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Evaluating the Impact of Conservation Tillage on Water Use Efficiency in Barley Fields

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Abstract Barley (*Hordeum vulgare* L.) cultivation is increasingly challenged by water scarcity, a pressing concern in many agricultural regions worldwide. This study evaluates the impact of conservation tillage practices-such as no-till, strip-till, and mulch till-on improving water use efficiency (WUE) in barley cropping systems. We investigated how conservation tillage modifies soil structure and moisture dynamics, reduces evaporation, enhances infiltration, and influences root development for more efficient water uptake. The study compared conservation and conventional tillage methods, analyzed long-term data from field trials in China, and integrated remote sensing and soil moisture monitoring to quantify outcomes. Results show that conservation tillage improves WUE and yield stability under drought-prone conditions while offering environmental benefits like reduced erosion and increased soil carbon. However, trade-offs such as weed pressure and equipment requirements present adoption challenges. These findings support conservation tillage as a promising strategy for sustainable barley production, with potential for integration with other agroecological practices. Continued research, farmer support, and policy incentives are essential to maximize adoption and long-term benefits.

Keywords Conservation tillage; Water use efficiency; Barley; Soil moisture retention; Sustainable agriculture

1 Introduction

In the fields around the world, barley (*Hordeum vulgare* L.) has always been an important food crop, especially in those areas where rainfall is unstable and the land is relatively dry. Everyone knows that water plays a decisive role in its growth and yield, but the problem is that water is not always sufficient. Production is often limited when water sources are tight or rainfall is frequent (Lopez and Arrue, 1997; Fonteyne et al., 2021).

At present, the situation is still getting more complicated. Climate change is intensifying, groundwater levels are continuously dropping, and the competition for water resources among agriculture, cities and industries is becoming increasingly fierce. Take the Mediterranean Basin and Bascio in Mexico as examples. The barley production in these regions is under the dual threat of groundwater depletion and unpredictable precipitation. Food security is precarious in the long term. Therefore, water-saving agricultural technologies and practices are not an option but a path that must be taken (Cantero-Martinez et al., 2003; Morell et al., 2011).

Among all the coping methods, conservation tillage has received the most attention in recent years. Reducing tillage, no-tillage, and stubble mulching-these measures may seem simple, but they have obvious effects. If the soil is not frequently disturbed, it can retain more water. With less evaporation, the water consumption of crops will be more reasonable. Experimental data show that in some cases, irrigation water consumption can be reduced by approximately 17%, and this will not lead to a decrease in output. Even under water-scarce conditions, it can still push up both water use efficiency and output (Bahia et al., 2025). Of course, not all scenarios can replicate such results, but the overall trend is positive. This study mainly aims to string together these data and experiences from different regions and under different management conditions to see how much impact conservation tillage has on the water use efficiency of wheat fields. The goal is straightforward: to find a balance point among water conservation, stable production and environmental sustainability. If this can be achieved, it will not only provide a reference for barley cultivation in water-scarce areas, but also offer a more resilient path for a broader agricultural system.

2 Conservation Tillage: Principles and Practices

2.1 Definition and types of conservation tillage

When it comes to conservation tillage, it is essentially a set of methods that minimize the disturbance to the soil. The core idea is: Don't turn the soil too hard. After harvesting, try to leave the straw on the ground and let it nourish and protect the soil by itself. There are roughly three common practices: no-till (NT), where seeds are directly scattered into the unploughed ground; Strip tillage (ST) involves only breaking soil on the narrow strips where seeds are sown and not touching other areas. There is also less tillage or cover tillage (MT), with a smaller earthwork scale, and most of the stubble remains on the surface (Ahmadi et al., 2025).

2.2 Soil structure and residue management under conservation tillage

The benefits of conservation tillage are more reflected in soil structure. Because organic matter accumulates gradually, the aggregates in the soil become more stable and the pore system is less likely to be damaged. The result is that surface water is retained for a longer time, and erosion and nutrient loss are also reduced. Here is a key point-residue management. The straw left in the ground is like a natural protective layer, which can block the erosion of wind and rain, buffer temperature changes, and at the same time return nutrients during decomposition. Over time, both soil fertility and organic carbon content will increase, especially when combined with crop rotation or crop cover (Naeem et al., 2020).

