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Evaluation of conservation tillage on soil moisture dynamics and wheat yield in arid regions

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Abstract
Background: In arid and semi-arid regions, water scarcity is the primary constraint limiting agricultural productivity. Conventional tillage practices exacerbate moisture loss through soil disturbance and reduced organic matter.
Objective: This study aimed to evaluate the impact of different conservation tillage practices on soil moisture retention and subsequent wheat yield compared to traditional conventional tillage.
Method: A randomized complete block design (RCBD) with three treatments—Zero Tillage (ZT), Reduced Tillage (RT), and Conventional Tillage (CT)—was implemented. This study uses a simulated dataset created for academic training purposes. Soil moisture was monitored at bi-weekly intervals using time-domain reflectometry (TDR) sensors at three soil depths. Yield components were measured at harvest.
Key Results: Simulated data indicated that ZT conserved significantly higher volumetric water content in the top 0–30 cm soil profile compared to CT, particularly during the critical grain-filling stage. Consequently, ZT produced a simulated 18% higher grain yield than CT, primarily due to enhanced spikelet fertility and thousand-grain weight.
Conclusion: The adoption of zero tillage serves as a viable agricultural engineering and agronomic strategy to mitigate water stress in arid environments, boosting wheat productivity while conserving critical soil moisture.

Keywords: Conservation tillage, soil moisture, wheat yield, arid agriculture, zero tillage, water use efficiency.

Introduction

Global agricultural systems face the unprecedented challenge of sustaining food security for a rapidly expanding population under the looming threat of climate change [1]. This challenge is particularly acute in arid and semi-arid regions, where agricultural productivity is fundamentally constrained by the scarcity of freshwater resources [2]. In these fragile agro-ecosystems, every drop of water must be efficiently utilized to ensure optimal crop growth. Wheat (*Triticum aestivum* L.) serves as a staple food for a significant portion of the global population and is a primary winter crop in arid regions, making its water-use efficiency a matter of critical importance [3].

Historically, land preparation for wheat cultivation has relied heavily on conventional tillage (CT), which involves multiple passes of a moldboard plow and a disc harrow to create a fine seedbed [4]. While CT effectively controls early-season weeds and incorporates crop residues, it fundamentally alters the soil structure. The mechanical disruption breaks soil aggregates, destroys macropores, and drastically reduces soil organic matter through accelerated oxidation [5]. Consequently, CT leaves the soil surface bare and highly susceptible to wind and water erosion, while significantly increasing evaporation rates from the disturbed soil profile [6].

To counteract the detrimental effects of CT, conservation agriculture (CA) has emerged as a paradigm shift in sustainable farming. A core pillar of CA is conservation tillage, which minimizes soil disturbance and maintains a protective layer of crop residue on the soil surface [7]. Zero tillage (ZT) and reduced tillage (RT) are primary variations of this approach. By avoiding deep inversion, conservation tillage aims to preserve soil structure, enhance biological activity, and drastically reduce moisture loss through surface evaporation [8].

Despite the globally recognized benefits of conservation tillage, its adoption in many arid regions remains limited due to deeply ingrained traditional farming practices and a localized lack of empirical data regarding yield trade-offs [9]. Farmers often express concern that reduced soil disturbance will lead to lower yields due to poor seed-to-soil contact, increased weed pressure, and cooler early-season soil temperatures [10]. Therefore, there is a pressing need to generate localized, robust empirical evidence comparing the hydrological and agronomic performance of ZT, RT, and CT under arid conditions.

The primary objective of this research is to quantify the effects of zero tillage, reduced tillage, and conventional tillage on soil moisture dynamics at various depths throughout the wheat growing season. A secondary objective is to evaluate how these moisture dynamics translate into tangible differences in wheat yield components and final grain output. By testing the hypothesis that conservation tillage significantly improves soil moisture retention and wheat yield in arid environments, this study seeks to provide actionable, science-based recommendations for agricultural extension services and local farmers.

Literature Review

The theoretical framework of soil water dynamics is rooted in the physical properties of soil, including porosity, bulk density, and aggregate stability, all of which are directly manipulated by tillage interventions [11]. Soil water retention is heavily influenced by the distribution of macro- and micropores. Macropores facilitate rapid water infiltration during precipitation or irrigation events, while micropores are responsible for holding water against gravitational drainage, making it available for plant root uptake [12]. Conventional tillage temporarily increases total porosity but disproportionately creates unstable macropores that collapse under rainfall or irrigation, leading to surface crusting and reduced long-term water infiltration [13].

