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(Citation)

Plant Production Science, 25(4):434-439

(Issue Date)

2022-10-20

(Resource Type)

journal article

(Version)

Version of Record

(Rights)

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<https://hdl.handle.net/20.500.14094/0100483382>



Ground rolling delays apical development and reduces frost injury in early-sown spring wheat

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ABSTRACT

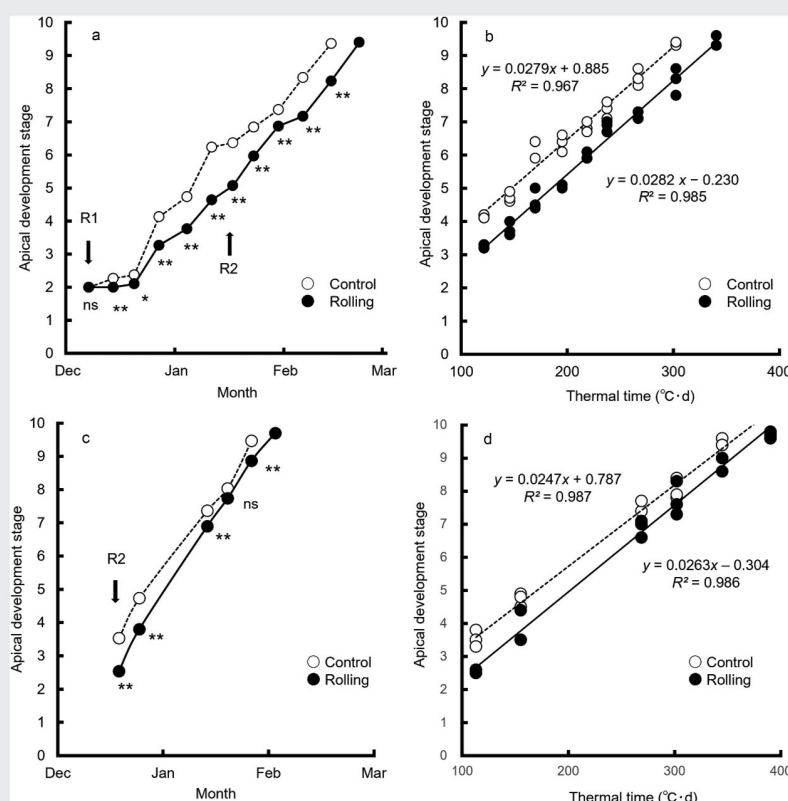
Frost injury is a concern in early-sown spring wheat (*Triticum aestivum*) in the Tokai region of Japan. To assess the efficacy of ground rolling as a technique for avoiding frost injury, we investigated its effects on the apical development and yield of ‘Ayahikari’ spring wheat. In both 2018–19 and 2019–20, rolling delayed spikelet initiation by 4–5 days, the start of internode elongation by 5–12 days, and jointing by 3–9 days, but did not affect the apical development rate, which depended on the thermal time. Ground rolling prevented frost injury in 2018–19 but not in 2019–20, probably because the warmer-than-average winter promoted earlier jointing, and so plants were exposed to later low temperatures in February. These results suggest that ground rolling is an effective method for avoiding frost injury in spring wheat during cold winters.

ARTICLE HISTORY

Received 2 June 2022
Revised 8 September 2022
Accepted 10 October 2022

KEYWORDS

Early sowing; frost injury; rolling; spikelet initiation; spring wheat



Introduction

Spring wheat cultivars are widely grown in the Tokai region (Gifu, Aichi, and Mie Prefectures) of Japan. In

2018–19, the area planted to spring wheat cultivars, such as ‘Ayahikari’ and ‘Kinuakari’, was ca. 12 000 ha, whereas that planted to winter wheat cultivars, such as

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Supplemental data for this article can be accessed online at <https://doi.org/10.1080/1343943X.2022.2136097>

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'Satonosora' and 'Iwainodaichi', was ca. 3000 ha. The optimum sowing time of spring wheat cultivars is narrower than that of winter wheat cultivars (Tanio et al., 2016), so as farmers have expanded their plantings, it has become more difficult to sow spring wheat cultivars within the optimum time. Late sowing decreases yield through lower biomass production and increases the risk of pre-harvest sprouting in the rainy season. Early sowing, on the other hand, increases the risk of frost injury in early spring because it advances internode elongation, which starts at the floret differentiation stage, owing to the low vernalization requirement of spring wheat cultivars (Inamura et al., 1958; Tanio et al., 2016). Frost injuries such as frozen, deformed, or sterilized spikes reduce grain yield and quality (Ohtani, 1942; Takeda, 1976; Uchijima, 1978a, b). Therefore, farmers must delay spikelet initiation (the transition from vegetative to reproductive phase) in early-sown spring wheat cultivars.