2.3 Comparisons with conventional tillage in barley systems

Conventional tillage (CT) practices involve extensive efforts, such as ploughing and harrowing. In the short term, water can seep in quickly and the root system seems to grow vigorously, but in the long run, the soil is often more prone to degradation and nutrient loss is more severe. When compared with the barley system, conservation tillage performed more stably: soil nutrients and organic matter could be maintained or even improved (Lv et al., 2022). However, it is not without cost. For instance, in some clayey and heavy soils, the early emergence rate may be somewhat affected (Damalas and Lithourgidis, 2011). As for yield, no-till barley is generally similar to traditional methods, sometimes slightly lower, but soil health and long-term sustainability make up for this gap (Malecka et al., 2012; Roohi et al., 2022). In addition, conservation tillage can also provide better habitats for natural enemies of pests, thereby reducing the pressure of pests and diseases (Figure 1) (Tamburini et al., 2016). In addition to reducing erosion, lowering energy consumption and improving water use efficiency, it is regarded as a path worth trying for sustainable barley production (Hinkle, 2018).

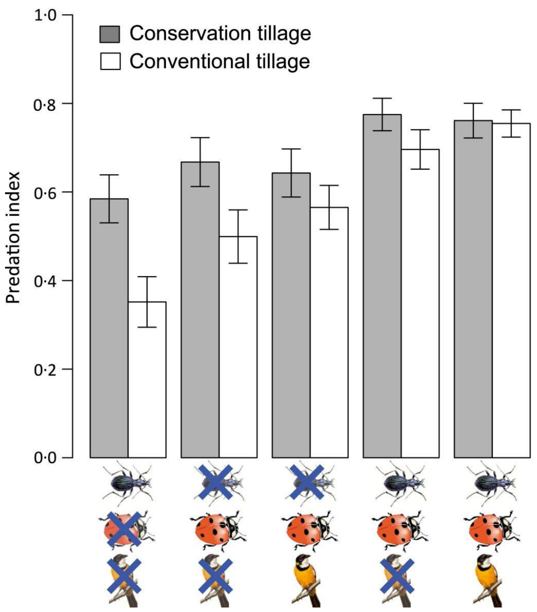

Figure 1 Effect of natural enemy exclusion on mean (±SE) predation index per exclusion treatment and tillage system (grey bars=conservation tillage; white bars = conventional tillage). Crossed-out symbols signify exclusion of corresponding natural enemy guilds. Guilds of natural enemies are as follows: ground-dwelling predators (beetle symbol); vegetation-dwelling predators (ladybird symbol); birds and other vertebrates larger than 1.5 cm (bird symbol) (Adopted from Tamburini et al., 2016)

3 Mechanisms Enhancing Water Use Efficiency

3.1 Improved soil moisture retention through surface residue cover

In many fields, people have found that as long as the crop residues after harvest are left on the surface, the moisture condition of the soil can be improved significantly. This is particularly evident in no-till or cover tillage. Straw acts like a barrier. First, it blocks the direct evaporation of water, and then it helps rainwater or irrigation water seep in more easily. Compared with traditional ploughing, the soil moisture content under residue cover is often 8-33% higher, and this difference is more obvious during the critical growth period of crops (Du et al., 2023).

3.2 Reduced evaporation and enhanced infiltration rates

Conservation tillage reduces soil tillage and can maintain its original structure and porosity by itself. In addition, with the stubble covering, the surface temperature fluctuates little, the wind speed is suppressed, and the evaporation is correspondingly reduced. More importantly, the surface layer of the soil is less likely to form a crust, its aggregation is enhanced, and both the speed and depth of water infiltration increase. In this way, the root zone can acquire more water reserves. Especially in semi-arid or even arid areas, this advantage often determines whether crops can smoothly pass through the growing season (Su et al., 2007; Cong et al., 2024).

