The Role of SWAT MAPS in Environmental Stewardship

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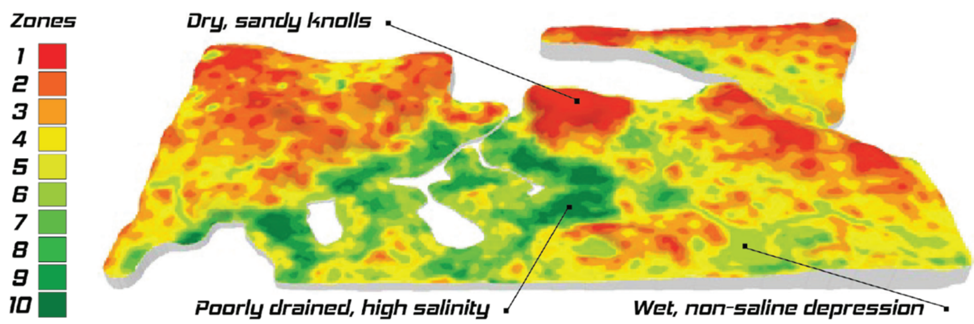
Wes Anderson, BSc. Ag
VP of Agronomy, Croptimistic Technology

Soil, water, and topography maps (SWAT MAPS) are soil management zone maps that are based on relatively stable soil and landscape properties. A SWAT MAP encompasses 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.

A SWAT MAP allows a farmer or agronomist to manage spatial variability across a landscape in several ways, including variable rate (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 part in how nutrients 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). When combined with soil properties, it is the primary determinant of yield potential across a landscape. It is the combination of these factors, as well as temporal variability like rainfall, that guide how a crop should be spatially managed with precision agriculture.



Zone	Depth	OM %	pH	EC 1:1	NO3 lbs	Olsen-P ppm	K ppm	S lbs	Cl lbs	Cu ppm	B ppm	Zn ppm
Zone 1-2	0-8"	1.9	5.4	0.06	15	40	166	43	3	0.39	0.17	0.84
Zone 3-4	0-8"	5.4	5.5	0.1	8	14	185	24	5	0.61	0.28	2.01
Zone 5-6	0-8"	6.9	6.2	0.23	15	18	372	48	36	0.69	0.59	2.61
Zone 7-8	0-8"	8	6.6	1.15	23	10	319	160+	28	0.76	1.06	3.22
Zone 9-10	0-8"	5.6	7.3	2.82	24	44	356	160+	36	1.09	1.25	2.94

Zone	Texture	CEC	Ca ppm	Mg ppm	Na ppm	% Ca	% Mg	% K	% Na	% H	K:Mg
Zone 1-2	Sandy loam	11	825	115	13	37	8.6	3.8	0.5	50	0.44
Zone 3-4	Loam	19	1616	171	17	43	7.5	2.5	0.4	46.9	0.33
Zone 5-6	Loam	20	2621	331	36	66	13.8	4.8	0.8	15.2	0.35
Zone 7-8	Clay loam	25	3756	414	137	75	13.7	3.2	2.4	6.1	0.23
Zone 9-10	Clay loam	29	3177	974	913	55	28.1	3.2	13.7	0	0.11

Figure 1. Example of a SWAT MAP with associated soil test properties.

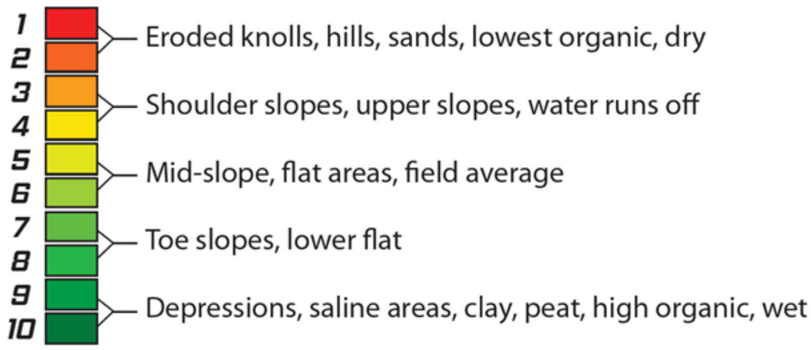


Figure 2. General concept of SWAT MAP zone delineation.

