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REVIEW

Research on Ground Rolling with Delayed Apical Development to Prevent Frost Injury in Autumn-Sown Spring Wheat

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Abstract

The practice of pressing down on young wheat plants by ground rolling or trampling has been used in Japan for a long time to increase yield. Among the reported effects of rolling are delays in spikelet formation, apical development, and internode elongation; however, the underlying mechanism is unknown. Wheat can be injured by frost if exposed to temperatures of −2°C or lower after the jointing stage, and the risk is increased by a warm winter and early sowing. This review presents the results of research on the prevention of frost injury by rolling, the conditions for effective rolling, and how rolling delays spike development.

Discipline: Crop Science
Additional key words: early sowing, ethylene, jointing stage, soil moisture, spikelet initiation

Introduction

In the western part of the Kanto region of Japan, where wheat is sown in November and harvested in June, the jointing stage, when the young spikes emerge from the ground surface, occurs in February and March. If the temperature falls below −2°C during this stage, there is a risk of frost injury and yield loss (Barlow et al. 2015); therefore, it is necessary to time planting so that the jointing stage does not occur too early. However, early sowing or warm winter conditions due to climate change can accelerate the jointing stage. Ground rolling is widely practiced by many farmers because it can increase tiller numbers and prevent lodging (Arai 1984). Ohtani (1950) found that rolling can delay apical development—we confirmed this phenomenon (Mizumoto et al. 2022, 2023). Delaying apical development may delay the jointing stage and help avoid frost injury. This review describes the effectiveness of rolling as a technique for avoiding frost injury, the conditions suitable for rolling, and how rolling delays apical development.

Why we noticed the effect of rolling

We initiated our study of rolling to verify the effects of labor-intensive cultivation practices on wheat yields and did not expect that it would reduce frost injury. In an experiment conducted in 2018 in a paddy rotation field in Tsu, Mie Prefecture, using the Ayahikari wheat variety (winter growth habit Class I–II [i.e., spring wheat]), rolling at the three-leaf stage increased yields by about 30% and delayed the jointing stage by nine days (Mizumoto et al. 2022). This yield increase was attributed mainly to an increase in the number of grains per spike, which was likely due to avoidance of frost injury. Unrolled plants encountered daily minimum temperatures below −2°C after jointing, whereas rolled plants encountered them before the delayed jointing, thereby avoiding frost injury. Because apical development was also clearly delayed, we concluded that the delay in jointing was due to delayed apical development caused by rolling.

This raises the question of whether the delay in

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Table 1. Mean jointing, heading, and maturity dates, frost injury score, and yield in 2018 (Mizumoto et al. 2022)

Treatment	Jointing date[1)]	Heading date	Maturity date[2)]	Frost injury score[3)]	Yield (g m^{-2})[4)]
Control	8 February	2 April	2 June	2.7	469
Rolling	17 February	5 April	4 June	0.7	611
Significance[5)]	–	**	*	*	**

n = 3. Sowing was conducted on 2 November 2018; rolling at the 3-leaf stage was performed on 7 December 2018; and the coldest temperature was recorded on 15 February 2019.

1) No statistical analysis was performed because the data were calculated from a regression analysis of the apical development stage (mean of repetitions) and thermal time.

2) Maturity date was the date when the grain water content reached 28%.

3) 0 (nil) to 5 (severe)

4) Yield is shown on a 12.5% moisture basis; n = 2

5) *$P < 0.05$; **$P < 0.01$

jointing would also delay maturity, pushing the harvest into the rainy season in June. However, in the 2018 experiment, the delay was reduced from nine days at jointing to three days at heading to two days at maturity (Table 1). This reduction can be explained by the fact that, although rolling delays spikelet initiation, subsequent apical development depends on thermal time (the accumulated daily mean temperature), as shown in Figure 1. The spikelet initiation stage covers the transition from vegetative growth to reproductive growth. It corresponds to Stage 3 of apical development (Fig. 1). The difference in thermal time between control and rolling was 37°C·days, indicating that the thermal time required to reach Stage 3 was estimated to be an additional 37°C·days due to the rolling. If apical development depends on thermal time and rolled plants require an additional 37°C·days to reach the same growth stage as the control plants, then during the jointing stage, when temperatures are lower, rolled plants would take an additional nine days to achieve 37°C·days. However, at maturity, when temperatures are higher, the number of additional days required decreases. This reduces the delay in maturity caused by rolling to two days. Thus, although rolling delays jointing, it causes little delay in growth until harvest and does not result in a significant delay in harvest. For the Ayahikari wheat used in this experiment, spikelet initiation usually occurs at the four-leaf stage, so rolling should be performed at least by then.

