PLANT AVAILABLE WATER MANAGEMENT

Crop production is fundamentally constrained by plant-available water: the portion of soil water held between an upper bound (near field capacity after drainage) and a lower bound (plant extraction limit/wilting threshold). Management that increases the amount of water stored within this plant-available water “bucket” and shifts water loss pathways toward productive transpiration (rather than unproductive evaporation or drainage) improves crop growth, yield stability, and water use efficiency (WUE) (Harder et al. 2023). In hydrological terms, the goal is to maximize infiltration, maximize storage within the root zone, and minimize non-productive losses while sustaining crop access to water during critical growth stages.

From a crop-physiology perspective, the value of any agricultural management is greatest when it reduces the frequency and severity of water stress during sensitive phases such as flowering and grain fill. Under high atmospheric demand (high radiation, vapour pressure deficit, wind, and heat), crops can lose water rapidly and WUE tends to decline, so management that conserves soil moisture and sustains transpiration becomes a key lever for productivity and resilience.

Many factors influence a soil’s plant-available WHC and how much water crops use. Plant-available WHC is typically estimated indirectly using soil texture relationships. SWAT MAPS add important spatial context that helps reveal and interpret variability in how water moves through agricultural landscapes. This spatial understanding is critical for implementing precision practices that optimize plant-available water. Topographic data identify water flow paths, watershed boundaries, and areas where water tends to accumulate. At the same time, soil information, such as horizontal and vertical variability in texture and organic matter, helps describe the complex interactions between soils, crops, and water.

Cold Region Dynamics

Agriculture in cold regions, areas with growing seasons interrupted by a winter with frozen soils and snow accumulation and melt, introduce additional and unique challenges. A substantial portion of annual precipitation arrives as snow, and the effectiveness of crop water management depends on how winter processes control snow redistribution, sublimation losses, melt timing, and meltwater infiltration. In many cold cropping systems, spring soil moisture, and therefore early-season plant available soil water, is strongly influenced by whether snow is trapped on fields or lost to wind transport and sublimation. Standing stubble is a major control on snow trapping: taller and denser stubble increases aerodynamic roughness, slows wind near the surface, and captures drifting snow, often increasing snow water storage available for melt and subsequent infiltration and later crop water use (Harder et al., 2025).

However, cold conditions also create infiltration constraints not common in warmer regions. Frozen or partially frozen soils, ice lenses, and low-permeability surface layers can limit meltwater infiltration, increasing the risk of runoff, ponding, or redistribution into depressions. Residue and stubble management interacts with these processes by altering snow accumulation patterns and melt energy, influencing where and when water becomes available to infiltrate. Consequently, residue practices in cold regions are not only about reducing evaporation during the growing season, but also about capturing, conserving, and converting winter precipitation into root-zone storage, which can be decisive for crop water availability and yield stability (Harder et al., 2019).

Passive Agricultural Water Management Practices

Passive management approaches leverage existing agricultural practices to meet ag-water objectives. Agricultural residue and stubble management are the most impactful, practical, and scalable tools to influence ag-water interactions. Maintaining surface cover and standing stubble protects the soil from raindrop impact, reduces surface sealing and crusting, and helps preserve soil structure and macropores that promote infiltration. Residue also increases surface roughness, slowing overland flow and encouraging water to infiltrate rather than run off. Once infiltrated, improving soil WHC (through aggregation, organic matter, and reduced disturbance) helps retain water within the plant-available water range, making it available for root uptake later in the season. Residue cover further reduces soil evaporation by shading the soil surface, lowering soil temperature, and limiting near-surface wind speed and turbulent exchange (Harder et al. 2018). These effects are particularly valuable early in the season when crop canopies are sparse and evaporation can dominate water loss. By conserving moisture at the surface and in the upper root zone, residue management increases the probability that a larger fraction of total evapotranspiration is transpiration, which is directly proportional to crop utilization and yield formation (Harder et al. 2023).

