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More Crop Per Drop: Soil-Moisture Conservation Through Smart Agronomic Practices

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INTRODUCTION

Water is one of the most important factors governing agricultural productivity, yet its availability is becoming increasingly uncertain because of irregular rainfall, rising temperatures, recurrent droughts, groundwater depletion and increasing competition among agricultural, domestic and industrial uses. Agriculture must therefore produce more food with less water while maintaining soil health and farm profitability. The concept of "More Crop Per Drop" represents this need by emphasizing efficient use of every unit of water available to the crop. The objective is not simply to apply less water, but to improve the proportion of available water that is stored in the root zone, accessed by plants and converted into useful biomass and economic yield.

Soil is the main reservoir through which rainfall and irrigation water become available to crops. However, a considerable fraction of incoming water may be lost through surface runoff, deep drainage, evaporation and inefficient irrigation. Poor soil structure, low organic matter, excessive soil disturbance, inadequate residue management and uncontrolled weeds can further reduce the amount of water available to crops. Smart agronomic management therefore needs to address the complete soil water balance rather than focusing on irrigation alone. Soil moisture conservation combines practices that increase infiltration, reduce evaporation, improve soil water storage, maintain crop residues, enhance root development and synchronize water availability with crop demand. Conservation agriculture, mulching, residue retention, improved tillage, diversified cropping, efficient irrigation, soil moisture monitoring and appropriate crop establishment can work together to improve water productivity. A global meta-analysis of long term dryland wheat experiments found that no tillage increased precipitation storage efficiency, soil water storage, grain yield and water use efficiency compared with conventional tillage, although responses varied with soil and climatic conditions (Adil *et al*., 2024).

The importance of soil moisture conservation is particularly high in rainfed and semi-arid agriculture. Rainfall may arrive in short, intense events followed by prolonged dry periods. If rainfall cannot infiltrate rapidly into the soil, much of it may be lost as runoff. Conversely, when soil is protected by residues and organic matter, rainfall infiltration can improve and evaporation from the soil surface can decline. Conservation agriculture practices based on reduced soil disturbance, crop diversification and residue retention have been associated with improved water availability and reduced evaporative losses, although the magnitude of improvement depends strongly on soil type, climate and management history (Abdallah *et al*., 2021).

Understanding the More Crop Per Drop Concept

The More Crop Per Drop approach is fundamentally based on improving water productivity. Water productivity can be expressed as the quantity of crop yield produced per unit of water consumed or supplied. A simplified expression is:

Water productivity = Crop yield ÷ Water used

A higher value means that a greater quantity of useful crop production is obtained from the available water. Water productivity should not be confused with simply reducing irrigation. If irrigation is reduced excessively during a sensitive growth stage, crop yield may decline more than the quantity of water saved. The most effective approach is therefore to provide water when the crop needs it, place water close to the active root zone, reduce unnecessary losses and improve the capacity of the soil to store water. Deficit irrigation provides an important example. A global meta-analysis involving maize, wheat, cotton, potato, tomato, apple and grape showed that deficit irrigation and alternate partial root zone irrigation can increase water use efficiency, although yield responses vary among crops and environments. Therefore, irrigation strategies need to consider crop sensitivity, soil texture, climate and the economic value of saved water rather than applying the same irrigation schedule everywhere (Cheng *et al*., 2021).

Building Soil Water Storage Capacity

The first principle of soil moisture conservation is to increase the ability of soil to capture and store rainfall or irrigation water. Soil structure has a major influence on infiltration, drainage, root growth and water availability. Soils with stable aggregates and sufficient organic matter generally provide a better environment for root growth and biological activity.

Organic matter contributes to aggregation and can influence soil pore structure. Crop residues, compost, farmyard manure, green manures and other organic inputs can therefore contribute to the long term improvement of soil physical conditions. However, the relationship between soil organic carbon and water holding capacity is not always simple. Abdallah *et al*. (2021) noted that conservation agriculture can improve infiltration and reduce evaporation, while increases in whole profile water holding capacity may be more variable because changes in organic carbon can be concentrated near the soil surface.

Conservation Tillage for Better Soil Moisture

Conventional intensive tillage can break soil aggregates, disturb biological channels and expose moist soil to atmospheric conditions. Repeated soil disturbance may increase evaporation and accelerate the decomposition of organic matter. Conservation tillage reduces unnecessary disturbance and can help maintain residues on the soil surface.

