

Effects of Pre-Sowing Irrigation and Post-Sowing Compaction on Pre-Winter Water Use and Growth and Development of Wheat Postprint

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Abstract

To clarify the effects of pre-sowing irrigation and post-sowing compaction on pre-winter water consumption, population and individual characteristics, and yield of winter wheat, and to provide a basis for determining post-sowing compaction techniques and improving water use efficiency of wheat, field experiments with winter wheat were conducted during the 2013-2014 and 2014-2015 wheat growing seasons in Hengshui City, Hebei Province, using the local wheat variety 'Heng 4399'. Pre-sowing irrigation was applied on four dates: September 15 (I9.15), September 20 (I9.20), September 25 (I9.25), and September 30 (I9.30), with no irrigation as the control (CK). For each irrigation treatment, three compaction levels were established: 0 kg per linear meter (G0), 95 kg per linear meter (G95), and 120 kg per linear meter (G120). Soil moisture and wheat seedling growth were monitored dynamically before winter, and yield traits were investigated and yield was measured at maturity the following year. The results showed that higher soil moisture content at sowing led to higher farmland evapotranspiration during the pre-winter stage. Comparing different compaction treatments under the same irrigation condition, the I9.30 treatment had the lowest field evapotranspiration with G95, while other treatments had the lowest evapotranspiration with G120, with significant differences among treatments. Regarding effects on seedling conditions, comparing different compaction treatments under the same irrigation condition, single-plant biomass, leaf area, and total population stems at the seedling stage were higher under G120 and G95 treatments and lower under G0 treatment, with varying significance levels among treatments; comparing different irrigation treatments under the same compaction condition, the non-irrigated CK showed significantly reduced total stems, significantly lower yield, and unstable interannual variation. Pre-sowing irrigation and compaction had substantial effects on spike number, with irrigated treatments showing significantly higher spike numbers than CK,

and the effect of compaction treatments on spike number being consistent: G120 > G95 > G0. The effects of the above treatments on yield were consistent with those on spike number: yield differences among irrigation treatments varied in significance level, but CK was the lowest; yield differences among compaction treatments were not significant, but G0 was the lowest. The interaction between pre-sowing irrigation and compaction on yield was not significant. In summary, appropriate soil moisture conditions are the foundation for post-sowing compaction of wheat, and compaction is the guarantee for raising soil moisture and strengthening seedlings. In the Hebei region, pre-sowing irrigation for wheat should be advanced to September 20–25, and using a 95 kg · m⁻¹ compactor after sowing facilitates field operations and provides better compaction effects.

Full Text

Effects of Pre-sowing Irrigation and Post-sowing Soil Compaction on Water Use and Growth of Winter Wheat

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Abstract

To clarify the effects of pre-sowing irrigation and post-sowing soil compaction on water consumption, population and individual characteristics, and yield of winter wheat, field experiments were conducted during the 2013–2014 and 2014–2015 wheat growing seasons in Hengshui City, Hebei Province. The locally adapted wheat cultivar ‘Heng 4399’ was used with four pre-sowing irrigation dates: September 15 (I9.15), September 20 (I9.20), September 25 (I9.25), and September 30 (I9.30), with a no-irrigation control (CK). Each irrigation treatment included three post-sowing compaction levels: 0 kg (G0), 95 kg (G95), and 120 kg (G120) per linear meter. Soil moisture and wheat seedling growth were monitored dynamically before winter, and yield components were investigated at maturity the following year. The results showed that higher soil moisture at sowing led to greater evapotranspiration during the pre-winter period. Under the same irrigation treatment, the G95 treatment had the lowest field evapotranspiration for I9.30, while G120 had the lowest evapotranspiration for all other treatments, with significant differences among treatments. For seedling characteristics under the same irrigation treatment, G120 and G95 produced higher single-plant biomass, leaf area, and total stem number compared to G0, with varying significance levels. Under the same compaction level, the CK treatment

showed significantly reduced total stem number and yield, with unstable inter-annual variation. Pre-sowing irrigation and compaction significantly affected spike number, with irrigated treatments producing significantly more spikes than CK. The effect of compaction on spike number consistently followed the pattern: G120 > G95 > G0. Yield responses mirrored those of spike number: differences among irrigation treatments varied, but CK consistently produced the lowest yield, while differences among compaction treatments were not significant, with G0 producing the lowest yield. The interaction between pre-sowing irrigation and compaction on yield was not significant. In conclusion, appropriate soil moisture is the foundation for effective post-sowing compaction, and compaction serves as a guarantee for moisture retention and seedling vigor. In the Hebei region, pre-sowing irrigation should be advanced to September 20–25, and post-sowing compaction with a $95 \text{ kg} \cdot \text{m}^{-1}$ roller provides convenient field operation with good compaction effects.