Stubble-Snow Management

Stubble management plays a key role in water management in seasonally frozen soils. Stubble height is directly related to snow capture. Not only can blowing snow move snow off a field, but sublimation rates dramatically increase such that there is a maximum distance that snow can blow before it is lost to the atmosphere. It is not the case that snow is simply redistributed. Regardless, it is important to limit the movement of snow as an even cover of snow will result in better infiltration and better soil moisture distribution (tall stubble illustrated in Figure 1). Improved infiltration increases availability of springtime moisture for germination and early growth in arid and semi-arid environments and decreases run-off and water erosion in all snowy environments but especially those that are wetter (Harder et al., 2019).

***Figure 1**. Short vs tall wheat stubble demonstrating the snow capture potential of standing crop stubble*

Active Agricultural Water Management Practices

Active management of agricultural water are actions that directly change water inputs, outputs, or storage terms such as increasing the amount of incoming water with irrigation or directly reducing water in the soil column with drainage.

Precision application of irrigation water, known as VRI, aligns with data captured in the SWAT MAPS approach. VRI opportunities are primarily limited by irrigation infrastructure and the spatial description of soil-crop interactions. The basic description of soil WHC from SWAT MAPS forms the basis for static VRI prescriptions. Incorporating soil or crop water monitoring allows for more dynamic VRI strategies. Regardless of complexity, SWAT-based precision agronomy with irrigation offers significant ag-water benefits:

1. Reducing waste of irrigation water.
2. Minimizing nutrient and pesticide leaching and runoff due to over-irrigation.
3. Minimizing water accumulation and saturation leading to poor yields and denitrification losses.

Drainage of periodically inundated land and saline land can improve productivity (Daigh et al., 2025) and SWAT MAPS provide an effective management framework to guide drainage development. Ultimately, excess moisture in a soil profile limits oxygen available for plant roots and can cause serious stress and mortality. Shallow groundwater can also limit the volume of soil that is available to plant roots. Excess water also results in greater denitrification and leaching. If land is being treated as crop land but suffers from shallow groundwater and/or periodic inundation, the potential for negative environmental consequences is high and the potential for crop production is low. Drainage can remove excess water thereby decreasing N_2O and CH_4 emissions and improve productivity.

Drainage is also important for the reclamation and improvement of saline soils. While crop choice and amendments can have some benefit, the only long-term solution is to improve drainage so that excess salts can be flushed from the soils. Remediation with flushing can be restricted when there is a shallow groundwater table. Introducing drainage can lower the groundwater table, allowing for salts to be leached out of the crop rooting zone. This is particularly important in irrigated soils with poor natural drainage. Irrigation with high quality water can accelerate this process while lower quality water compounds the problem.

Within the agro-ecosystem, it is important to note that we are not advocating for the drainage of wetlands to increase arable acres but rather the drainage of wet land that is already in production and underperforming. It is also important to consider where the excess water will be drained. Increasing drainage also increases the potential for leaching of nutrients and pesticides as well as increasing the peak flow of streams which can lead to flooding particularly in large integrated networks.

Wherever possible, drainage should direct water from temporarily flooded depression to permanent wetland/lower areas within the same field (consolidation). Best practice would consolidate drainage water into areas rich in high water use plants (i.e. alfalfa and willow) that can utilize the excess water thereby limiting transfer of nutrients, pesticides, and salts before being introduced to existing wetlands and/or stream networks.

Using Water Data to Improve Decision Making

By leveraging SWAT MAPS together with moisture monitoring technologies, producers can fine-tune fertility management to match the unique variability of their fields, identify areas that would benefit from different tillage or surface residue management practice, and improve irrigation schedules and input application. This approach allows for targeted interventions in areas prone to water stress or excess, ensuring that plant-available water is maintained optimally throughout the root zone. SWAT WATER, a model that integrates SWAT MAPS with real-time soil moisture data, provides a spatially- and temporally-varying perspective of plant-available water and identifies management opportunities (Figure 2).

