Driving Regenerative and Sustainable Agricultural Practices with Precision

MARCH 2026

Foreword

There are roughly 8.26 billion people on the planet today. To put that population in perspective, only ~117 billion people have ever lived (our cumulative population over the last 200,000 years; Kaneda & Haub, 2022) meaning that *1 out of every 15 humans who have ever lived is alive right now*. The food production required to support 8.26 billion people is staggering. A key reason that our population has increased so dramatically has been due to the intensification of food production, which has provided more abundant, reliable, and lower cost food.

However, intensification of food production takes it toll on our planet. Seven out of the nine planetary boundaries have been exceeded and all seven are impacted by agriculture (PBScience, 2025). To support our current population, it is urgent that we figure out how to intensely grow food in a way that minimizes negative impacts on the environment while still supporting the livelihoods of the farmers who grow it.

There are many global voices speaking out on how to grow food sustainably. Farming is variable not only in terms of the products grown and the variability in geography and climate, but in the economic structures of the farm businesses and the markets into which they sell. A one-size-fits-all template for sustainable farming is not possible. Too many sustainable agriculture programs are formulaic or designed for specific commodities, clients, or communities.

There are tools today that allow agronomists, soil scientists, and hydrologists to understand the critical requirements for crop production with a level of detail previously unheard of. Instead of developing generic, formulaic programs, we can develop bespoke, customized programs at a sub-field resolution that truly integrate the variability needed to balance intensive food production with environmental and economic sustainability. At Croptimistic, our value to our farmers is through optimizing their outcomes, and one important benefit is maintaining and improving the ability of their land to produce food now and in the future—this comes from practices that improve soil health and fertility.

Croptimistic sees a need for a sustainable/regenerative agriculture guidance document that comes from a technologically advanced agronomic perspective. While this is an industry white paper, our team also brings a depth academic expertise. The agronomic perspectives and data come from over 20 years of working directly with farmers in North America and Australia.

We feel that the future to farm big is to look small—understand and embrace micro-scale variability. Looking small means looking at the soil and the regional topography and understanding it in detail—not relying solely on macro scale empirical data coming from imagery. We have the tools today due to computing power that was unheard of even a decade ago.

We hope that you find our perspective on best practices for sustainable and regenerative agriculture useful and we welcome your thoughts and feedback.

EDITOR:

Bonnie Dobchuk, MSc, PEng, is the Sustainability Director at Croptimistic Technology, where she strives to drive sustainability initiatives in the ag tech sector. She grew up on a small family grain farm near Speers, Saskatchewan, Canada and obtained her BSc in Agricultural and Bioresource Engineering and her MSc in Environmental Engineering from the University of Saskatchewan. She spent >20 years in the mining industry rehabilitating landscapes before coming back to her agriculture roots. Her expertise lies in promoting the value of regenerative agriculture, biodiversity conservation, and precision agriculture through a sustainability lens. With strategic guidance and a passion for sustainable development, Bonnie positions Croptimistic as a market leader, pioneering innovative practices that benefit both the environment and the industry.

Authors

Wes Anderson is the VP of Agronomy for Croptimistic Technology. He grew up on a mixed farm near Theodore, Saskatchewan, Canada and obtained his Bachelor's Degree in Agriculture from University of Saskatchewan in 2001. Since then, he's worked in various agronomy leadership roles in Canada and Australia, giving him exposure to a broad range of crops and agricultural practices in different climates. Wes works with farms using SWAT MAPS variable rate technology and supports the rest of the Croptimistic agronomy staff and third-party agronomists around the world that are using the SWAT ECOSYSTEM of products. Wes is passionate about using technology in agriculture to improve the economic viability and environmental sustainability of farms.

Phillip Harder, PhD, is the VP of Data Science at Croptimistic Technology, where he leads the scientifically based and data driven evolution of SWAT MAPS. Raised on a family farm near Saskatoon, now operated by him and his family, Phillip combines practical farming experience with advanced training in hydrology, earning his PhD from the University of Saskatchewan in 2018. His academic research focused on understanding water–soil–crop interactions on the Canadian Prairies and translating that science into agriculturally actionable information and tools. With Croptimistic, he supports the integration of data and information with analytical tools across all scales of the SWAT ECOSYSTEM to empower producers to better manage risk, optimize their input use, and achieve superior sustainability and productivity outcomes.

Joel Ens, PhD, is a Soil Scientist at Croptimistic Technology, where he applies scientific knowledge and principles to emerging technologies in precision and digital agriculture. Joel completed his PhD in Soil Science in 2012 at the University of Saskatchewan where he continued to teach and conduct research at the intersection of agriculture and environment for over a decade. His research has largely centred around the impact of land use and management practices on fertility and greenhouse gas emissions. His teaching portfolio ranged from introductory agricultural, environmental, and soil science courses to global food security, to soil sampling, research and statistical design in Soil Science. Joel strengthens scientific rigour in Croptimistic's solutions, uniting established soil science with state-of-the-art data analytics.

Contents

Executive Summary

Sustainable agriculture requires the active management of the interactions and flows between farming systems and their surrounding environment. Two key areas of active management form the pillars of sustainable agriculture:

- **Soil Health and Agricultural Productivity**: Preserve or enhance the health and productive potential of soil ensuring that agricultural lands remain viable and fertile for future generations, supporting consistent and reliable crop yields.
- **Integration with Agro-ecosystems:** Recognition that farms function within larger ecological systems, with ongoing exchanges of energy, nutrients, and organisms. Managing these interactions promotes overall ecosystem health and resilience.

Within each of these pillars, there are key principles that must be met. For maintaining and optimizing soil health and agricultural productivity, this requires:

- Conserving soil organic matter,
- Erosion prevention and soil cover maintenance, and
- Fertility optimization.

For integration with agro-ecosystems, this requires:

- Supporting biodiversity,
- Integrated pest management, and
- Managing plant-available water.

The principles presented are universal and applicable to all crops in all climates. Best management practices to meet the guiding principles of sustainable agriculture will be different depending on the climate and the crop. There will be environmental conditions where some practices may be appropriate and environmental conditions where they may be inappropriate. A clear understanding of the principles informs the choice of practices and ensures that the interdependence of the principles is acknowledged.

The following best management practices are examples that satisfy the principles and are appropriate in most agriculture conditions: no-till/conservation tillage, soil cover (living or non-living), precision applied fertility, drainage (only where appropriate), crop rotations, and pest and disease management.

When appropriate practices are integrated and adapted to each field's unique conditions, they reinforce each other to boost soil health, ecological resilience, nutrient and water efficiency, and overall productivity. The key is that the practices are implemented *appropriately within their spatial context* (the variability within a field). A blanket application of a practice may not serve to meet the objectives of sustainable/regenerative principles if it is applied out of context and/or in inappropriate locations within a field.

Precision application of best management practices is required to ensure that the sustainable and regenerative principles are applied appropriately. Precision agriculture moves beyond generalized recommendations, allowing for site-specific management of soil health, fertility, erosion control, biodiversity, and water resources. To inform on these practices, high resolution data is required to map out the variability in each field (spatially and temporally).

The Croptimistic-developed Soil, Water, and Topography (SWAT) management zones, along with associated precision agriculture tools within the SWAT ECOSYSTEM, offer a scientifically-grounded framework for applying sustainable agricultural practices at appropriate scales. Practitioners can systematically relate sustainable agriculture principles to real-world management, meeting both environmental and economic objectives required for the long-term sustainability of modern agriculture.

SWAT MAPS provide the data driven spatial foundation required to build sustainable intensification, resulting in more resilient, sustainable and profitable management.

Part 1: Sustainable and Regenerative Agriculture Framework

Sustainable and regenerative agriculture currently lack universally accepted definitions, yet most interpretations converge on two core objectives: maintaining or enhancing soil health and productive capacity, and positioning agricultural systems as integrated components of broader agro-ecosystems and biodiversity (Schreefel et al., 2025). Consequently, the interactions and flows between farming systems and their surrounding environments must be intentionally managed to maximize ecological benefits and support long-term ecosystem resilience.

PILLARS OF SUSTAINABLE AGRICULTURE:

- **Soil Health and Agricultural Productivity**: Sustainable agricultural practices aim to preserve or enhance the health and productive potential of soil over time. This ensures that agricultural lands remain viable and fertile for future generations, supporting consistent and reliable crop yields.
- **Integration with Agro-ecosystems**: Sustainable agricultural practices recognize that farms do not exist in isolation. Instead, they function within larger ecological systems, with ongoing exchanges of energy, nutrients, and organisms. By managing these interactions, sustainable agriculture promotes overall ecosystem health and resilience.

For the purposes of this white paper, the term “sustainable agricultural practices” encompasses both sustainable intensification and regenerative approaches. The implementation of these practices is increasingly informed by precision agriculture (PA), which addresses the high spatial and temporal variability in soil potential that is often overlooked. Effective sustainable agriculture requires that management strategies be tailored not just at the field level, but at finer scales—such as individual hillslopes—so that outcomes are optimized according to local conditions.

There is no single sustainable or regenerative agricultural practice that will work for all fields and farms equally. For agriculture practices to be sustainable or regenerative, an examination of the interactions occurring in each agro-ecosystem is first required and then agricultural practices must be layered on within a spatial framework. Likewise, soil health is a rather nebulous term with frequently ill-defined metrics. Maximizing soil organic matter (SOM), minimizing compaction and erosion, eliminating contamination, and optimizing soil biota are all a part of maintaining or improving soil health for agriculture. Yet, the optimal conditions for each field and area within a field are highly variable and depend on the soil parent material, climate, duration of soil formation, historical vegetation, topography, groundwater interactions, and the history of human management. As such regenerative agriculture practices need to be applied in context of the soil variability within the agro-ecosystem of any area.

Metrics of regenerative agriculture have often focused only on temporal dynamics of field (or even regional level) averages. This focus on temporal dynamics is to the detriment of a focus on spatial dynamics at a scale relevant to the variability within a field. This trend has largely been due to smaller-scale spatial dynamics being challenging to reliably quantify. Understanding these dynamics is necessary to guide the effective spatial implementation of best management practices (BMPs).

KEY PRINCIPLES

In alignment with the two pillars, our sustainable and regenerative agriculture framework has six principles: conservation of organic matter, erosion prevention and soil cover maintenance, biodiversity enhancement, crop rotation and integrated pest management, fertility optimization, and plant-available water management where the practices are implemented *appropriately within their spatial context* (the variability within a field). A blanket application of a practice may not serve to meet the objectives of sustainable and regenerative principles if it is applied out of context and/or in inappropriate locations within a field. Each of these principles are described in further detail in this section. A discussion of BMPs that may be appropriate for each of these principles are provided in Part 2 of this document.

To summarize, the key principles of sustainable agriculture are:

- Soil Organic Matter Conservation
- Erosion Prevention and Soil Cover
- Biodiversity Enhancement
- Integrated Pest Management
- Fertility Optimization
- Plant Available Water Management

Figure 1-1. *Framework for Sustainable and Regenerative Agriculture.*

Principles of Sustainable Agriculture: Defined

SOIL ORGANIC MATTER CONSERVATION

Soil organic matter (SOM) is the principal basis for soil health and long-term sustained productivity. Agricultural systems should seek to at least maintain and generally increase SOM where possible. SOM consists of decomposed fungi, bacteria, plant material, feces, and any other once-living matter that is at various stages of decomposition and gives soil its color (Ontl and Schulte, 2012). Soil organic carbon (SOC) is specifically a measure of the carbon contained within SOM. The two terms are frequently used interchangeably though there is a numerical difference between the two (the mass of SOC is roughly 58% the mass of SOM).

SOC levels are a direct result of historical plant biomass production in combination with decomposition rates driven mostly by climate, litter quality, and management. Warm, humid climates have higher organic matter decomposition rates than cool, arid climates. Plant matter with a C:N ratio between 20:1 and 30:1 will decompose faster than residues with higher C:N ratios. Tillage increases decomposition rates as it increases microbial activity through

increasing surface areas and oxygenation. More recently, scientists have discovered that mineral associated organic matter is a particularly important stable fraction of SOC, highly linked to soil clay content (Cotrufo et al. 2019; Haddix et al., 2020), so soil texture also influences the SOC storage potential in any given environment. Regardless of what the levels are, SOC is sequestered carbon that can be stored in the soil for very long periods of time, rather than as atmospheric carbon dioxide (CO_2).

SOM loss is accelerated through enhanced decomposition that occurs when soils are tilled. Therefore, soils that are minimally tilled will gradually increase in SOM until they reach their carbon saturation point. At saturation, very small amounts of SOM can continue to accumulate, but these amounts are negligible at decadal scales in most agriculturally productive soils. Introducing tillage to a carbon saturated soil will result in a loss of SOM. There are some instances where tillage may still have a net benefit: incorporating manures into the soil, harrowing to fill rills and therefore manage erosion, or deep ripping to improve drainage of poorly structured subsoils.

EROSION PREVENTION AND SOIL COVER

Exposed soils are vulnerable to erosion. The most productive soil is a very thin layer at the surface and losing even a few centimeters of these surface soils can greatly diminish the capacity of the whole soil profile. Additionally, eroded soil can end up being a pollutant, causing siltation and nutrient loading in water bodies and, in extreme conditions, causing dust storms. Figure 1-2 illustrates the change in soil carbon distribution following a history of tillage.

Soil erosion occurs from three processes: wind, water, and tillage:

1. Wind erosion is controlled by maintaining soil cover. Soil cover is increased by living plants, stubble (the taller the more effective), and maintaining residues on the soil surface. Additionally, shelterbelts reduce windspeeds across a field and therefore decrease wind erosion (as well as reduce water losses in semi-arid environments).
2. Water erosion is also decreased by soil cover but is largely affected by slope angle and length. Fields lacking long or steep slopes will often only require residue management to prevent water erosion. The longer and steeper the slope, particularly in channels where water collects and runs, will require the most aggressive water erosion prevention. Dense perennial grasses are often the most effective means of controlling water erosion.
3. Tillage erosion is minimized by using no-till agriculture. If tillage is going to be used, tilling across slopes rather than up and down results in reduced tillage erosion.

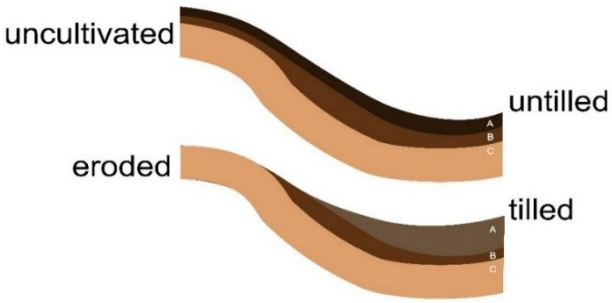


***Figure 1-2**: Typical soil carbon distribution following a history of tillage. Erosion, from tillage, water, and wind, erodes topsoil from the tops of hills and deposits in lower positions. Once erosion reaches B or even C horizons these carbon poor horizons are mixed with topsoil and result in a carbon diluted topsoil and, at worst, exposed C horizons (parent material). Tillage enhances SOM decomposition and decreases soil carbon of all locations.*

Maintaining living cover is the most effective way to prevent all types of soil erosion; however, maintaining soil cover with residues and stubble is sufficient in many fields with lower soil erosion potential (and many areas within fields with higher erosion potential).

All soils have some potential for erosion, but type and severity are closely related to topography and soil texture. Steeper slopes accelerate tillage erosion as the net downslope pull of gravity increases. Steep slopes also increase water erosion with the pull of gravity determining the energy of flowing water and therefore its erosive power. However, an increase in topographic variation generally decreases wind erosion as the topography serves to slow wind speeds near the surface. Exposed hilltops remain susceptible but lower positions remain sheltered. Soils containing plenty of clay form strong aggregates that are difficult to detach from the rest of the soil but once detached can be transported long distances from the source. Coarse soils increase infiltration and limit runoff and therefore are less prone to water erosion. However, these same drier conditions lead to less cohesion of soil particles making them susceptible to wind erosion. Understanding the erosion risk including the type of erosion risk allows for appropriate measures to be

taken. A flat, medium to coarse textured field will benefit from practices controlling wind, perhaps through a shelterbelt. A steeply sloping, finer textured soil will benefit from permanent vegetation in water courses to minimize the velocity of flowing water and trap suspended silt and clay. Types of erosion mitigation are illustrated in Figure 1-3.

BIODIVERSITY ENHANCEMENT

Agriculture functions within the larger agro-ecosystem and is supported by ecosystem services. The larger agro-ecosystems are equally affected by the management of the agricultural systems within. Increasing biodiversity leads to improved ecological stability of the entire agro-ecosystem. This can range from flood control to providing nesting habitat for pest eating birds. Pollination of certain crops is greatly enhanced by providing habitat for pollinating species of insects. There are many ways biodiversity can be increased. Looking for locations and options where multiple benefits occur will yield the greatest return.

Biodiversity also includes soil biodiversity. Soil microbes are resilient and populations can recover under good conditions, but it is also good practice to limit pesticide usage that can disrupt populations of beneficial microbes. Fungicides will kill both pathogenic and beneficial fungi.

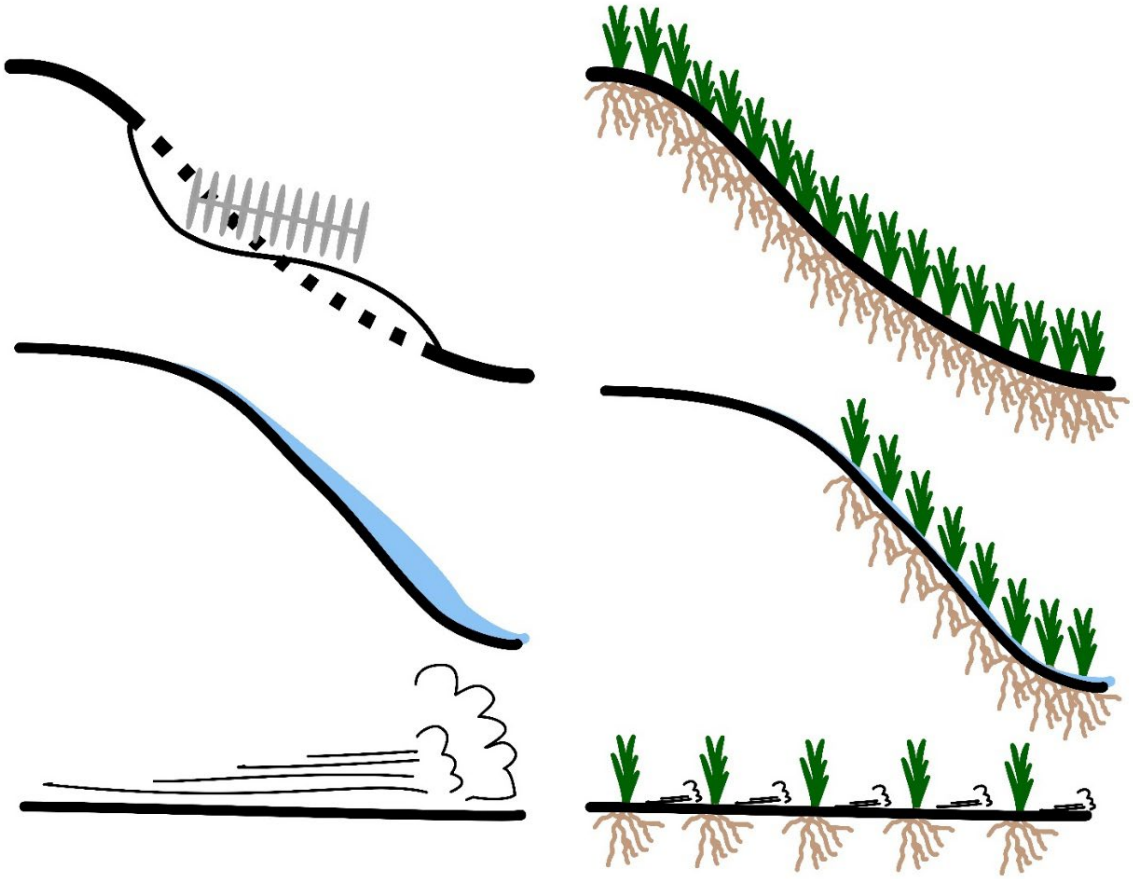


Figure 1-3: Types of erosion and mitigation with soil cover. Top left: tillage erosion causes a downslope net movement of disturbed soil. Top right: no-till and continuous cover eliminates tillage erosion. Middle left: long steep uninterrupted slopes where water converges results in the most (and fastest moving) runoff resulting in the greatest water erosion. Middle right: interrupting water flow and increasing infiltration with cover decreases the amount of runoff and the speed at which it flows. Bottom left: uninterrupted flat fields allow wind to gather speed and pick up soil particles. Bottom right: vegetation and non-living soil cover slow wind speeds so that soil particles cannot be entrained.

