2008–2017; NSTAC 2019). High yields are achieved in the UK by the use of semi-dwarf cultivars (Berry et al. 2015),
plant growth regulators (PGRs) to reduce lodging, and fungicides to control foliar diseases, under high rates of nitrogen (N) split between a low basal dressing and a large topdressing (AHDB 2005, 2009, 2016, 2018). In the Tokai region, on the other hand, wheat is grown without PGRs or foliar fungicides under low N rates to reduce labor. These facts suggest the possibility of increasing yields in Japan by adopting intensive management practices.

To do so, we need to solve the problems caused by high N use: increased lodging (Eguchi 1983) and decreased yield through reduced photoassimilate supply (Fischer and Stapper 1987). Lodging resistance is related to bending moment (shoot leverage), which is associated with culm length, stem strength (the strength of the stem base), and anchorage strength (the strength of the root/soil system) (Pinthus 1973; Berry et al. 2004). Ways to reduce lodging include growing semi-dwarf wheat, which decreases bending moment; reducing sowing rate, which increases stem and anchorage strengths; rolling, which increases anchorage strength; the PGR chlormequat (2-chloroethyl trimethylammonium chloride; GA-inhibitor), which shortens the lower internodes when applied at the start of internode elongation; and the PGR ethephon (2-chloroethyl phosphonic acid; ethylene-generator), which shortens the upper internodes when applied at the boot stage (Pinthus 1973; Berry et al. 2004). High N also increases infection by foliar diseases such as brown rust (Puccinia triticina), powdery mildew (Blumeria graminis), and leaf blotch (Zymoseptoria tritici) (Boquet and Johnson 1987; Leitch and Jenkins 1995), which reduce yield by inhibiting photosynthesis (by reducing green leaf area index) and reduce grain protein content by inhibiting the translocation of N from leaves to grains (Conner et al. 2003; Bancal et al. 2007). Since the upper three leaves contribute greatly to photosynthesis during ripening, fungicide sprays at both the third-leaf-below-flag-leaf and flag-leaf stages are effective (Royse et al. 1980; Paveley et al. 2000). Metconazole, a foliar fungicide, has broad-spectrum fungicidal activity (Kumazawa et al. 2000). In addition, high N split between a low basal dressing and a large topdressing delays maturity by lengthening ripening period (Matsuyama et al. 2016; Mochizuki et al. 2016; Watanabe et al. 2016).

In the warm Tokai region of Japan, conflicting late internode elongation and early maturation are both required to avoid frost injury to young spikes in early spring and to avoid preharvest sprouting in the rainy season, which begins around June 8 (Inamura et al. 1958; Yoshida et al. 1985; Derera 1990). Early sowing of spring wheat accelerates heading, flowering, and maturation, but accelerates internode elongation as well, which increases the risk of frost injury (Tanio et al. 2016). Early sowing of winter wheat, on the other hand, delays internode elongation owing to vernalization sensitivity and advances maturation owing to early heading and flowering (Fukushima et al. 2005; Kamada et al. 2013; Mochizuki et al. 2013; Tanio et al. 2016). These facts suggest that early sowing of winter wheat can avoid both frost injury and preharvest sprouting under a high N condition, even if the ripening period is long.

In this study, to develop a high-yielding wheat production system in the warm Tokai region, we investigated whether early sowing of winter wheat could avoid both frost injury and preharvest sprouting under a high N condition, and analyzed the effects of rolling, the PGR ethephon, and the foliar fungicide metconazole under a high N condition on the agronomic characteristics and grain quality of early-sown winter wheat in factorial experiments in 2016–17 and 2017–18. We refer to the production system that combines rolling, ethephon, and metconazole (REM) under a high N condition as the “intensive production system” (IPS). We assessed the performance of this system in large-plot experiments. The profitability of this system is discussed.

2. Materials and Methods

1) Factorial experiments

(1) Sowing method

Factorial experiments were carried out at Tsu (34°46′N, 136°26′E) in 2016–17 and 2017–18, using a randomized block design with 3 factors—rolling (R) × ethephon (E) × metconazole (M)—and 3 replicates (24 plots, each 2.1 m × 5.0 m) in a drained paddy field.
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Table 1  Calendar dates and target stages (times) of management actions in factorial experiments in 2016–17 and 2017–18.

