Effects of Tillage and Fertilization on Soil Water Consumption and Water Use Efficiency in Dryland Maize Fields: Postprint

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Abstract

To investigate the effects of conservation tillage and fertilization on soil water consumption and water use efficiency in spring corn fields in the Weibei dryland area, aiming to achieve efficient production. A field experiment on spring corn tillage and fertilization was conducted on the Weibei dry plateau from 2013 to 2015, with six tillage and fertilization treatments: conventional tillage + low fertilizer (A1), no-tillage + high fertilizer (A2), subsoiling + balanced fertilization (A3), conventional tillage + no fertilizer (B1), no-tillage + no fertilizer (B2), and subsoiling + no fertilizer (B3). Soil water storage in the 0–200 cm soil layer during the fallow period and growth stages, as well as grain yield at harvest, were measured. The results showed that: 1) Conservation tillage could significantly improve the soil water storage and moisture conservation capacity in dryland corn fields. Compared with the conventional tillage treatment B1, during the fallow period, the pre-sowing soil water storage in B2 and B3 increased by 23.39 mm and 27.73 mm, respectively ($P<0.05$); in the tillage treatment zone, the soil water storage during the entire growth period in B2 and B3 increased by an average of 13.41 mm and 15.70 mm, respectively; in the tillage and fertilization treatment zone, the soil water storage in A2 and A3 increased by 13.15 mm and 19.54 mm, respectively, compared with A1. 2) Balanced fertilization could effectively increase the average soil water storage during the entire corn growth period; compared with the no-fertilizer treatment, the soil water storage during the entire growth period increased by an average of 6.79 mm ($P<0.05$). 3) Conservation tillage and fertilization could increase corn grain yield and water use efficiency. In the tillage without fertilizer zone, compared with B1, the yield in the B3 treatment increased by 212~576 kg hm 2, and water use efficiency increased by 0.83~2.21 kg hm 2 mm 1; in the tillage with fertilization zone, A3 showed the most significant increase in yield and water use efficiency, with yield increasing by 659~1 495 kg hm 2 compared with A1, and water use efficiency increasing by 0.65~3.82 kg hm 2 mm 1 ($P<0.05$). Among the three fertilization methods, balanced nitrogen, phosphorus, and potassium fertilization resulted in the greatest increase in yield and water use efficiency. 4) Correlation analysis between water consumption and yield revealed that soil water consumption during the tasseling-grain filling growth stage was significantly positively correlated with yield. Conservation tillage improved the soil water storage and moisture conservation capacity during the early growth stage of corn, increased soil moisture during the tasseling-grain filling stage of spring corn, enhanced water use efficiency during the critical period of crop growth, and was beneficial for increasing corn grain yield. Therefore, in spring corn fields in the Weibei dryland area, the combination of subsoiling and balanced fertilization can increase spring corn yield and water use efficiency, representing a relatively suitable cropping pattern for efficient corn production in this region.

Full Text

Preamble

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Effects of Tillage and Fertilization on Soil Water Consumption and Water Use Efficiency in Dryland Maize Fields*

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Abstract: To investigate the effects of conservation tillage and fertilization on soil water consumption and water use efficiency (WUE) in spring maize fields in the Weibei dryland region and to achieve efficient production, a field experiment was conducted from 2013 to 2015. Six tillage and fertilization treatments were established: conventional tillage with low fertilizer (A1), no-tillage with high fertilizer (A2), subsoiling with balanced fertilization (A3), conventional tillage without fertilizer (B1), no-tillage without fertilizer (B2), and subsoiling without fertilizer (B3). Soil water storage in the 0-200 cm layer was measured during the fallow period and maize growth stages, and grain yield was determined at harvest. The results showed that: (1) Conservation tillage significantly improved soil water storage capacity in dryland maize fields. During the fallow period, compared with conventional tillage treatment B1, pre-sowing soil water storage increased by 23.39 mm and 27.73 mm ($P<0.05$) under B2 and B3, respectively. During the growth period, B2 and B3 increased average soil water storage by 13.41 mm and 15.70 mm compared with B1. In the tillage with fertilization zone, A2 and A3 increased soil water storage by 13.15 mm and 19.54 mm compared with A1. (2) Balanced fertilization effectively improved average soil water storage during the entire growth period, increasing it by 6.79 mm ($P<0.05$) compared with no-fertilizer treatments. (3) Conservation tillage combined with fertilization increased grain yield and WUE. In the tillage without fertilizer zone, compared with B1, B3 increased yield by 212–576 $kg \cdot hm^{2}$ and WUE by 0.83–2.21 $kg \cdot hm^{2} \cdot mm^{1}$. In the tillage with fertilization zone, A3 showed the most significant increases, with yield rising by 659–1,495 $kg \cdot hm^{2}$ and WUE by 0.65–3.82 $kg \cdot hm^{2} \cdot mm^{1}$ ($P<0.05$) compared with A1. Among the three fertilization methods, balanced N-P-K application produced the greatest improvements in yield and WUE. (4) Correlation analysis revealed a significant positive correlation between soil water consumption during the tasseling–grain filling stage and yield. Conservation tillage improved soil water storage capacity during early growth, increased soil moisture during the critical tasseling–grain filling period, and enhanced WUE during key growth stages, thereby promoting grain yield. Therefore, the combination of subsoiling with balanced fertilization is a suitable planting pattern for improving spring maize yield and WUE in the Weibei dryland region.