Agricultural runoff and subsurface flow can contain agrichemicals (nutrients and/or pesticides) that detrimentally impact wetlands and subsequently impact downstream- and ground-water quality. Riparian buffers can intercept this runoff and subsurface flow to prevent contamination of wetlands and water. Additionally, wetlands that are high in soluble salts can contribute to soil salinity in the surrounding fields. High-water-using plants such as trees, shrubs, and deep-rooted perennials like alfalfa are best at intercepting water in the soil and diverting it to transpiration. Dense perennial grasses are best at intercepting overland runoff including any particulate matter it contains. Riparian buffers are therefore beneficial to the wetlands they surround and often are also beneficial by controlling the flow of soluble salt-rich water into the field. Riparian buffers will also increase biodiversity. Increasing biodiversity does not necessarily come at the cost of efficiency. Careful planning can result in multiple benefits and minimal drawbacks.

An example of biodiversity support is illustrated in Figure 1-4. This example shows how practices that are sensitive to the spatial variability of the landscape can address multiple issues at once.

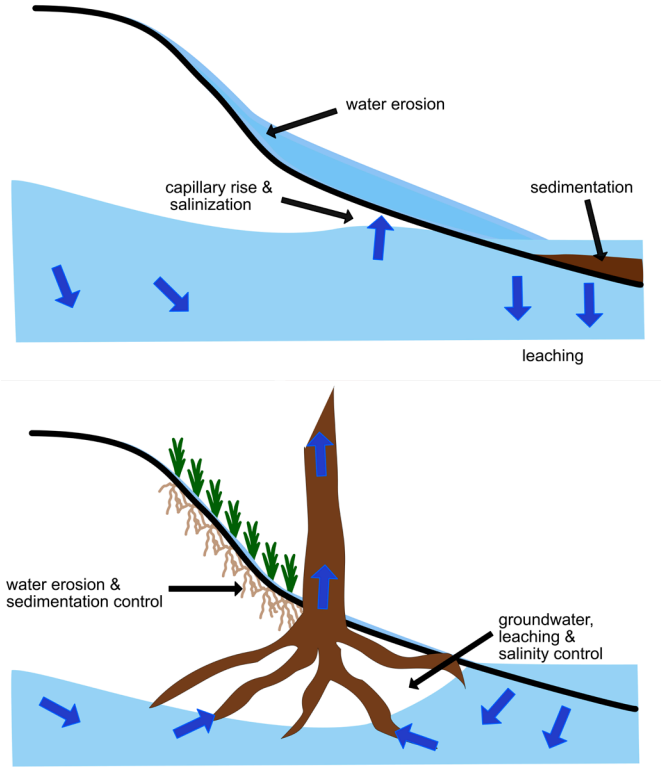


***Figure 1-4**: Permanent vegetation (bottom) used to address erosion, sedimentation, nutrient loading, leaching, and salinity caused when annual cropping is the sole land use (top) while simultaneously increasing biodiversity.*

INTEGRATED PEST MANAGEMENT

Pest management is best accomplished through a mixed approach that involves prevention, monitoring, and effective responses. Prevention includes crop rotation, biosecurity, and pest and disease breaks (biodiversity, riparian buffers, shelterbelts).

Each crop has its own advantages and disadvantages. The choice of crop should reflect the potential of that field to produce as well as the complimentary nature of crops within a crop rotation (or in some cases within a multi-crop field). Crop rotations are crucial for disease management as they interrupt the build up of soil borne pathogens. They are also important for nutrient management and SOM accumulation. Introducing a legume provides a source of natural nitrogen fixation. Legumes are helpful for microbial populations due to their high C:N ratio residues. Deep rooted cereals like wheat are beneficial for scavenging for nutrients that may have escaped the rooting zone of shallower rooted crops. Additionally, their considerable root mass lends itself to accumulation of SOM, which is particularly important if lower residue crops are included in the rotation.

Monitoring allows for pests to be addressed before they become established or to prevent applying pesticides when they are not necessary. Pests rarely occur evenly across a field. Many of the same factors governing crop growth also affect the distribution of pests. Effective management includes pesticides. Using two pesticides from different classes increases efficacy and helps prevent pesticide resistance. Pesticide applications should aim to eliminate the problem. Figure 1-5 illustrates an example where targeted application of fungicide would be appropriate.

FERTILITY OPTIMIZATION

The objective of fertility management is to optimize the most appropriate amendments for the crop and soil. Ideally nutrient availability matches the crop demand. This is achievable through choice of the appropriate source, timing, placement, and rate (commonly referred to as 4R Practices). Determining the correct fertility plan requires good information about the demand of the crop, the amount of plant nutrition that can be derived from the existing soil, as well as likely rates of loss of nutrients through leaching, gaseous losses, or fixation. All these factors vary within a field so the ideal fertility plan is adjusted to match the actual conditions and variability of the field rather than a generalized field average prescription. This concept is illustrated in Figure 1-6.

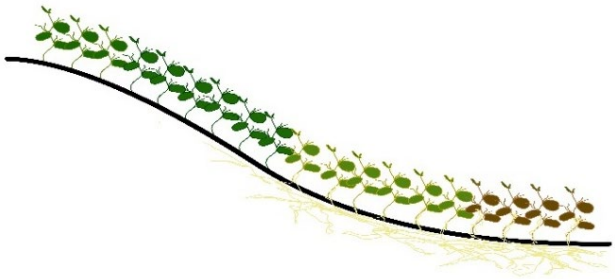


Figure 1-5: *Fungi tend to proliferate in moist to wet soils (pictured above). Since these conditions are not uniform throughout the field, targeted, not uniform, applications of fungicides are warranted for their control.*

Excess fertilization increases production costs and environmental consequences like agricultural runoff and greenhouse gas emissions. Under-fertilization results in poor yields and under-utilization of production capacity. Within-field variation in agricultural systems is often high and a single fertilizer application rate will under-fertilize some parts of the field and over-fertilize others. This results in reduced yield per unit of applied fertilizer and typically increased nitrous oxide emissions. Over-fertilization can also increase the speed at which decomposition occurs, which is counterproductive to accumulating SOM. Under-fertilization reduces the quantity of residues that accumulate and is also counterproductive to accumulating SOM.

PLANT AVAILABLE WATER MANAGEMENT

Water is frequently the limiting factor of crop productivity (Henry, 2018). In semi-arid to arid environments a water deficit is typically the limiting factor, whereas in more humid environments, the limiting factor is typically water excess. However, both excess and deficit situations can occur within the same field and growing season, which complicates the practices required to improve outcomes. At a fundamental level, practices to improve plant-available water will either increase water infiltration, reduce non-transpiration water outputs, and/or increase soil water holding capacity (WHC) (Harder et al., 2023).

In semi-arid environments, plant-available water can be manipulated using various practices. Water losses can be minimized using residue management. Increasing soil cover reduces soil evaporation and can increase infiltration and reduce runoff (Harder et al., 2024). This results in a better distribution of water across the field. In cold regions, that experience winter and snow accumulation, water inputs can be increased by maintaining/maximizing standing stubble. This increases snow accumulation, through a reduction in blowing snow export and sublimation losses, to increase snowmelt amounts and snowmelt infiltration potential (Harder et al. 2019).

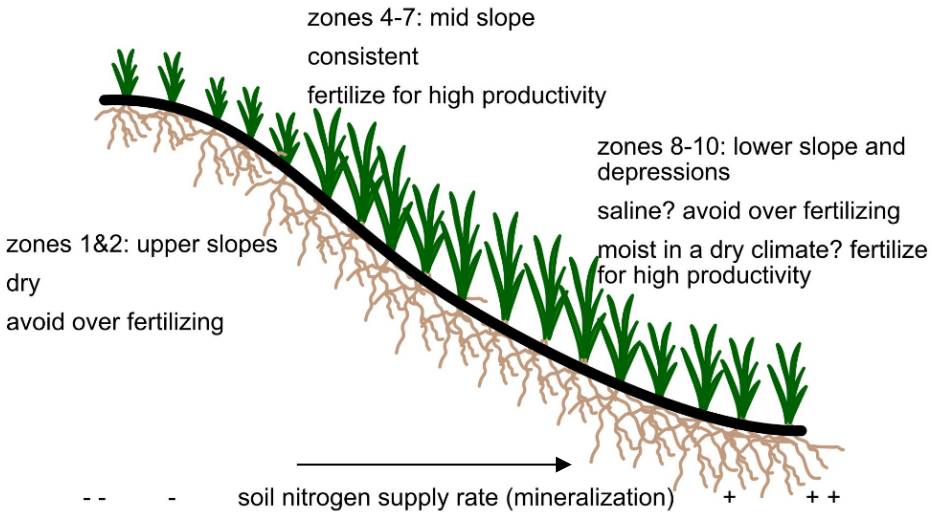


Figure 1-6*: Soil fertility, production potential, and soil nitrogen supply rates vary across a field. The right time, place, source, and rate (4R) for fertilizers also varies across a field in response.* ***True 4R fertility cannot be practiced uniformly across a field based on field averages.***

Shelterbelts are an additional practice used for reducing drought stress in crops. Windspeeds are decreased reducing evapotranspiration demand and losses.

Excess moisture can also occur in semi-arid environments, particularly in depressions and during prolonged periods of saturation. Excess water drastically impacts plant health and transpiration potential leading to a negative feedback loop of water accumulation and decreased crop water utilization. Saturation-prone areas within a field, typically depressions that are inundated with water during spring melt or rainfall events, require landscape-specific management practices.

Drainage, when applied correctly to land that is already in production but suffers from periodic inundation, can alleviate the negative effects of excess moisture from spring melt and rainstorms. It can also have a net benefit on biodiversity when this excess water is diverted to non-production areas, which can then support increased biodiversity in constructed wetlands. This concept is illustrated in Figure 1-7.

INTERDEPENDENCE OF PRINCIPLES

Sustainable agriculture is defined by the interaction of all its core principles—such as maintaining SOM, protecting soil cover, and enhancing biodiversity—within a unified system. When appropriate practices are integrated and adapted to each field's unique conditions, they reinforce each other to boost soil health, ecological resilience, nutrient and water efficiency, and overall productivity. Strategies like crop rotation, integrated pest management, and optimized nutrient and water management collectively build stronger soils and more sustainable agro-ecosystems. PA tools help tailor these approaches, allowing farmers to maximize sustainable outcomes across diverse landscapes

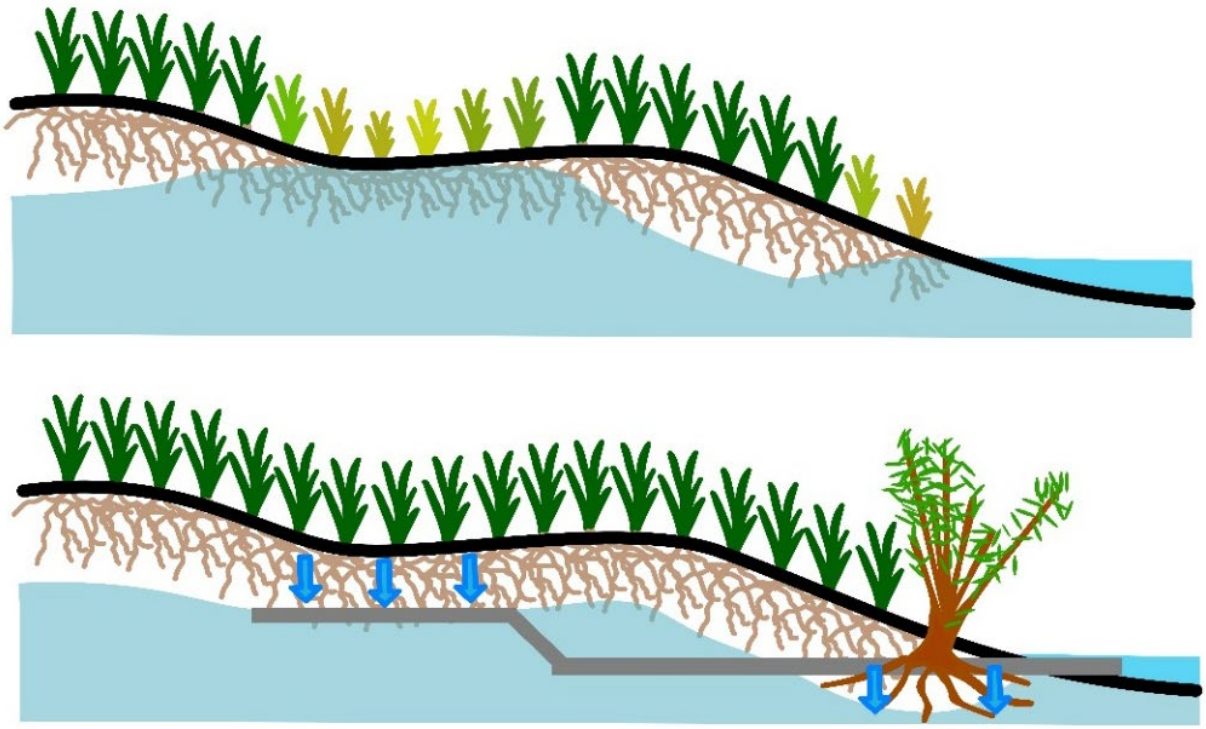


***Figure 1-7**: Wet areas of a field can under-perform due to periodic inundation (inadequate soil oxygen), salinity, or both. Drainage, when applied correctly, can alleviate these issues thereby improving the productive capability of a field. Drainage (using drainage tile in this graphic) allows excess water and salts to drain through the soil and below the rooting zone of crops (bottom). Drainage, combined with wetland management and/or construction can simultaneously increase biodiversity while providing a field with protection from salinity and inundation near wetland borders as well as providing flooding and nutrient loading control for wetlands.*

Part 2: Moving from Principles to Practices

The principles for sustainable agriculture outlined in Part 1 are universal and applicable to all crops and all climates. Many sustainable/regenerative agriculture frameworks skip over the principles and jump directly to specific practices. Principles are akin to a roadmap that ensures you are headed in the right direction. Practices are akin to the vehicle and route you choose to get there. Without the roadmap (principles) you can wind up heading in the wrong direction, even if you choose the right vehicle (practice). A clear understanding of the principles informs the choice of practices and ensures that the interdependence of the principles is acknowledged.

BMPs to meet the guiding principles of sustainable agriculture will be different depending on the climate and the crop. There will be environmental conditions where they may be appropriate and environmental conditions where they may be inappropriate. Practices can have a compounding positive impact when layered appropriately (or negative if applied inappropriately).

BMPs are most effective when integrated within a PA framework. The objective of PA is to tailor BMPs to the unique variability of each field, optimizing outcomes for both productivity and environmental stewardship. Single, blanket management strategies intended to improve sustainability and regenerative outcomes rarely reflect the reality of variability that exists both within individual fields and across an entire farm. PA moves beyond generalized recommendations, allowing for site-specific management of soil health, fertility, erosion control, biodiversity, and water resources.

We present in Part 2 a summary of the most impactful BMPs that would be applicable to most crops and climates. These are followed by case studies showing real world examples of these practices in action.

The Croptimistic-developed Soil, Water, and Topography (SWAT) management zones, along with associated PA tools within the SWAT ECOSYSTEM, offer a scientifically grounded and agronomically relevant framework for applying sustainable agricultural practices at appropriate scales. By utilizing SWAT-based agronomy, practitioners can systematically relate sustainable agriculture principles to real-world management, meeting both environmental and economic objectives required for the long-term sustainability of modern agriculture. An introduction to PA and the SWAT ECOSYSTEM is provided in the following section prior to introducing the BMPs.

Environmental Stewardship with Precision Agriculture

Significant progress has been made since the early days of PA. Variable rate (VR) technology introduced the fundamental concept that fields are not uniform. However, in practice, VR has often been applied within a narrow decision-making framework that limits its value. Most VR implementations focus on adjusting a small number of crop inputs (typically fertilizer and seed application rates) based on limited drivers such as soil test values, satellite imagery-based productivity maps, or yield targets.

In many cases, variability is accepted rather than explored. Exploration of why different areas of a field perform differently, which constraints limit productivity, and which management levers could be adjusted to improve long-term value are rarely executed. As a result, VR can become an oversimplified response to a complex system.

True PA operates at the level of systems thinking rather than focusing solely on rate adjustment. PA, when applied properly, integrates spatial and temporal intelligence across soil properties, water movement, topography, crop response, and varying environmental conditions to guide a broad range of agronomic decisions. Once the underlying drivers of variability are identified, a comprehensive set of potential practices and management changes can be evaluated to address those challenges.

The solution should never be reduced to “vary fertilizer rates based on soil nutrient variability or yield potential.” While that may be part of the solution, true

optimization often requires additional or alternative changes that deliver greater value over time. Premium PA focuses on identifying and implementing the combination of actions that produces optimized outcomes.

PA is most effective when guided by spatially-explicit tools like SWAT MAPS to identify the underlying drivers of field variability. This requires an understanding of the stable soil and landscape properties that drive yield potential beyond soil test values, satellite imagery-based productivity maps, or yield targets.

PRECISION AGRICULTURE: CURRENT & FUTURE OPPORTUNITIES

With a full understanding of the spatial and temporal variability of a field, there are substantial opportunities to manage practices using PA. With technology in farm equipment and data collection advancing quickly, the opportunities far exceed what is currently done on most farms today. This section provides a summary of PA opportunities that can be accomplished with existing technology such as GPS guided tractors and seeding and spraying equipment that can vary inputs within the same field based on zone-based input application prescriptions.

Application Rate Control

Variable Rate (VR)

Varying application rates (variable rate, or VR) is the original technology developed in PA and still gets the most focus. However, varying application rates should only be used in zones that are demonstrably different in properties and fertility and where varying rates is agronomically and economically justified. In some cases, varying one nutrient may deliver substantial value while varying another provides no benefit.

VR is commonly confused with PA and the terminology used interchangeably. *VR is a single component of the spectrum of PA opportunities*.

On/Off Decisions

Certain products should only be applied where the product delivers a positive return on investment (ROI). In certain zones, applications may not be varied at all or may be shut off entirely. Salt-affected soils, poorly established areas, or chronically flooded zones are examples where applying products may result in negative or zero ROI. Only recently were some types of equipment (such as wide boom sprayers and wide frame seeders) able to successfully execute this at the resolution required to be agronomically accurate.

Optimum Field Average Rate

When a field does not exhibit meaningful variability for a specific input, good PA should identify this and recommend the optimum uniform rate. *Inputs should only be varied when doing so creates value.* In some cases, the analysis may reveal that no VR application is required anywhere within a field. The absence of a VR application does not indicate a lack of value in the process. The value lies in the decision-making framework that optimizes outcomes, not in the act of varying rates. Until all the data has been collected, the correct application prescription for a crop input is unknown.

Field versus Farm Perspective

Analyzing only one or two fields in detail does not define value optimization for a farm. Fields selected for analysis may be highly uniform and present few challenges, but will not represent the entire farm. In practice, variability between fields is often as significant as variability within fields. While VR decisions are frequently evaluated at the field level, PA considers the broader farm context. For example, if 20% of fields are deficient in a nutrient while another 20% have excess levels, nutrient budgets can be reallocated between the fields to optimize value at the farm scale. Within-field variability is not the only objective; farm-level optimization may still deliver substantial benefits. A certain BMP may work great on a well-drained field at high elevation, whereas it may constitute total failure in a field with saturation issues at low elevation where water collects and subsoil water tables are high.

Product Switching

All inputs for crop production (seed, fertilizer, crop protection products) can be applied with precision when the spatial variability of a field is well understood. Product switching refers to the mechanism by which an input is switched to another within the same field.

Hybrid, Variety, and Crop Type Switching

Crop type can be varied within a field based on crop characteristics. Drought-tolerant hybrids / varieties / crop types may be selected for dry hilltops, while flood-tolerant ones are better suited to wet depressions. For example, a field with a mix of productive soils and saline soils could be seeded to two different forages. A high yielding option could be seeded on the productive soils and a saline tolerant option in the salt affected areas to maximize crop establishment, survival, and land use.

Fertilizer Product Switching
Fertilizer product type can be switched within a field based on the product attributes. Standard nitrogen fertilizer products (nitrate and ammonium based) may be appropriate on well-drained hills and mid-slopes, while stabilized or enhanced-efficiency nitrogen products are better suited to wetter zones prone to loss.

Specialty fertilizer products often carry price premiums of 30% or more and thus, should be applied only where they deliver measurable value. Regulators and sustainability programs tend to promote these products to be used on entire farms (if an entire farm region is typically wet then this may be a great policy). However, in areas where hilltops may be drought stressed and depressions may be too wet, a farmer may actually reduce their yields in these areas *without seeing the corresponding reduction in losses*. It is problematic to have blanket policies for product applications without intimate field and farm knowledge.

Crop Protection Strategy Switching
Crop protection products and strategies may vary spatially based on disease pressure, moisture conditions, or other environmental risk factors. An example is sclerotinia, in conditions where thin / short canopies and dry soil surfaces may persist on hills and thick / tall canopies and moist soil surfaces persist in depressions. In depressions, the sclerotia will thrive and the canopy will be ripe for disease. It may only make sense in some years to target the disease in field areas where the pathogen, environment, and crop characteristics favour this disease. Soil applied biocontrol agents that target sclerotia may be used in only these areas, preventing application of a product in an area where it will have no positive impact.