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. 4Rs are governed by properties like soil texture, soil moisture, crop yield potential, pH, mineralization potential, and soil nutrient levels – all which vary across a field landscape (Burton, 2018). True 4R nutrient management must acknowledge this variability for full economic, environmental, and social benefit.

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 4Rs 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 variable rate 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 greenhouse gas (GHG) emissions related to production of lime and its reactions in soil that emit carbon dioxide (CO2).

The Role of Soil, Water, and Topography

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 in Table 1 show some typical soil texture variation across a glacial till landscape from a field in north central Alberta, Canada.

Table 1. Soil test properties of the 0-20 cm depth.

SWAT Zone	% area	USDA Texture Class	% sand	% silt	% clay	OM%	pH	EC 1:1
1-2	9	Sandy Loam	63%	24%	13%	2.7	5.8	0.17
3-4	20	Sandy Loam	55%	26%	19%	3.9	6.4	0.27
5-6	33	Loam	51%	30%	19%	5.0	7.5	0.39
7-8	27	Sandy clay loam	51%	26%	23%	5.2	7.6	0.39
9-10	11	Loam	43%	32%	25%	10.2	7.7	1.48

The variability of soil texture in this field was primarily mapped using electrical conductivity from a SWAT BOX (Croptimistic Technology, 2024). The texture variation in this field happens to be well correlated to topography as well, both of which have a strong influence on water infiltration and accumulation. So, it is not just texture that influences variability in this field, but also topography and its effect on water flow and accumulation.

The dominant role of soil texture is water holding capacity and subsequent yield potential of agriculture crops. But 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. On the other hand, in a high rainfall environment, a clay loam soil may not have good enough drainage and yield potential would be reduced due to frequent saturation. This is the case in the above field shown in Table 1; 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.

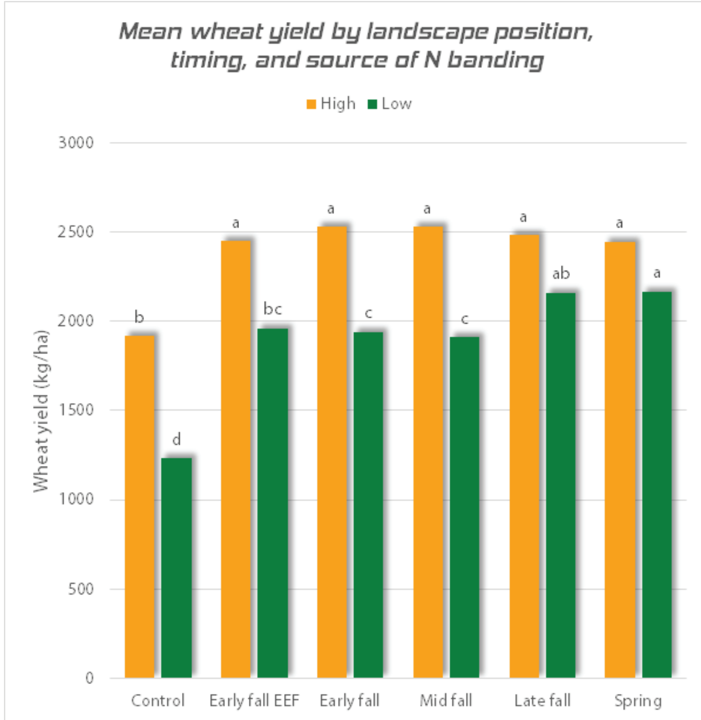


Figure 3. Evidence of N loss due to denitrification in low landscape positions. Tiessen et al. 2005.

Texture alone rarely represents all the variability in a field though. 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 precision agriculture.