| Calendar date of year | Target stage or time | Management | Note |
|-----------------------|----------------------|------------|------|
| 2016–17               |                      |            |      |
| Nov. 7                | Nov. 6               | Seeding    | 205 seeds m⁻² |
| do.                   | do.                  | Nitrogen   | 2 g m⁻² |
| do.                   | do.                  | Prosulfocarb | 39 mg a.i. m⁻² |
| Dec. 19               | Dec. 14              | Nitrogen   | 6 g m⁻² |
| Feb. 8 (3)            | Jan. 30              | Spikelet differentiation | Rolling (R) | 6 kPa |
| Feb. 22               | Feb. 21              | Start of internode elongation | Nitrogen | 12 g m⁻² |
| Mar. 23               | Mar. 15              | 3rd leaf below flag-leaf | Metconazole (M) | 9 mg a.i. m⁻² |
| Apr. 5                | Apr. 2               | Flag-leaf  | Metconazole (M) | 9 mg a.i. m⁻² |
| Apr. 10               | Apr. 4               | Start of heading | Ethephon (E) | 30 mg a.i. m⁻² |
| Apr. 25               | Apr. 20              | Half flowering | Kresoxim-methy | 22 mg a.i. m⁻² |
| Apr. 28               | Apr. 23              | Full flowering | Kresoxim-methy | 22 mg a.i. m⁻² |
| Jun. 5 (9)            | Jun. 1 (4)           | Harvest maturity | Harvest | Grain moisture ≤28% |

1) Date in large-plot experiment is shown in parentheses when it differs from that in factorial experiment.
2) The 3 factors are underlined.

Table 2  Soil properties of fields before and after cultivation in 2016–17 and 2017–18.

| Year      | Soil taxonomy (texture) | Sampling date | pH (H₂O) | Total N (% | Nitrate N (mg N kg⁻¹) | Ammonium N (mg N kg⁻¹) | Available N (mg N kg⁻¹) | Available P (mg P₂O₅ kg⁻¹) | Exchangeable K (mg K₂O kg⁻¹) |
|-----------|------------------------|---------------|----------|------------|-----------------------|------------------------|------------------------|-------------------------|----------------------------|
| 2016–17   | Ultisol (light clay)   | 2016 Oct. 13  | 6.10     | 0.17       | 0.7                   | 12.6                   | 48.5                   | 193                     | 253                       |
| 2017–18   | Ultisol (light clay)   | 2017 Oct. 31  | 6.36     | 0.20       | 1.7                   | 13.1                   | 45.7                   | 240                     | 352                       |

Soil analysis was done with a sample of equal composites of 5 spots (15 cm depth).

1) Hot-water extraction method (HRO 2012).
2) Truog method (HRO 2012).
3) Schollenberger method (HRO 2012).

(ca. 3000 m²) after rice harvest in each year (Table 1). The two fields had similar soil properties (Table 2). Before sowing, the fields were prepared by flail mower, ditcher, subsoiler, herbicide, and rotary tiller. We grew the semi-dwarf ‘Satonosora’ winter wheat, which is used for noodles, has a winter growth habit of Class IV (Kakizaki and Suzuki 1937), and has strong resistance to brown rust and powdery mildew, but its resistance to leaf blotch is unknown (Takahashi et al. 2010; Osawa et al. 2012). In the Tokai region it was planted to 2250 ha in 2016–17 and 2033 ha in 2017–18. Seeds were sown in early November at 205 m⁻² in rows 0.24 m apart at a depth of about 2 cm with a shallow-tillage drill seeder (tractor MZ655-PC, Kubota Co., Osaka, Japan; rotary tiller SXR2010, Matsuyama Plow Mfg. Co., Ltd., Ueda, Japan; side disk NSD401-LXR10, Matsuyama Plow Mfg. Co.; attachment Assy-SXR10, Jonishi Co., Ltd., Koka, Japan; seeder and fertilizer applicator RXGS-820R, Agritecno Yazaki Co., Ltd., Himeji, Japan; Watanabe et al. 2009). The herbicide prosulfocarb (Boxer, Syngenta Japan K. K., Tokyo, Japan) was applied with a built-in power sprayer (MS90DC, Maruyama Mfg. Co., Inc., Tokyo, Japan) at the same time. The
Daily mean temperature and daily precipitation were recorded at the Institute of Vegetable and Floriculture Science, 0.5 km away, and the average daily mean temperature for the last 30 years was supplied by the Japan Meteorological Agency, Tsu (Fig. 1).