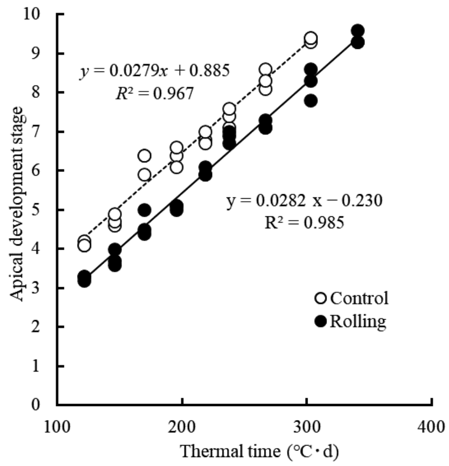

Fig. 1. Regression between apical development stage and thermal time (Mizumoto et al. 2022)
Apical development stages 2-10 equate to those of Inamura et al. (1955). The accumulated daily mean temperature was calculated as thermal time (°C·d) above a base temperature of 0°C from the date of 3-leaf-stage rolling. Stage 3 of apical development corresponds to the spikelet initiation stage, equivalent to stage VI in Inamura (1958).

Effective timing of rolling to delay apical development

To clarify the timing of rolling that is most effective in delaying jointing, we rolled early-sown Ayahikari at each of the one- to four-leaf stages and compared its jointing delay with that of the control plants (Mizumoto et al. 2023). Rolling at the one-leaf stage was most effective in delaying jointing (Fig. 2). In conventional rolling practice, rolling is typically performed during the agricultural off-season, from the three-leaf stage to the jointing stage. However, earlier rolling delays jointing because apical development depends on thermal time, suggesting that if the objective is to delay jointing, rolling should be conducted earlier than in conventional practice (Fig. 1). The greater the additional thermal time necessitated by rolling, the greater is the effect of delaying young spikes. Later experiments found that the additional thermal time required by rolling varied from 22 to 37°C·days per year, depending on the year, although the cause of this variation is unknown (Mizumoto et al. 2023).

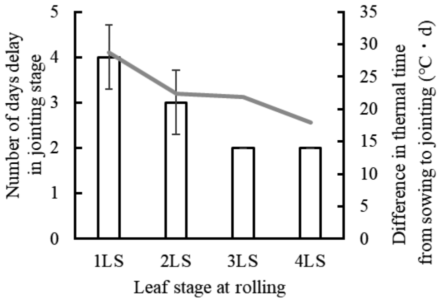

Fig. 2. Effect of rolling timing on jointing stage delay (Mizumoto et al. 2023)
Columns indicate the number of days delay in the jointing stage relative to the control; error bars indicate standard errors. The gray line indicates the difference in thermal time accumulated from sowing to jointing from the control. *n* = 3 for the 1- and 2-leaf stages, *n* = 2 for the 3- and 4-leaf stages.

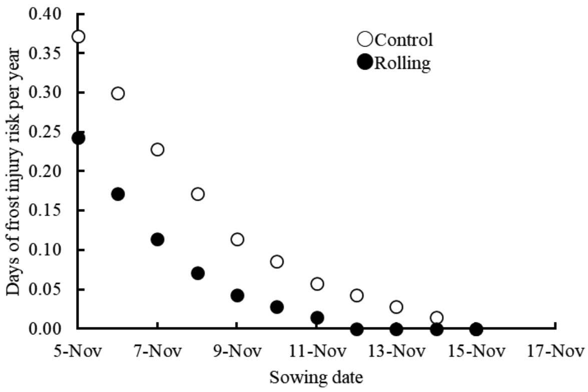

Fig. 3. Relationship between sowing date and frost injury risk (Mizumoto et al. 2023)
Plots indicate the 7-day-centered moving average of the number of days with daily minimum temperatures below −2°C after the jointing stage for the 10 years from 2012 to 2021 in Tsu, Mie Prefecture. Plants were rolled at the 1-leaf stage.

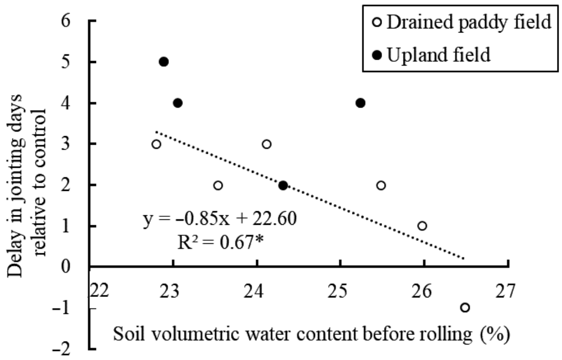

Fig. 4. Relationship between volumetric soil water content before rolling and delay in jointing (Mizumoto et al. 2024)
The dotted line is the regression line for drained paddy field plots; the coefficient of determination is significant at *5%.