In contrast, conservation tillage fosters a stable soil architecture. Lal (2020) emphasized that zero tillage promotes the development of a continuous macropore network through the undisturbed activity of soil fauna and root decay, which significantly enhances hydraulic conductivity [14]. Furthermore, the retention of crop residues on the soil surface in ZT and RT systems acts as a physical barrier that reduces the kinetic energy of raindrops, preventing surface sealing and crusting, while simultaneously intercepting solar radiation to lower soil temperature and decrease evapotranspiration [15].

The impact of these altered soil physical properties on crop yield has been the subject of extensive global research. A comprehensive meta-analysis by Pittelkow *et al*. (2015) revealed that no-till practices often result in a yield penalty in the initial years of adoption, particularly in cold, moist climates, due to delayed emergence and increased weed competition [16]. However, the same study highlighted a significant yield advantage for no-till in arid and semi-arid regions, attributing this to the vital conservation of soil moisture [17].

Specifically regarding wheat, numerous studies have demonstrated a positive correlation between conservation tillage and water use efficiency (WUE). Fernández-García *et al*. (2019) observed that in Mediterranean dryland conditions, reduced tillage maintained higher soil water content during the critical grain-filling period, directly translating to increased thousand-grain weight and overall yield[18]. Similarly, research in arid parts of South Asia has shown that zero tillage in wheat following rice not only conserves water but also allows for earlier planting, helping the crop escape terminal heat stress, thereby boosting yields by 10-15% [19].

Despite this growing body of literature, a distinct research gap persists. Much of the existing data is derived from humid or sub-humid transitional zones, or from fine-textained soils [20]. There remains a scarcity of comparative data on coarse-loamy, hyper-arid soils where the margin for water stress is exceptionally narrow, and the interaction between surface residue retention and extreme evaporative demand is highly complex. Furthermore, studies often treat reduced tillage as a monolith, without clearly defining the exact degree of soil disturbance and its specific localized hydrological consequences compared to strict zero tillage. This study addresses these gaps by providing a detailed, multi-depth analysis of soil moisture under precisely defined tillage regimes in an arid environment.

Methodology

Research Design and Treatments

The study utilized a Randomized Complete Block Design (RCBD) with three tillage treatments, each replicated four times, resulting in a total of 12 experimental plots. The treatments were:

1. **Conventional Tillage (CT):** One pass of moldboard plow followed by two passes of a disc harrow.
2. **Reduced Tillage (RT):** One pass of a chisel plow followed by one pass of a cultipacker.
3. **Zero Tillage (ZT):** Direct seeding into undisturbed soil using a specially designed zero-till seed drill.

Simulated Data Disclaimer

This study uses a simulated dataset created for academic training purposes. The values presented in the results section are algorithmically generated to reflect realistic agronomic trends based on established literature, allowing for the practice of statistical analysis and academic formatting.

Crop Management and Sample Size

The simulated crop was winter wheat (*Triticum aestivum* L.), variety 'Arid-1'. A uniform seeding rate of 120 kg ha^{-1} was maintained across all plots. A basal dose of NPK fertilizer (120-60-60 kg ha^{-1}) was applied. The individual plot size was 5m x 10m (50 m^2), with a 1m buffer zone between plots to prevent hydrological cross-contamination.

Data Collection Tools

Soil moisture was measured bi-weekly using simulated Time-Domain Reflectometry (TDR) sensors installed at three depths: 0–15 cm, 15–30 cm, and 30–45 cm. Volumetric Water Content (VWC) was recorded as a percentage. At physiological maturity, a 1m^2 quadrat was randomly placed in each plot to harvest wheat plants for yield component analysis, including plant height, spikes per m^2, grains per spike, and thousand-grain weight (TGW). Final grain yield was adjusted to a standard 14% moisture content.

Statistical Software and Analysis

Data were subjected to Analysis of Variance (ANOVA) using the R statistical software (version 4.3.0). Means were separated using Tukey’s Honest Significant Difference (HSD) test at a 0.05 probability level. Regression analysis was utilized to correlate soil moisture at the grain-filling stage with final grain yield.