Takeda (1976) reported that when spikes grow to ≥ 3 mm, they become susceptible to frost damage, and the temperature at which the damage occurs depends on the developmental stage of spikes: spikes with a length of about 3 mm froze to death at a minimum temperature of $\leq -2^{\circ}\text{C}$, and spikes with a length of 20–30 mm froze to death at a minimum temperature of $\leq 0^{\circ}\text{C}$; in addition, spikes 8–10 days before heading became sterile when exposed to temperatures below -1°C for several hours (Takeda, 1976). Inamura et al.

(1958) showed that early internode elongation caused the early emergence of young spikes above ground, exposing them to freezing temperatures.

The practice of pressing down on young wheat plants by ground rolling or trampling has been used in Japan for a long time, but the effect of trampling on yield has not yet been established (Ohtani, 1950). On the other hand, rolling at the seedling stage can delay spikelet initiation, apical development, and internode elongation (Ohtani, 1950), although the mechanisms responsible are not well understood. It would be expected, therefore, that ground rolling at the seedling stage could be used to avoid frost injury in early-sown cultivation of spring wheat.

Here, to test the possibility of avoiding frost injury by ground rolling, we sowed wheat early in 2018–19 and 2019–20 to determine the effects of rolling on the timing of spikelet initiation and on yield.

Materials and methods

Plant materials and cultivation methods

After rice harvest, we sowed 'Ayahikari' spring wheat (winter growth habit Class I–II) on 2 November 2018 and 1 November 2019 (2 weeks earlier than standard) in a drained paddy field at Tsu ($34^{\circ}46'\text{N}$, $136^{\circ}26'\text{E}$, different plots about 200 m apart between years). With a shallow-tillage drill-seeder, seeds were sown in nine



Figure 1. Rolling in the experimental field (7 December 2018).

Table 1. Calendar dates of sowing, rolling, and ethephon spraying.

Sowing year	Sowing date	First rolling date	Second rolling date	Ethephon spraying date
2018	2 Nov	7 Dec (3-leaf stage)	15 Jan (5-leaf stage)	2 Apr
2019	1 Nov	21 Nov (2-leaf stage)	4 Dec (3-leaf stage)	13 Mar

broad beds (2.1 m × 85 m) at ~180 seeds m⁻² in rows 0.24 m apart at a depth of about 2 cm (Watanabe et al., 2009). Plants were grown according to the intensive production system of Tanio et al. (2019). One bed each was used for the rolling and control treatments (Figure 1). The rolling beds were rolled twice – at the three-leaf stage (GS13 of Zadoks et al., 1974) and five-leaf stage (GS15) in 2018–19 and at the two-leaf stage (GS12) and three-leaf stage (GS13) in 2019–20 (Table 1) – with a rolling machine (a small tractor with two rollers measuring 45 cm diameter × 48 cm wide, total 114 kg, and a stand-on roller measuring 32 cm diameter × 40 cm wide, total 79 kg). Another five beds were used for a large-plot experiment (900 m²), rolled as above. The remaining two beds (either side of the rolling experiment) were used as borders (Figure 1). Fertilizer was supplied at 2.0 g N m⁻², 0.87 g P m⁻², and 1.66 g K m⁻² at sowing as a basal dressing, and at 6.0 g N m⁻² at the three-leaf stage and 12.0 g N m⁻² at the start of internode elongation as topdressing. Weeds and diseases were controlled with the standard agrochemicals used in the region. Ethephon was sprayed at 30 mg m⁻² on 2 April 2019 and 13 March 2020 to prevent lodging.

Evaluation of developmental and agronomic characteristics, and statistical analysis

Three plots of 2.1 m × 5.0 m were allocated to each treatment. Ten plants per plot were dug out at about weekly intervals during winter (December to February). We examined their main shoots under a stereomicroscope and determined apical development stage, spike length, and stem length. After categorization by the method of Inamura et al. (1955), the apical development stages were numbered from 2 to 10 for statistical analysis (see footnotes to Figure 2 for details). The mean of the 10 plants in each sample was calculated, unless otherwise noted. Agronomic characteristics (Tables 2, 3) were measured in two or three plots. The date when 50% of spikes headed was recorded as the heading date. Frost injury (22 April 2019; 10 April 2020) was scored by eye according to NARC (1986). The undisturbed central part of each plot (2.1 m × 1.0 m, 2.1 m²) was harvested by hand. The

temperature in the field was recorded at three points, 5 cm above the ground, at 30-min intervals, and averaged. The accumulated daily mean temperature was calculated as thermal time (°C-d) above a base temperature of 0°C from the date of the 3-leaf-stage rolling in each year. Regression analyses (apical development stage *x* vs. log-transformed stem or spike length *y*; thermal time *x* vs. apical development stage *y*) were carried out according to the method of Kawabata (1989), and the Student's *t*-test was used to compare agronomic characteristics between the rolling and control treatments.