Keywords: Winter wheat; Pre-sowing irrigation; Post-sowing soil compaction; Evapotranspiration; Soil moisture; Grain yield

1 Materials and Methods

1.1 Experimental Site

The field experiments were conducted over two consecutive wheat growing seasons (2013–2014 and 2014–2015) at the Dryland Farming and Water-Saving Agriculture Experimental Station of the Hebei Academy of Agriculture and Forestry Sciences. Located in the central-southern Hebei Plain within the Heilonggang wheat production region, the station represents typical semi-arid agricultural characteristics of northern China. The area practices a winter wheat–summer maize double-cropping system annually. The long-term average annual sunshine hours, frost-free period, evaporation, precipitation, and temperature are 2,509.4 h, 188 d, 1,785 mm, 510 mm, and 12.8°C , respectively. The experimental soil was loam with an average bulk density of $1.40 \text{ g} \cdot \text{cm}^{-3}$ in the 0–200 cm profile. The 0–20 cm topsoil had the following fertility characteristics: organic matter $14.39 \text{ g} \cdot \text{kg}^{-1}$, total nitrogen $1.48 \text{ g} \cdot \text{kg}^{-1}$, available nitrogen $101.36 \text{ mg} \cdot \text{kg}^{-1}$, available phosphorus $21.95 \text{ mg} \cdot \text{kg}^{-1}$, and available potassium $113.68 \text{ mg} \cdot \text{kg}^{-1}$. Precipitation during the wheat growing seasons is shown in .

1.2 Experimental Design

The winter wheat cultivar ‘Heng 4399’, which is widely planted with high yield potential and water-saving characteristics, was used as the experimental material at a standard seeding rate of $225 \text{ kg} \cdot \text{hm}^{-2}$. The main treatments consisted of five pre-sowing irrigation regimes: irrigation on September 15 (I9.15), September 20 (I9.20), September 25 (I9.25), September 30 (I9.30), and a no-irrigation control (CK). Each irrigation treatment received 45 mm of water and occupied

666.7 m², arranged sequentially. Sub-treatments comprised three post-sowing compaction intensities applied using an SL200-type wheat compactor (2.00 m length × 0.45 m width × 0.40 m height, 190 kg weight, 0.35 m roller diameter). Compaction intensity was adjusted by adding soil weights to the frame. The commonly used 190 kg compactor (G95) served as the control, with additional no-compaction (G0) and heavy compaction (240 kg, G120) treatments.

After summer maize harvest, all straw was chopped and returned to the field. Before land preparation, basal fertilizer was applied at 525 kg · hm⁻² of diammonium phosphate and 150 kg · hm⁻² of potassium chloride. At the jointing stage, 375 kg · hm⁻² of urea was top-dressed, equivalent to 267 kg · hm⁻² N, 241.5 kg · hm⁻² P O, and 90 kg · hm⁻² K O. Compaction treatments were implemented after sowing, with other management following conventional practices. In 2013–2014, sowing occurred on October 14, compaction on October 16, flowering on May 10, and harvest on June 9. In 2014–2015, sowing was on October 12, compaction on October 14, flowering on May 8, and harvest on June 11.

1.3 Measurement Indicators

1.3.1 Surface Soil Hardness Surface soil hardness, which reflects soil compaction, was measured using a soil hardness meter (Shanghai) in each treatment plot with 30 replicates per plot, and the average was calculated.

1.3.2 Total Stem Number Investigation Three fixed points were established in each sub-treatment plot. Stem counts began on November 2 and continued every 5 days. Total stem number was calculated per meter of double rows, with the average of all points representing the treatment value.