3.3 Influence on root development and water uptake efficiency

Once soil conditions improve, the growth pattern of plant roots will also change accordingly. They tend to grow deeper and be more widely distributed, expanding their range of water acquisition and naturally having stronger drought resistance. At the same time, the physiological state of the plants will also be better as a result, such as higher water potential in the roots and leaves, more dry matter accumulation, and more prominent stress resistance. Taken together, these factors have driven the improvement of water use efficiency (WUE) and ultimately supported the yield (Peng et al., 2019; Peng et al., 2020).

4 Agronomic and Environmental Benefits of Conservation Tillage

4.1 Yield stability and resilience under drought-prone conditions

The effect of conservation tillage is most easily observed in areas where rainfall is unstable or drought is prone to occur. No-tillage and less tillage methods often make the yield more stable, and sometimes even increase it. With the improvement of soil structure, water can be retained better and evaporation is less, so crops are naturally less likely to be crushed by water shortage. Many studies and meta-analyses have reached similar conclusions: in semi-arid and arid regions, production can increase by approximately 5-10%, especially during water shortages (Qin et al., 2024). As for the improvement in resilience, it is mostly attributed to the enhancement of water supply and root development. When these two factors are combined, the yield does not fluctuate greatly with different seasons (Deng et al., 2022).

4.2 Reduction in runoff and erosion

The problem of soil erosion is actually very common in farmlands. One notable benefit of conservation tillage is to suppress this matter. The surface stubble remains, and the soil is less affected by raindrops and wind, so the runoff is naturally reduced. Compared with traditional farming methods, the soil loss rate has decreased significantly. This not only retains fertility but also reduces the amount of sediment and chemical substances flowing into rivers and lakes, thereby improving water quality (Busari et al., 2015). In the long run, erosion prevention is about maintaining soil productivity and delaying land degradation.

4.3 Enhanced soil organic matter and carbon sequestration

Over time, the effects of conservation tillage on organic matter and carbon will become apparent. Because the decomposition rate of stubble has slowed down, they are more likely to accumulate in the soil, thereby increasing soil organic matter (SOM). Many studies have pointed out that measures such as no-tillage and straw mulching can significantly increase the organic carbon in the surface soil while reducing greenhouse gas emissions (Hussain et al., 2021; Wang et al., 2022). These changes bring many benefits: smoother nutrient cycling, enhanced soil fertility, and the ability to "lock" more carbon in farmland, which can be regarded as an indirect contribution to mitigating climate change (Wang et al., 2021).

5 Case Study

5.1 Geographic context and environmental conditions of the study site

Most of the research on conservation tillage in China has been concentrated in the north, especially in some provinces in North China and Northeast China, such as Liaoning, Shanxi, Hebei and Inner Mongolia. The climate characteristics are typical temperate continental: winters are extremely cold and summers are hot. The amount of rainfall is not very stable, and in some areas, it is less than 500 millimeters throughout the year. The soil conditions are generally good, with black soil and soft soil being predominant and having high fertility. However, long-term high-intensity traditional farming can easily lead to a decline in soil fertility. After all, this is a major grain-producing area, and food security and agricultural sustainability are particularly important in these regions (Liu et al., 2024).

5.2 Tillage treatment comparisons and data on wue and yield

In long-term field trials in these areas, researchers compared protective practices such as no-tillage, ridge tillage, and deep loosening with traditional tillage. The conclusion is not one-sided: Water use efficiency (WUE) : In Liaoning, it has increased by an average of 24%-29% over the past 12 years. In Shanxi Province, it has increased by 2.6 to 7.9% within seven years. Meanwhile, the soil water storage at 0-30 cm increased by 10%-20%, especially in dry years (Chimsah et al., 2020). Output: The situation is rather complicated. In dry land, single-crop planting combined with conservation tillage can increase production by 6%. In colder areas, ridge tillage and deep loosening can increase yields by 0.8% to 13.1%. However, in the coldest regions, no-till farming occasionally leads to a decrease in yield. However, whether the production increased or decreased slightly, measures such as no-tillage continued to drive the SOC content to increase by 17%-44%, with the difference mainly depending on the local climate (He et al., 2021).