Results and discussion

Effect of rolling on apical development

Rolling significantly delayed apical development in both years (Figure 2A; *P* < 0.05). Apical development stage was highly correlated with thermal time in a single regression analysis in each treatment (Figure 2B; *P* < 0.001). In both years, the slopes were not significantly different between treatments but the intercepts were different, indicating that rolling delayed spikelet initiation but did not affect apical development rate. In addition, rolling after spikelet initiation (GS15) in 2018–19 had no effect on apical development rate over thermal time (Figure 2A).

The developmental delay due to rolling can be estimated as a developmental stage of nearly 1.0 in 2018–19, equivalent to 37°C-d of thermal time, and of nearly 0.7 in 2019–20, equivalent to 27°C-d of thermal time (Figure 2B). Rolling before spikelet initiation delayed spikelet initiation in early-sown spring wheat in both years, but this effect was smaller in 2019–20. The difference in the delay effect of rolling between 2018–19 and 2019–20 may have arisen before spikelet initiation, because ground rolling after spikelet initiation did not affect apical development rate (Figure 2B). The small delay effect in 2019–20 can be explained by the higher temperatures during several weeks following rolling, which helped to recover the delay in apical development caused by rolling.

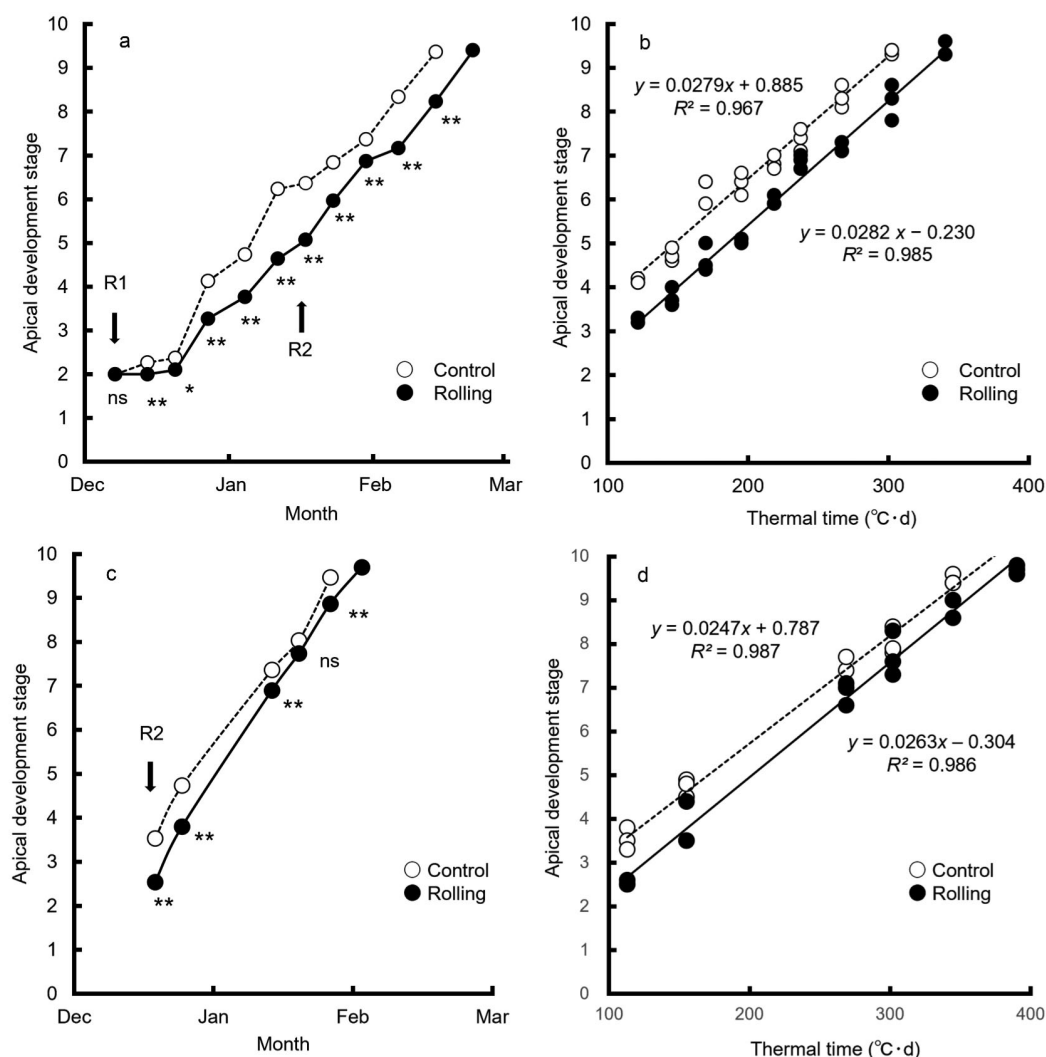


Figure 2. Time course of apical development in (a) 2018–19 and (c) 2019–20, and regression analysis between apical development stage and thermal time in (b) 2018–19 and (d) 2019–20. ‘R1’ and ‘R2’ indicate the first and second rollings (see, Table 1). ns, not significant; * $P < 0.05$; ** $P < 0.01$ (t -test, $n = 30$). Apical development stages 2–10 equate to those of Inamura et al. (1955) as follows: 2 = V (spikelet primordia cannot be observed). 