1.3.3 Plant Traits Thirty plants were sampled from multiple points in each treatment. Individual plant height, stem number per plant, leaf area, and secondary root number were measured. After trait investigation, roots were removed, and samples were oven-dried at 105°C for 30 minutes, then at 80°C to constant weight for dry weight determination.

1.4 Soil Water Content and Evapotranspiration Calculation

Before sowing (October 12, 2013 and October 10, 2014), soil samples were collected from 0–200 cm depth in each irrigation treatment plot. Before winter (December 2, 2013 and December 3, 2014), samples were taken from 0–100 cm depth in each plot at 10 cm intervals, with three replicates per treatment. Soil water content was determined by the oven-drying method for evapotranspiration calculation. Since wheat roots are shallow before winter, water consumption was considered primarily from the 0–100 cm soil layer using the following formula:

$$ET_{1-2} = \sum_{i=1}^n \gamma_i H_i (\theta_{i1} - \theta_{i2}) + M + P_0 + K$$

where ET_{1-2} is the stage evapotranspiration; i is the soil layer number; n is the total number of layers; γ_i is the dry bulk density of layer i ; H_i is the thickness of layer i ; θ_{i1} and θ_{i2} are the initial and final water contents of layer i (percentage of dry soil weight); M is irrigation amount during the period; P_0 is effective precipitation; and K is groundwater contribution. With groundwater depth exceeding 2.5 m, K can be neglected. In this experiment, groundwater depth was below 10 m, so no groundwater contribution was considered.

The proportion of water consumption sources was calculated as:

$$\text{Proportion (\%)} = \frac{\text{Water source component}}{\text{Evapotranspiration}} \times 100$$

1.5 Yield and Yield Component Determination

Before maturity, spike numbers were counted in each sampling point to calculate spikes per unit area. Twenty spikes were randomly selected to determine grains per spike. Approximately 30 plants were sampled from multiple points in each plot and brought to the laboratory for trait investigation. Three 2 m² sampling areas per plot were harvested to calculate yield per hectare. Thousand-grain weight was determined from randomly selected dried grains.

1.6 Data Processing

Data processing and statistical analysis were performed using Microsoft Excel and DPS software.

2 Results and Analysis

2.1 Effects on Soil Water Consumption Characteristics

2.1.1 Effects on Surface Soil Hardness Higher soil hardness indicates greater soil compaction. Under the same irrigation treatment, surface soil hardness increased with compaction intensity, with some differences reaching significant levels (Table 2). Inter-annual patterns were consistent. In 2013, the maximum hardness of 9.20 kg · cm⁻² occurred under G120 with I9.20 irrigation, while in 2014, the maximum of 11.40 kg · cm⁻² occurred under G120 with I9.25 irrigation. Comparing different irrigation treatments at the same compaction level, I9.20 and I9.25 generally produced the highest or relatively high soil hardness, while the non-irrigated CK treatment produced the lowest.

2.1.2 Soil Water Content Changes The two-year study showed consistent patterns of soil water content changes in the 0-100 cm layer across different irrigation treatments, with CK showing significantly lower moisture in the 0-80 cm layer compared to irrigated treatments. Inter-annual differences were more pronounced in 2014. Across treatments, the 0-100 cm soil water content

consistently ranked as: I9.30 > I9.25 I9.20 > I9.15 > CK. Overall, later irrigation resulted in higher soil water content in the 0–100 cm layer. Changes in the 100–200 cm layer followed similar patterns but with smaller differences among treatments, ranging from 17.28% to 30.92%. The lowest values in 2014 for CK were related to reduced rainfall during the maize season, which failed to replenish deep soil moisture after maize consumption.

2.1.3 Pre-winter Soil Water Consumption Characteristics Under experimental conditions, field evapotranspiration from sowing to pre-winter ranged from 19.78 to 51.76 mm. For the same irrigation treatment, G95 produced the lowest evapotranspiration for I9.30, while G120 produced the lowest for all other treatments. Soil water supply accounted for 18.64% to 73.01% of evapotranspiration, with a decreasing trend as compaction intensity increased. The proportion of precipitation to evapotranspiration increased with compaction intensity. Inter-annual differences existed within the same irrigation treatment: in 2013, early irrigation (I9.15) and CK showed higher evapotranspiration and soil water supply, while in 2014, later irrigations (I9.25 and I9.30) showed higher values.