Keywords: spring maize; conservation tillage; soil water consumption; water use efficiency; yield

1. Materials and Methods

1.1 Study Area

The experiment was conducted from 2013 to 2015 in Ganjing Town, Heyang County, eastern Weibei dryland region, Shaanxi Province (35°19 54.45 N, 110°05 58.35 E). The experimental area is a typical semi-humid drought-prone region with an average annual precipitation of 536.6 mm, mean annual temperature of 9–10°C, average evaporation of 1,832.8 mm, 10°C accumulated temperature of 2,800–4,000°C · d, and a frost-free period of 160–200 days. The experimental site was flat with dark loessial soil, having an average bulk density of 1.33 $g \cdot cm^{3}$ and strong water and nutrient retention capacity. Basic soil nutrients are shown in Table 1 . Precipitation during the spring maize growing season is shown in Figure 1 [Figure 1: see original paper].

1.2 Experimental Design

The experiment was established on three farmland plots with six comparative treatments of tillage and fertilization (Table 2), using a two-factor split-plot design. Tillage was the main plot factor (three levels: conventional tillage, no-tillage, and subsoiling), and fertilization was the subplot factor (two levels: with and without fertilizer), forming three tillage-fertilization zones and three tillage-without-fertilizer zones (Table 2). In the tillage-fertilization zone (A1, A2, A3), plot size was 25 m × 8 m; in the tillage-without-fertilizer zone (B1, B2, B3), plot size was 25 m × 4 m, with four replications. Nitrogen, phosphorus, and potassium fertilizers were applied as urea, diammonium phosphate, and potassium chloride, respectively, broadcast in a single application before rotary tillage to incorporate them into the 0–10 cm soil layer. Maize was sown using a planter with 30 cm spacing between plants and 60 cm between rows at a density of 55,500 plants · hm ^{2}, using the cultivar 'Zhengdan 958'. The cropping system was one season per year, with sowing in late April and harvest in mid-September.

1.3 Measurement and Calculation Methods

1.3.1 Measurement Methods

1) **Water measurement**: From March to November each year, soil moisture in the 0–200 cm layer was measured around the 20th of each month using the soil auger method. Samples were taken every 20 cm, weighed wet, then dried at 105°C for 8 hours and weighed dry. Four parallel measurements were taken for each treatment and averaged to calculate soil water content.
2) **Yield measurement**: At maize harvest, grain yield was determined using multi-point sampling. Twenty plants were collected from each plot and separated into grain and straw (all aboveground parts except grain) to determine grain yield and biomass.

1.3.2 Calculation Formulas Soil gravimetric water content = (wet soil mass - dry soil mass) / dry soil mass × 100% (1)

Soil water storage (w, mm) = × h × × 10 (2)

where is soil bulk density (g · cm ^{3}), h is soil layer thickness (cm), and is soil gravimetric water content (g · g ^{1}).

Crop water consumption at different growth stages (ET, mm) = P + U - R - F ± ΔW (3)

where P is precipitation (mm), R is runoff (mm), U is groundwater recharge (mm), F is deep percolation (mm), and ΔW is the difference between soil water storage at the end and beginning of the growth stage (mm). The experimental area had dark loessial soil that was loose and porous, with flat terrain resulting in minimal surface runoff. Groundwater depth exceeded 40 m, making upward recharge unlikely. In cropped fields, precipitation infiltration depth did not exceed 2 m even in wet years, so F, U, and R were negligible. Therefore, the formula was simplified to:

ET = P ± ΔW (4)

Water use efficiency (WUE, kg · hm ^{2} · mm ^{1}) = Y / ET (5)

where Y is grain yield at harvest.