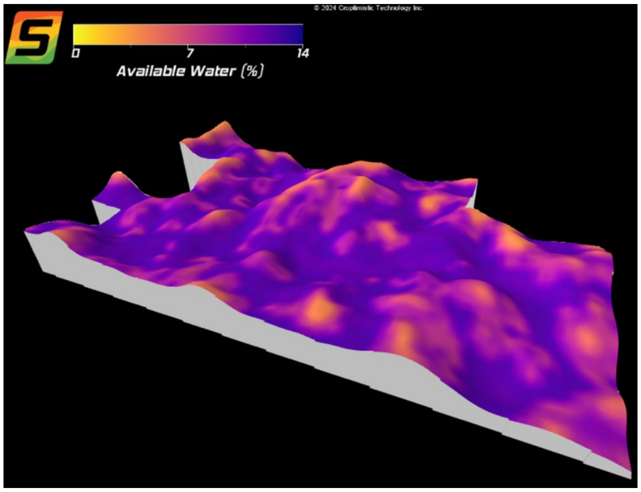

***Figure 2**: Spatial variability of plant-available water (as % of soil volume) within the potential rooting depth of a crop as estimated by SWAT WATER at a point in time.*

A SWAT-guided perspective of ag-water interactions is critical for farmers to also mitigate adverse consequences. This information is critical to identify high risk source areas of contamination (Cornell University Cooperative Extension, 2021). Management could include reducing nutrient application, avoiding manure application, VRI (McDowell, 2017), or even seeding the area to a different crop species. This is a tactic already used in many agriculture areas where waterways or salt-affected areas are seeded to perennial grasses that reduce erosion and can provide feed for livestock. SWAT MAPS identify the location of these high-risk areas so they can be targeted with greater precision.

Managing the Moisture-Nitrogen Loss Relationship

The management of nitrous oxide emissions has largely been focused on the application rates, timing, and product types in nitrogen applications. Nitrous oxide emissions are highly linked to soil nitrate availability but also are dependent on soil moisture, with relatively wet soils (60 to 80% water-filled pore space) having much higher risk (Wang et al., 2021). An underappreciated lever in the management of nitrous oxide emissions is to consider soil moisture variability. However, both spatial and temporal variability in soil moisture needs to be considered for loss potential (Corre et al., 1996; Mosier et al., 2002, Eagle et al., 2020).

Many studies have shown the effect of landscape position and water-filled pore space in soils, and the impact this has on denitrification and N_2O emissions (Butterbach-Bahl et al., 2013; Corre et al., 1995; Corre et al., 1996; Dunmola et al., 2010; Elliot and de Jong, 1992; Izaurralde et al., 2004; Jamali et al., 2016; Pennock et al., 1992; Schelde et al., 2012; Soon and Malhi, 2005; van Kessel et al., 1993). A depressional area in a dry season does not have the same loss potential as in a wet season when it floods or is saturated. A knoll has fewer denitrification losses as it rarely stays saturated long enough for significant quantities of N loss to occur.

Elliot and de Jong (1992) demonstrated the effects of both spatial and temporal variability of denitrification losses across a variable, hummocky landscape (Figure 3). Similarly, a well-drained sandy loam depression would have less risk of denitrification losses than a poorly drained clay depression that holds water or stays saturated for a longer period, particularly if yield potential is reduced. For example, Fiedler et al. (2021) showed 57 to 84% higher N_2O emissions from saline-sodic soils compared to more productive non-saline soils.

Metrics

Quantifying the implications of agricultural practices upon the optimization of plant-available water is challenging. Metrics that capture the effectiveness of plant-available water and management interactions need to consider the capacity of soils to store water and the efficiency with which crops convert that water into yield, while accounting for constraints such as soil salinity that directly alter water availability to plants.

Landscape Element	SWAT Zone	1986 Wheat	1987 Fallow	1988 Canola
DS	1	1.0	4.7	1.1
DB	4	0.8	3.1	1.1
CFd	8	7.6	31.7	10.8
LL	10	8.4	50.5	11.3

***Figure 3**. Denitrification estimates (kg N/ha) between April and October at different landscape positions and estimated SWAT zones. DS = diverging shoulder; DB = diverging backslope; CFd = depositional converging footslope, LL = low level (adapted from Elliott and de Jong, 1992).*

Plant-Available Water Holding Capacity (WHC)

Plant-available WHC represents the volume of water that a soil can store and supply to crops between field capacity and the plant wilting point. WHC varies spatially due to differences in soil texture, structure, organic matter, depth, and salinity. It can be estimated using multiple complimentary approaches. Soil moisture probes provide direct, time-resolved measurements of volumetric water content at multiple depths, allowing estimation of effective rooting depth, seasonal water storage, and depletion patterns. Soil texture–based methods (pedo-transfer functions) offer first-order estimates of WHC based on sand, silt, clay, and organic matter content, particularly where in-situ monitoring is limited but these methods struggle with the precision to capture potential changes over time.