No tillage and reduced tillage can increase rainfall infiltration and reduce the loss of water through surface runoff. They can also maintain crop residues that act as a protective

layer over the soil. A global meta-analysis of long-term dryland wheat systems reported that no tillage increased precipitation storage efficiency, soil water storage, grain yield and water use efficiency compared with conventional tillage. Reduced tillage and subsoil tillage also improved several soil water and yield indicators, although the response depended on soil texture and climatic conditions (Adil *et al*., 2024). Conservation tillage should not be regarded as a universal prescription. Heavy soils, compacted soils and fields with specific drainage problems may require carefully selected tillage operations. The appropriate system should maintain sufficient soil cover while ensuring adequate seed placement, root development and infiltration.

Mulching: A Simple Tool for Moisture Conservation

- Mulching is one of the most practical methods of conserving soil moisture. A mulch layer creates a physical barrier between the soil and atmosphere. It reduces direct exposure of soil to sunlight and wind, moderates soil temperature and reduces evaporation.
- Organic mulches include straw, crop residues, leaves, composted materials and other locally available biomass. Synthetic mulches include plastic films and biodegradable films. Organic materials provide an additional benefit because they can contribute organic matter as they decompose.
- A meta-analysis involving 1,310 observations from 74 studies conducted in 19 countries found that soil mulching significantly improved yield, water use efficiency and nitrogen use efficiency in maize and wheat compared with no mulching, although responses varied according to crop, climate and mulch type (Qin *et al*., 2015).
- A recent review also highlighted the role of mulching in reducing soil evaporation, maintaining root zone moisture, regulating soil temperature and improving soil conditions in dryland agriculture (Demo & Asefa Bogale, 2024).
- The choice of mulch should be based on availability, cost, crop requirements and environmental considerations. Crop residues are often particularly attractive because they are available directly on the farm. However, excessive removal of residues for fodder or fuel can reduce the amount available for soil protection. Therefore, residue allocation should consider the overall needs of the farming system.

Crop Residue Management

Crop residues are an important component of soil moisture conservation. Leaving suitable quantities of straw, stalks, leaves and other residues on the soil surface reduces the direct impact of raindrops, slows runoff and reduces evaporation. Residues also contribute organic carbon to soil when they decompose. Over time, this can support aggregation, microbial activity and nutrient cycling. Residue retention is particularly important in dryland farming where rainfall is limited and every rainfall event represents a valuable opportunity to replenish soil water. Residue management should be based on local conditions. Thick residue layers may interfere with seed placement or early crop establishment in some systems, while insufficient residue may provide inadequate soil protection. The objective should therefore be an appropriate level of residue retention rather than maximum residue accumulation.

Cover Crops and Living Soil Cover

Cover crops provide another biological approach to soil moisture conservation. Legumes, grasses and mixtures can protect the soil surface from direct rainfall impact and solar radiation while their roots contribute to soil

biological activity. Cover crops can improve soil structure and reduce erosion, but their water consumption must also be considered. In water limited environments, a cover crop may compete with the following cash crop for stored soil moisture if termination is poorly timed. Therefore, species selection, planting density and termination timing should be matched with rainfall patterns and soil water availability. The central principle is to maintain living roots and soil cover when they provide a net benefit to the cropping system without creating excessive competition for limited water.

Crop Rotation and Diversification

Crop rotation influences soil moisture conservation through changes in rooting patterns, residue quality, soil structure and biological activity. Different crops explore different soil layers and use water at different times. A well designed rotation can therefore reduce excessive depletion of a particular soil layer. Deep rooted crops may access water from deeper soil zones, while shallow rooted crops primarily exploit upper soil layers. Including legumes can also improve biological nitrogen fixation and contribute to soil fertility. Crop diversification may therefore indirectly improve water productivity by improving soil condition and reducing production risks. Crop diversification is one of the important components of conservation agriculture. However, the water demand of each crop must be considered when designing rotations for dryland environments. A diversified rotation should be based on the actual rainfall and soil water conditions of the region rather than simply increasing the number of crops.

Efficient Irrigation Management

Efficient irrigation is essential wherever supplemental or full irrigation is available. Traditional calendar-based irrigation can result in water being applied when the crop does not require it. Scientific scheduling aims to match irrigation timing and quantity with soil moisture, crop growth stage and atmospheric demand. Drip irrigation delivers water close to the crop root zone and can reduce unnecessary wetting of the soil surface. Subsurface drip systems can further alter the location of water application and reduce direct surface evaporation. However, the performance of irrigation systems depends on system design, maintenance, soil texture, emitter placement, crop spacing and management.

Film mulching combined with drip irrigation has also been studied extensively. A meta-analysis of 54 studies reported that film mulching with drip irrigation increased crop yield and water use efficiency compared with drip irrigation without film mulch, although the response depended on climate, soil, crop type and water supply (Zhang *et al*., 2022).