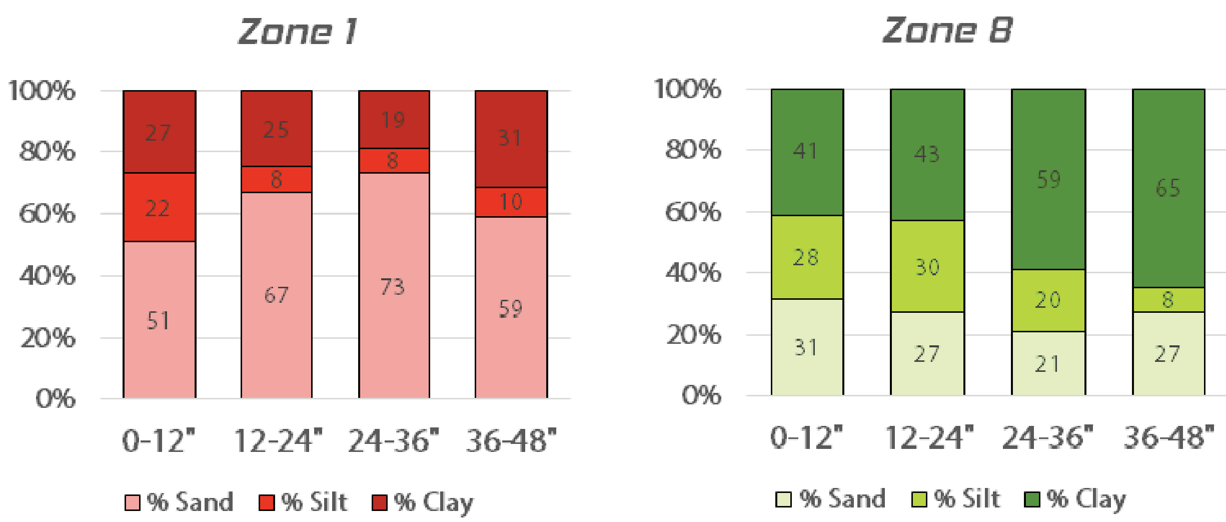


Figure 4. Two texture profiles of SWAT zone 1 and zone 8 in a field from central Saskatchewan, Canada.

Protecting the Air

Climate change caused by 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 large 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).

Nitrous Oxide

One of the most significant GHG concerns from cropland is nitrous oxide (N2O). While total emissions of N2O are typically only 0.5 to 2 kg N2O-N per ha (Shcherbak et al, 2014), it is a potent greenhouse gas with a global warming potential of approximately 265 times CO2. Globally, emissions from agriculture have increased 28% since 1990, to a total estimate of over 2,330 Mt CO2e in 2020 (Climate Watch, 2023). N2O is produced from fertilizer N as a biproduct of the nitrification process and from soil nitrates through a process called denitrification.

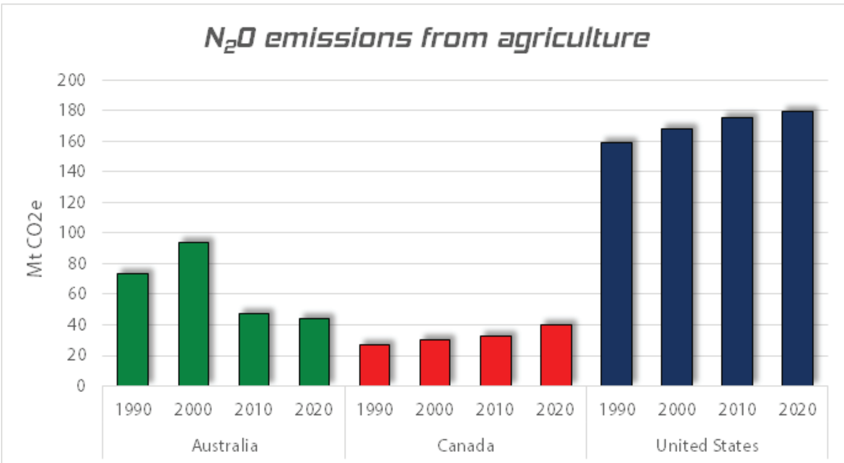


Figure 5. N2O emissions from agriculture in Australia, Canada, and USA . Source: Climate Watch, 2023.