(2) Fertilizer application

A basal dressing of compound NPK fertilizer (2.0 g m\(^{-2}\) of each of N, P\(_2\)O\(_5\)-equivalent, and K\(_2\)O-equivalent) was supplied with the drill seeder at sowing. A topdressing of N (ammonium sulfate) in 2016–17 and compound NPK fertilizer in 2017–18 (6.0 g m\(^{-2}\) of each of N, P\(_2\)O\(_5\)-equivalent, and K\(_2\)O-equivalent) was applied by hand at the 3-leaf stage. Later, N (ammonium sulfate) in 2016–17 and compound NK fertilizer in 2017–18 (12 g m\(^{-2}\) of each of N and K\(_2\)O-equivalent) was applied by hand at the start of internode elongation. Total N, P\(_2\)O\(_5\)-equivalent, and K\(_2\)O-equivalent were 20, 2, and 2 g m\(^{-2}\), respectively, in 2016–17; and 20, 8, and 20 g m\(^{-2}\), respectively, in 2017–18 (saved on PK in 2016–17 and almost equal to total nutrient uptake in 2017–18). The start of internode elongation was taken to be when the pseudostem length was 10 cm (Tanio et al. 2012, 2016), which was confirmed by carefully stripping the folded leaves, in plants from a REM plot. Metconazole (Workup Flowable, Hokko Chemical Industry Co., Ltd., Tokyo, Japan) was sprayed at both the third-leaf-below-flag-leaf and flag-leaf stages. The former stage was taken to be when the pseudostem length was 10 cm (Tanio et al. 2012, 2016), which was confirmed by carefully stripping the folded leaves, in plants from a REM plot. Ethephon (Ethrel 10, ISK Biosciences K. K., Tokyo, Japan) was sprayed at the start of heading. Metconazole and ethephon were sprayed from a hand-held sprayer (BH-595P, Panasonic Co., Osaka, Japan). To treat ear diseases such as *Fusarium*, kresoxim-methyl (Strobi Flowable, Nissan Chemical Co., Tokyo, Japan) was sprayed on all plots (as a non-factor) at both half and full flowering stages from a power sprayer (MS415R4CF, Maruyama Mfg. Co.). Water solutions of these agrochemicals (including prosulfocarb herbicide) were sprayed at 100 mL m\(^{-2}\) (rates of active ingredients are shown in Table 1).

(4) Evaluation of agronomic characteristics and grain quality

The date when 50% of spikes headed or flowered was recorded as the heading or flowering date. Dates of physiological and harvest maturity (40% and 28% moisture, respectively) were determined according to Takahashi (2002); the latter date was confirmed with a moisture meter (SB-5, Shizuoka Seiki Co., Ltd., Shizuoka, Japan). Foliar disease symptoms on the upper 3 leaves at the milky-ripe stage were
scored on a scale from 0 (nil) to 5 (severe). Lodging was scored on a scale of 0 (all plants upright) to 5 (all plants horizontal). At the harvest maturity stage, 20 plants per plot were dug out, and their culm length (from crown to base of spike), the length of each internode, and spike length of the longest shoot were measured and averaged. At the same time, the undisturbed central part of each plot (2.1 m × 1.0 m) was harvested by hand, and yield, spike number m⁻², grain number per spike, and 1000-grain weight were calculated. Grain appearance based on the fullness and glossiness of harvested grains was scored by eye on a scale from 1 (very good) to 9 (very bad). Grain quality (Brauer volume weight, grain protein content by Kjeldahl method, grain ash content, and Hagberg falling number) of 8 samples each of equal composites of 3 replicates, were analyzed according to MAFF (2001) by the Japan Grain Inspection Association, Kobe.

(5) Statistical analysis

Statistics were analyzed in Excel 2016 software (Microsoft Co., Redmond, WA, USA) using a factorial ANOVA to test the effects of each factor on agronomic characteristics, and a factorial ANOVA without replications to analyze their main effects on grain quality.

2) Large-plot experiments

We also carried out large-plot experiments of the intensive production system in both years, using plots of 1639 m² in 2016–17 and 1727 m² in 2017–18 in the same fields as the factorial experiments. The procedures were almost the same as in the factorial experiments (Table 1), with the exceptions that topdressing was applied with a knapsack fertilizer applicator (MDJ41G-23, Maruyama Mfg. Co.), rolling was carried out with a small tractor (TA7, Kubota Co.; 94 kg) fitted with iron rollers (SS450F, Jonishi Co.; two at 45 cm diameter × 48 cm wide, total 20 kg), ethephon and metconazole were sprayed from a power sprayer (MS415R4CF, Maruyama Mfg. Co.), grain was harvested by a combine harvester (ER467, Kubota Co.), and grain appearance and quality were averages of two samples.

3) Standard production system

We examined the agronomic characteristics of wheat grown in the “standard production system” (SPS), in two fields (of another experiment) that were adjacent to the factorial experiment field in each year. The soil properties of those fields were similar to those in the factorial experiments (data not shown). The procedures were almost the same as in the factorial experiments, with the following exceptions: The experiments used a completely randomized design with 13 replicates in 2016–17 and 8 in 2017–18 (plot size, ca. 100 m²; harvest size, 2.1 m × 1.5 m). Seeds were sown in mid-November. A basal dressing of compound NPK fertilizer (7.0 g m⁻² of each of N, P₂O₅-equivalent, and K₂O-equivalent) was supplied at sowing. A topdressing of N (ammonium sulfate) was applied at 3.0 g m⁻² at each of the first-node-detectable and flag-leaf-visible stages. Total N, P₂O₅-equivalent, and K₂O-equivalent were 13, 7, and 7 g m⁻², respectively, in both years. Rolling, ethephon, and metconazole were not used.