1.4 Data Processing and Analysis

Data entry and calculations were performed using Microsoft Excel 2013 and Origin for graphing. Statistical analysis was conducted using SPSS 19 software for ANOVA and correlation analysis.

2. Results

2.1 Soil Water Storage in 0-200 cm Layer at Different Growth Stages of Spring Maize

Soil water storage at different growth stages is shown in Figure 2 [Figure 2: see original paper]. Sowing-stage soil water storage reflected the water conservation effect of conservation tillage during the fallow period. Both straw mulch no-tillage and straw mulch subsoiling significantly increased soil water storage at sowing compared with conventional tillage, with three-year averages showing increases of 23.39 mm and 27.73 mm, respectively, demonstrating that conservation tillage improved soil water storage capacity during the fallow period and enhanced pre-sowing soil moisture. Correlation analysis between soil water storage and yield (Table 3) revealed that during the growth period, A2 and A3 increased soil water storage by 13.15 mm and 19.54 mm compared with A1. At the jointing stage, A1 had the lowest soil water storage, while A2 and A3 showed no significant difference between them; A3 increased soil water storage by 31.85 mm, 9.38 mm, and 47.37 mm compared with A1 across the three years. At the heading stage, soil water storage followed the pattern A3 > A2 > A1, with A3 being significantly higher than A2 and A1. A3 increased soil water storage by 59.51 mm, 9.04 mm, and 55.28 mm compared with A1, and by 25.26 mm, 9.01 mm, and 27.39 mm compared with A2 across the three years. This indicates that A3 was beneficial for increasing soil water storage at the jointing and heading stages, contributing to yield improvement.

In the tillage treatment zone, soil water storage at jointing and heading stages showed no significant difference between B2 and B3, but both were significantly higher than B1. Average soil water storage during the entire growth period increased by 13.41 mm and 15.70 mm compared with B1. The difference between tillage-fertilization and tillage-without-fertilization zones reflected the water effect of fertilization. Under the same tillage practice, soil water storage in the fertilization zone was generally higher than in the no-fertilization zone during early growth, likely due to fertilizer promoting growth and reducing evaporation between plants. However, during the grain filling stage (2014 and 2015) and maturity stage (2013-2015), soil water storage in the fertilization zone was lower than in the no-fertilization zone, indicating that fertilization enhanced soil water utilization during critical growth periods and promoted grain development.

2.2 Soil Water Consumption at Different Growth Stages of Spring Maize

Soil water consumption was calculated from the change in soil water storage between the beginning and end of each growth stage, and daily average consumption was computed based on the observation interval days (Figure 3 [Figure 3: see original paper]). During sowing–emergence, soil water consumption was low in 2013 and 2014, but varied significantly among treatments in 2015. Treatments A1, A2, B1, and B2 consumed soil water, while A3 and B3 showed soil water replenishment, primarily due to inter-annual rainfall differences (Figure 1 [Figure 1: see original paper]) and demonstrating that straw mulch with subsoiling improved soil water storage capacity during early maize growth. The jointing-grain filling period was the main water consumption stage. Differences in soil water consumption among no-fertilizer treatments reflected the water consumption effects of different tillage methods. During jointing–heading and heading–grain filling, there were no significant differences among the three tillage methods in 2013, but in 2014 and 2015, B1 had the lowest water consumption while B2 and B3 showed no significant difference, indicating that straw mulch conservation tillage increased soil water consumption during these growth stages. Correlation analysis (Table 4) showed a positive relationship between water consumption during this period and yield, suggesting that B2 and B3 increased soil water consumption during critical growth stages, promoting yield improvement.

In the tillage-fertilization zone, water consumption patterns reflected different model characteristics. During jointing–grain filling, different models significantly affected soil water consumption. At jointing–heading, A2 showed significantly increased water consumption, while at heading–grain filling, A3 showed obvious increases. Correlation analysis revealed that A3' s water consumption pattern was more conducive to yield improvement. The difference between tillage-fertilization and tillage-without-fertilization zones reflected fertilization effects on water consumption. During the main water consumption period (jointing–grain filling), fertilization significantly increased soil water consumption. The three-year average daily water consumption during the entire growth period increased by 0.11 mm, 0.14 mm, and 0.25 mm for A1, A2, and A3 compared with B1, B2, and B3, respectively, with A3 showing the most pronounced increase, enhancing crop water utilization during critical periods.