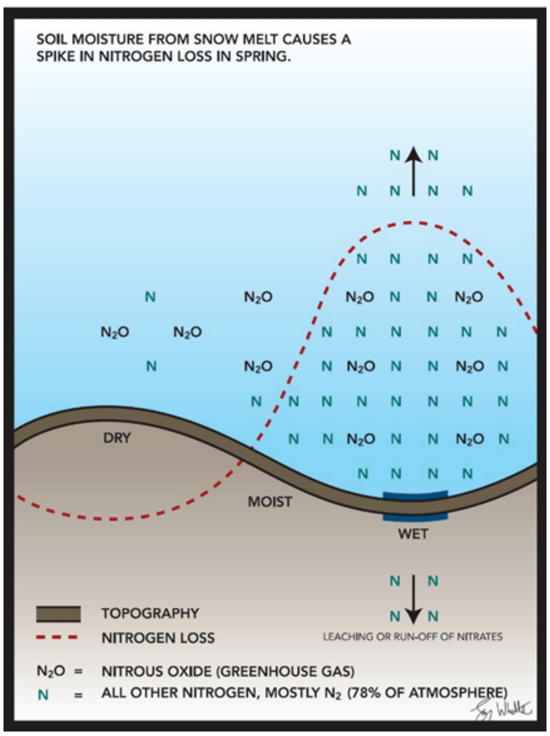


Figure 6. Diagram of N loss variability by landscape position. Source: Jay Whetter, Canola Council of Canada.

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 (NO3-) to NO, N2O, and N2 releasing these gases to the atmosphere (Maharjan et al., 2024). Under completely flooded, anaerobic conditions nitrate will be reduced completely to N2, a harmless and abundant atmospheric gas. It is primarily the wet areas surrounding wetlands that have high N2O emission potential, as depicted in Figure 6. 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.

Nitrous oxide fluxes are highly linked to soil nitrate availability – higher soil nitrates lead to higher N2O potential. Fertilized annual cropland is a particularly significant source. Water filled pore space also contributes to denitrification and N2O emissions with relatively wet soils (60 to 80% water-filled pore space) having much higher risk (Wang et al., 2021). However, both spatial and temporal variability 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 N2O 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 7). 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 N2O emissions from saline-sodic soils compared to more productive non-saline soils.

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 7. 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).

The significance of organic matter and subsequent mineralization of nitrogen in-season should also be considered. Many hummocky landscapes characteristic of the U.S. 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 N2O "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 8 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 variable rate to lower rates in those areas, they would unfortunately be prone to high N2O emissions.