3. Results

1) Factorial experiments

(1) Development

Rolling and metconazole did not affect dates of heading, flowering, or physiological or harvest maturity. Ethephon delayed heading, flowering, and physiological and harvest maturity by 1 day in 2016–17, and delayed heading by 1 day but did not affect dates of flowering, or physiological or harvest maturity in 2017–18. The start of internode elongation was 12 to 13 days earlier in IPS (REM treatments) than in SPS (Table 3); however, that in IPS (February 25) was much later than the coldest time (around February 1) in the cropping season (Fig. 1). There was no frost injury to spikes in either year. Heading and flowering dates were significantly earlier in IPS than in SPS (Table 3); however, that in IPS (February 25) was much later than the coldest time (around February 1) in the cropping season (Fig. 1). There was no frost injury to spikes in either year. Heading and flowering dates were significantly earlier in IPS than in SPS; consequently, although the ripening period was significantly longer in IPS than in SPS, there was no significant difference in dates of physiological or harvest maturity between the two systems (Table 3). There was no preharvest sprouting in either year.

(2) Lodging and foliar disease

Rolling significantly reduced lodging but scarcely affected culm length in both years: in 2016–17
it shortened culm length by only 1.2 cm (slight shortening of internode 3), and in 2017–18 it had no overall effect (slight lengthening of internode 1 and slight shortening of internodes 5 and 6) (Figs. 2, 3A; Table 4). These results indicate that rolling reduced lodging in a different manner from ethephon. Ethephon significantly reduced lodging and significantly shortened culm length (by 8.8 cm in 2016–17; 9.8 cm in 2017–18; clear shortening of the upper two internodes) in both years (Figs. 2, 3A; Table 4). Ethephon had a stronger effect than rolling on reducing lodging (Table 4). These results indicate that ethephon reduced lodging by shortening culm length. Rolling and ethephon had an additive effect on reducing lodging in 2016–17 but not in 2017–18; however, rolling plus ethephon gave the lowest lodging score in both years (Fig. 3A; Table 4). There were no obvious foliar diseases in 2016–17. On the other hand, leaf blotch occurred in 2017–18 and metconazole decreased the foliar disease score from 2.4 to 1.3 (Fig. 3B; Table 4).
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Fig. 3 Means of lodging score, foliar disease (leaf blotch) score, and grain appearance score in factorial experiments in 2016–17 and 2017–18. There was no obvious foliar disease during 2016–17. Leaf blotch was observed during 2017–18. “–”, R, E, and M indicate no treatment, rolling, ethephon, and metconazol, respectively. Bar indicates standard error (n = 3).

Table 4 Factorial ANOVA (F-values) of culm length, internode length, lodging score, and foliar disease score in 2016–17 and 2017–18.

| Year     | Factor | Culm length | Length of internode | Lodging score | Foliar disease score |
|----------|--------|-------------|---------------------|---------------|----------------------|
|          |        | 1 2 3 4 5 6 |                     |               |                      |
| 2016–17  | R      | 10.1**     | 4.1 ns 2.2 ns 20.8** | 0.2 ns 0.9 ns | 8.5– –              |
| 2016–17  | E      | 521.6**    | 451.6** 42.7** 0.0 ns | 3.3 ns 4.1 ns | 87.9**–  –         |
| 2016–17  | M      | 3.2 ns     | 0.5 ns 0.6 ns 0.6 ns | 0.8 ns 0.8 ns | 0.1 ns  –           |
| 2016–17  | R × E  | 0.1 ns     | 1.4 ns 0.7 ns 0.1 ns | 2.4 ns 0.9 ns | 0.9 ns  –           |
| 2016–17  | R × M  | 0.4 ns     | 2.6 ns 0.4 ns 0.3 ns | 1.4 ns 10.1** | 0.1 ns  –           |
| 2016–17  | E × M  | 0.1 ns     | 0.2 ns 0.2 ns 0.7 ns | 0.0 ns 0.6 ns | 0.9 ns  –           |
| 2016–17  | R × E × M | 0.5 ns 0.8 ns | 1.1 ns 0.2 ns 0.0 ns | 0.6 ns 0.4 ns | 0.1 ns  –           |
| 2017–18  | R      | 0.4 ns     | 13.1** 2.3 ns 0.4 ns | 2.8 ns 12.0** | 4.7– 16.2** 0.2 ns |
| 2017–18  | E      | 209.9**    | 222.2** 277.9** 4.9** | 0.4 ns 2.9 ns | 71.0** 4.5 ns      |
| 2017–18  | M      | 0.6 ns     | 0.3 ns 0.0 ns 0.1 ns | 0.0 ns 0.0 ns | 1.7 ns 30.3**– 1.6 ns |
| 2017–18  | R × E  | 3.1 ns     | 0.4 ns 0.9 ns 0.6 ns | 1.5 ns 0.9 ns | 0.1 ns 13.0** 1.6 ns |
| 2017–18  | R × M  | 0.8 ns     | 0.0 ns 2.2 ns 1.0 ns | 0.5 ns 1.0 ns | 0.0 ns 0.8 ns 0.2 ns |
| 2017–18  | E × M  | 0.0 ns     | 0.0 ns 0.4 ns 0.8 ns | 0.7 ns 0.1 ns | 0.3 ns 0.2 ns 0.2 ns |
| 2017–18  | R × E × M | 0.2 ns 3.3 ns | 0.4 ns 0.0 ns 2.1 ns | 3.8 ns 0.0 ns | 0.5 ns 0.2 ns      |