The SWAT ECOSYSTEM, including SWAT MAPS and SWAT WATER enables spatial extrapolation of WHC by linking soil texture, landscape position, and organic matter variability to observed moisture dynamics. Tracking WHC spatially allows identification of zones where water storage limits yield potential and where management practices (e.g. residue retention, organic matter improvement, drainage) are most likely to deliver benefits.

Crop Water Use Efficiency (WUE)

Crop WUE quantifies how effectively water is converted into biomass or yield (Harder et al., 2023) and is typically expressed as:

WUE = Crop Yield ÷ Crop Water Use

Crop water use is derived from soil moisture depletion over the growing season, adjusted for precipitation and irrigation inputs, while yield is measured spatially using calibrated yield monitors. Evaluating WUE across SWAT zones enables

- Identification of yield gaps where water availability is adequate, but productivity is limited by other constraints (e.g., nutrients, salinity, soil structure).
- Detection of zones with high water loss and low yield return, indicating opportunities for improved residue management, crop selection, or fertility alignment.
- Assessment of year-to-year resilience by comparing WUE under contrasting moisture conditions.

WUE is a critical metric for distinguishing between water-limited and management-limited production and for prioritizing interventions that improve the productivity of each unit of water used.

Soil Salinity and Its Influence on Plant Available Water

Soil salinity directly reduces plant-available water by increasing osmotic stress, meaning crops must expend more energy to extract water from the soil even when moisture is present. As salinity increases, the effective WHC decreases. Salinity should therefore be treated as a core ag-water metric and monitored using:

- EC mapping, which provides high-resolution spatial identification of saline and sodic zones and tracks changes over time.
- Soil testing, including soluble salts and exchangeable ions, to quantify severity and diagnose underlying processes such as groundwater discharge or poor drainage.

Monitoring trends in salinity alongside soil moisture and yield data allows practitioners to evaluate whether water management strategies (e.g., drainage, perennial vegetation, targeted fertilizer reduction) are improving or degrading the effective availability of water to crops.

Recommended Metrics:

- Spatial estimation of plant-available WHC using soil moisture probes and soil texture data.
- Crop WUE (yield per unit of crop water use) evaluated spatially and temporally.
- Soil salinity monitored through EC mapping and soil testing, with trend analysis over time.

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Acronym & Abbreviation Guide

CH_4 — Methane
Emitted from saturated soils; referenced in drainage and water management sections.

EC — Electrical Conductivity
Measure of soluble salts in soil; used to infer salinity, texture variability, and water movement.

GHG — Greenhouse Gas
Gases whose emissions contribute to climate change (e.g., CO_2, N_2O, CH_4). Frequently discussed in relation to fertilizer and soil management.

N_2O — Nitrous Oxide
Potent GHG (265× CO_2) emitted from soils through nitrification/denitrification, especially in wet zones.

NDVI — Normalized Difference Vegetation Index
Satellite-based index for monitoring vegetation vigor, used to compare pre/post drainage performance.

SOC — Soil Organic Carbon
Carbon component of SOM (~58% of SOM mass); key indicator of carbon sequestration potential.

SOM — Soil Organic Matter
Decomposed biological material in soil essential for fertility, structure, water retention, and long-term soil health.

SWAT — Soil, Water, and Topography
A spatial soil landscape framework for mapping stable properties that drive yield potential and environmental interactions.

SWAT MAPS
High-resolution soil, water, and topography maps forming the foundation of precision agronomy within the SWAT ECOSYSTEM.

SWAT WATER

A modelled layer integrating SWAT MAPS with soil moisture probe data to estimate spatial plant-available water.

VRI — Variable Rate Irrigation

Irrigation water applied at different rates across a field based on soil water holding capacity and moisture demand.

WHC — Water Holding Capacity

Volume of plant-available water stored between field capacity and wilting point across soil profiles.

WUE — Water Use Efficiency

Crop yield per unit of water used; helps diagnose water-limited vs management-limited yield.