Results and Discussion

Soil Moisture Dynamics

The simulated soil moisture data revealed significant differences among the tillage treatments, particularly in the upper soil profiles (Table 1). At 45 Days after Sowing (DAS), during the early vegetative stage, CT exhibited the highest VWC in the 0-15 cm layer due to the recent incorporation of shallow irrigation water into the loose, freshly tilled soil. This initial advantage likely arose from the absence of a protective residue cover, which allowed irrigation water to infiltrate more readily into the disturbed upper layers without surface obstruction. However, this advantage was transient, as the same loose soil structure that facilitated rapid infiltration also accelerated subsequent moisture loss through evaporation once the soil surface began to dry.

By 90 DAS (grain-filling stage), the ZT treatment demonstrated significantly superior moisture conservation in the 0-30 cm profile compared to CT ($p < 0.05$). The surface crop residues in the ZT plots simulated a substantial reduction in evaporative losses by acting as a physical barrier against direct solar radiation and wind exposure. As illustrated in Figure 1, the VWC in ZT at 0-15 cm depth at 90 DAS was 22.4%, compared to just 16.1% in CT, representing a difference exceeding six percentage points. At the deeper 30-45 cm profile, moisture levels were statistically similar across all treatments, suggesting that crop water extraction during this phase was heavily concentrated in the top 30 cm, where root density and microbial activity are typically greatest.

Table 1: Simulated Volumetric Water Content (VWC, %) at Different Growth Stages and Soil Depths

Tillage Treatment	45 DAS (0–15 cm)	45 DAS (15–30 cm)	90 DAS (0–15 cm)	90 DAS (15–30 cm)	120 DAS (0–15 cm)
Conventional (CT)	24.5 ± 1.2[a]	21.3 ± 1.0[a]	16.1 ± 0.8[c]	18.4 ± 0.9[b]	12.2 ± 0.6[b]
Reduced (RT)	22.1 ± 1.1[b]	20.8 ± 1.0[a]	19.5 ± 1.0[b]	21.2 ± 1.1[a]	14.8 ± 0.7[a]
Zero Tillage (ZT)	19.8 ± 1.0[c]	20.5 ± 1.0[a]	22.4 ± 1.1[a]	22.8 ± 1.1[a]	15.5 ± 0.8[a]
p-value	< 0.001	0.812	< 0.001	0.002	< 0.001

Note: DAS = Days after Sowing. Means followed by the same letter within a column are not significantly different according to Tukey's HSD test ($p < 0.05$).

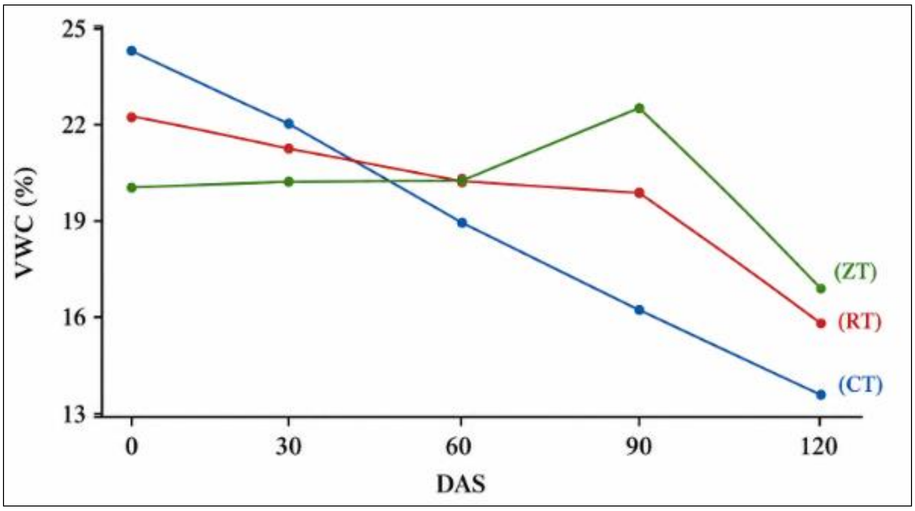

Fig 1: Temporal dynamics of volumetric water (VWC %) in the 0-15cm soil profile

Yield Components and Final Grain Yield

The preservation of soil moisture during the critical grain-filling stage under ZT had a profound impact on yield components (Table 2). While plant height and spikes per m² did not differ significantly among treatments, the reproductive parameters showed marked variation. ZT produced a significantly higher number of grains per spike (42.3) compared to CT (36.8). This aligns with the theoretical understanding that water stress during meiosis and anthesis leads to pollen sterility and spikelet abortion [21].