Strategic Management Adjustments

Drydown and Harvest Management
Spatial management can be used to influence crop ripening patterns, enabling more uniform drydown, earlier harvest timing, improved grain quality, reduced green and high moisture kernels, and less storage losses. In many cases, farmers in areas with short seasons of good harvest weather would be willing to sacrifice small yield improvements to have an earlier, more efficient harvest. Even crops often provide better crop quality and in some specialty crops, quality may be the difference between human food or animal feed price mechanisms, differences that may provide a 2X value on price.

Lodging Reduction Strategies
Depressions with high organic matter content that are prone to lodging can be targeted with tailored management strategies to reduce lodging risk. In these areas, a variety with shorter, stronger standability characteristics may be preferred. Nitrogen fertility can be adjusted to lower rates or use products that offer controlled release. Potassium or copper could be low in high organic matter soils and may require additional attention to optimize nutrient balance. Plant growth regulators to shorten crop height may benefit lodging prone areas but have no value or negative value on the drier areas. Lodging risk reduction is an art best dealt with using PA.

Soil Organic Matter (SOM) Driven Strategies
SOM is fundamental to soil structure, nutrient mineralization, water retention, nutrient cycling, and overall soil health. Dry, low SOM, thin topsoil areas affected by historical erosion may require targeted SOM improvement programs. In contrast, wet depressions with accumulated topsoil and high SOM may already possess adequate SOM resources that just need to be maintained. Amendments (such as manure or humic products) and strategies (such as residue management that is taller and accumulating over time) for such SOM improvement programs can be slow and costly and may be more affordable if they focus on areas within fields that benefit the most.

Salinity and Water Stress Management
Zone-specific strategies for wet and saline areas may include targeted product selection and management practices designed to reduce evaporation, manage waterlogging, or improve stand establishment. This can be performed through adjusted seeding rates or selection of crop species adapted to specific stress conditions. Additional approaches may include increasing water use in recharge areas and implementing drainage or tile systems in discharge zones. PA allows detailed data collection on the variables and helps design the best strategies to see what could be accomplished.

Regenerative frameworks often recommend removing all wet areas from production, yet they rarely acknowledge the practical constraints farmers face. Many fields contain numerous small, wet areas, and farming around them can introduce logistical inefficiencies and create new environmental challenges that may outweigh the intended benefits. The most effective approach is to develop field-specific strategies using PA on a field-by-field and farm-by-farm basis.

Multi-Input, Multi-Layer Spatial Strategies

Crop Establishment Optimization

When multiple spatial challenges exist, multi-pronged strategies are required. For example, poor crop establishment on dry, low-OM, hard clay hilltops may result from limitations in seeding depth control. A single depth setting optimized for field averages may leave seed too shallow on hills and too deep in wet depressions. Options include varying seeding rates to compensate for mortality, adopting technology that enables variable or improved seed depth control, or implementing agronomic strategies that conserve moisture, increase SOM, and improve infiltration. Traditional residue management practices applied uniformly may be replaced with zone-specific approaches, such as lifting harrows and tillage tools on hills to maintain and increase surface residues and soil moisture at the surface to promote germination. Managing residue in depressions may be completely different, where strategies that promote a slight drying / warming trend and improved aeration may optimize germination and reduce mortality.

Nutrient Rate Optimization

Fields often contain multiple nutrient challenges that require distinct strategies. Nitrogen, phosphorus, potassium, sulphur, and micronutrients frequently vary spatially. Low OM, eroded clay hilltops may respond strongly to sulphur but show little response to potassium, while high OM depressions may require significant potassium and copper but have no response to nitrogen or sulphur. Nutrient response is influenced by soil texture, clay mineralogy, and parent material. Long-term nutrient strategies may include building micronutrient levels with single applications or addressing deficiencies over multiple seasons. Optimization requires evaluating whether nutrients can be targeted individually, applied as blends, or delivered through alternative timing or placement strategies. VR applications are a solution but the logistics issues of application due to the diversity of nutrient based needs can be very complex. True optimization using PA requires a comprehensive, long-term strategy to correct problems.

Soil Structure and Soil Health Improvement

Tillage intensity and practices can be adjusted spatially based on microtopography and soil type, consolidating or reducing tillage where appropriate. Compaction problems can be identified using PA equipment and then appropriate deep ripping could occur in those areas. Amendments could also be appropriate, once the specifics of the physical and chemical attributes are known. Then long-term strategies that support deeper root growth and proliferation would be added. A single VR application of a “silver bullet” product never works, and many types of soil structure problems require a site-specific, long-term PA strategy to improve soil structures over time.

Performance Metrics and Proving Value

Profit Maps

Profit maps are often used to demonstrate the value of VR by comparing yield outcomes against input costs. While useful as an annual snapshot, profit maps are often misused as a direct decision driver. If a zone shows low profitability, the solution should never be to automatically reduce all crop inputs, which is a common approach that many VR-based companies utilize. The solution is to start with understanding why the performance of each area is low and understanding the limiting factors driving the issue. True PA will focus on diagnosing the underlying constraints. In some cases, constraints cannot be economically addressed, and an overall crop input reduction may be appropriate. More often, however, poor productivity zones may require special attention and, in some cases, even higher rates of certain inputs. An example is sulphur in canola grown on low OM, coarse textured soils. Reducing sulphur in these areas with this crop would further depress yields and cause even further lost productivity. Profit maps should drive the precision agronomist into understanding the why and holistically managing the issues.

Field Trials

Field trials within fields on farms are often touted as the holy grail of value metrics. However, similar to profit maps, they must be designed and dissected properly over a period of years and conditions to arrive at successful conclusions that change management practices. To address spatial variability, PA trials must be replicated so several zones can be assessed, and the zones need to be large enough to provide accurate data with field equipment. Strip trials with single measurements for the trial have limited value, as they have no ability to tease out the differences in responses that happen spatially. Temporal challenges also exist, because climatic conditions for Year 1 may be significantly different the next year, and many products and strategies have no effect in certain environmental conditions and large effects in others.

Short-Term versus Long-Term Analytics

Whether using profit maps or field trials, it is important to know which changes can be evaluated on a single-season profitability basis, such as nitrogen response, and which changes require a longer-term lens. As OM improvements and soil moisture conservation efforts improve, the short-term responses can change. Other

strategies that may or may not show up in a single year evaluation include management of phosphorus, potassium, liming, drainage, soil amendments, cover crops, and perennial systems. There are also examples of products that are long-term sources and a single-year analysis of their application would fail to capture the full value of these investments. For example, sulphur needs may be addressed annually with sulphate sources or through long-term strategies using slow-release sources that contain mostly elemental S. It is very difficult to measure long-term programs accurately. The benefits are there and they are real, but almost impossible to quantify on a field by field basis without high resolution spatial and temporal data.

Climate Change-Based Metrics
Proven reductions of greenhouse gas (GHG) emissions have been shown from using stabilized nitrogen forms in high-risk areas of fields (versus using nitrate-based forms). However, measurement of nitrous oxide production/reduction is impractical on a spatially relevant basis for the average farm. SOC, which varies spatially and temporally, is also challenging to quantify. Carbon markets are evolving, but there is no universally standardized system on measuring carbon removals or GHG avoidance in agriculture. Farmers could be building carbon in soils and avoiding nitrous oxide production, but there is no clear value metric in place. Tremendous climate change value is being created by using PA, but the metrics and recognition are not currently in place to reward them.

Sustainability Value Chains and Markets
Premium PA inherently generates documentation and data supporting sustainability outcomes. *Emerging markets related to carbon sequestration, greenhouse gas reduction, and regenerative agriculture can be accessed through PA based data management systems.* With the current global movement towards rewarding these practices and perhaps regulating practices that are poor, PA enabled sustainability systems will hold value that has yet to be realized.

Summary

The opportunities to utilize PA to optimize outcomes for farmers and the environment are immense. In nearly all cases, a win-win scenario is presented because anything that results in inefficient use of products or management means a loss of production and profitability for a farmer. These same inefficiencies will lead to a negative effect on the environment.

The concept of PA needs a much deeper understanding than what most observers, and even most in the industry, have. The most common PA technology is VR, yet VR is fundamentally about adjusting input quantities spatially, with yield quantity as the primary outcome metric. This leads to weak value metrics because the focus becomes fertilizer and seed costs versus annual yield increases relative to constant-rate applications. Such metrics ignore the deeper agronomic understanding required to identify productivity constraints and develop long-term, more sustainable solutions.

True PA digs much deeper with more data, more knowledge, more analytics, and a much longer-term focus to overall strategy. VR should not be the standard, it is often just a rate adjustment exercise, a single tool within a vast toolbox, a small component of a much larger machine, a common entry point into basic PA practices. *True PA is an outcome optimization discipline that integrates agronomic principles, BMPs, spatial intelligence, and economic analytics to answer a broader question: "What combination of actions will optimize value over time?" The answer lies with the experts and the farmers who together, are adopting the principles and executing on the practices.*

SWAT MAPS: THE ROLE OF SOIL, WATER, AND TOPOGRAPHY

Soil, water, and topography maps (SWAT MAPS) are soil management zone maps that are based on relatively stable soil and landscape properties. SWAT MAPS encompass multiple soil and water attributes that affect crop variability in any given field, including texture, dissolved salts, organic matter, topography, elevation, water flow paths, and relative water potential.

SWAT MAPS allow a farmer or agronomist to use PA to manage spatial variability across a landscape in several ways, including VR fertility, seed, soil amendments, or soil applied herbicides, all of which have responses based on soil and water variability. It becomes a powerful tool when combining temporal variability such as relative soil moisture content with the application of fertilizers to mitigate negative environmental effects.

Parent material is the foundation from which a soil is formed and as a result is the basis for soil properties including texture, pH, bulk density, and mineral composition (Canadian Society of Soil Science, 2020).

These properties can all play a role in how nutrients, soil amendments, and pesticides should be managed. Topography determines where water sheds (runs off) or collects. Water movement across a landscape is a major driver of soil formation (pedogenesis), soil erosion, movement of nutrients and pesticides, and redistribution of organic carbon rich topsoil (Malo and Worcester, 1975). Les Henry, well known Canadian soil scientist often cited the importance of topography, and it's influence on water and soil formation. He wrote, "Water passing through a soil leaves a signature – and that signature is the soil profile. As we study the A,B,Cs of soil we are examining the effects of 10,000 years of water passing through the soil. If a lot of water passes through the soil we can expect a deep, well developed soil profile. If little water passes through a soil, we can expect a shallow profile with anemic features" (Henry, 2018). In the Canadian Prairies, a lime layer can be found in the soil profile, and the depth to lime layer is indicative of the topographic-driven water flows (Figure 2-1).

When combined with soil properties, topography is the primary determinant of yield potential within a landscape that shares common parent material. It is the combination of these factors, as well as temporal variability like rainfall, that guide how a crop should be spatially managed with PA. An example SWAT MAP is provided in Figure 2-2.

The amount of soil variability within a field boundary can vary significantly depending on field location and how the soil was formed. For example, glacial till soils in western Canada are often considered to be relatively heterogeneous (Pennock et al. 1987), while lacustrine, Vertisolic clays tend to be less variable in respect to texture and development of A horizon. The soil properties presented in Figure 2-2 are an example of soil texture variation across a typical glacial till landscape from a field in north central Alberta, Canada. Variability of soil texture in this field was strongly correlated to electrical conductivity (EC) as mapped with a SWAT BOX (Croptimistic Technology, 2024). EC, as a measure of accumulation or depletion of salts in the soil, is an indicator of the presence of groundwater, and the magnitude and direction of groundwater movement. The flow of groundwater is inherently controlled by topography and texture as well as the abundance of water. As such, the texture variation in this field is also well correlated to topography.

A dominant role of soil texture is WHC and subsequently has a large impact on yield potential of agricultural crops (see Figure 2-3 and Figure 2-4 showing texture variability within a single field). Additionally, yield potential is a function of temporal and spatial variability. For example, loamy sand soil in a water limited environment will typically have poor yield potential compared to a clay loam soil, all other factors being equal. However, in a high rainfall environment, a clay loam soil may not have sufficient drainage, and yield potential would be reduced due to frequent saturation. This is the case in the field shown in Figure 2-2; SWAT zone 10s are frequently flooded in-season and rarely yield well, while zones 1 and 2 have demonstrated high yield potential in a high rainfall season.

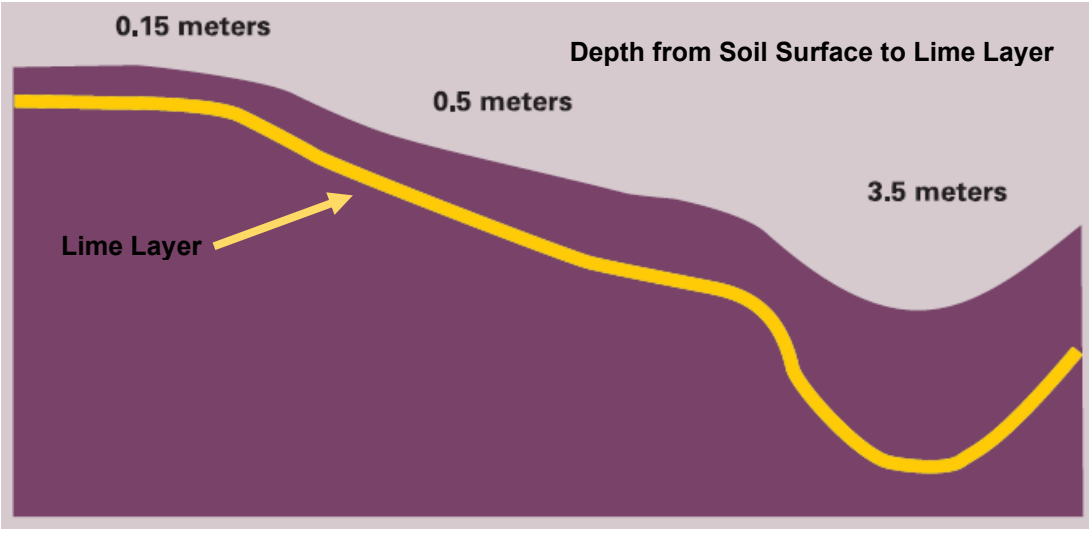
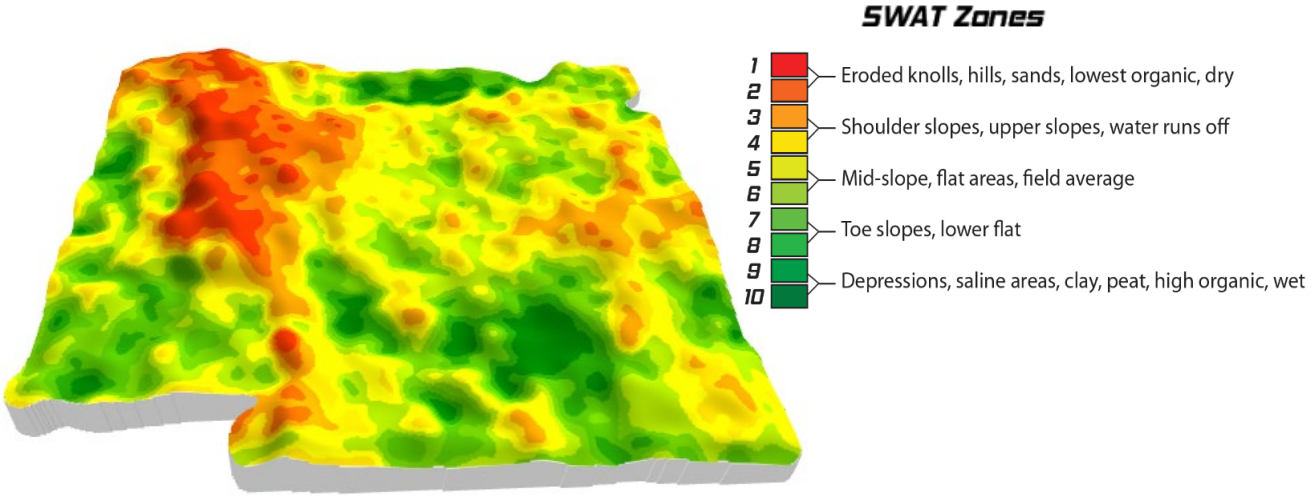


Figure 2-1. *Depth-to-lime from knoll to slough in typical glaciated environment of Canadian Prairies. Depth to lime layer indicates historical water movement through the profile as driven by topography (used with permission (Henry, 2018)).*



Field Area	Depth	OM (%)	pH (H2O)	Texture	Sand (%)	Silt (%)	Clay (%)	CEC (meq)	Ca (%)
zone 1,2	0-8 in	2.10	5.40	Sandy loam	63.0	24.0	13.0	12.9	66.0
zone 3,4	0-8 in	5.50	6.30	Sandy loam	55.0	26.0	19.0	20.8	72.9
zone 5,6	0-8 in	5.40	6.60	Loam	51.0	30.0	19.0	24.3	80.0
zone 7,8	0-8 in	6.10	6.90	Sandy clay loam	51.0	26.0	23.0	24.2	84.6
zone 9,10	0-8 in	9.60	7.60	Loam	43.0	32.0	25.0	35.0	86.5

Field Area	Depth	Mg (%)	K (%)	Na (%)	P Olsen (ppm)	K (ppm)	S (lbs)	Cl (lbs)	Ca (ppm)
zone 1,2	0-8 in	13.2	3.2	0.4	14	161	43	31	1697
zone 3,4	0-8 in	12.2	2.0	0.5	14	160	53	52	3038
zone 5,6	0-8 in	12.1	1.3	0.5	10	124	93	64	3885
zone 7,8	0-8 in	10.9	1.6	0.5	20	153	109	68	4096
zone 9,10	0-8 in	11.9	0.9	0.7	24	121	160	100	6060

Field Area	Depth	Mg (ppm)	Cu (ppm)	Zn (ppm)	B (ppm)	EC (dS/m)
zone 1,2	0-8 in	203	0.6	0.6	0.4	0.17
zone 3,4	0-8 in	304	1.0	1.2	0.7	0.31
zone 5,6	0-8 in	353	0.7	1.1	1.0	0.47
zone 7,8	0-8 in	317	1.6	1.5	1.2	0.39
zone 9,10	0-8 in	501	0.9	2.6	2.8	1.38

***Figure 2-2**. Example of a SWAT MAP (top) with associated soil test properties (bottom tables) from Alberta, Canada.*

Texture alone rarely represents all the variability in a field, however. A clay depression will behave and respond to nutrients differently than a clay hill. A sandy hill will often have poor yield potential due to water limitations, but a sandy depression may be productive due to constant accumulation of water from upper landscape positions. *Because topography drives water flow across a landscape, it inherently affects productivity, organic matter, erosion, and nutrient movement. It is the interaction of all these factors that affect how we can mitigate environmental impacts of nutrients and pesticides using spatial management in PA.*

While the origins of SWAT MAPS are in the Canadian Prairies the approach is equally applicable to other regions with different soil formation processes.

Figure 2-3. *Example of soil variability in a central Queensland, Australia field; well oxidized, freely draining loamy sand in zone 1 (left) to a poorly drained clay loam in zone 10 (right).*

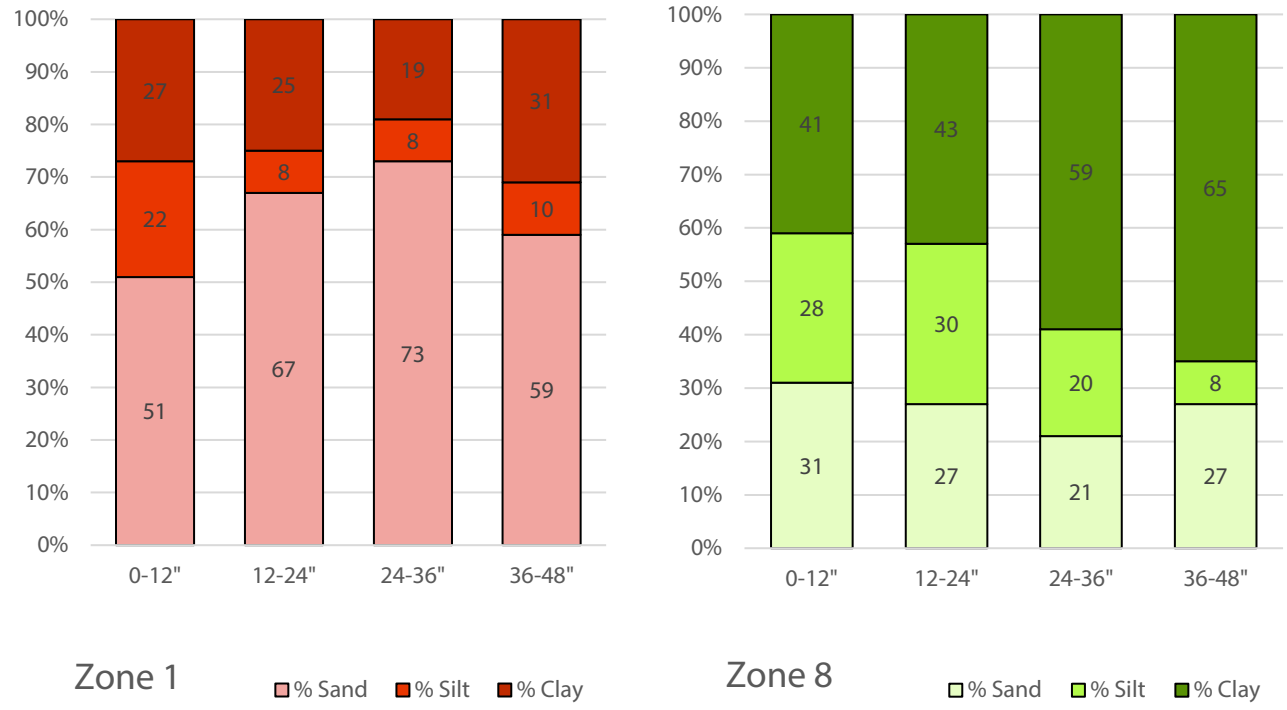


Figure 2-4*. Two texture profiles of SWAT zone 1 and zone 8 in a field from central Saskatchewan, Canada.*

Sustainable/Regenerative Best Management Practices

Over recent decades, BMPs in agriculture have undergone significant development, rigorous demonstration, and widespread adoption across diverse farming systems. These practices are designed not only to enhance productivity but also to address the complex environmental challenges facing modern agriculture. As the sector evolves, BMPs such as conservation tillage, soil cover maintenance, VR fertility, crop rotations, biodiversity enhancement, and strategic water management have become central to both sustainable and regenerative approaches. Their effectiveness is continually validated through research, field trials, and real-world implementation, providing a robust foundation for responsible and resilient agricultural management.