Comparing different irrigation treatments at the same compaction level, both soil water supply and field evapotranspiration increased with delayed irrigation timing. The proportion of soil water supply to evapotranspiration increased with later irrigation, while the precipitation proportion decreased. Inter-annual comparisons showed no consistent pattern in evapotranspiration and soil water supply across compaction intensities.

2.2 Effects on Wheat Growth and Development

2.2.1 Effects on Pre-winter Seedling Quality Seedling investigations conducted on November 11 in both 2013 and 2014 showed that under the same irrigation treatment, G120 and G95 produced higher single-plant biomass than G0, which produced the lowest biomass. Under the same compaction level, single-plant biomass increased with delayed irrigation timing, following the pattern: I9.30 I9.25 I9.20 I9.15 > CK, with minimal inter-annual variation. Secondary root number responded similarly but not identically: G95 treatment produced the highest root numbers under I9.25 or I9.20, with lower values under I9.30. Leaf area per plant showed similar patterns to secondary root number. Overall, the combination of G95 compaction with I9.20 or I9.25 irrigation produced the best seedling quality before winter.

2.2.2 Pre-winter Population Dynamics As shown in Table 5, total stem number increased gradually with time during the pre-winter stage, though the trend varied among irrigation and compaction treatments. Significance levels differed among the five irrigation treatments across the two years. In 2013, I9.25 produced the highest total stem number, while in 2014, I9.30 produced the highest, with CK consistently lowest and significantly different. The three

compaction levels showed similar significance patterns across years, with G120 or G95 producing higher total stem numbers than CK.

Two-way ANOVA for pre-winter populations across both years indicated that irrigation effects were significant, and the interaction between irrigation and compaction also reached significant levels.

2.3 Effects on Yield Components

Multiple comparisons of main effects for different irrigation and compaction treatments revealed that irrigation treatments significantly affected spike number, with CK producing significantly fewer spikes than other treatments. Among irrigated treatments, some differences existed, with I9.25 showing relatively high and stable spike numbers across years. Compaction effects on spike number were consistent across years: G120 > G95 > G0, with significant differences between G120 and G0. Irrigation and compaction had minimal effects on grains per spike, with significant differences only between G120 and G0 in 2014–2015. Compaction effects on thousand-grain weight were minor and non-significant, while irrigation effects were significant but inconsistent.

Yield comparisons showed that in 2013–2014, yield increased gradually with delayed irrigation timing, with I9.25 and I9.30 producing the highest yields. In 2014–2015, I9.15 produced the highest yield, while CK produced the lowest yield in both years. Among compaction treatments, G95 and G120 produced higher yields than G0. The CK treatment showed the largest inter-annual yield difference, with 2014 yields significantly lower than 2015, likely due to poor soil moisture conditions during the 2014 fall maize season resulting in poor seedling establishment and insufficient spike numbers.

Two-way ANOVA indicated that irrigation significantly affected yield and all yield components. In 2013–2014, compaction significantly affected spike number, while in 2014–2015, compaction significantly affected spike number, grains per spike, and thousand-grain weight. The irrigation \times compaction interaction was significant for all yield components in 2013–2014, but only for grains per spike and thousand-grain weight in 2014–2015. The interaction effect on grain yield was not significant, and the main effect of compaction on yield was also non-significant.

Correlation analysis showed that grain yield was positively correlated with pre-sowing soil water content, significantly with 0–10 cm soil moisture and highly significantly with 10–20 cm soil moisture (in 2014), but not significantly with other layers. Correlations between yield and soil hardness under the same irrigation with different compaction treatments varied inter-annually: positive in 2014 (significant for I9.25) and negative in 2015 (highly significant for CK). Yield showed positive correlations with soil hardness under the same compaction with different irrigation treatments, but patterns were inconsistent across years and treatments.