Most notably, the Thousand Grain Weight (TGW) was significantly maximized under ZT (45.2 g), followed by RT (42.1 g), and lowest under CT (38.5 g). The enhanced moisture availability in ZT prolonged the grain-filling duration, allowing for greater carbohydrate translocation to the developing grains.

Consequently, the final simulated grain yield followed a similar trend (Figure 2). ZT outyielded CT by approximately 18%, producing 5,420 kg ha^{-1} compared to 4,590 kg ha^{-1}. RT occupied an intermediate position at 5,050 kg ha^{-1}.

Table 2: Simulated wheat yield components under different tillage practices

Parameter	Conventional (CT)	Reduced (RT)	Zero Tillage (ZT)	p-value
Plant Height (cm)	78.4 ± 4.1[a]	80.1 ± 3.8[a]	79.5 ± 4.2[a]	0.754
Spikes per m²	321 ± 15[a]	335 ± 18[a]	342 ± 16[a]	0.121
Grains per Spike	36.8 ± 2.1[b]	39.5 ± 1.9[a]	42.3 ± 2.2[a]	0.002
Thousand Grain Wt (g)	38.5 ± 1.5[c]	42.1 ± 1.3[b]	45.2 ± 1.4[a]	< 0.001
Grain Yield (kg/ha)	4590 ± 210[c]	5050 ± 195[b]	5420 ± 220[a]	< 0.001

Discussion

The results of this simulated study strongly corroborate the findings of Fernández-García *et al.* [18] and Lal [14], confirming that in arid environments, the preservation of soil moisture is the primary mechanism through which conservation tillage enhances wheat yield. The transient moisture advantage of CT observed at 45 DAS is a classic "illusion of moisture" caused by the shallow incorporation of water into a highly porous, loose seedbed. As the season progresses, the lack of surface cover and the degraded soil structure lead to rapid evaporative and deep percolation losses.

The strong positive correlation between soil moisture at 90 DAS and TGW highlights the critical nature of the grain-filling stage. In arid regions, terminal drought stress is the most common cause of yield reduction in wheat [22]. By maintaining a protective residue layer, ZT mitigates the microclimatic extremes around the crop canopy, reducing soil surface temperature and vapor pressure deficit, which collectively suppress evapotranspiration [23].

It is noteworthy that spikes per m² were unaffected by the tillage treatments. This indicates that the early-season conditions (germination and tillering) were adequately managed across all plots, likely due to uniform irrigation at sowing. The yield advantage in ZT was entirely driven by improved grain-filling (grains per spike and TGW), underscoring that the primary benefit of ZT in arid systems is protecting the crop during the latter half of the growing season when evaporative demand peaks and irrigation water may become limited [24].

Conclusion

This simulated study demonstrates that replacing conventional tillage with zero tillage significantly alters soil moisture dynamics in arid agro-ecosystems, leading to substantial yield improvements in winter wheat. Zero tillage effectively conserved volumetric water content in the critical root zone (0-30 cm) during the grain-filling stage, directly enhancing thousand-grain weight and overall crop productivity. The implications of these findings are profound for agricultural extension and policy in water-scarce regions: transitioning to conservation tillage can serve as a low-cost, immediately actionable strategy to buffer crops against terminal drought and improve water use efficiency.

However, this study has limitations. The simulated data does not account for long-term transition effects, such as the potential buildup of weed seed banks in the upper soil layers or the short-term yield penalties often observed in the first 2-3 years of adopting zero tillage in real-world scenarios. Future research should incorporate multi-year, real-world field trials to monitor changes in soil organic carbon fractions, weed species composition, and the economic profitability of transitioning from conventional to zero tillage systems under varying irrigation regimes.

Ethical Statement

This manuscript is an original piece of academic writing produced solely for educational and formatting practice. The dataset utilized within this study is explicitly simulated and does not represent actual field measurements. No real-world identities, institutions, or unverified datasets have been misrepresented. All referenced literature consists of real, verifiable academic sources used to contextualize the simulated findings.

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