3 = VI (spikelet primordia, which can be seen as double ridges, initiate in the middle of the spike). 4 = VIIe (spikelet primordia initiate at the base of the spike). 5 = VIIl (double ridges become less distinct). 6 = VIII (spikelet primordia begin to differentiate empty glumes, and the terminal spikelet initiates). 7 = IXe (spikelet primordia differentiate into florets). 8 = IXm (first florets differentiate into lemma, palea, stamen, and pistil). 9 = IXl (all florets differentiate into lemma, palea, stamen, and pistil). 10 = X (empty glume and awn begin to elongate).

Table 2. Calendar dates of spikelet initiation, start of internode elongation, and jointing stages in rolling treatment and control estimated from regression analysis.

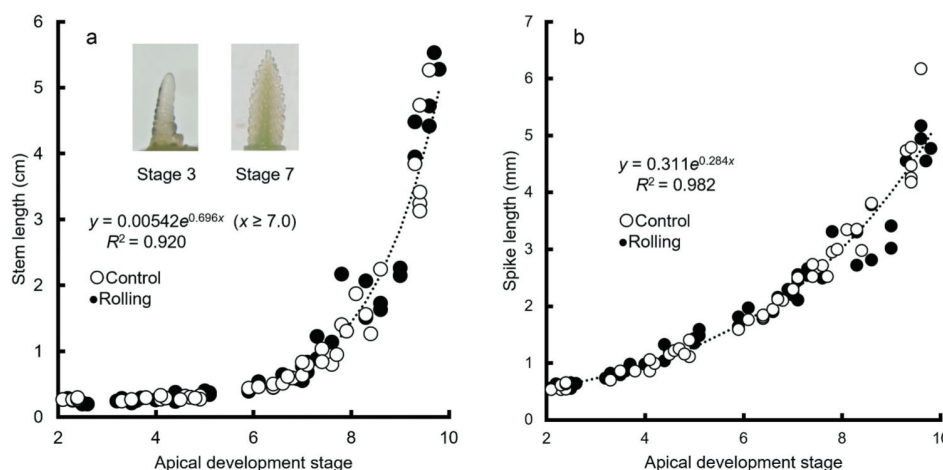
Sowing year	Developmental stage	Apical development stage	Control(A)	Rolling(B)	Difference (days) (B – A)
2018	Spikelet initiation stage	3.0	21 Dec	26 Dec	5
	Start of internode elongation stage	7.0	24 Jan	5 Feb	12
	Jointing stage	8.5	8 Feb	17 Feb	9
2019	Spikelet initiation stage	3.0	17 Dec	21 Dec	4
	Start of internode elongation stage	7.0	11 Jan	16 Jan	5
	Jointing stage	8.5	23 Jan	26 Jan	3

Table 3. Means heading and maturity dates; score of frost injury; lengths of spike and culm; and yield.

Sowing year	Treatment	Headingdate	Maturitydate ¹⁾	Frost injury score ²⁾	Spike length (cm)	Culm length(cm)	Yield(g m ⁻²) ³⁾
2018 (n = 3)	Control	2 Apr	2 Jun	2.7	10.3	94.1	469
	Rolling	5 Apr	4 Jun	0.7	10.1	91.7	611
	Significance	**	*	*	ns	ns	**
2019 (n = 3)	Control	25 Mar	25 May	2.7	ND	ND	436
	Rolling	25 Mar	24 May	1.7	ND	ND	428
	Significance	ns	ns	ns			ns

¹⁾Grain moisture 28%.²⁾0 (nil) to 5 (severe).³⁾Yield is shown on a 12.5% moisture basis; n = 2.

ns, not significant; *P < 0.05; **P < 0.01. ND, no data.