Soil Moisture Sensor Based Irrigation Scheduling

Modern soil moisture sensors provide an opportunity to move from fixed irrigation schedules toward demand based irrigation. Sensors can monitor soil water conditions at selected depths and help farmers determine when irrigation is required. Sensor based irrigation scheduling is especially useful where irrigation water is limited or electricity costs are high. A systematic review of soil water sensor studies found that sensor based scheduling generally reduced water use compared with several conventional scheduling approaches while maintaining similar or higher crop yields. The review also emphasized that sensor accuracy depends strongly on calibration and installation conditions (Datta & Taghvaeian, 2023). Sensors should therefore not simply be installed and left without calibration. Soil texture, salinity, sensor depth and crop rooting depth should be considered. Measurements should also be interpreted alongside weather forecasts, crop growth stage and recent irrigation or rainfall.

Matching Irrigation with Crop Growth Stages

Not all stages of crop development have equal sensitivity to water stress. Germination, flowering, pollination, grain formation and fruit

development may be particularly important in many crops. Water management should therefore prioritize periods when moisture stress can cause irreversible yield reduction. During less sensitive growth stages, controlled reductions in irrigation may sometimes increase water productivity. Deficit irrigation research demonstrates that the relationship between saved water and yield reduction is highly crop and environment dependent (Cheng *et al*., 2021). The objective should therefore be strategic irrigation rather than uniform irrigation throughout the season. Water should be allocated according to crop demand and the economic importance of each growth stage.

Weed Management and Soil Moisture Conservation

Weeds compete directly with crops for water. In rainfed systems, uncontrolled weeds can consume a significant fraction of available soil moisture before the crop can use it. Early weed management is therefore an important component of soil moisture conservation. Mulching can contribute to weed suppression by reducing the amount of light reaching the soil surface. Mechanical weed control can also be useful, although excessive soil disturbance should be avoided because it can increase evaporation and disrupt soil structure. Integrated weed management combining appropriate crop establishment, mulching, timely mechanical control and selective herbicide use can reduce unnecessary water consumption by weeds while maintaining soil cover.

Crop Establishment and Plant Population

Crop establishment influences how efficiently available soil water is converted into biomass. Poor establishment can leave large areas of soil exposed and allow greater evaporation. Excessively dense planting, however, can create strong competition for water during dry periods. Plant population should therefore be adjusted according to crop type, soil fertility, expected rainfall and available irrigation. Uniform emergence is particularly important because plants that emerge at different times may develop different root systems and water requirements. Appropriate seed placement, suitable sowing depth and timely sowing can improve early root establishment and help crops access stored soil moisture.

Rainwater Harvesting and In Situ Moisture Conservation

Rainwater harvesting should complement soil moisture conservation. Small field structures such as contour-based practices, ridges, furrows, tied ridges, vegetative barriers and suitable field bunds can slow water movement and encourage infiltration. The main principle is to retain rainfall within the field for as long as possible while avoiding excessive ponding or erosion. These practices are especially relevant on sloping land where rainfall can rapidly move downslope. The effectiveness of such practices depends on slope, soil texture, rainfall intensity, crop arrangement and field layout. Consequently, field level design should be based on local soil and rainfall conditions.

Integrated Smart Agronomic Management

No single practice can guarantee high water productivity under all agricultural conditions. The strongest approach is to combine complementary practices.

The integration of these practices creates a more resilient soil water management system. For example, residue retention can reduce evaporation, conservation tillage can improve infiltration, organic inputs can support soil structure and sensor based irrigation can ensure that supplemental water is applied only when required. Such combinations can be more effective than depending on a single technology.

Table 1: Major smart agronomic practices for soil moisture conservation and their principal contributions

Agronomic practice	Main mechanism	Major soil or crop benefit	Best management consideration
Mulching	Reduces evaporation and soil temperature fluctuation	Higher root zone moisture and improved soil protection	Select locally available material and suitable thickness
Crop residue retention	Protects soil surface and increases organic inputs	Reduced runoff, erosion and evaporation	Balance residue for soil cover, livestock and other uses
Conservation tillage	Reduces soil disturbance and maintains soil structure	Improved infiltration and soil water storage	Adapt intensity to soil texture and compaction
Crop rotation	Diversifies rooting patterns and residue inputs	Better soil structure and resource use	Select crops according to rainfall and water demand
Cover crops	Provides living soil cover and root activity	Reduced erosion and improved soil biological activity	Avoid excessive water use in dry periods
Drip irrigation	Applies water close to the root zone	Improved irrigation efficiency	Maintain emitters and schedule according to crop demand
Soil moisture sensors	Measures soil water status for irrigation decisions	Avoids unnecessary irrigation	Requires correct calibration and placement
Deficit irrigation	Applies controlled water stress during suitable stages	Higher water productivity in appropriate situations	Avoid during highly water sensitive stages
Rainwater harvesting	Increases infiltration and reduces runoff	Greater soil water storage	Design according to slope and rainfall intensity
Weed management	Reduces non crop water consumption	Greater water availability for crops	Control weeds early while protecting soil structure
Organic amendments	Improves soil physical and biological condition	Better aggregation and nutrient cycling	Use mature and properly processed materials