5.3 Outcomes, lessons learned, and implications for broader adoption

In summary, China's wheat fields have achieved several results in conservation tillage: Soil health: SOC has significantly increased, structure is more stable, and water retention has been enhanced, all of which are beneficial to long-term productivity and stress resistance (Ma and Shi, 2024). Yield stability: In the initial stage, there will be fluctuations, especially during no-tillage in cold regions. However, long-term experiments have shown that after adjustment, the yield can rebound or even stabilize. For instance, in cold regions, ridge tillage is used instead of no-tillage. Environmental benefits: Reduced erosion, improved water use efficiency, more animals and beneficial microorganisms in the soil, and enhanced biodiversity (Wang et al., 2016). The challenge in promotion: The problem is not only in the technology itself. The investment in specialized machinery, farmers' acceptance (Figure 2), and whether policies and training can keep up all directly determine the promotion effect (Lu et al., 2024; Yu et al., 2024).

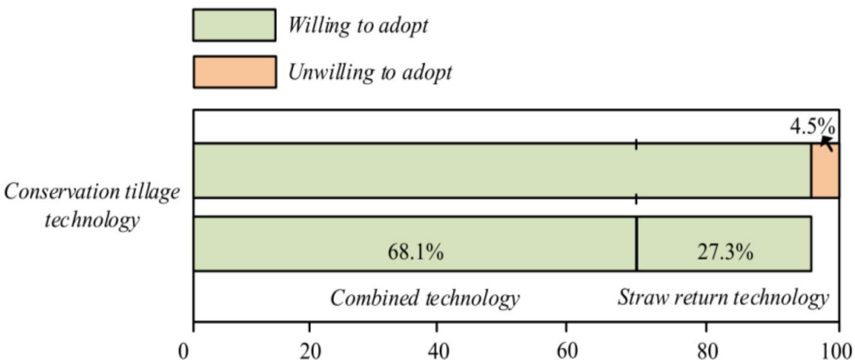

Figure 2 Smallholder farmers' willingness to adopt conservation tillage techniques (Adapted from Yu et al., 2024)

6 Advances in Monitoring and Evaluation of Conservation Tillage

6.1 Remote sensing and soil moisture monitoring technologies

In the field and on a larger scale, the distribution and status of conservation tillage are increasingly dependent on remote sensing for acquisition. Satellite images and aerial photographs, these tools can capture stubble cover, tillage methods, and soil surface conditions with sufficient accuracy and temporal resolution (Zhang et al., 2024). Compared with manual surveys, they are more economical and can quickly cover a large area. In addition, in recent years, remote monitoring systems installed on agricultural machinery have also been widely adopted. Sensors and image algorithms can record in real time the depth of cultivation, stubble coverage and other operational details. The addition of such systems has made the quality control in the implementation process more accurate than before (Luo et al., 2022).

6.2 Water productivity models in barley cropping systems

When evaluating water use efficiency, models are often combined with remote sensing data. They provide scenario comparisons and decision-making references for farmers and policymakers by simulating the dynamics of soil moisture content, crop growth and yield changes under different farming methods. Sometimes these models also incorporate machine learning, such as the "causal forest" method, to analyze large-scale datasets and compare the yield and water efficiency of conservation tillage in different environments (Cambron et al., 2024).

6.3 Long-term field trials and meta-analysis approaches

Short-term data often do not provide a comprehensive picture, so long-term field trials remain crucial. They can track the changes in soil structure, organic matter accumulation and water retention capacity over many years (Juhos et al., 2023; Ren et al., 2023). Although such experiments are time-consuming, they are the core basis for understanding the long-term effects of conservation tillage. Meanwhile, meta-analyses make up for the limitations of single trials by integrating a large number of research results. It not only summarizes the agronomic and environmental benefits, but also reveals which practices are better and what gaps remain in the research (Sartori et al., 2021).