1) R, rolling; E, ethephon; M, metconazole. ns, not significant; *P < 0.05, **P < 0.01; + positive, – negative.

(3) Yield and quality
The effect of rolling on yield depended on year: in 2016–17 it significantly decreased yield by 61 g m⁻² through the reduction of spike number m⁻², whereas in 2017–18 it significantly increased yield by 17 g m⁻² (Fig. 4; Table 5). Ethephon and metconazole did not affect yield or its components in either year. The yield in IPS was 750 g m⁻² in 2016–17 and 676 g m⁻² in 2017–18 (Table 3). On the other hand, the yield in SPS was 363 g m⁻² in 2016–17 and 425 g m⁻² in 2017–18. These results indicate that IPS yielded significantly more than SPS, by 387 g m⁻² in 2016–17 and by 251 g m⁻² in 2017–18. Rolling and metconazole did not affect grain quality (Figs. 3C, 5; Table 5). Ethephon significantly improved grain appearance score by 1.0 in both years and significantly increased Brauer volume weight by 7 g in 2016–17. Grain quality (except for Brauer volume weight) of IPS satisfied the standard values for noodle quality (Fig. 5).
Fig. 4 Means of yield and its components in factorial experiments in 2016–17 and 2017–18. "–", R, E, and M indicate no treatment, rolling, ethephon, and metconazole, respectively. Yield and 1000-grain weight are shown on a 12.5% moisture basis. Bar indicates standard error ($n = 3$).

Table 5 Factorial ANOVA ($F$-values) of yield, its components, grain appearance score, and grain quality in 2016–17 and 2017–18.

| Year   | Factor 1) | Yield | Spike number | Grain number per spike | 1000-grain weight | Grain appearance score | Brauer volume weight | Grain protein content | Grain ash content | Hagberg falling number |
|--------|-----------|-------|--------------|------------------------|-------------------|------------------------|----------------------|----------------------|----------------------|------------------------|
| 2016–17| R         | 8.4*  | 5.2**        | 0.7 ns                 | 1.5 ns            | 0.6 ns                 | 1.3 ns               | 3.5 ns               | 0.2 ns               | 0.1 ns                 |
|        | E         | 0.1 ns| 1.5 ns       | 1.7 ns                 | 1.0 ns            | 22.4**                | 22.7**               | 0.0 ns               | 0.4 ns               | 7.5 ns                 |
|        | M         | 0.3 ns| 0.6 ns       | 0.2 ns                 | 0.2 ns            | 2.5 ns                 | 0.0 ns               | 0.4 ns               | 7.5 ns               | 0.3 ns                 |
|        | R × E     | 0.6 ns| 4.1 ns       | 6.1*                   | 0.1 ns            | 0.0 ns                 | –                    | –                    | –                    | –                      |
|        | R × M     | 0.6 ns| 4.2 ns       | 5.3*                   | 0.0 ns            | 0.0 ns                 | –                    | –                    | –                    | –                      |
|        | E × M     | 0.0 ns| 1.0 ns       | 3.4 ns                 | 0.6 ns            | 5.6*                  | –                    | –                    | –                    | –                      |
|        | R × E × M | 0.2 ns| 1.5 ns       | 2.2 ns                 | 0.1 ns            | 0.6 ns                 | –                    | –                    | –                    | –                      |
|        | R         | 5.0** | 1.1 ns       | 0.7 ns                 | 1.2 ns            | 4.0 ns                 | 0.4 ns               | 0.3 ns               | 0.3 ns               | 0.2 ns                 |
|        | E         | 0.0 ns| 2.1 ns       | 4.0 ns                 | 0.3 ns            | 36.0**                | 5.8 ns               | 0.9 ns               | 0.3 ns               | 1.4 ns                 |
|        | M         | 1.3 ns| 0.6 ns       | 0.9 ns                 | 1.3 ns            | 1.0 ns                 | 0.0 ns               | 0.9 ns               | 0.3 ns               | 0.1 ns                 |
| 2017–18| R × E     | 0.9 ns| 0.4 ns       | 0.8 ns                 | 7.1*              | 1.0 ns                 | –                    | –                    | –                    | –                      |
|        | R × M     | 1.3 ns| 2.7 ns       | 0.5 ns                 | 0.2 ns            | 0.0 ns                 | –                    | –                    | –                    | –                      |
|        | E × M     | 1.0 ns| 0.5 ns       | 0.3 ns                 | 3.4 ns            | 0.0 ns                 | –                    | –                    | –                    | –                      |
|        | R × E × M | 0.4 ns| 0.3 ns       | 0.2 ns                 | 0.7 ns            | 1.0 ns                 | –                    | –                    | –                    | –                      |