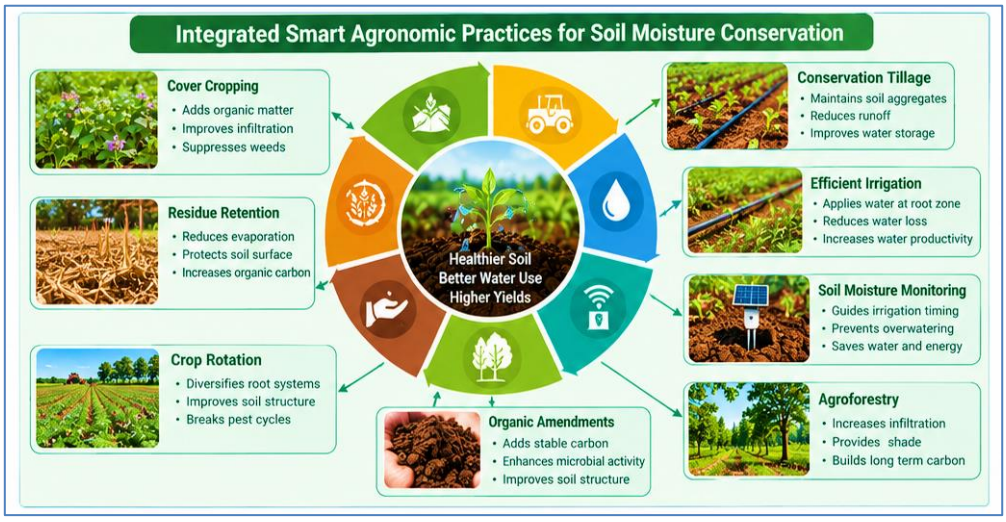


Figure 1: Integrated smart agronomic practices of soil moisture conservation and improved crop productivity.

Climate Smart Agriculture and Water Conservation

Soil moisture conservation is also closely connected with climate resilience. Higher temperatures can increase evapotranspiration and accelerate depletion of soil water. At the same time, rainfall may become more variable, creating a combination of intense rainfall events and prolonged dry periods. Conservation agriculture can help moderate some of these pressures by improving infiltration, maintaining soil cover and reducing evaporation. However, the effects are strongly dependent on local conditions. Abdallah et al. (2021) emphasized that the water saving benefits of conservation agriculture are more consistently associated with improved infiltration and reduced surface evaporation than with a universal increase in whole profile water holding capacity. Therefore, climate-smart soil moisture management should combine soil conservation, crop planning, irrigation management and weather-based decision-making.

Economic Importance of More Crop Per Drop

Water saving is valuable not only environmentally but also economically. Irrigation water requires energy for pumping and distribution. Reducing unnecessary irrigation can lower energy consumption and labor requirements. Improved water productivity can also stabilize production where water availability is uncertain. Farmers should nevertheless consider the cost of adopting new technologies. Drip irrigation, sensors and automated systems can require initial investment. Organic mulching and residue retention may have low direct financial costs but can compete with livestock feeding or fuel needs. Therefore, technology selection should consider both water savings and whole farm economics. Low-cost practices such as residue retention, timely weed control, improved crop establishment and appropriate crop rotation can often be combined with higher technology approaches such as drip irrigation and soil moisture sensors.

Challenges in Soil Moisture Conservation

- Several constraints can limit adoption of soil moisture conservation practices. Small land holdings, limited access to irrigation equipment, high initial costs, lack of technical knowledge and competing uses of crop residues can reduce adoption.
- Conservation practices may also require several seasons before their full benefits become visible. Farmers may hesitate to change established practices if immediate economic returns are uncertain.
- Another challenge is that soil moisture conservation is highly location specific. A practice that performs well in a dry sandy soil may produce different results in a heavy clay soil. Similarly, a mulch that is beneficial in a hot, dry environment may create different temperature and disease conditions in a cool, humid environment.
- Scientific management should therefore replace one size fits all recommendations. Soil testing, rainfall analysis, crop water requirement assessment and field level observation should guide the selection of practices.

CONCLUSION

Soil moisture conservation is essential for achieving higher crop productivity with limited water resources. Practices such as mulching, crop residue retention, conservation tillage, crop diversification, efficient irrigation, soil moisture monitoring and rainwater harvesting can reduce water losses and improve water use efficiency. Integrating these smart agronomic practices can help farmers produce more crop per unit of water while improving soil health, climate resilience and long term agricultural sustainability.

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