This section highlights the most common and impactful BMPs, their expected benefits, and the environmental contexts in which they are most appropriately applied. A reference table summarizing the practices and their appropriate usage is provided in Table 2-1. Through the SWAT ECOSYSTEM, farms can systematically relate sustainable and regenerative principles to real-world management decisions, ensuring that BMPs are applied where they will have the greatest impact and aligning agronomic practices with both economic and ecological objectives. The practices and case studies discussed in the remainder of this document are presented within the context of PA, and specifically within the context of the capabilities of the SWAT ECOSYSTEM.

Zone	Acres	Trueman Layer 1	Imperial Layer 2
1	1.8		10
2	7.7		10
3	14		10
4	17.1		10
5	17.2	3	7
6	18.7	7	3
7	14.5	10	
8	7.4	10	
9	3	10	
10	2.4	10	
	Average:	4.4	5.6

Figure 2-5. *Example of a sustainable/regenerative best management practice: underseeded alfalfa in canola crop. High performing alfalfa variety seeded on hills and mid-slopes (Imperial variety) and flood tolerant variety seeded in wet areas (Trueman variety) where alfalfa would normally flood out. Middle graphic shows seeding rate prescription by zone.*

Table 2-1. *BMPs aligned with sustainable/regenerative agriculture principles. Aligning principles in bold represent primary aligning principles. Aligning principles in regular text represent secondary aligning principles.*

	Practice	Aligning Principles	Expected Benefit	Appropriate Environmental Conditions
Soil Health and Productivity	No-till/Conservation tillage	• **Soil Organic Matter Conservation** • Erosion Prevention and Soil Cover	• Increased SOM • Improved soil structure and reduced compaction	• Default practice for all fields • Exceptions for incorporating manures, harrowing small rills and other imperfections, deep ripping subsoil to improve drainage
	Maintain soil cover • Non-Living (stubble or trash) • Living (cover crop)	• **Erosion Prevention and Soil Cover** • **Plant Available Water Management** • Soil Organic Matter Conservation	• Erosion control • Improved infiltration • Snow capture	• Default practice for all fields • Steep slopes will require more soil cover • Reductions in soil cover may be necessary in extremely productive fields with excess residues that impede crop establishment • Living cover (cover crops) are more suitable for higher rainfall regions. Arid, water limited climates are better suited to residue cover during non-crop periods. • ***Inappropriate Conditions:*** *Excessive residue can hinder seedbed preparation at certain times of the year (e.g. in flood irrigated systems where hills or beds need to be formed).*
	Precision applied fertility	• **Fertility Optimization** • Soil Organic Matter Conservation	• Improved crop nutrition • Carbon sequestration • Reduction in GHG emissions • Mitigation of fertilizer induced water pollution	• Applicable to all fields • If organic fertilizers are available they should be integrated into the VR fertility plan appropriately
	Crop rotations	• **Integrated Pest Management** • Soil Organic Matter Conservation • Biodiversity Enhancement • Fertility Optimization	• Reduction in pests and disease • Carbon sequestration (integration of high residue crops) • Reduced inorganic fertilizer requirements (integration of pulses)	• All fields, no exceptions • Crop rotations can be different in different parts of the field in highly variable fields (e.g. pea is included in upper slope positions and canola is included in lower slope positions)
Integration with Agro-ecosystems	Drainage (passive or active)	• **Plant Available Water Management** • Biodiversity Enhancement	• Remediation of salt affected soils • Remediation of inundated soils • Establishment/expansion of constructed wetlands • Reduction in GHG emissions	• Land that is inundated with water to the point that agricultural productivity is negatively impacted, not conversion of permanent wetlands to agricultural land • Remediation of salt affected soils with poor natural drainage and/or high water tables • Drained water should have an appropriate end point that integrates with the local ecosystems, e.g. consolidation to constructed wetlands
	Integrated pest management • Biosecurity • Precision applied pesticides • Crop rotations	• **Integrated Pest Management** • Biodiversity Enhancement	• Reduction in pests and disease spread and severity • Improved productivity	• All fields but exact practices need to be in response to pest and disease pressures and effective solutions

SOIL ORGANIC MATTER CONSERVATION

Uncultivated land typically exhibits a more uniform distribution of SOM and A horizon depth compared to eroded agricultural land. In agricultural settings, the process of cultivation has led to the redistribution of organic matter-rich topsoil, particularly from upper slope positions to lower slope positions. As a result, upper slopes have become degraded, with reduced organic matter content, while lower slopes possess artificially deepened A horizons. This redistribution has significant implications for the carbon sequestration potential of soils in different landscape positions, as well as their response to further tillage interventions. Figures 2-6 and 2-7 illustrate real examples of variability in SOM within two fields of agricultural land.

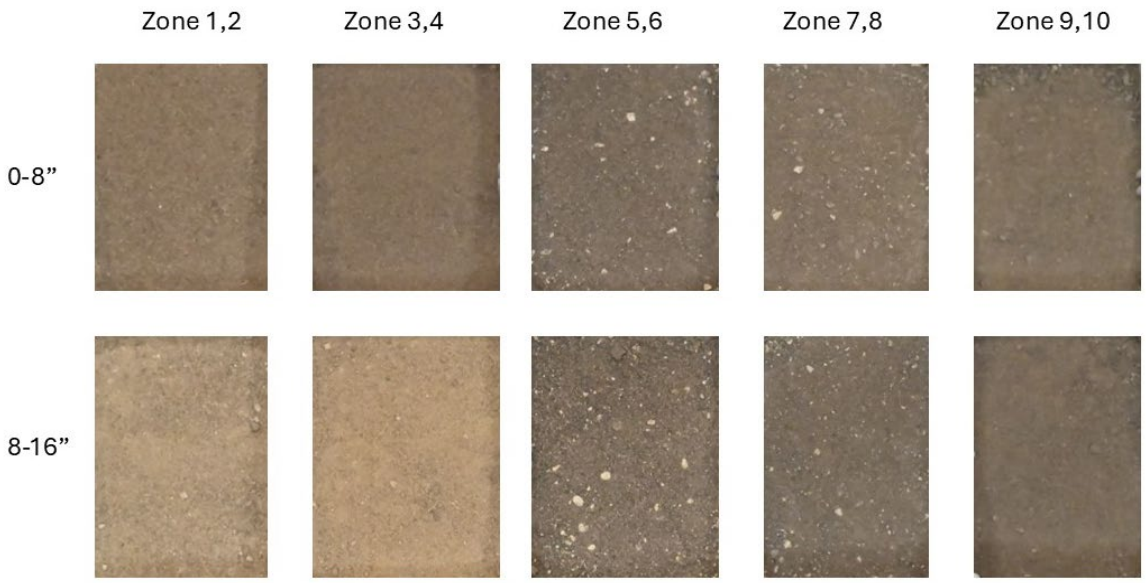


***Figure 2-6**. Topsoil (0-8") and subsoil (8-16") samples from five SWAT zones demonstrating variable organic matter levels within a single field. Note the dramatic change in colour from 0-8" to 0-16" zones 1-4. This indicates shallower topsoil and less total carbon.*

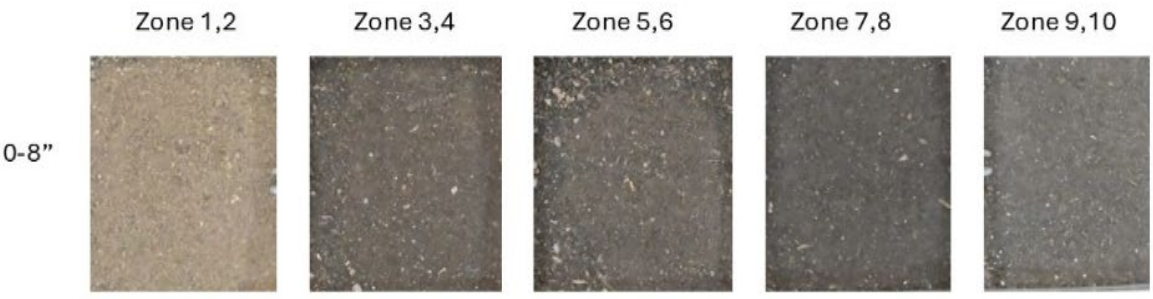


***Figure 2-7**. Topsoil (0-8") samples from five SWAT zones demonstrating variable organic matter levels within a single field. Note the dramatically lighter zone 1,2 topsoil indicating erosion to the point that the topsoil has largely been removed. From zone 3-8 there is a slight gradually darkening in colour as soil carbon increases. Zone 9,10 is a lighter grey colour related to the influence of trees that would have been present pre-cultivation.*

Degraded soils on upper slope positions possess a higher carbon sequestration potential than soils on lower slopes, as they are further from reaching their carbon saturation point. However, in severe cases, the low SOM content of upper slopes may limit their ability to support sufficient plant growth, which is critical for the rapid accumulation of SOM. To address this, amendments such as animal manures or green manures should be targeted to these degraded areas. Once SOM levels have been initially increased, regular cropping and appropriate fertilizer practices may become feasible for continued improvement.

In contrast, lower slope positions that have developed unnaturally deep A horizons are unlikely to benefit significantly from such amendments. In fact, applying animal manures high in soluble salts to these areas may be detrimental. The increased organic matter in these zones results in greater nutrient availability as decomposition occurs, and when combined with increased moisture, there is a higher risk of nutrient leaching and contamination of surface water bodies and groundwater.

Within the same landscape, uncultivated soils generally display minimal differences in SOM, except in depressions with poor drainage where decomposition rates are slowed by prolonged saturation. The act of cultivation—including tillage, wind, and water erosion—has led to the redistribution of SOM alongside the movement of topsoil. Tillage moves soil in all directions, but unless specifically managed to move soil upslope, the net effect is a downhill shift.

As SOM builds up through the deposition of plant residues, it becomes a larger food source for microbes, leading to increased decomposition rates. Over time, as SOM accumulates year over year, decomposition rates rise until an equilibrium is reached between accumulation and decomposition. At this point, the soil achieves SOC saturation, and net carbon sequestration slows to negligible rates. Improved management practices—including the adoption of no or conservation tillage, continuous cropping, and enhanced fertility—can result in carbon sequestration and SOM accumulation. However, the rate of SOM increase is strongly influenced by how much the current SOM concentration is below the carbon saturation point. Consequently, management practices impacting SOM will have different effects depending on the SWAT zone (landscape position) in which they are applied.

Organic matter offers numerous benefits to soil, including improved tilth, greater WHC, and enhanced nutrient supply. It sustains microbial life, facilitating nutrient cycling and additional carbon sequestration. Maintaining or increasing SOM levels is in the best interest of farmers for long-term productivity, and it also benefits society by contributing to the mitigation of rising atmospheric CO_2 levels associated with climate change.

Microbial communities require the proper combination of nutrients, water, and soil physical properties to thrive. Fertilization has a direct impact on the rate of SOM decomposition: when fertility matches plant demand, SOM can accumulate due to increased plant residue input. Conversely, if fertility exceeds plant demand, the resulting soil environment accelerates microbial activity and the decomposition of plant residues, which can ultimately reduce the total SOM stored in the long term. *Zone-specific fertility prescriptions are important not only for optimizing crop productivity but also for managing the soil carbon balance*.

For farmers, SWAT MAPS provide the information needed to identify nutrient deficiencies or pH extremes that limit crop biomass and yields, which subsequently limit carbon sequestration potential (Aulakh and Malhi, 2005; Coonan et al., 2019; Lam et al., 2013). A common example would be identifying areas where topsoil has eroded from upper landscape positions. These areas can benefit significantly from composts, manures, and specific nutrients to increase productivity, allowing the soil to increase in organic matter closer to its original state prior to cultivation.

Because SOM improves water and nutrient holding capacities of soils, composts, and animal and green manures can be particularly effective in eroded soils that are low in clay. An initial investment in increasing SOM through amendments can support plant productivity and kick off a feedback loop that drives SOM still higher as increased SOM increases plant productivity (which in turn increases SOM). It is important to understand and connect these amendments to the drainage potential, which is an inherent property of SWAT MAPS zones. Animal manures tend to be high in salts. This will have little negative effect on low EC soils with ample drainage. However, they make a poor amendment to depressions particularly if the soils there are already saline. Additionally, organic matter amendments applied to poorly drained zones already high in organic matter can increase nitrous oxide (N_2O) and methane (CH_4) emissions as well as leaching, not to mention the potential for contamination of surface water bodies and groundwater if animal manures are used.

Management of SOM is one part of CO_2 management at the farm level. There are many sources of CO_2 emissions in agriculture and fertilizer use has opportunity for improvement. Efficient fertilizer use is critical to minimize the environmental impact as previously discussed. Agricultural lime is also a source of CO_2 in agriculture and can be included in a similar category as fertilizers. Lime is a commonly used pH amendment in many parts of the world, used to improve acid soils that limit production. A biproduct of its chemical reaction in the soil is CO_2. For this reason, and because it is a significant cost, lime is well suited to a VR application where only areas of the field that have a low soil pH are treated (Bongiovanni and Lowenberg-DeBoer, 2000).

Decreasing tillage and increasing SOM in general has a long-term effect of improving soil structure. Tillage loosens soil temporarily but, as SOM is depleted and soil aggregates are broken, the longer-term effect is that the soil will collapse leading to compaction. However, there are instances where some types of tillage may be beneficial. In soils that are affected by high sodium and dense subsoil structures, deep ripping can be done to provide drainage channels for soil water as well as enhancing oxygenation and root penetration. This is particularly effective in sodium-affected soils if gypsum is applied to mitigate the dispersion effects of sodium. Additionally, the incorporation of manures into the topsoil can enhance the SOM within the mineral soil. This leads to better structure and more likely organo-mineral complexation leading to enhanced SOM stabilization. As discussed earlier, most tillage results in undesirable soil redistribution but targeted efforts can mitigate erosion. Harrowing to smooth out small rills can prevent the development or deeper stream channels that have more erosive power.

Metrics

Due to carbon credit and offset payment schemes, there is a broad desire to measure and track SOC levels in agriculture. This is not a simple task to do accurately and with repeatability over time. Organic carbon can vary greatly across a landscape, both horizontally and vertically (Meersmans et al., 2009; Olson and Al-Kaisi, 2015). A single point measurement in a field could yield quite different results depending on where it is taken (see Figure 2-8 illustrating the variable depth and amount of SOM in a single field). Over multiple years, some areas within a field could lose SOC, and other areas could gain. Not only that, but a specific point could gain SOC in the topsoil but lose in the subsoil (Olson and Al-Kaisi, 2015). For accurate tracking, the points of measurement should be based on spatial soil data considering soil texture variation and landscape position. Research has shown the complexity of influencers on SOC and soil health measurements, finding some of the best predictors include apparent EC, landscape position, wetness index, and topographic position index (Adhikari et al., 2022), which are all attributes inherent to SWAT MAPS.

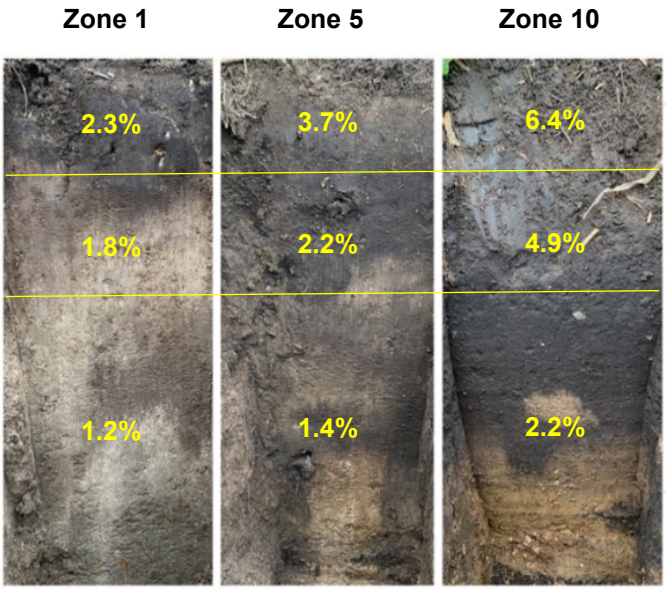


***Figure 2-8**. Soil profiles (0–15 cm; 15–30 cm; 30–60 cm)) from three SWAT zones demonstrating variable depth and amount of SOM.*

Monitoring changes in SOM from decreasing tillage requires a long-term approach if direct measurements are to be used. As mentioned previously, whenever the soil is not frozen there is a constant balance between the decomposition and deposition of SOM. This balance shifts through time in response to environmental conditions and plant growth stage as well as the addition of any amendments. Therefore, there are cycles of accumulation and ablation of SOM. There is an annual cycle linked to the growth and senescence of plants as well as annual changes in soil temperature and moisture. There are cycles that are the length of the crop rotation as differing crops input different quantities and qualities of litter. There are also cycles that are in response to drought cycles as drought lessens productivity and therefore inputs of SOM. *This means that, for accurate descriptions of the trends of SOM accumulation and carbon sequestration to be ascertained, soils need to be analyzed for soil carbon at the same time of year, every year. They need to be analyzed year over year for the duration of these crop rotation and drought cycles as well.* Furthermore, as SOM increases so does the microbial decomposition in response such that microbial

decomposition rates equal the average annual input of fresh organic matter and the soil reaches an equilibrium or carbon saturation point. As such, it is not appropriate to extrapolate a linear increase in soil carbon sequestration. For these reasons, *monitoring short term changes in carbon in soils through direct measurement is dubious and always needs to be in context.*

SOM can be quantified and characterized in many ways. For purposes of carbon sequestration, direct quantification of %C is preferable to %SOM. Microbial biomass carbon is also potentially usable as a metric for the capacity of a soil to support healthy levels of microbial activity. This is highly affected by the current conditions of the soil. Microbial biomass carbon after a standard incubation period allows for comparable results.

SWAT MAPS offer a practical way of improving the accuracy of measuring and tracking SOC over time by creating a stratified sampling protocol. Stratified sampling is especially important to tracking SOC due to the combination of spatial and temporal variability. It gives a methodology to group similar soils together for measurement, balancing cost versus accuracy. Unlike methodology using satellite imagery and modelling, SWAT MAPS are ground-truthed and either SOM or SOC is measured through accredited soil laboratories. Currently it is not practical to measure every square meter of soil, nor is it accurate to base measurements on a single point representing 100+ acres. SWAT MAPS allow a practical solution to map SOC in heterogeneous soils and give farmers insight into where and how SOC levels could be improved. More importantly, it offers a management tool to help use crop inputs more efficiently to reduce total GHG emissions per unit of production.

Recommended Metric:

- **Recurring measurement of SOC using stratified sampling protocol with ground truthing.**

***Figure 2-9**. Uncultivated Chernozem in the Canadian Prairies illustrating a system in equilibrium (at carbon saturation) with net carbon sequestration negligible.*

EROSION PREVENTION AND SOIL COVER

There is no environment on Earth where the rate of soil formation exceeds the rate of soil erosion in poorly managed exposed soil. It is therefore imperative that soil erosion be minimized as much as possible. Erosion is effectively managed by maintaining a living cover of vegetation at all times. There are three types of erosion: tillage, wind and water. Tillage erosion is essentially eliminated by switching to no-till agricultural practices. Not only is the practice of tillage eliminated but soil aggregation can recover over time and the binding of soil aggregates by roots, living and dead, reduces other forms of erosion as well.