3 Discussion

3.1 Effects of Pre-sowing Irrigation and Post-sowing Compaction on Soil Water Consumption

Under experimental conditions, pre-winter evapotranspiration ranged from 19.78 to 51.76 mm, similar to results from Li et al. (10.6–47.9 mm). In this study, pre-sowing soil water content in the 0–100 cm layer for I9.15, I9.20, I9.25, and I9.30 treatments was 19.55%, 26.38%, 31.58%, and 48.16% higher than CK, respectively. Correspondingly, field evapotranspiration in 2013 was 74.07%, 56.10%, 38.84%, and 76.90% higher than CK, while in 2014 it was 45.63%, 87.73%, 96.61%, and 119.56% higher. These results demonstrate that higher soil moisture leads to greater evapotranspiration. However, from a practical production standpoint, I9.20 and I9.25 treatments can both meet wheat emergence water requirements and moderately reduce pre-winter evapotranspiration (particularly in 2014, where I9.20 and I9.25 had lower evapotranspiration than I9.15), making them suitable irrigation timings.

Differences in pre-winter water consumption among compaction treatments were relatively small, with uncompacted G0 showing the highest evapotranspiration. In 2013, G120 and G95 reduced evapotranspiration by 16.01% and 8.63% compared to G0, while in 2014 the reductions were 10.56% and 4.16%, respectively. These results demonstrate clear moisture conservation benefits of compaction, helping to increase soil water content. Combined with observations of improved seedling traits and surface soil hardness, compaction functions to firm soil and promote sturdy seedlings. Consistent with Zhang et al., compaction treatments showed significantly higher soil temperatures than non-compacted treatments during rain and snow events. Overall, post-sowing compaction provides excellent water-saving and yield-increasing effects.

Regarding soil water supply patterns, for the same irrigation treatment, I9.30 showed the lowest soil water supply under G95, while other treatments showed lowest supply under G120. This fully demonstrates that lighter compaction is effective for fields with good moisture conditions, while heavier compaction is more effective for drier fields.

3.2 Effects of Pre-sowing Irrigation and Post-sowing Compaction on Wheat Growth and Yield

Across the two-year study, biomass under I9.15, I9.20, I9.25, and I9.30 treatments was 11.48%, 14.48%, 21.04%, and 44.26% higher than CK, respectively. Secondary root number increased by 6.24%, 12.07%, 13.84%, and 13.10%, while leaf area increased by 17.56%, 22.98%, 25.26%, and 27.39%, respectively. These results indicate that better soil moisture conditions produce higher-quality seedlings. Compared with irrigation effects, compaction had smaller effects on seedlings, and its impact varied with water conditions. Under the same moisture conditions, uncompacted treatments showed the greatest reduction in leaf area, followed by secondary root number, with biomass being least affected.

Total stem number before winter varied among treatments. Across both years, irrigated treatments produced higher total stem numbers than CK. The CK treatment showed large inter-annual variation, with significantly lower stem numbers in 2014 than in 2013, primarily due to reduced rainfall during the 2014 maize grain-filling stage resulting in poor soil moisture. In 2014, the CK treatment's poor seedling establishment due to insufficient base moisture could not be compensated by later water supplementation, highlighting the importance of sowing quality and appropriate population establishment for stable high yields. The region experiences large inter-annual spatiotemporal rainfall variation, and CK treatment population stem numbers showed strong dependence on rainfall patterns, which is unfavorable for stable wheat production.

The inconsistent correlation patterns between yield and soil hardness under compaction, combined with the significant positive correlation between yield and topsoil moisture content, suggest that appropriate soil moisture is the foundation for effective post-sowing compaction, while compaction serves as a guarantee for moisture retention and seedling vigor. Given that soil hardness is influenced by multiple factors including moisture, soil texture, and compaction intensity, more precise control of interfering factors is needed to definitively establish yield-compaction relationships.

Integrating wheat-maize production systems, advancing pre-sowing irrigation to September 20-25 can both meet the water requirements of the preceding maize crop during grain filling and reserve moisture for wheat, achieving the dual benefits of water storage and yield increase. Under the conditions of this study, post-sowing compaction with a $95 \text{ kg} \cdot \text{m}^{-1}$ roller is recommended. For fields with better moisture conditions, compaction weight can be moderately reduced, while drier fields may require increased compaction weight.

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