To clarify whether rolling could allow for an earlier sowing date while avoiding frost injury, we used a wheat development model (Nakazono et al. 2014) to determine the earliest sowing date that would avoid temperatures below −2°C after jointing. Days of frost injury risk were defined as the number of days with temperatures below −2°C after the jointing stage. For the ten-year period from 2012 to 2021, we plotted the seven-day-centered moving average of the number of days with minimum daily temperatures below −2°C after jointing. The model assumed that apical development of plants rolled at the one-leaf stage remains stagnant until the thermal time since rolling reaches 29°C·days. As a result, it was shown that the sowing dates at which the days of frost injury risk become 0 were 15 November for the control and 12 November for rolling (Fig. 3). It suggested that in the Tokai region, growing spring wheat with rolling at the one-leaf stage could advance the sowing date to avoid frost injury (the sowing date with no days of frost injury risk) by three days (Fig. 3). It also became clear that the risk of frost injury increases exponentially as the sowing date is advanced.

Relationship between rolling and soil moisture

If plants are rolled when the soil is wet, such as after heavy rainfall, the soil will harden, inhibiting the growth of the roots and thus the plants. Thus, the effectiveness of rolling can be affected by soil moisture. We assessed the relationship between the jointing stage delay and volumetric soil water content (SWC) before rolling in a drained paddy field (moist brown forest soil) and an upland field (non-allophenic Andosol) (Mizumoto et al. 2024). Rolling was conducted at the one- and two-leaf stage. We found a significant negative correlation in the drained paddy field: the pre-rolling SWC at which there was no jointing stage delay was estimated to be 26.7% (Fig. 4). This indicates that in drained paddy fields, jointing is not delayed by rolling at an SWC ≥ 26.7%. Furthermore, a combined analysis of the data from both fields showed that the soil air content after rolling did not significantly correlate with the jointing delay. However, the SWC after rolling significantly negatively correlated with it (Fig. 5). It also suggested that jointing would not be delayed if the SWC after rolling was > 44% (Fig. 5B). In general, rolling should be done when the soil is dry: the same is true for the delayed jointing stage effect.

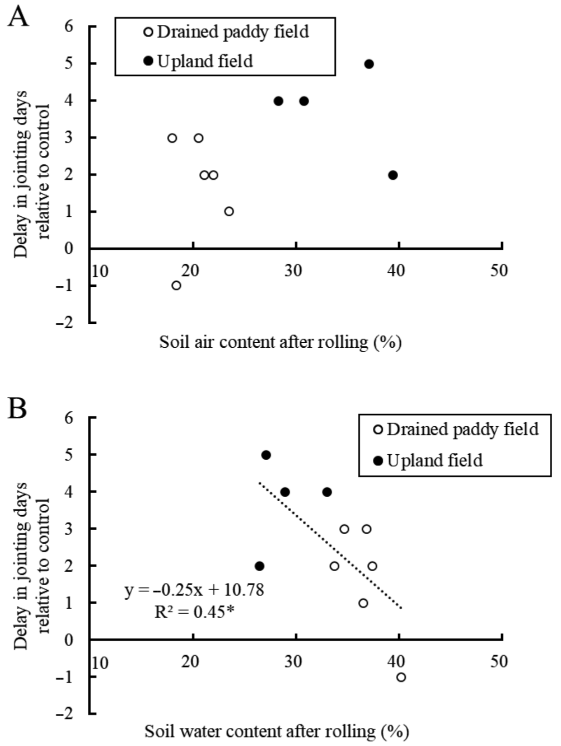

Fig. 5. Relationship between (A) soil air content or (B) soil water content after rolling and delay in jointing (Mizumoto et al. 2024)

The dotted line is the regression line for all plots; the coefficient of determination is significant at *5%.

How rolling delays apical development

How rolling affects plants is not fully understood. Soil compaction increases ethylene production in the aboveground parts of plants (Suh & Ota 1981), as does rolling (our unpublished data). It has also been reported that soil compaction reduces pore space and increases ethylene concentration in the rhizosphere (Pandey et al. 2021). An increase in ethylene concentration in the rhizosphere may lead to higher ethylene levels within the plant. At low SWC, rolling reduces the air phase around the roots and thus increases the ethylene concentration, delaying apical development. At high SWC, on the other hand, the pore spaces fill with water, resulting in hypoxia and anoxia; and since 1-aminocyclopropane-1-carboxylic acid (ACC) oxidase, which catalyzes the synthesis of ethylene from ACC, has a high oxygen demand (Adams & Yang 1979), ethylene production is inhibited. Therefore, the suppression of ethylene production may be a factor in the acceleration of apical development due to rolling at a high SWC instead of a delay.

Ohtani (1950) studied how rolling delays apical development, though at that time it was difficult to investigate the relationship with phytohormones and genes. Much later, Suh & Ota (1981) found that rolling promoted ethylene production. We hypothesize that the expression of genes related to spikelet initiation may also be delayed. Significant genes related to spikelet initiation in wheat are *Flowering Locus T* (*FT*) and *Vernalization 1* (*VRN1*). We found that rolling delayed their expression (unpublished data). Since rolling increases ethylene production, we think that this ethylene suppresses the expression of *FT* and *VRN1*, which in turn delays apical development. Nevertheless, many aspects of the rolling effect mechanism remain unclear, such as its relationship with the soil and how ethylene suppresses the expression of *FT* and *VRN1*. Further investigation is required.

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