Wind erosion is exponentially related to amount of soil cover. This is a physical process and does not require that the soil cover is living. Maintaining stubble and residue covers are effective as is using living cover crops. Dry and/or cold conditions will necessitate non-living soil cover. Water use is increased when plants are present through transpiration. Therefore, living cover crops in arid regions will deplete soil moisture such that the cash crop productivity may be hindered. The biomass returned to the soil by these crops is also reduced. Wind erosion is also affected by soil texture and landform. Coarse textured soils tend to dry out quicker and are less cohesive making them susceptible to wind erosion. Sand sized particles do not tend to travel far and wind erosion of sands tends to be limited to within a field. Silts and clays are harder to detach but once suspended are easily transported long distances. Exposed hilltops are much more susceptible to wind erosion but long stretches of flat land can lead to even greater wind erosion as windspeeds increase along the uninterrupted terrain.

Water erosion has some similarities to wind erosion in that well aggregated clays are difficult to detach but can travel greater distances once they are detached. However, water erosion tends to be concentrated in different areas of a field, particularly within water flow paths. The longer and steeper the flow path, as well as the larger the catchment area, the greater the potential for water erosion. The erosivity of water is related to the velocity at which the water is flowing. Steep slopes contribute to increased velocity but so do long slopes where water can gain momentum and depth. Any interruption to the flow of water reduces the erosive power. Residue cover plays an important role in interrupting the flow of water and is sufficient for limiting water erosion throughout much of a field. Areas where water collects and flows may need more aggressive erosion prevention. Permanent vegetation is the most effective mechanism for preventing water erosion. Silt traps can be used if necessary to trap sediment to prevent downstream impacts.

In highly productive areas, there may be excessive crop residues such that seeding operations and crop emergence are hindered (see Figure 2-10). In these situations, a reduction in the amount of crop residues retained may be necessary for farm operations, yet, some residues do still need to be retained for nutrient cycling, carbon sequestration, and preventing erosion. Because SWAT MAPS integrate topographic and soil texture information, they can be used effectively to identify erosion risks and develop an erosion prevention plan. Additionally, in-season imagery (such as with SWAT CAM) can be used to assess soil cover to ensure that management practices are retaining adequate soil cover, living or non-living.

***Figure 2-10**. Examples of the impact of crop residues in different zones. Top image shows light residue in a Zone 1 with excellent early growth. Bottom image shows thick residue in a Zone 10 with excess moisture and cold soil slowing emergence.*

Phosphorus (P) runoff into surface waters is a major issue worldwide, particularly in areas of intensive agriculture. In high enough concentrations, phosphorus causes eutrophication of water bodies, leading to algae blooms, death of fish and other aquatic wildlife, and in some cases toxins in the water rendering it unusable for livestock (Government of Canada, 2020; Alexander et al. 2008). Studies have shown that the amount of P measured in runoff from fields is highly correlated to soil test P in the soil surface (Duncan, et al., 2017; Little et al. 2006; Cornell University Cooperative Extension, 2021). Agriculture must strive to achieve a level of soil P that doesn't result in loss of productivity, balanced against any risk to the environment. Fortunately, advanced 4R Nutrient Stewardship guidelines for phosphorus—that help guide the right source, rate, time and place of phosphate fertilizers and manures—help reduce the potential of high soil P loading that leads to increased runoff. While 4R practices cannot directly quantify reductions in P loss, the guidelines may currently be the most practical tool available to farms to mitigate environmental loss of P without compromising soil productivity (Bruulsema, 2017). SWAT MAPS allow a farm to identify areas with high soil P levels, allowing reduced P applications in these areas to draw down excess soil P levels. *Phosphorus typically has low mobility in soils and much of the contamination of surface water bodies is through soil erosion, where soil particles containing excess P are eroded from fields and deposited in surface water.* As such, mitigating soil erosion along with appropriate 4R phosphorus management prevents most phosphorus contamination from fertilizers.

Metrics

Stubble height is an important contributor to the efficacy of stubble to mitigate wind driven erosion. However, the achievable stubble height is highly dependent on the crop type and how tall the crop grew in that particular field, zone, and year. As such, actual field measurements of stubble height should be limited to checks as to whether the farmer is following this general principle rather than measuring actual stubble heights. Soil cover by trash and living plants can be estimated from manually analyzing quadrats within a field for percent coverage or by automated imagery instruments and analyses such as SWAT CAM (example image shown in Figure 2-11). The duration that bare soil persists is more important than the percent coverage averaged over the course of the year provided that there is at least a modest amount of soil cover.

Recommended Metric: Soil cover presence measured by automated imagery (such as SWAT CAM).

Figure 2-11. *A SWAT CAM picture showing two years of crop residue and stubble from durum (2022) and canola (2023). Picture was taken after snow melt on April 22, 2024, prior to sowing lentil with a low disturbance drill*.

CASE STUDY 1: MAINTAINING SOIL COVER & MANAGING PHOSPHATE TO REDUCE EROSION & RUNOFF

Hummocky landscapes often have eroded hilltops, caused by many years by tillage, wind, and water erosion. This eroded soil results in challenges with good seed placement and emergence, often resulting in low plant populations and exposed soil that increases susceptibility to further erosion.

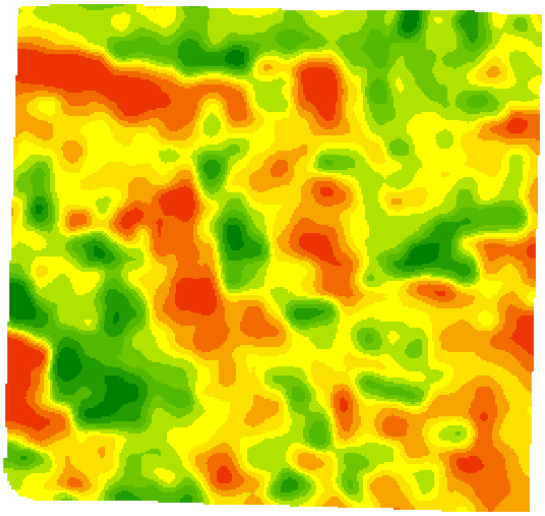
One successful solution has been to increase seed rates in these areas to ensure crop establishment, protect soil, and allow the plant roots to regenerate the soil. Over a period of 2-4 years, the increased crop roots and biomass returned to the soil improves soil health, lowering seedling mortality rates. Eventually seeding rates can return to normal. One modest example of this is shown below (Figure 2-12) for canola, where the seeding rate was increased 6% to partially compensate for the expected higher mortality rates (actual mortality rates in zone 1 were 24% vs. field average of 18%). Rates were also increased in zones 7 to 10 due to poor soil structure and salts; the goal being to establish enough canola to achieve ground cover, use water, and protect the soil from further degradation. To minimize excessive phosphate accumulation, potential runoff, and help minimize any additional salt toxicity in the seed row, phosphate rates were adjusted in SWAT zones based on expected soil P supply and yield removal. This combination of VR seed and phosphate is easy to execute with modern air seeder technology.

APPLICATION SUMMARY

Zone	Area Acres	Yield Goal bu/ac	Layer 1 Canola	Layer 2 MAP	Layer 3 Urea	Layer 4 PS	Applied Actuals
1	3.8	40	5.3	40	175	140	110-45-0-23
2	8.4	45	5.1	40	180	140	112-45-0-23
3	10.1	50	4.9	40	185	130	113-43-0-21
4	11.4	55	4.9	40	180	120	108-41-0-19
5	10.9	60	4.9	40	175	110	104-40-0-18
6	9.6	65	5	40	165	100	98-38-0-16
7	6.3	55	5.1	35	140	80	82-32-0-13
8	6.6	45	5.2	25	110	50	62-22-0-8
9	2.3	30	5.4	25	85	35	48-19-0-6
10	1.1	10	5.6	15	60	35	35-14-0-6
	70.5	**52**	**5**	**37.3**	**162.5**	**106.4**	98-38-0-17

SOIL TESTS

Zone	Area %	N '19	OM %	pH	P Olsen	K	S	Cl	Zn	Cu	EC
1-2	17	17	4.5	7.1	7	394	29	7	1.2	0.6	0.33
3-4	30	27	5.6	7.6	8	443	160	16	1.2	0.6	1.93
5-6	29	19	4.4	7.3	9	491	160	16	1.2	0.7	0.90
7-8	18	63	4.1	7.0	10	445	160	80	1.1	0.7	2.34
9-10	5	29	5.0	7.7	31	458	160	61	1.6	0.9	3.19



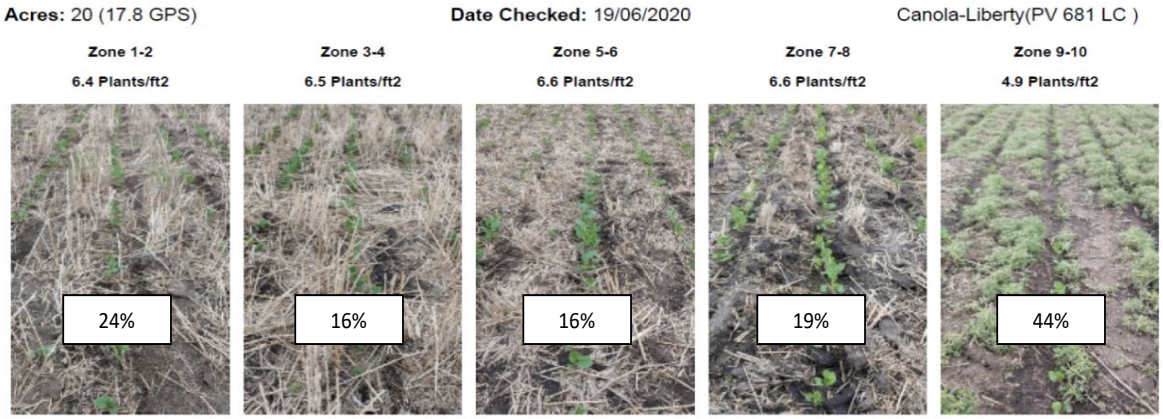


***Figure 2-12**: VR prescription (top, seed rates in Layer 1) and soil tests (middle) and resulting plant populations (bottom) in five SWAT zones, including calculated mortality rates in white text boxes (field average: 6.5 plants/ft2 and 18% mortality).*

BIODIVERSITY ENHANCEMENT

Biodiversity can be a sensitive topic in agriculture and is highly contextual. A diverse mix of native plant species in an arid grassland of southern Alberta, Canada, is entirely different than a diverse mix of native plants in a coastal subtropical region of south-eastern Queensland, Australia. The commonality though, is that different soils and landscape positions favour certain species over another, regardless of what that landscape is growing. This provides opportunity to use the landscape in a way that supports profitable agriculture as well as biodiversity.

As an example, salt-affected soils are not well suited to most annual grain crops, but there are many different perennial forage species that are adapted to these soils (Figure 2-13). *The ability to map areas that do not economically support annual crops supports changes in land use that will benefit the farm economically, improve soil health, and support plant and animal biodiversity.* As salinity is related to groundwater discharge it is also related to plant water use. Annual crops in a saline area that are unproductive will not use much water. In a case like this, planting high water use perennials like alfalfa or trees can increase water use, draw down the water table and protect the surrounding crop from salinity. This provides enhanced productivity of the marginal areas and generally a reduction of inputs. Additionally, the increased water use can intercept dissolved nutrients and pesticides preventing them from contaminating groundwater or surface water bodies.

Historically, farms have been reluctant to surrender annual cash crop land to perennial forages or other species for several reasons. Changing of field boundaries can increase overlap and over-application of inputs, or cause application inefficiency due to implement turning. But increasing adoption of technology with automated sectional control, row, or nozzle shut off has greatly reduced the negative consequences of irregularly shaped boundaries. It also helps reduce off-target application of pesticides, for example overspray of an insecticide onto flowering native species in non-crop areas where pollinators are active.

***Figure 2-13**. Productive perennial grass hay mix growing in a flood prone sodic soil (SWAT zone 10) in SE Queensland, Australia.*

Research on diverse, non-crop areas has reported several benefits, such as pollination services, biocontrol of pests through habitat for beneficial insects, sequestration of carbon, protection of crops from wind, improvements in water quality (Muringai & Goddard, 2019), as well as increased species richness and abundance (Outhwaite et al., 2022). Others have reported mixed results; for example water use by trees potentially outweighing the benefits they provide (Robinson et al., 2022). Shelterbelts have been used extensively for wind erosion control. In arid to semi-arid environments they have the additional benefit of reducing evapotranspiration rates on windy days. In water limited regions this can amount to productivity increases. Brandle (2000) reported yield increases from shelterbelts of 6-44% depending on crop type and conditions. The net effect is that there is greater productivity of the field overall despite a smaller land base being cultivated.

Biodiversity does not always need to be at the expense of arable acres. Under-seeding can provide erosion control particularly in water erosion sensitive areas. Planting a leguminous cover crop can provide nitrogen fixation and green manure for the next season provided there is adequate moisture support. Timing of under-seeding is important to reduce competition between the cash crop and the cover crop. Growth rates and maturation times are linked to availability of moisture and as such SWAT MAPS can be a valuable tool in determining where and when to under-seed. *Understanding the spatial variability of a field highlights the opportunities to increase productivity and sustainability of the whole system, including cash crops, rather than merely decreasing the arable land base for production.*

SWAT MAPS combined with yield data to calculate spatial returns allows a farm to analyze fields in detail, making land use change decisions easier and more informed. The example shown in Figure 2-14 would suggest that SWAT zones 9-10 may be better suited to a different purpose. The farm could potentially plant less acres, improve profits, and contribute to the ecosystem by adding species diversity. Multiple years of spatial data can reinforce land use change decisions, such as a yield stability map produced from multiple years of yield data (Figure 2-15).

Metrics

Biodiversity can be assessed by extent of non-crop area and/or species richness. Both are important but extent is often a more accessible metric for biodiversity. Extent can be measured as the percentage of a field that is in non-crop perennial vegetation. An additional measurement is the percentage of the linear extent of boundaries in the field (field edges, water bodies, etc.) that contains some type of non-crop/buffer land use. The extent of biodiversity can also be measured as the distance within a field to a non-crop area. This metric can be used to set a maximum acceptable distance to avoid extensive monocultures. It is also helpful to assess the potential of pollinator species to reach the interior of large fields.

Recommended Metrics:

- **Extent of non-crop area;**
- **% of linear extent of field boundaries in non-crop use;**
- **maximum distance in field to non-crop area**

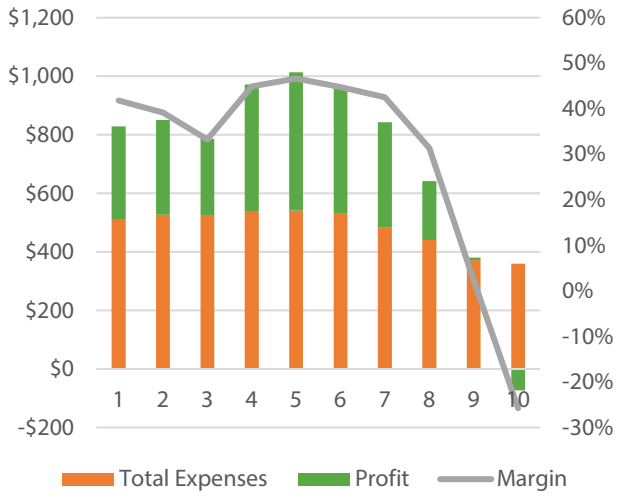


***Figure 2-14**. Example of a profit analysis by SWAT zone.*

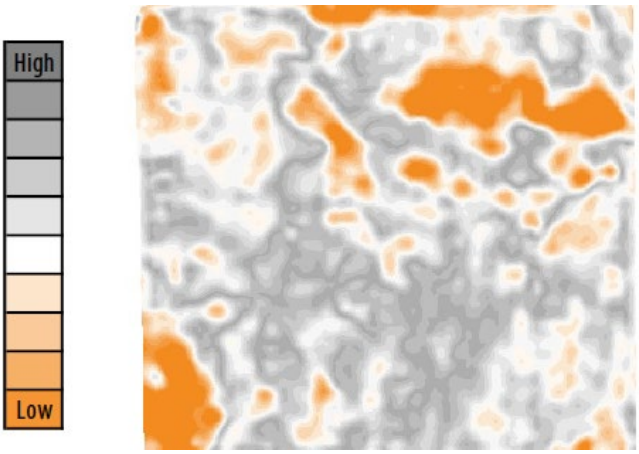


***Figure 2-15**. Yield stability map delineating areas of a field with yield instability and higher risk of negative returns.*

CASE STUDY 2: SWAT MAPS DRIVING POSITIVE LAND USE CHANGE

One example of land use change to manage ground water levels and subsequent salinity has been used extensively on Olee Acres Inc., a farm located in the Quill Lake area of east central Saskatchewan, Canada. As a long-time farmer and owner, Dwight Odelein recognized it was going to take management change to avoid further production losses to salinization on his land. The farm began implementing targeted forage seeding, followed by VR management of seed and fertility with SWAT MAPS in 2021. Many of these areas of the farm are still in forages or have successfully been regenerated and are back in annual grain production. An example of this is illustrated in Figure 2-16, which shows imagery from 2016 and 2025 both mid-season and post-harvest. Historically the NE corner of the field was badly affected by salinity and poor drainage.

***Figure 2-16**. True color satellite images of a field mid-season (left) and post- harvest (right). Top images are prior to implementation of forages to manage water.*

The poor productivity is visible in the July 2016 image, as well as lack of growing cover in September later that year. But as of 2025, much of the salt affected area is now growing perennial forages, and adjacent crop is profitable. The growing forages continue to use water late in season, long after the annual crop has matured (image dated 30-9-2025) and provided two cuts of hay in 2025 (Figure 2-17). The adjacent areas that are still at risk of salinization are typically managed with lower fertilizer rates but higher seeding rates to ensure crop establishment and provide ground cover.

***Figure 2-17**. Photos of targeted area growing perennial forage (upper) and first cut (lower).*

INTEGRATED PEST MANAGEMENT

Crop Rotation

Crop rotation is an essential part of agriculture. Without proper crop rotations, weeds, insects, and diseases are much harder to manage. Changing crop types removes the host or food source for pests and diseases causing populations to drop rather than to build up over time. Introducing a new crop also allows for changes in integrated pest management strategies including the pesticide class being used. Rotating through pesticide classes and using two or more effective ingredients is a very important step in reducing pesticide resistance.

Pesticide resistance builds when pest and diseases are not fully eliminated by a pesticide. The pests and diseases that have genetic attributes that afford some protection survive at a higher rate than those without leading to a resistant population. Changing the effective ingredient year after year and using more than one at a time decreases the likelihood of a pest or disease population simultaneously achieving pesticide resistance to all the applied pesticides. If they have developed resistance to one they will be eliminated by the other. A pesticide strategy that is intensively and carefully managed like this will result in less pesticide use in the long term, which benefits farmers and the environment.

Crop rotations have additional benefits especially if crops are chosen for complimentary soil improving properties. It is common practice to include a pulse crop to benefit from biological nitrogen fixation. Deep rooted graminoids like wheat are excellent at increasing belowground residue inputs as well as scavenging for nutrients that have leached below the rooting zone of more shallow rooted crops. Improved nutrient cycling and soil structure is thought to contribute to the higher yields seen with crops grown in rotation. Crop rotation improves overall farm level crop diversification. Crop diversification is beneficial as it promotes stability in production and markets as well as spreads out the timing of management practices.

SWAT MAPS can be used to take crop rotations and diversification further by targeting certain crops to their optimal locations within a field. For example, peas are prone to fungal root diseases and as such are not well suited to moist soil conditions found in many depressions. Conversely, canola is a high water use crop that can benefit from this increased moisture. Seeding peas in drier SWAT zones and canola in wetter SWAT zones optimizes the heterogeneity of the field. Pea and canola tend to also be a good mix as their vastly different seed sizes makes sorting post harvest far easier than more similarly sized grains (see Figure 2-18).

***Figure 2-18**. "Peola" (Pea-Canola) intercrop applied with a VR prescription targeting dominantly peas in SWAT zones 1-3 (left photo) and mostly canola in SWAT zones 7-10 (right photo).*

Integrated Pest Management

Like nutrients, some pesticides are at risk of movement into aquifers or surface waters (Grover, 1973; Ritter et al., 1994). This risk is specific to individual chemicals and their solubility in water, adsorption characteristics and persistence (Congreve and Cameron, 2019). Relatively soluble pesticides (e.g. atrazine) can easily leach into subsoil water or surface waters. Others are bound tightly to soil particles (e.g. trifluralin) and are at negligible risk of movement unless there is soil erosion. Off-target movement of pesticides in this manner should be treated as seriously as spray drift from one field to another. Understanding the leaching potential of the soil, as well as organic matter and total WHC, can help reduce movement of pesticides off site (Futch and Singh, 1999). Well drained irrigated soils are a considerable risk, but precise management of irrigation schedules is one of the most impactful ways to minimize this risk. Variable rate irrigation (VRI), using soil moisture probes and SWAT WATER maps, is a valuable solution for this problem, much like managing nitrogen and phosphorus losses.

Any way pesticide rates can be reduced without resulting in a loss in weed control is an opportunity for reducing environmental impact and managing farm input costs. VR herbicide application has potential in some landscapes that are variable enough to justify different rates based on soil type or weed population (see Figure 2-19). Gaston et al. (2001) noted an example in cotton where a reduced soil-applied herbicide rate prior to cotton could be used in coarser textured soils with lower organic matter. This was both due to lower weed density in these areas, as well as varying herbicide effectiveness based on the soil properties.