2.3 Maize Yield and Water Use Efficiency Under Different Tillage and Fertilization Treatments

Grain yield and WUE under different tillage-fertilization combinations are shown in Table 5 . In the tillage treatment zone, straw mulch no-tillage and straw mulch subsoiling significantly increased grain yield, with three-year averages showing increases of 3.09% and 4.14% compared with B1, respectively. WUE increased by 3.6% and 8.2%, respectively, demonstrating that conservation tillage in dryland maize fields was beneficial for yield improvement and efficient water use. In the tillage-fertilization zone, differences in WUE and yield reflected the combined effects of tillage and fertilization patterns. Both A2 and A3 improved yield and WUE, with yield increases of 559–1,326 kg · hm ^{2} and 659–1,495 kg · hm ^{2}, and WUE improvements of 0.99–3.37 kg · hm ^{2} · mm ^{1} and 0.65–3.82 kg · hm ^{2} · mm ^{1}, respectively, both showing efficient production compared with A1. The difference between tillage-fertilization and tillage-without-fertilization zones reflected fertilization effects under different tillage practices. Fertilization significantly increased yield and WUE, with three-year averages showing yield increases of 1,065 kg · hm ^{2}, 1,790 kg · hm ^{2}, and 1,909 kg · hm ^{2}, and WUE improvements of 2.0 kg · hm ^{2} · mm ^{1}, 3.45 kg · hm ^{2} · mm ^{1}, and 3.33 kg · hm ^{2} · mm ^{1} for A1, A2, and A3, respectively. Balanced N-P-K fertilization produced the greatest improvements in yield and WUE. Therefore, the combination of subsoiling with balanced fertilization substantially improved spring maize yield and WUE, achieving efficient water production in dryland maize.

3. Discussion and Conclusion

Correlation analysis showed that soil water storage at the jointing stage had the greatest impact on spring maize yield, followed by the heading stage, which differs from traditional understanding [23-25]. This may be because rainfall is insufficient in this region, and stored soil water supplies most of the water consumed during later growth stages. Therefore, adequate soil moisture should be ensured before critical growth periods. Qin et al. [26] also noted that regardless of tillage method, stored soil water is an important component of water supply besides rainfall during the growth period, and improving soil water storage at jointing and heading stages can effectively increase grain yield in dryland maize.

Many researchers have confirmed that conservation tillage improves water storage, WUE, and yield compared with conventional tillage [27-29]. This study demonstrated that straw mulch no-tillage (B2) and straw mulch subsoiling (B3) significantly increased pre-sowing soil water storage compared with conventional tillage (B1), significantly enhancing soil water storage capacity. These practices also effectively reduced ineffective evaporation from exposed surfaces during early growth, increased soil water storage during critical growth periods, and directed limited soil water toward grain production. Further correlation analysis between water consumption and yield revealed a significant positive correlation between soil water consumption during the heading–grain filling stage and yield. Conservation tillage improved soil water storage during early growth, increased soil moisture during the heading-grain filling period, and enhanced WUE during critical periods, thereby promoting yield improvement. This aligns with the water consumption pattern of spring maize—conserving water early and supplying it during later growth stages. Thus, conservation tillage regulates water consumption during the growth period to match maize water requirements, which is a primary reason for yield improvement.

Increasing fertilizer application can significantly improve maize WUE and yield [33-34]. This study also found that fertilization effectively increased soil water storage during early growth and significantly improved WUE and grain yield. Balanced N-P-K fertilization produced the most obvious improvements in WUE and yield. Therefore, the improvements in yield and WUE under conservation tillage resulted from both the water conservation effects that increased soil moisture during critical growth periods and the increased fertilizer rates that enhanced grain production per unit of water resources. The combination of subsoiling with balanced fertilization is a suitable cultivation pattern for efficient maize production in this region. Implementing conservation tillage in dryland maize fields can fully utilize limited water resources and is of great significance for efficient maize production in arid regions.

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Note: Figure translations are in progress. See original paper for figures.