1) R, rolling; E, ethephon; M, metconazole.
ns, not significant; *$P < 0.05$, **$P < 0.01$; + positive, – negative.
In the large-plot IPS experiments, there were no obvious foliar diseases and only slight lodging in a small area in both years. The dates of harvest maturity were almost the same as in the factorial experiments in both years. Combine-harvest yields were 698 g m$^{-2}$ in 2016–17 and 669 g m$^{-2}$ in 2017–18 (on a 12.5% moisture basis). Grain appearance scores were 4.0 in both years. Grain quality (except for Brauer volume weight) satisfied the standard values for noodle quality in both years (Fig. 5).

4. Discussion

In the Tokai region, it is necessary to avoid frost injury in early spring and preharvest sprouting in the rainy season. To reduce these risks requires conflicting developmental characteristics: late internode elongation but early maturation (Yoshida et al. 1985). However, high N split between a low basal dressing and a large topdressing lengthens the ripening period and therefore delays maturation, but increases preharvest sprouting risk (Matsuyama et al. 2016; Mochizuki et al. 2016; Watanabe et al. 2016). Our early-sown winter wheat showed late internode elongation due to vernalization sensitivity and early maturation due to early heading and flowering, even though the ripening period was long (Table 3). Therefore, the IPS of early-sown winter wheat avoided both frost injury and preharvest sprouting. On the other hand, as is well known, early-sown spring wheat shows early internode elongation, the timing of which differs among vernalization-insensitive genes, which increases frost injury risk (Tanio et al. 2016). Interestingly, it has been reported that rolling before the double-ridge formation stage, which marks the transition from vegetative to reproductive development (Bonnett 1936), delays double-ridge formation and subsequent internode elongation (Ohtani 1950; Nakatsukasa et al. 2002). These facts suggest that rolling of early-sown spring wheat before double-ridge formation could prevent both frost injury and
preharvest sprouting. Genetically, the earliness of internode elongation and of heading are controlled mainly by vernalization- and photoperiod-response genes, respectively; the stronger the vernalization sensitivity is, the later internode elongation occurs, and the stronger the photoperiod insensitivity is, the earlier heading occurs (Inamura et al. 1958; Yasuda and Shimoyama 1965). It has been shown that winter wheat with photoperiod-insensitive genes Ppd-B1a Ppd-D1a (the former having stronger insensitivity than the latter; Tanio and Kato 2007) showed similarly late internode elongation as but much earlier heading than winter wheat with only Ppd-D1a, as in ‘Satonosora’ (Fujita et al. 1995; Seki et al. 2011). These facts suggest that extremely early-heading winter wheat could be suitable for an IPS.

To increase lodging resistance, it is important to combine reducing sowing rate, rolling, and PGRs, taking account of their effects, varietal characters, and environmental conditions. Rolling at the spikelet differentiation stage did not reduce culm length but did reduce lodging (Figs. 2A, 3A; Table 4), in agreement with previous results (Nakatsukasa et al. 2002) and in support of the concept that rolling reduces lodging through greater anchorage strength (Tabata et al. 1938; Berry et al. 2004). However, rolling had a small effect on internode length (Figs. 2B, 2C; Table 4). In rice, light prevents internode elongation and shading promotes it (Takahashi and Wada 1972; Kamiji et al. 1993). Therefore, rolling might have affected canopy architecture and thus changed solar radiation conditions in the canopy, causing the small effect on internode length. Rolling decreased yield in 2016–17 but increased it in 2017–18 (Fig. 4A; Table 5). The soil conditions appeared to be relatively wet during rolling in 2016–17 but dry in 2017–18 (Fig. 1). Therefore, rolling at wet soil condition in 2016–17 might have injured roots (Ohtani 1950). For the same reason, the difference in soil moisture on rolling dates in 2016–17 might be responsible for the difference in yield between the factorial experiment (February 8; 750 g m⁻²) and the large-plot experiment (February 3; 698 g m⁻²) (Table 1). These results suggest that rolling should be applied at dry soil condition at the spikelet differentiation stage. Ethephon at the start of heading strongly reduced lodging by shortening the upper internodes (Figs. 2, 3A; Table 4), in agreement with previous results (Duke and Rutger 1970; de Wilde 1971; Brown and Earley 1973; Crook and Ennos 1995). Ethephon shortened internodes 1, 2, and 3 by 4.8–5.2, 2.8–4.1, and