Pesticides are valuable tools to produce healthy, high yielding crops, but it is imperative to use them according to label guidelines. Knowledge of soil and water variability across a landscape, which SWAT MAPS can provide, is the foundation for proper soil-applied pesticide application decisions. Pesticides should always be used in conjunction with other integrated pest management practices like crop rotations and general biosecurity including sanitizing equipment moving from field to field and especially farm to farm.

Metrics

Crop rotation metrics should be assessed during planning of the crop rotation. Metrics for good rotation planning include the incorporation of at least one legume, the inclusion of sufficient biomass yielding crops (e.g. wheat) to maintain SOM and be at minimum three years. Long term measurements of the efficacy of crop rotations include measuring SOM as mentioned previously. Additionally, pest monitoring can be useful in determining if the rotation has been effective and if the rotation needs to be modified. Furthermore, pest control measures need to be complimentary for pesticide carry over and ensuring that there is variability in the classes of pesticides being used.

Recommended Metrics:

- **Crop rotation: Inclusion of one legume, one biomass-yielding crop and minimum of 3-year crop rotation;**
- **Insect, weed, and disease monitoring**

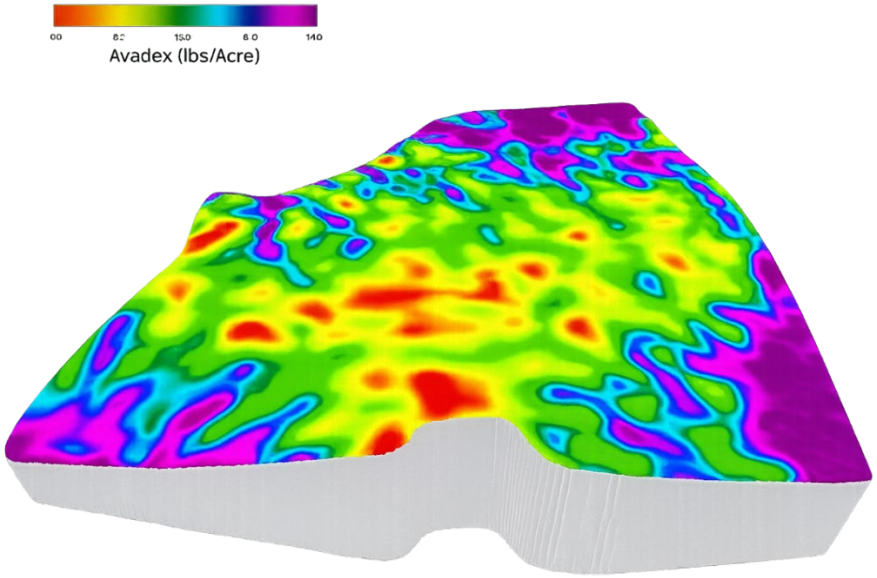


***Figure 2-19**. Herbicide applied using variable rates based on SOM and texture.*

CASE STUDY 3: INTERCROPPING WITH SWAT MAPS

In 2019, Croft Farms Ltd. near Melfort, Saskatchewan, Canada, seeded the field illustrated in Figure 2-20 to Maple peas and Clearfield canola. Phosphate was included to provide some starter nutrition. The peas were inoculated with rhizobia to fix their own nitrogen. In this region of northeastern Saskatchewan, peas tend to yield best on well drained, upper landscape positions (SWAT zones 1-4 in this field) and canola can yield better in lower landscape positions (zones 6-10). By leveraging the farm's VR capability and the strengths of each crop, the relative density of peas was decreased from zone 1 to 10 (layer 1), while canola was increased (layer 2).

APPLICATION SUMMARY

Zone	Area	Yield Goal	Layer 1	Layer 2	Layer 3
	Acres	bu/ac	Peas 1	Canola 2	Phos
1	18.9	50	110	2.4	65
2	9.4	55	105	2.4	65
3	12.9	60	100	2.4	65
4	14.1	65	95	2.6	60
5	14.7	70	95	2.6	60
6	14.6	70	90	2.6	60
7	16.7	70	90	2.8	55
8	15.8	70	85	3	55
9	19.4	60	75	3.3	50
10	24.2	50	65	3.6	50
	160.7	**61.3**	**88.9**	**2.8**	**57.6**

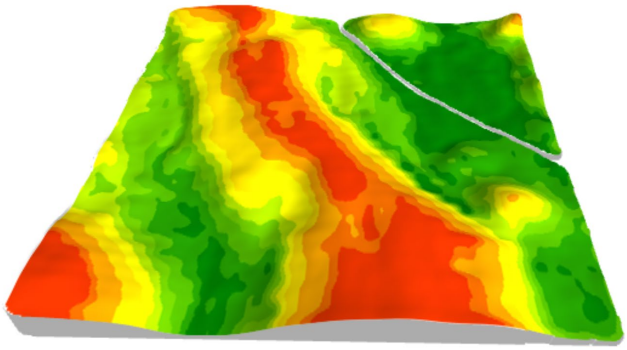


***Figure 2-20**. Pea-Canola intercrop prescription targeting canola dominant population in wet lower landscape positions.*

Some benefits of a pea-canola intercrop include:

- Nitrogen fixation in peas reduce synthetic nitrogen requirements.
- Better harvestability compared to monocrop peas.
- Plant diversity.
- Potentially better land use efficiency (higher combined yields than individual monocrops).

Considerations:

- Grain separation and cleaning after harvest adds significant time and cost.
- Selecting the right species is important for weed control. Peas and Clearfield canola offer several options, which is why it is a popular intercropping option.
- If the peas do not survive in parts of the field, nitrogen fertilizer may be needed to maintain yield potential of the canola, adding logistical complexity.
- Disease is still a concern in a high rainfall environment. There are intercrop options such as flax-chickpea that have shown potential to reduce disease transfer and require less fungicide.

***Figure 2-21**. Pea-Canola intercrop.*

CASE STUDY 4: INTEGRATED PEST MANAGEMENT FOR WEED CONTROL

A demonstration at the Glacier Farm Media (GFM) Discovery Farm at Langham, Saskatchewan, Canada, explored the use of multiple strategies to manage Kochia (Kochia scoparia (L.) Schrad.). Kochia is a problematic weed in much of western United States and Canada with growing herbicide resistance (Friesen et al., 2009). It tolerates salinity well and as a result takes advantage of poor crop competition in salt affected soils. The project at the GFM Discovery Farm highlighted the use of SWAT CAM to map weed leaf area, kochia leaf area, and crop leaf area (Figure 2-22). Once collected, these data layers were used to apply different rates of herbicides to specific areas in the field with varying weed density, reducing total pesticide load, reducing cost, and minimizing crop injury potential. In spring of 2021, sulfentrazone was applied prior to sowing spring wheat only in the areas with expected high kochia density, based on the previous season SWAT CAM map (Figure 2-23). This simple on/off prescription reduced the applied amount by 54%.

The second cultural strategy to control kochia included higher seeding rates to improve crop competition. SWAT zones 7 to 10 in this field have high exchangeable sodium and moderate to high salinity, so wheat seed rates were increased as much as 30% in zone 10 to account for increased mortality in these soils (seeding prescription shown in Figure 2-24). This is just one example of how using multiple layers of spatial data can not only reduce pesticide use but also improve ROI and provide long-term management of a problematic weed species.

Crop and Weeds

Detection Type	Mask	% Coverage	Processing Date	Model
Kochia	☐	0.2	4/6/2023	2022-10-19-Kochia
Vegetation	☐	23.6	4/6/2023	2022-05-24-Vegetation
Crop_Early	☐	22.4	4/6/2023	2022-09-15-Early_Stage_Canola
Crop_Mid	☐	22.7	4/6/2023	2023-03-24_Mid_Stage_Canola

***Figure 2-22**. Example of SWAT CAM image used to map weed leaf area, kochia leaf area, and crop leaf area.*

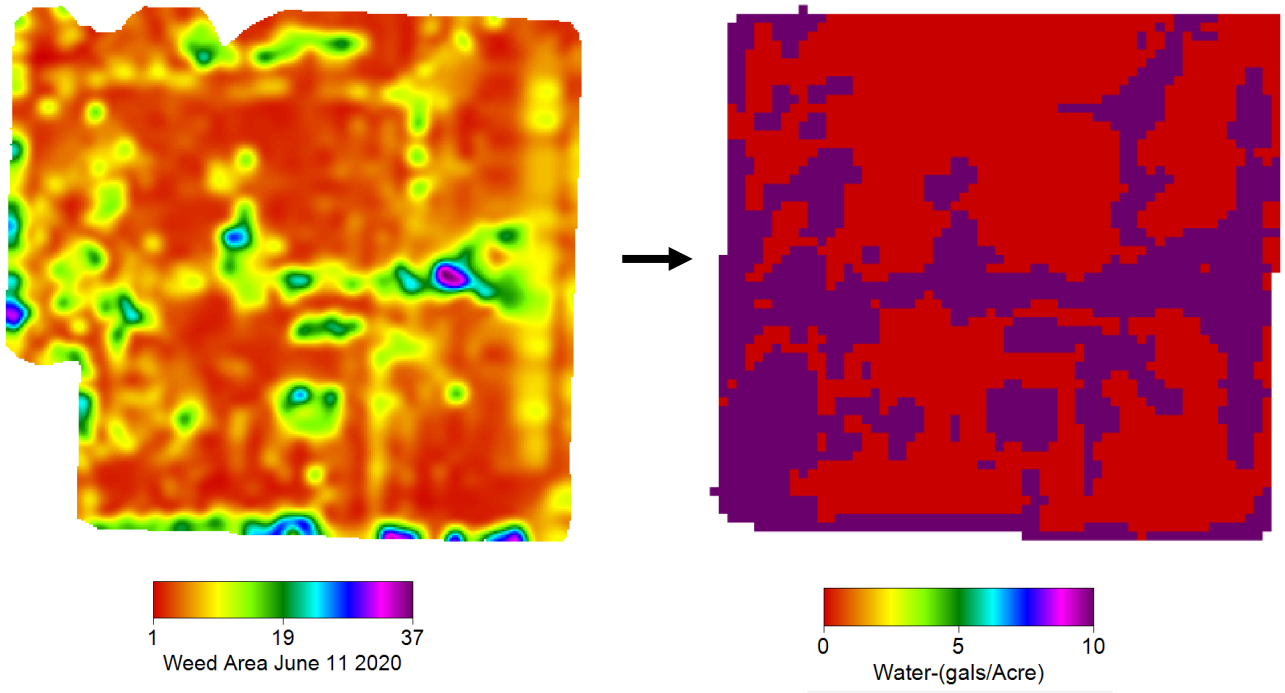


***Figure 2-23**. SWAT CAM map of weed leaf area (left) and the sulfentrazone herbicide prescription derived from it (right).*

APPLICATION SUMMARY

Zone	Area	Yield Goal	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Applied Actuals
	Acres	bu/ac	Wheat	MAP SR	NPKS	MAP SB		
1	3.6	55	125	25	250	40		77-53-12-12
2	6.8	65	120	25	270	40		82-55-13-13
3	8.6	75	115	25	290	40		88-56-14-14
4	10.3	85	115	30	300	45		92-62-14-14
5	10.9	80	120	30	290	45		89-62-14-14
6	10.8	75	125	25	250	35		76-51-12-12
7	10.4	65	130	20	200	30		61-42-10-10
8	4.7	55	135	15	150	30		47-35-7-7
9	2.8	40	145	10	100	20		31-23-5-5
10	1.2	25	150	10	70	10		22-16-3-3
	70.1	**70.2**	**123.7**	**24.2**	**247.2**	**37.3**		76-51-12-12

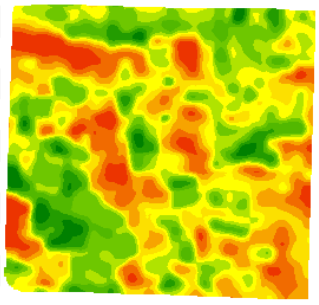


***Figure 2-24**. 2021 prescription for sowing wheat (Layer 1, lbs/ac of seed) with seed row P (Layer 2) and additional NPKS in sideband (layers 3,4).*

FERTILITY OPTIMIZATION

Climate change caused by greenhouse gas (GHG) emissions has risen to the forefront of many government policies around the world, and emissions caused by agriculture have received their share of attention. The positive side of this attention, though, is funding and research initiatives into better understanding emissions from cropping systems and how to reduce them. The research has reinforced how valuable the 4R nutrient stewardship guidelines are, and that there are opportunities to not just reduce GHG emissions but reduce N losses in all forms to improve nitrogen use efficiency (NUE) and economic return from applied N (Norton, Gourley, & Grace, 2023).

4R Nutrient stewardship is a framework developed to guide farmers toward responsible use of nutrients for economic, environmental, and social benefit (The Fertilizer Institute, 2021; Bruulsema, 2022). This framework guides nutrient applications to be applied at the right time, right place, right rate, and with the right source. Historically these 4R principles have been applied at a field scale; in other words, the whole field has been treated the same based on an average soil type. But 4R nutrient guidelines should not be applied using arbitrary field boundaries. *4R practices are governed by properties like soil texture, soil moisture, crop yield potential, pH, mineralization potential, and soil nutrient levels—all of which vary across a field landscape (Burton, 2018). True 4R nutrient management must acknowledge this variability for full economic, environmental, and social benefit.*

Gaseous Nitrogen Loss

One of the most significant GHG concerns from cropland is nitrous oxide (N_2O). While total emissions of N_2O are typically only 0.5 to 2 kg N_2O-N per ha (Shcherbak et al, 2014), it is a potent greenhouse gas with a global warming potential of approximately 265 times CO_2. Globally, annual emissions from agriculture have increased 28% since 1990, to a total estimate of over 2.07 billion t CO_2eq in 2022 (Climate Watch, 2025). Annual emissions from USA, Australia, and Canada are show in Figure 2-25. N_2O is produced from fertilizer N as a biproduct of the nitrification process and from soil nitrates through a process called denitrification.

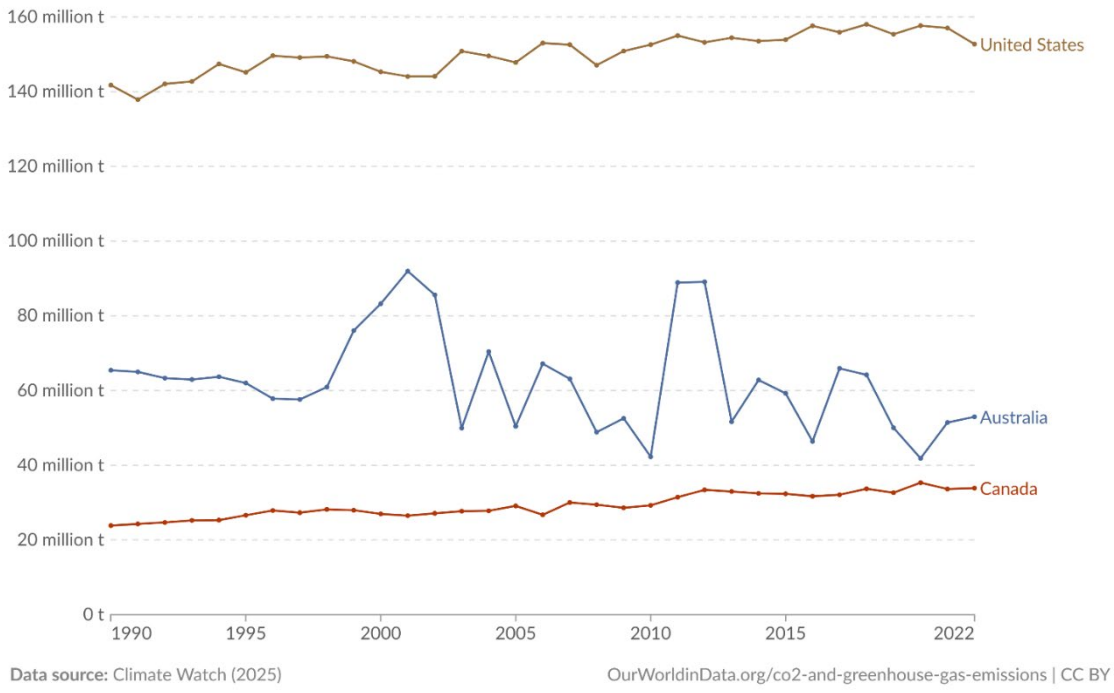


***Figure 2-25**. N_2O emissions (expressed as tonnes of CO_2eq) from agriculture in Australia, Canada, and USA. Source: Climate Watch, 2025.*

Denitrification is a significant nitrogen loss mechanism in agriculture globally (IPNI, 2021; Stark and Richards 2008). It is largely the result of relatively saturated soil conditions causing a biological reaction to occur via bacteria, converting soil nitrate (NO_3^-) to NO, N_2O, and N_2 releasing these gases to the atmosphere (Maharjan et al., 2024). Under completely flooded, anaerobic conditions nitrate will be reduced completely to N_2, a harmless and abundant atmospheric gas. It is primarily the wet areas surrounding wetlands that have high N_2O emission potential, as depicted in Figure 2-26. From a farm economics perspective, in what form N is lost does not matter—all lost N results in lower productivity or increased expenses to replace it in the future. Figure 2-27 shows productivity loss due to N loss in low landscape positions.

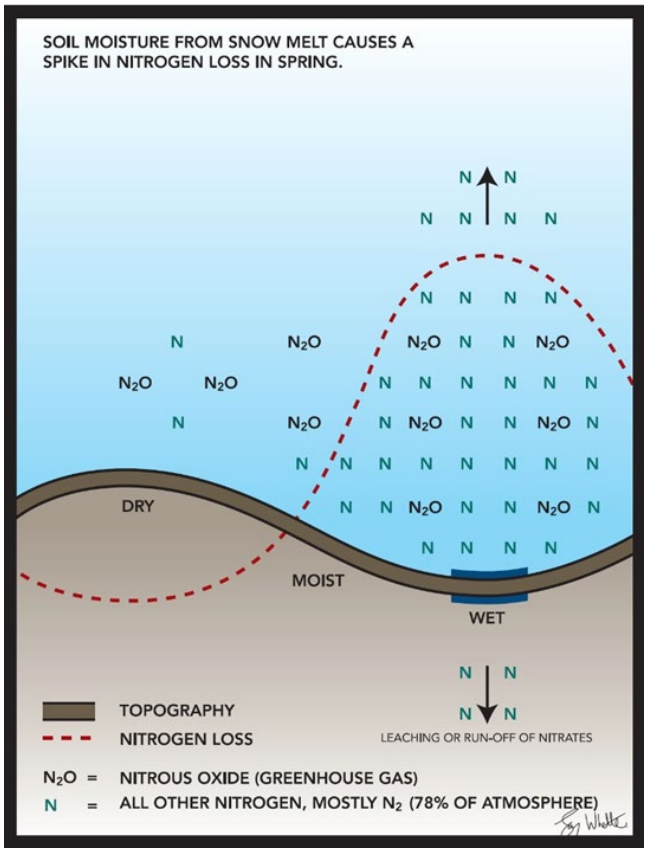


***Figure 2-26**. Diagram of N loss variability by landscape position. Source: Jay Whetter, Canola Council of Canada*

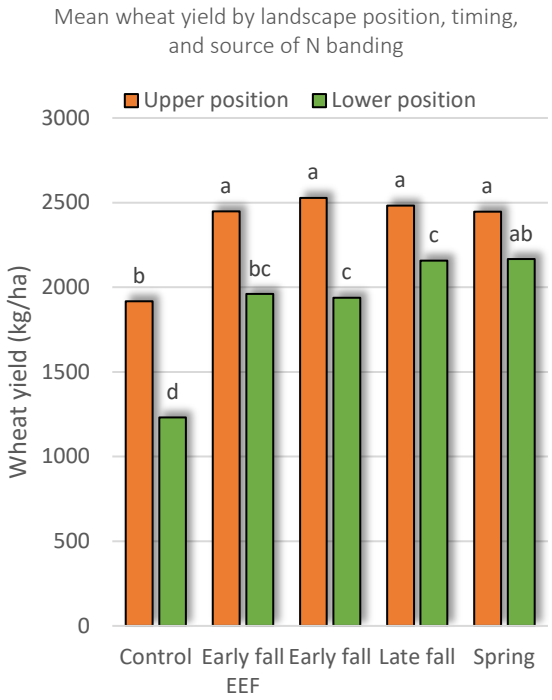


***Figure 2-27**. Evidence of N loss due to denitrification in low landscape positions. Source: Tiessen et al. 2005.*

The significance of organic matter and subsequent mineralization of nitrogen in-season should also be considered. Many hummocky landscapes characteristic of the USA northern great plains and western Canada have significant organic matter variability (and variable depth of A horizon or topsoil) that result in variable mineralization and soil nitrates (Beckie et al., 1997; Malo and Worcester, 1975; Pennock et al., 1987). This difference can lead to N_2O "hotspots" in high organic carbon soils in lower landscape positions, as reported by Dunmola et al. (2010). Therefore, proper nitrogen rates need to consider mineralization potential along with crop uptake requirements and available soil nitrate at sowing. Figure 2-28 shows mean topsoil nitrate levels from thousands of fields in western Canada, showing a distinct trend of increased nitrate in SWAT zones 9-10, often due to poor production and/or high organic matter mineralization rates. These are also the wettest areas of the landscape and therefore, without using VR to lower rates in those areas, they would unfortunately be prone to high N_2O emissions.