**Figure 3.** Relationships of apical development stage with (a) stem length and (b) spike length (pooled data of 2018–19 and 2019–20).

Relationships of apical development stage with stem length and spike length

The relationships of apical development stage with stem length and spike length did not differ between years or treatments, so we analyzed the 2 years of data combined. The rate of stem length elongation increased at stage 7, irrespective of rolling or year (Figure 3A). The jointing stage (stem length $y = 2.0$ cm) was estimated as stage 8.5 (95% confidence interval [CI] 7.9–9.1) in single regression analysis with pooled data. Spike length was also closely related to apical development stage (Figure 3B), and the regression lines differed little between treatments (data not shown). The spike length at the start of internode elongation (apical development stage $x = 7.0$) was estimated to be 2.3 mm (95% CI 1.9–2.7 mm) in a single regression analysis with pooled data. That at the jointing stage (apical development stage $x = 8.5$) was estimated to be 3.5 mm (95% CI 2.9–4.2 mm). Takeda (1976) reported that when spikes grow to ≥ 3 mm, they become susceptible to frost injury; therefore, the spikes after this stage were considered to be at high risk of frost injury.

Effect of rolling on agronomic characteristics

The two regression equations shown in Figure 2 indicate that in 2018–19, rolling delayed spikelet initiation by 5 days, the start of internode elongation by 12 days, and jointing by 9 days compared with the control (Table 2). It significantly reduced frost injury and significantly increased yield (Table 3). In addition, it slightly but significantly delayed heading and maturity but did not affect culm or spike length (Table 3). In 2019–20, rolling delayed spikelet initiation by 4 days, the start of internode elongation by 5 days, and jointing by 3 days. There was no significant difference in either frost injury or yield in 2019–20 (Table 3).

In 2018–19, the daily minimum temperatures during the 2 months immediately following the first rolling fluctuated around the 30-year average (Figure S1). Control plants jointed at the time of the lowest minimum temperature (-1.85°C on 15 Feb; Figure S1), but rolled plants jointed 9 days later, avoiding the coldest day. Thus, control plants suffered significant frost injury owing to early internode elongation, whereas young spikes of rolled plants avoided freezing temperatures owing to delayed internode elongation, explaining rolling's significant effect on reducing frost injury and increasing yields (Table 3). However, there were

then several days with minimum temperatures around 0°C before ear emergence. These low temperatures may have caused some frost injury to both control and rolling plants, as shown in Table 3.

On the other hand, in 2019–20, the daily minimum temperatures during the 2 months immediately following the first rolling were considerably higher than the average for the last 30 years (Figure S1). As a result, jointing of control plants grown in this winter season occurred about 2 weeks earlier than that of control plants grown in the last winter season, and the delay of jointing of rolled plants compared to that of control plants was only 3 days (Table 2). After the jointing, the rolled plants, as well as the control plants, were exposed to the lowest minimum temperatures. Therefore, the ground rolling in 2019–20 may not induce the avoidance of frost injury and yield increase.

Future prospects for studies of ground rolling

These results indicate that rolling before spikelet initiation is useful for avoiding frost injury in early-sown spring wheat. However, its effect is related to the temperature between rolling and jointing, and if the temperature is high enough, jointing is accelerated, exposing plants to potential frost injury. To induce a stable effect of rolling, it will be important to investigate the most effective timing, numbers, and intensity of rolling treatments. In addition, as ethylene treatment delays the transition from vegetative to reproductive phase in spring wheat (Mizumoto, unpublished data), ethylene may be involved in the effect of rolling, so it will be necessary to clarify the relationship between rolling and ethylene production.

Acknowledgments

We thank Hiroshi Saito, Katsuyuki Yamauchi, Yukio Araki, Naoto Minamikurosawa (National Institute of Vegetable and Floriculture Science, NARO), and Miki Arakaki (Central Region Agricultural Research Center: CARC, NARO) for their technical assistance. We express our sincere thanks to Satoshi Yoshinaga (CARC) for his critical reading of this manuscript. We are grateful to the Iwaki Farmer Group for the use of the field, to the Tokai Regional Agricultural Administration Office for planted area data, and to the Japan Meteorological Agency for temperature data.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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