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**Table 6  Economic evaluation of intensive production system in 2016–17 and 2017–18.**

| Item                        | Year 2016–17 | Unit 1000 JPY ha⁻¹ | Note | Item                        | Year 2017–18 | Unit 1000 JPY ha⁻¹ | Note |
|-----------------------------|--------------|--------------------|------|-----------------------------|--------------|--------------------|------|
| Increment of income        | 599          | 387                | a=d(e+f) | Increment of cost         | 290          | 297                | g=h+i+j+k+d(m+n) |
| Yield of IPS 1)            | 7.50         | 6.76               | t ha⁻¹ | Yield of SPS 2)            | 3.63         | 4.25               | t ha⁻¹ |
| Yield increase             | 3.87         | 2.51               | t ha⁻¹ | Yield increase             | 16           | 16                 | t ha⁻¹ |
| Wheat price 3)             | 43           | 43                 | 1000 JPY t⁻¹ | Wheat price 4)            | 43           | 43                 | 1000 JPY t⁻¹ |
| Subsidy 5)                 | 112          | 112                | 1000 JPY t⁻¹ | Subsidy 5)                 | 112          | 112                | 1000 JPY t⁻¹ |
| Offset yield               | 1.06         | 1.69               | t ha⁻¹ | Offset yield               | 1.06         | 1.69               | t ha⁻¹ |
| Gain                       | 309          | 90                 | 1000 JPY ha⁻¹ | Gain                       | 309          | 90                 | 1000 JPY ha⁻¹ |

1) IPS, intensive production system.
2) SPS, standard production system.
3) Quality of grade 1A grain.
4) Cost of work for rolling, ethephon, and metconazole in large-plot experiment. The machinery depreciation costs are not included.

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| Item                        | Year 2016–17 | Unit 1000 JPY ha⁻¹ | Note | Item                        | Year 2017–18 | Unit 1000 JPY ha⁻¹ | Note |
|-----------------------------|--------------|--------------------|------|-----------------------------|--------------|--------------------|------|
| Increment of income        | 599          | 387                | a=d(e+f) | Increment of cost         | 290          | 297                | g=h+i+j+k+d(m+n) |
| Yield of IPS 1)            | 7.50         | 6.76               | t ha⁻¹ | Yield of SPS 2)            | 3.63         | 4.25               | t ha⁻¹ |
| Yield increase             | 3.87         | 2.51               | t ha⁻¹ | Yield increase             | 16           | 16                 | t ha⁻¹ |
| Wheat price 3)             | 43           | 43                 | 1000 JPY t⁻¹ | Wheat price 4)            | 43           | 43                 | 1000 JPY t⁻¹ |
| Subsidy 5)                 | 112          | 112                | 1000 JPY t⁻¹ | Subsidy 5)                 | 112          | 112                | 1000 JPY t⁻¹ |
| Offset yield               | 1.06         | 1.69               | t ha⁻¹ | Offset yield               | 1.06         | 1.69               | t ha⁻¹ |
| Gain                       | 309          | 90                 | 1000 JPY ha⁻¹ | Gain                       | 309          | 90                 | 1000 JPY ha⁻¹ |

1) IPS, intensive production system.
2) SPS, standard production system.
3) Quality of grade 1A grain.
4) Cost of work for rolling, ethephon, and metconazole in large-plot experiment. The machinery depreciation costs are not included.
0.4–0.5 cm, respectively (Figs. 2B, 2C; Table 4). The period between the late boot stage and the start of heading corresponds to the time when internodes 1 and 2, which are the longest and second-longest internodes, are elongating (Ichii 1978). These results indicate that ethephon prevents the elongation of the internodes that are elongating when it is applied. Therefore, ethephon should be applied between the late boot stage and the start of heading. Ethephon did not affect yield (Fig. 4A; Table 5). Whether it increases yield or not depends on the severity of lodging (Webster and Jackson 1993). In addition, the critical time when lodging affects yield the most is up to about 20 days after flowering (Fischer and Stapper 1987), whereas lodging began at around 20 days after flowering in our study (data not shown). This is a probable reason why ethephon did not increase yield in our study.