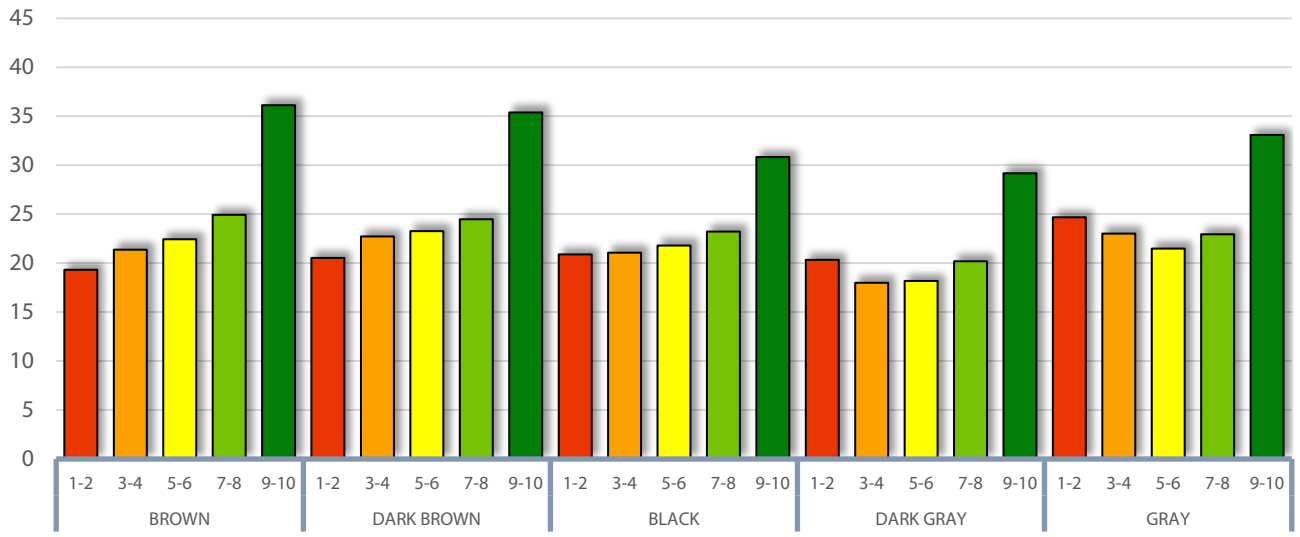


***Figure 2-28**. Soil nitrate (lbs/ac, 0-20 cm) by SWAT zone and major soil zone in western Canada (mean of 52,000 samples).*

Glenn et al. (2021) concluded that using VR can mitigate N_2O emissions from soils. In this study, the "high yield zones" had the lowest emission factors (N_2O per kg fertilizer N) despite having 50% more nitrogen applied, while the low yield zones had higher emission factors despite receiving 50% less nitrogen than field average. In other words, *N_2O emissions are not directly correlated to the nitrogen fertilizer rate applied, but rather how much of that N is needed (or not needed) for crop growth*. **That difference—the ideal rate of N needed—is what varies across the landscape, and is what we can measure and manage with SWAT MAPS.** *It is also why simply reducing total N applied but maintaining flat rates will not necessarily meet emission reduction goals. That strategy could not only hurt output by limiting yields in areas of the field that need high N rates but may also not be enough reduction to address the "hot spots" that have high emissions. VR N may be the only way to address this scenario.*

In another recent study by Hangs et al. (2024) on VR feedlot manure in Saskatchewan, Canada, VR manure resulted in a 23.7% lower N_2O emissions factor than flat rate manure. The study cited higher soil moisture, SOC, and nitrogen supply in large depressional catchment areas as significant influences on large N_2O fluxes. This reinforces that 4R nutrient stewardship applies to all sources of nutrients, whether they are organic or synthetic.

Use of nitrification inhibitors and polymer coated urea have significantly reduced N_2O emissions in many studies (Calderon et al., 2005; Chen et al., 2008; Chen et al., 2010; Hargreaves et al., 2021; Lin and Hernandez-Ramirez, 2020; Maaz & Snyder, 2018; Misselbrook et al., 2014; Raza et al., 2019; Snyder, 2017; Zebarth et al., 2019), and are no doubt a useful tool to mitigate losses. However, the high upfront cost has held back adoption of these products and, to date, do not make up a large percentage of nitrogen sources used in most regions. Regardless, from a broad perspective, any agronomic practice that delays the availability of nitrate to better match timing of crop uptake will theoretically minimize nitrogen losses—including the use of enhanced efficiency fertilizers (EEFs), timing of application, and VR nitrogen application.

While there are currently no formal guidelines for other inputs such as lime, gypsum, manure, and pesticides—we could apply similar 4R principles of time, place, rate, and source to these products as well. For example, basic 4R practices for lime could be:

- Right time: Several months prior to pH change needed.
- Right place: Areas of field that are acidic, and to the depth acidity occurs.
- Right rate: The rate needed to adjust soil pH to the desired pH based on soil buffer pH and quality of lime.
- Right source: A material with sufficient calcium carbonate equivalence and fineness to adjust pH within the desired timeframe.

Advanced 4R practices would simply take the above considerations and apply them spatially within a field based on mapping of soil properties using

SWAT MAPS, to potentially utilize VR applications where it makes sense to do so and reduce the amount of lime needed. This supports a stronger return on investment as well as a reduction in GHG emissions related to production of lime and its reactions in soil that emit carbon dioxide.

While there is not one simple solution to mitigating nitrogen losses and N_2O emissions, a better understanding of where losses are most likely to occur within a field is an important first step in managing the problem. Because water potential, organic matter differences, and crop N uptake are so closely linked to field areas delineated by SWAT MAPS, they offer a valuable PA tool to better manage N and reduce emissions through a variety of stacked agronomic strategies.

Nitrogen Loss via Leaching

Nitrogen can also be lost from cropland via leaching. Texture variation has a substantial effect on nitrogen losses and thus leaching is a well-known problem in sandy soils (Gurevich et al., 2021; IPNI, 2021; Sandercock et al., 1993; Spackman et al., 2019) and is a significant environmental concern in many agricultural regions of the world (Cameron et al., 2002; Shukla and Saxena., 2018; Wang et al., 2015; Nakagawa et al., 2021; Zhou et al., 2015). Excess nitrites (caused by reduction of nitrates) that have leached into aquifers or surface waters used for drinking water can cause what is commonly known as blue baby syndrome (methemoglobinemia), a symptom of nitrite toxicity. High nitrate levels in drinking water can also be fatal to ruminant livestock (Government of Canada, 2020). Nitrates in these water sources are typically caused by over-application of fertilizer or manures to soils that are susceptible to leaching—particularly coarser textured, sandier soils.

There are several solutions to manage nitrate leaching. Timing of application has demonstrated value in some studies (Spackman et al., 2019; Davies et al., 2020), utilizing in-season application of a portion of nitrogen to match crop uptake demand and improve NUE. Organic nitrogen and ammonium are relatively immobile in the soil. They can be moved through soil erosion but largely do not move with the soil solution. Nitrate, being an anion, is present in the soil solution and cannot be bound to the cation exchange complex. Therefore, it is highly mobile and will easily travel with water passing through the soil towards the groundwater. If the availability of nitrate is matched to plant uptake there is little leaching that occurs even if there are large stores of nitrogen in ammonium and organic forms. The impact that split nitrogen applications and EEFs have on reducing nitrate leaching depends on leaching potential, primarily driven by soil texture, crop water use, and rainfall or irrigation.

Nitrogen losses are not just based on soil nitrate levels; excess water is also needed to saturate the soil and move down through the profile carrying nitrate with it. While there is no way to control rainfall, irrigation can be managed to reduce this problem (McDowell, 2017). Irrigated production systems are particularly susceptible to nitrogen losses through leaching and denitrification. Crop water requirements, and the soil's ability to hold water, can vary across the landscape significantly and as a result variable rate irrigation (VRI) systems are slowly being adopted in many regions (Lo et al., 2017). The concept of VRI is simple, yet like soil fertility requirements, can be complex to put into practice (Barker et al., 2017). Regardless, studies have reported opportunity for 8 to 20% in water savings using VRI technology (Sadler et al., 2005).

Use of SWAT MAPS to Optimize Fertility and Reduce Nitrogen Losses

SWAT MAPS allow farms to spatially apply several best practices at once to reduce nitrogen losses. SWAT MAPS consider the spatial variability of water flow and accumulation, differences in soil texture, and crop yield potential across a landscape. With this information a farm can use several different strategies (or combinations of strategies) to reduce nitrogen losses:

1. *Target proper nitrogen rates* based on crop yield potential, soil nitrogen supply, and estimated in-season nitrogen soil supply rate (mineralization).
2. *Utilize protected nitrogen sources* (i.e. nitrification inhibitors or polymer coated urea), especially in parts of the field at highest risk of loss such as coarse textured soils and poorly drained depressions.
3. *Top-dress nitrogen in-season* based on current soil moisture variability across the landscape, yield potential, and expected nitrogen loss. The accuracy of this application can be enhanced even further utilizing soil moisture probes and detailed texture data to make SWAT WATER maps – spatial soil water maps that model the soil water content across a landscape.
4. *Use SWAT WATER maps and VRI technology* to more accurately apply water based on WHC and landscape position in different parts of the field.

Nutrient balance also plays a role in managing nitrate accumulation and leaching by promoting crop health, which increases yield and nitrogen uptake in the crop.

This has been demonstrated in wheat and canola (Malhi et al., 2009) and in corn and rice (Duan et al., 2014). This reinforces the complexity of soil and plant nutrition and interactions that exist between nutrients to maximize their use and uptake. Liebig's Law of the Minimum will come into effect, where nitrogen response and uptake can be limited by other nutrients such as phosphorus, potassium, sulfur, micronutrients, or available water. Therefore, a holistic approach based on soils and water is needed to manage nitrogen rates and minimize environmental impact from leaching.

Metrics

The easiest way to assess the efficacy of a fertility prescription is to look at the crop yield and residual nutrients. Did the crop yield achieve its target (assuming no major pests, disease or extreme weather)? If so, are there large amounts of residual nutrients. An underperforming crop can be indicative of under-fertilization, especially if there are little residual nutrients. Excessive residual nutrients means the crop was over fertilized. For more in depth analysis tissue testing can be done to assess for sufficiency, deficiency, or luxury consumption.

Recommended Metrics:

- **Crop yield (compared to target)**
- **Nutrient use efficiency (compared to target)**
- **Regular soil testing to monitor soil nutrient levels, pH, organic matter, and salts**
- **Tissue testing to measure plant nutrient uptake**
- **Use of soil moisture probes to measure soil water for guiding nutrient application decisions**

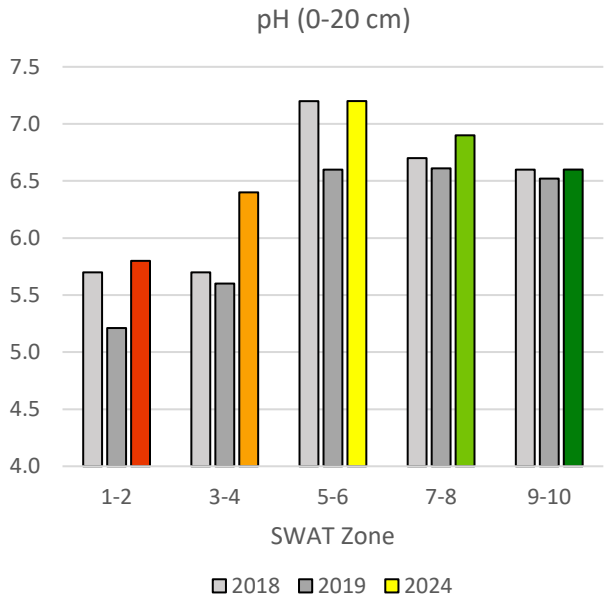
Figure 2-29. *Example of a saline area (SWAT zone 10) in a wheat field in southeast Queensland, Australia. This area tested excessively high in soil nitrates and presented an opportunity for using VR technology to reduce fertilizer cost and environmental loss.*

CASE STUDY 5: VARIABLE RATE LIME

Liming of acid soils is a common practice in many parts of the world. Very acid soils (pH < 5.5) can severely limit yield and nutrient use efficiency leading to loss of nitrogen, phosphorus, and organic carbon. pH can vary across many landscapes, often based on parent material, soil texture, and buffer capacity. This presents a significant opportunity to apply pH amendments only to areas that need it, such as wood ash in this case study (Figure 2-30). In many cases, this can be a simple on/off prescription, or when needed, a prescription with multiple rates.

In this example, soil pH was tested in 2018 and again in 2019, confirming SWAT zones 1-4 had low enough pH to justify liming, and without treatment would continue to acidify further due to relatively low buffer capacity. In 2022 a prescription was used to apply wood ash in zones 1-4, and in 2024 a follow up pH test showed an increase in pH, with further improvement likely as the ash has more time to react. Rather than applying product to the entire field, treating only the areas that needed it reduced the amount of product used by 60%. The soil pH test results and the variable lime application rate are shown in Figure 2-31.

Figure 2-30. *Wood ash used to amend pH. Wood ash is also a source of carbon and several essential nutrients.*



APPLICATION SUMMARY

Zone	Area	Yield Goal	Layer 1
	Acres	bu/ac	Ash
1	9.7	75	6
2	34.1	80	6
3	40.5	85	6
4	42.7	90	6
5	40.3	100	0
6	43.2	95	0
7	38.9	90	0
8	31.2	85	0
9	20.7	75	0
10	10.4	70	0
	311.7	**87.6**	**2.4**

Figure 2-31*. Results from soil pH tests in 2018 and 2019 (top) used to develop prescription for wood ash application for zones 1-4 (bottom). Soil pH response tested again in 2024 showed the improvement (top).*

CASE STUDY 6: ENHANCED EFFICIENCY FERTILIZER

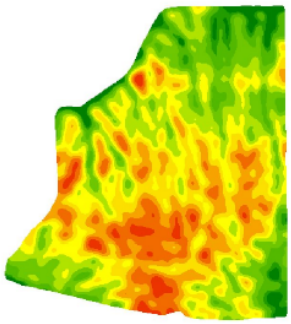
Modern air seeders have incredible logistical capability, enabling multiple products to be applied with VR, and often with different placement options. This case study highlights the use of an EEF to mitigate nitrogen losses in wetter parts of the landscape (zones 7-10 in this field) in a field near Naicam, Saskatchewan, Canada, in 2020. Figure 2-32 presents the seed/fertilizer prescription, as well as a heatmap of as-applied EEF.

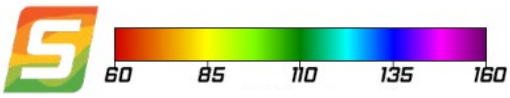
Two forms of nitrogen were applied: layer 4 contained SuperUë , a product with dual nitrification and urease inhibitors, while layer 5 contained untreated urea. While every part of the field had a mix of N sources, the percent of protected urea varied by zone. For example, while both zones 2 and 9 had the same amount of total N applied (98 lb/ac), only 28% of N in zone 2 was protected while 75% of N in zone 9 was protected. *By focusing the EEF in areas prone to losses, most of the benefits of the inhibitors can be realized without the significant cost of applying them at full rate over the entire field.*

A similar strategy could be applied to areas with sandy soil types prone to leaching; the point being variable landscapes result in varying risk of nitrogen loss that can be precisely managed with SWAT MAPS and EEFs.

APPLICATION SUMMARY

Zone	Area	Yield Goal	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Applied Actuals
	Acres	bu/ac	L233	L255	PK Blend	Super U	Urea	
1	2.2	45	0	4.5	170	60	120	98-69-20-0
2	9	50	0	4.5	170	60	120	98-69-20-0
3	14.8	60	0	4.5	170	60	120	98-69-20-0
4	17	65	0	4.5	180	60	130	103-73-22-0
5	17.5	80	1.5	3	190	80	130	113-78-23-0
6	18.8	80	3	1.5	190	120	110	123-78-23-0
7	13.9	80	4.5	0	170	140	60	107-69-20-0
8	8.4	75	5.7	0	140	150	50	104-57-17-0
9	2.9	65	6.1	0	120	160	30	98-49-14-0
10	3.4	50	6.2	0	110	160	30	97-45-13-0
	107.9	**69.9**	**2.1**	**2.5**	**172.7**	**96.8**	**103**	107-70-21-0





Super U (lbs/ac)

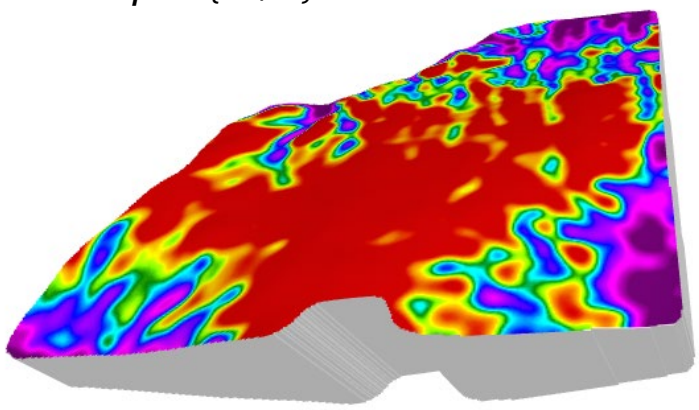


***Figure 2-32**. Prescription for SuperU™ layer (top, Layer 4) showing higher rates in lower landscape areas and heatmap of as-applied SuperU™ (bottom).*

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. 2918). 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 2-33). 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 2-33*. 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 2-34).

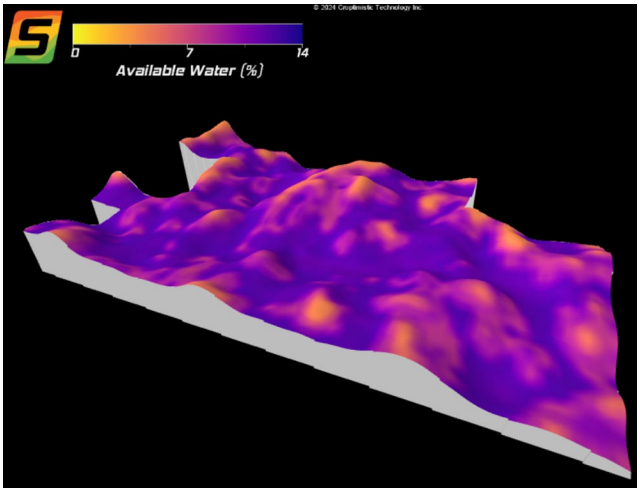


***Figure 2-34**: Spatial variability of plant-available water (as % of soil volume) within the potential rooting depth of a crop as estimated by SWAT WATER at a point in time.*

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 2-35). 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 2-35**. 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.

CASE STUDY 7: MONITORING AND IMPROVING CROP-SOIL-WATER DYNAMICS ACROSS SWAT ZONES

Moisture variability across a field and throughout a growing season was measured through the 2025 growing season for a wheat crop in Saskatchewan (Figure 2-36). Crop water use varied substantially by SWAT zone, ranging from approximately 145 mm to over 220 mm of cumulative water use, despite uniform weather and crop type. These differences evolved through the season as rooting depth expanded at different rates across zones, influencing access to stored soil water. Daily changes in volumetric water content (VWC) revealed distinct patterns of water gain and loss at multiple soil depths, highlighting how the crops located in the mid slope (6) and depression (9) consistently retained and utilized water more effectively than those on the hilltop (4).

The addition of SWAT CAM bare soil exposure (Figure 2-37) from an early growing season sprayer pass was critical for explaining the low water use of Zone 4. The SWAT CAM imagery identified that the Zone 4 corresponded to hilltop areas with higher bare soil exposure (up to 40% bare soil) versus mid slope and depressional areas with minimal soil exposure (<5%). Bare soil has much higher soil evaporation and runoff potential thus limiting the amount of water available for infiltration and subsequent crop uptake. By integrating surface condition indicators with soil moisture and crop water use data, cause-and-effect understanding is possible.

With the extent of bare soil exposure clearly delineated targeted intervention strategies are possible. Runoff and soil evaporation prevention measures, specifically those aimed at increasing surface residue, can now be focused on the SWAT CAM identified hilltop areas with high soil exposure. Continued observation of soil moisture dynamics, crop water use, and surface residue provides the opportunity to evaluate and validate the impact of an intervention over time. By tracking whether soil water retention improves and whether seasonal crop water use increases in treated zones, farmers can directly assess whether the chosen practices are sufficient or if further adjustment is required.