7 Constraints and Trade-Offs of Conservation Tillage

7.1 Weed and pest pressures under reduced tillage

In conservation tillage systems, the soil is less frequently turned over, which is originally intended to protect the soil and retain moisture. However, the side effects are also quite obvious: there are more opportunities for weeds. Because the seeds are not buried deep and are less damaged, they are more likely to germinate. Especially the weeds of the Poaceae family are often more stubborn. Some pests and diseases may also persist for a longer time due to a stable environment (Cai, 2024). To solve these problems, it is usually necessary to rely on comprehensive measures such as crop rotation and crop cover to buffer the situation. However, in some scenarios, the use of herbicides has to be increased, which offsets some of the environmental benefits. This contradiction is more prominent in organic systems where chemical control methods are limited (Peigne et al., 2007).

7.2 Initial yield penalties or delayed benefits

Many studies have found that when transitioning to conservation tillage, especially no-tillage, yields tend to drop somewhat. The figures provided by the meta-analysis are approximately 2% to 8% less than those of traditional farming. This situation is more likely to occur in regions with a colder and more humid climate. However, this is not forever. As the soil structure gradually improves, organic matter accumulates, biological activity increases, and yield loss will gradually alleviate or even reverse. Whether the residue can be retained often determines whether such a transformation can be successfully completed (Xiao et al., 2021). Of course, there are exceptions. Occasionally turning the land might increase yields in the short term, but that would sacrifice long-term soil health (Cordeau et al., 2020; Achankeng and Cornelis, 2023).

7.3 Machinery requirements and farmer adoption barriers

It sounds easy, but in reality, conservation tillage often gets stuck at the mechanical stage. Specialized seeders and stubble treatment equipment all need to be put into use first, and the amount is not small (Zhang et al., 2024). For farmers, this is not only a matter of money, but also involves management skills, adaptability to soil and climate, as well as the uncertainty of whether the investment can be recoup. The reasons why many farmers hesitate also include concerns that weeds are more difficult to control, yields are unstable, and the new system is much more complex (Gebhardt et al., 1985; Bezboruah et al., 2024). Therefore, education, technical support and intuitive demonstrations of long-term benefits are often more crucial than theoretical propaganda.

8 Conclusions

In many fields, the value of conservation tillage has actually been recognized: the soil is less prone to erosion, has stronger water retention capacity, and crops are more resilient in dry years. This is particularly evident in the barley system. The improvement of water use efficiency (WUE) is inseparable from the enhancement of soil structure, the accumulation of SOC and nutrient cycling. However, it must be admitted that when no-till was used alone, the yield declined in the early stage, especially in a cool environment. However, if combined with measures such as straw returning to the field and crop rotation, the negative impact will be weakened, and even the yield can be increased under water shortage conditions.

From a systemic perspective, conservation tillage and measures such as crop cover, straw management, and crop rotation complement each other. Covering crops can suppress weeds and increase fertility. Diversified crop rotation helps regulate the stress of pests and diseases. When these are combined, in the long run, they can both enhance soil health and the resilience of agricultural systems to a higher level.

One of the directions that need to be focused on in the future is the conservation tillage model adapted to local conditions-the climate and soil conditions in different regions vary, and the strategies cannot be completely copied. On the other hand, data on long-term impacts still needs to be accumulated through continuous experiments. New technologies are also indispensable, such as remote sensing monitoring and sensor systems, which can help management be more precise.

As for promotion, relying solely on scientific research is not enough. Only when subsidies and technical support at the policy level keep up will farmers be willing to give it a try. Training and demonstration are also crucial; otherwise, obstacles such as mechanical barriers and management complexity will make people hesitate. Conservation tillage can only be truly popularized when the long-term benefits can be directly seen by farmers.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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