Profitability is important for wheat producers. This IPS made economic gains in both years, especially in 2016–17 (Table 6). Taking into account the average yield of the Tokai region (ca. 3 t ha\(^{-1}\); NSTAC 2019), the offset yield (<2 t ha\(^{-1}\), Table 6), and the yields of IPS in our results (>6.5 t ha\(^{-1}\), Fig. 5A), we expect this IPS to be cost-effective in the Tokai region. The yield was significantly lower in 2017–18 than in 2016–17 (\(t\)-test: \(P < 0.01\); Fig. 4A), probably because in 2017–18 the low temperatures between emergence and the start of internode elongation, which corresponds to the maximum tiller stage and the spikelet number determination stage, decreased biomass production and significantly reduced spike number m\(^{-2}\) and grain number per spike (\(t\)-test: \(P < 0.01\); Figs. 1B, 4B, 4C). It is important to determine how much NPK to apply according to soil and nutrient diagnoses, and to improve fertilizer use efficiency through split application (Sato 2000; Hawkesford 2014). Leaf blotch occurred in 2017–18 and was controlled effectively by metconazole (Fig. 3B; Table 4), but with no effect on yield or quality, probably because the infection was weak (Figs. 4, 5; Table 5). Brown rust and powdery mildew occurred in 2015–16 (preliminary experiment) but not in the main study. Epidemics of foliar diseases are associated closely with precipitation, temperature, and humidity (Gladders et al. 2001; Te Beest et al. 2008; El Jarroudi et al. 2014a), and future climate change (IPCC 2013) is projected to affect them (Juroszek and von Tiedemann 2013). These facts suggest that it is important to determine the need for foliar fungicide sprays by forecasting foliar disease occurrence (El Jarroudi et al. 2014b). Saving on fertilizers and fungicides will allow substantial economic gains in the IPS and support sustainable production.

Acknowledgements

We thank Katsuyuki Yamauchi, Hiroshi Saito, Sho Sawada, Hisakazu Mogi (Institute of Vegetable and Floriculture Science: NIVFS, NARO), Miki Arakaki (Central Region Agricultural Research Center: CARC, NARO), Takuya Kabuki (Nagoya University), Nobuhiro Sekiya, and many students (Mie University) for their technical assistance. Thanks are due to Tetsuya Ishikawa (Headquarters, NARO), Morio Matsuzaki, Hiromi Matsuyama, and Hiroko Sawada (CARC) for their research support. We express our sincere thanks to Satoshi Yoshinaga (CARC) for his helpful comments on this manuscript. We extend our gratitude to the Iwaki Farmer Group for allowing us to use their fields. We are deeply grateful to NIVFS and the Japan Meteorological Agency for the meteorological data, to the JA Tsuage for information about income and cost, and to the Tokai Regional Agricultural Administration Office for planted area data. We are greatly indebted to the Tokachi Nokyoren Agrochemical Institute for soil analyses, and to the Japan Grain Inspection Association for grain quality analyses. This study was supported by a Grant-in-Aid for Research 10201 and Pilot Project ‘high-yielding wheat’ from the Ministry of Agriculture, Forestry and Fisheries of Japan.

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摘要
日本において小麦の収量を高めることが重要である。そこで、東海地域における高収量の生産体系を開発するため、高窒素施肥条件において、麦栽み、植物調節剤エチュオン及び殺菌剤メトコナゾールが早播の秋播性小麦「さとのぞら」の農業特性及び原粒品質に及ぼす効果を2年（2017-2018年）解析した。秋播性小麦を早播することによって、早春の凍霜害と梅雨の穂発芽被害を回避できた。麦栽み（小穂分化期）は稲長にほとんど影響なく、エチュオン（出穂始期）は短稲化によって、倒伏を軽減し、麦栽みとエチュオンの組合せは倒伏軽減効果が最も高かった。メトコナゾール（葉芽マイナス2葉期と出穂期）は葉の病気を軽減した。麦栽みの収量への効果は試験年（土壤水分条件）によって異なった。エチュオンとメトコナゾールは、倒伏と病気の程度が小さかったため、収量に影響はなかった。麦栽み、エチュオン及びメトコナゾールを組合わせた生産体系は、高い収量を示し（2017年：750 gm⁻²、2018年：676 gm⁻²）、その原粒品質は趣味品質基準を満たした。また、高い収量と品質は大規模試験でも実証された。これらの結果から、東海地域において、早播の秋播性小麦における集約的生産体系は収量及び品質が高いと考えられた。

キーワード
エチュオン、小麦、収量、麦栽み、メトコナゾール