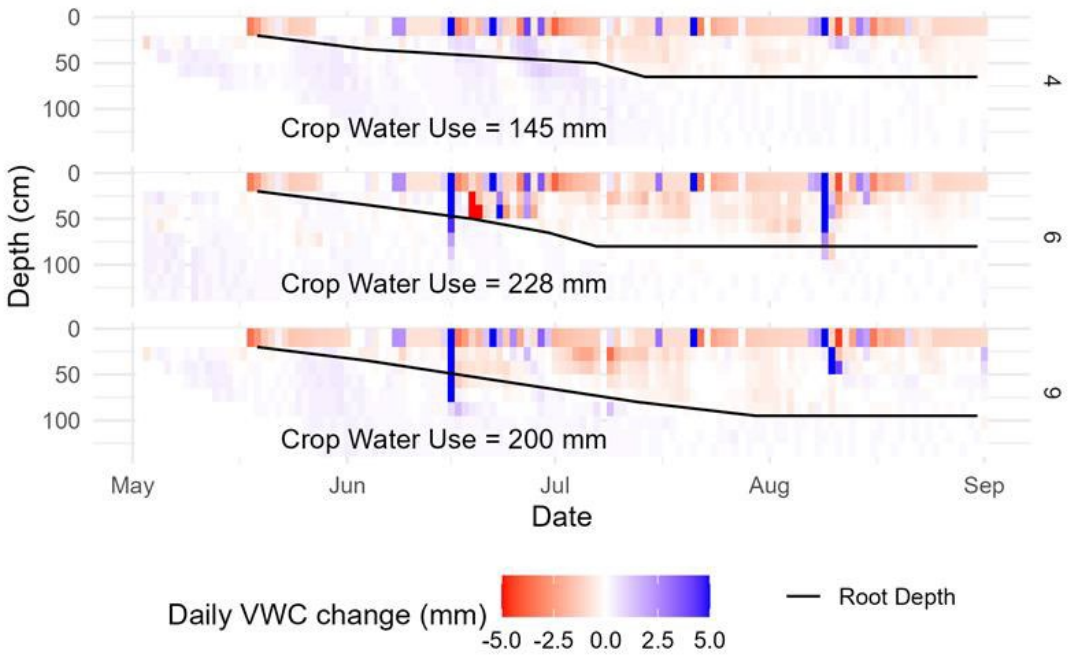


Figure 2-36: *Daily soil water change for an array of soil moisture probes installed across a SWAT zone gradient (Zone 4, 6, and 9). Blue colors indicate an increase in soil moisture (infiltration/redistribution) and red indicates a decrease in soil moisture (plant uptake/soil evaporation). Total change in soil moisture over the growing season is summarized as crop water use. Root depth progression is estimated by the black line.*

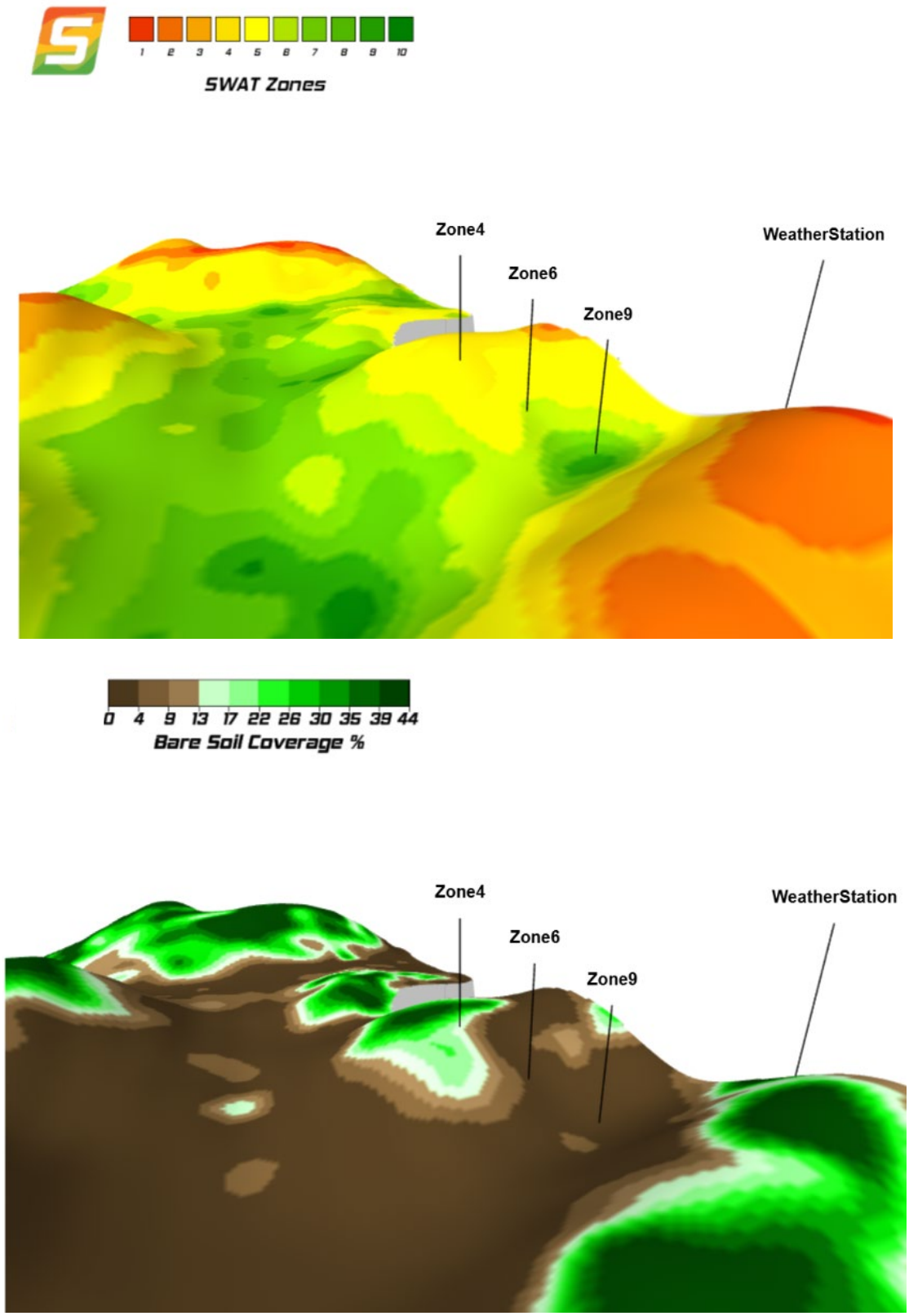


Figure 2-37: *(top) SWAT MAP with location of soil probes identified and (bottom) bare soil coverage as quantified by SWAT CAM at the start of the growing season.*

CASE STUDY 8: STRATEGIC SUBSURFACE DRAINAGE

Poorly drained soil types in lower landscape positions are often subject to significant loss of soil nitrate, loss of applied fertilizer N, and high crop mortality. They cause application inefficiency (tractor ruts and overlap areas), and when crops struggle to successfully grow, these areas are at risk of salinization and further soil degradation. The case study field is located in Manitoba, Canada. Some areas (mainly SWAT zones 9-10) were consistently unproductive or too wet to be seeded, prior to subsurface drainage installation (field NDVI shown in Figure 2-38, SWAT MAP and soil tests shown in Figure 2-39).

Targeted drainage lines were installed in June 2021, with these areas showing significant improvement over time (Figure 2-38, right). In situations like this, it can take several years for salts to leach to the drainage lines and reduce impact on crop yields. Once crops are able to grow, they help use excess surface water and regenerate soil productivity even further.

The risk of subsurface drainage is that nitrates, or even phosphates, can leach with water and end up in surface waters further downstream. But leaching of these nutrients can be managed well with consistent soil testing and VR application to manage soil nutrient levels. In this field, phosphorus leaching is not a concern due to pH and texture, and nitrogen rates have been reduced by 45-95% in zone 10 since drainage was installed. Once productivity is restored, the crop is using available nitrates, and nutrients are managed well, risk of nutrient loss is relatively low.

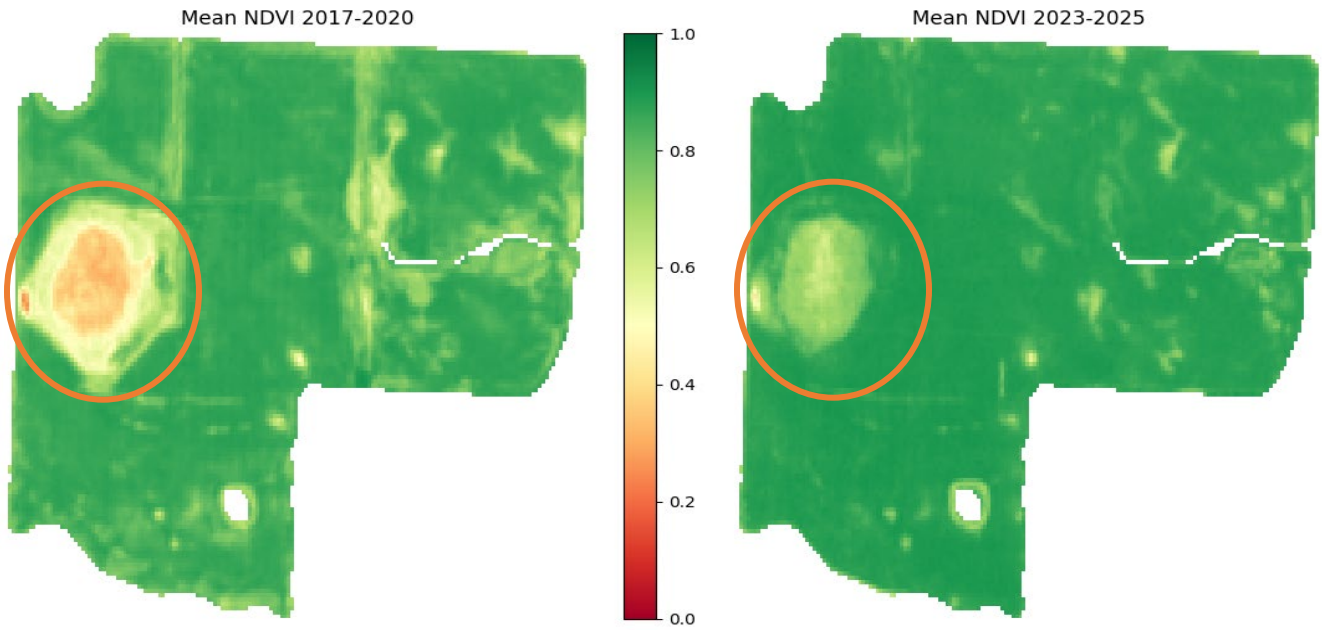
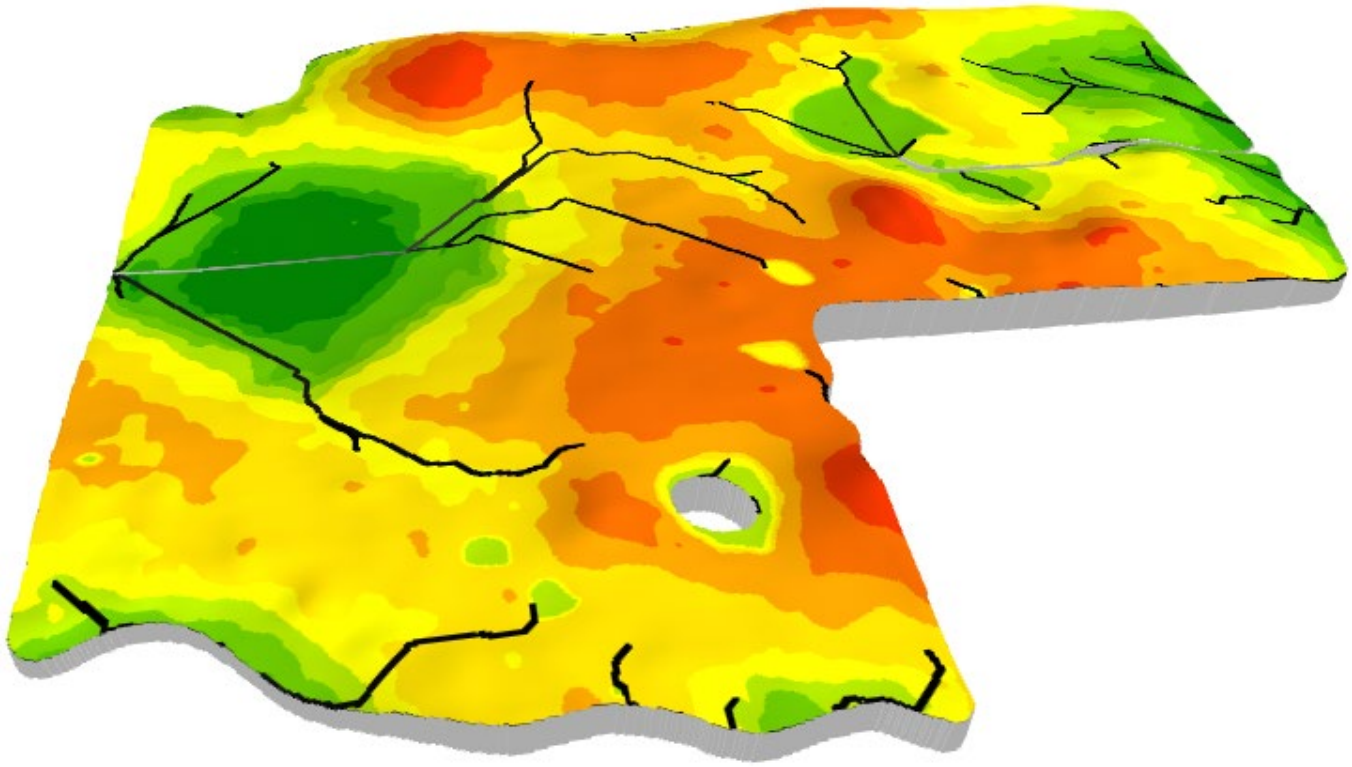


***Figure 2-38**. Mean Normalized Difference Vegetation Index (NDVI) before (left) and after (right) drainage installation. Key impact area circled.*



Field Area	Depth	N Year	OM (%)	pH (H2O)	NO3 (lbs)	P Olsen (ppm)	K (ppm)	S (lbs)	Cl (lbs)	Na (%)	EC (dS/m)
zone 1,2	0-8 in	2021	8.5	6	63	28	486	27	7	0.2	0.34
zone 3,4	0-8 in	2021	9.9	6.1	63	26	682	40	5	0.2	0.4
zone 5,6	0-8 in	2021	8.4	5.8	49	26	488	37	4	0.2	0.34
zone 7,8	0-8 in	2021	9.3	6.4	60	50	614	160	9	0.5	0.97
zone 9,10	0-8 in	2021	13.8	7.9	61	36	951	160	135	7.0	5.4

***Figure 2-39**. 3D SWAT MAP and soil tests taken shortly after drainage installation showing Na, S, and Cl based salts contributing to high EC that limited productivity in zones 9-10.*

Sustainable & Regenerative Agriculture Framework: Summary

The need to move towards sustainable, yet intensive, food production is urgent due to the world's large and growing population and the crises facing many of our key planetary boundaries. We propose a framework for sustainable agriculture that acknowledges that appropriate practices are highly dependent on spatial and temporal variability: not only climate region variability, but sub-field level variability. Unlike other frameworks that state that detailed farm level data is still too difficult (or costly) to measure and therefore shifts metrics away from those requiring detailed farm level data, our framework is focused on the detailed farm level data. This is data that is measured on the ground, at high spatial and temporal resolution, which is possible with today's technology. Our framework guides farmers and agronomists with the principles to farm sustainably, with precision.

Our Sustainable and Regenerative Agriculture Framework outlines two foundational pillars, each with 3 key principles to focus on:

- **Soil Health and Agricultural Productivity**: Sustainable agricultural practices aim to preserve or enhance the health and productive potential of soil over time. This ensures that agricultural lands remain viable and fertile for future generations, supporting consistent and reliable crop yields. This requires a focus on:
    - Soil Organic Matter Conservation
    - Erosion Prevention and Soil Cover
    - Fertility Optimization

- **Integration with Agro-ecosystems**: Sustainable agricultural practices recognize that farms do not exist in isolation. Instead, they function within larger ecological systems, with ongoing exchanges of energy, nutrients, and organisms. By managing these interactions, sustainable agriculture promotes overall ecosystem health and resilience. This requires a focus on:
    - Biodiversity Enhancement
    - Integrated Pest Management
    - Plant Available Water Management

While the principles are universal and applicable to all crops in all climates, the BMPs to meet the guiding principles of sustainable agriculture will be different depending on the climate and the crop. The pillars, principles, and BMPs appropriate in most agricultural conditions are summarized in Table 2-2.

When appropriate practices are integrated and adapted to each field's unique conditions, they reinforce each other to boost soil health, ecological resilience, nutrient and water efficiency, and overall productivity. The future for sustainable agriculture is via PA applied appropriately. Whether the issues are nutrient losses, pesticide runoff, water use, soil carbon loss, or GHG emissions, the solution is largely the same – better understanding of water, soils, and their variability across a landscape. Improving our knowledge of this variability will inevitably help farms manage inputs more accurately and efficiently, leading to economic, environmental, and even social benefits.

The SWAT ECOSYSTEM is a valuable tool that can be part of the solution, and when combined with other technology such as VR capable equipment, EEFs, VRI, and soil moisture probes, the future of environmentally sustainable agriculture is promising.

Table 2.2 *Sustainable and Regenerative Framework Summary*

	Principle	Practices *(appropriateness of each practice determined by environmental factors)*	Recommended Metrics
Soil Health and Agricultural Productivity	**Soil Organic Matter Conservation**	• No-till • Conservation tillage • Maintain living soil cover (e.g. cover crops) • Maintain non-living soil cover (e.g. residue) • Precision applied fertility and soil amendments • Crop rotation	• Recurring measurement of SOC using stratified sampling protocol with ground truthing.
	Erosion Prevention and Soil Cover	• No-till • Conservation tillage • Maintain living soil cover (e.g. cover crops) • Maintain non-living soil cover (e.g. stubble or trash) • Alternative cropping areas • Shelterbelts	• Bare soil measured by automated imagery during non-crop season (such as SWAT CAM). • Target <10% bare soil in non-crop season. • Water quality testing (surface water/groundwater, where appropriate)
	Fertility Optimization	• 4R fertility management • Precision applied fertility and soil amendments • Crop rotation	• Crop yield (compared to target) • Nutrient use efficiency (compared to target) • Regular soil testing (residual soil nutrient levels, pH, organic matter, salts) • Tissue testing to measure plant nutrient uptake • Water quality testing (surface water/groundwater, where appropriate)
Integration with Agro-ecosystems	**Biodiversity Enhancement**	• Riparian buffers • Alternative cropping areas • Crop rotation • Precision applied pesticides • Shelterbelts	• % of linear extent of field boundaries in non-crop use. • Maximum distance in field to non-crop area. • Water quality testing (surface water/groundwater, where appropriate). • Species counts (optional).
	Integrated Pest Management	• Crop rotation • Precision applied pesticides • Biosecurity • Rotation in chemical mode of action used to control weeds, diseases, and insects • Incorporation of a variety of chemical, cultural, physical, and biological pest control methods • Management of soil and irrigation water to minimize off-target movement of pesticides	• Inclusion of one legume, one biomass-yielding crop and minimum of 3-year crop rotation. • Insect, weed, and disease monitoring.
	Plant Available Water Management	• Maintain living soil cover (e.g. cover crops) • Maintain non-living soil cover (e.g. residue) • Active drainage (only if warranted) • Maintain standing crop stubble in non-growing season • Riparian buffers • Alternative cropping areas • Shelterbelts	Monitoring Salinity: • EC mapping • Soil testing Monitor Plant Available WHC: • Soil moisture probes to measure spatial variability of plant-available water. Monitor Crop WUE: • Relate crop yield with crop water usage (from soil moisture sensors/modelling) to diagnose/monitor productivity limitations associated with soil salinity, water deficit or excess stresses, and/or nutrient imbalances.

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Acronym & Abbreviation Guide

4R — Right Source, Right Rate, Right Time, Right Place
Nutrient stewardship framework to optimize nutrient use efficiency and reduce losses.

BMP — Best Management Practice
Practices shown that meet the foundational principles of sustainable and regenerative agriculture.

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

CO_2 — Carbon Dioxide
Discussed in relation to soil carbon sequestration and lime-related emissions.

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

EEF — Enhanced Efficiency Fertilizer
Nitrogen fertilizers with inhibitors or coatings reducing loss through volatilization, leaching, and denitrification.

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.

NUE — Nitrogen Use Efficiency
Fraction of applied nitrogen taken up by crops; used to evaluate the effectiveness of fertility programs.

PA — Precision Agriculture
A spatially explicit, data-driven approach to agronomy that integrates soil, water, and landscape variability for optimal decision making.

ROI — Return On Investment
Common financial indicator indicating the profitability of an investment.

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 BOX
A sensor platform (EC and related measurements) used to collect field data for SWAT MAPS development.

SWAT CAM
High-resolution imaging tool used to measure bare soil, residue, crop canopy, and weed distribution.

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.

VR — Variable Rate
Varying seed, fertilizer, or pesticide applications within a field based on mapped variability.

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.