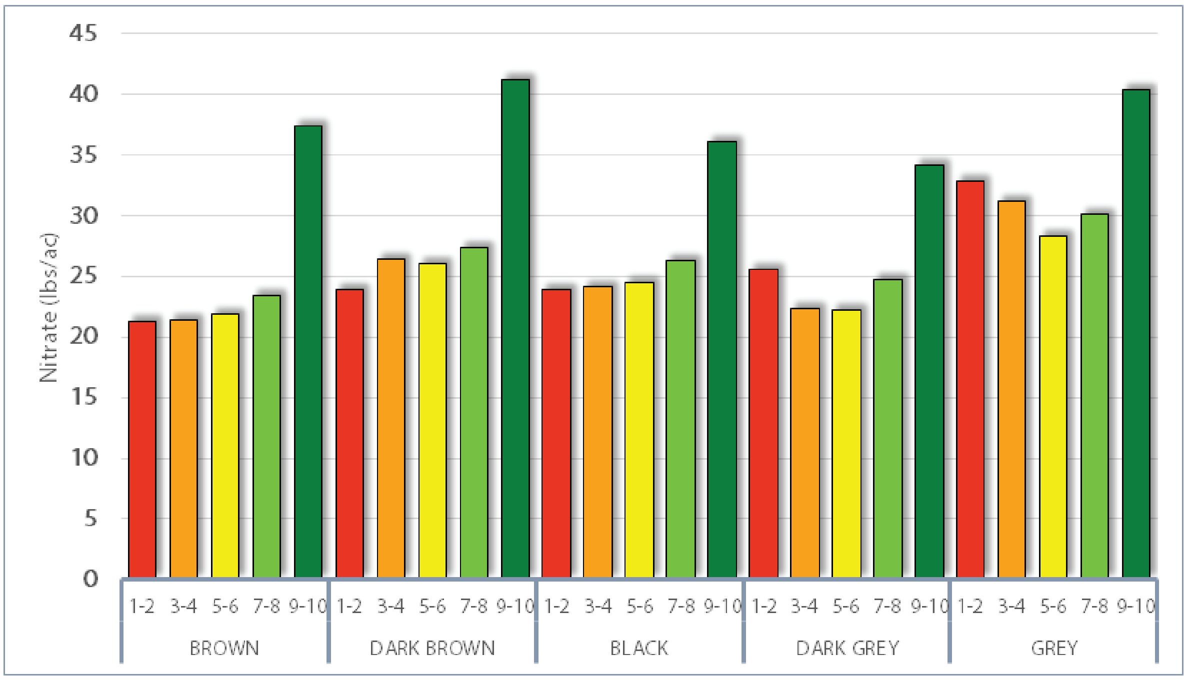


Figure 8. Soil nitrate (0-20 cm) by SWAT zone and major soil zone in western Canada (mean of 1000s of samples).

Glenn et al., 2021 concluded that using variable rates can mitigate N2O emissions from soils. In this study, the "high yield zones" had the lowest emission factors (N2O 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, N2O 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 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. Variable rate 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, VR manure resulted in a 23.7% lower N2O emissions factor than flat rate manure, citing higher soil moisture, SOC, and nitrogen supply in large depressional catchment areas as significant influences on large N2O 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 N2O 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 use of enhanced efficiency fertilizers, timing of application, and variable rate nitrogen.

While there is not one simple solution to mitigating nitrogen losses and N2O emissions, a better understanding of where losses are most likely to occur with a SWAT MAP 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 a SWAT MAP, it offers a valuable precision ag tool to better manage N and reduce emissions through a variety of stacked agronomic strategies.

Carbon Dioxide

Soil organic carbon (SOC) is a measure of all the organic carbon in the soil which is directly related to organic matter, a commonly measured property in soil tests. Organic matter 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 levels are a direct result of historical plant biomass production in combination with decomposition rates driven mostly by climate. Warm, humid climates have higher organic matter decomposition rates than cool, arid climates. 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 ability of 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.

Organic matter is good for the soil. It improves soil tilth, water holding capacity, and nutrient supply. It sustains microbial life in the soil, providing nutrient cycling and additional carbon sequestration (Horwath and Kuzyakov, 2018). It is in farmers' best interest to maintain or increase organic matter levels for long-term productivity. This also impacts the whole of society since increasing CO2 levels in the atmosphere are linked to climate change. There are two important ways farmers can help change the CO2 balance – emit less CO2 with more efficient use of inputs and sequester more CO2 in the soil by improving soil management and crop health.

Figure 9. Topsoil samples (0-15 cm) from five SWAT Zones demonstrating variable organic matter levels within a single field.

Due to carbon credit and offset payment schemes, there is a broad desire to measure and track SOC levels in agriculture. But 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. 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 electrical conductivity, landscape position, wetness index, and topographic position index (Adhikari et al., 2022) which are all attributes inherent to a SWAT MAP.

For farmers, a SWAT MAP provides the information needed to identify nutrient deficiencies or pH extremes that limit crop biomass and yields, which subsequently limits 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 its original state prior to it being farmed.

There are many sources of CO2 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 CO2 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 CO2. For this reason, and because it is a significant cost, lime is well suited to a variable rate application where only areas of the field that have a low soil pH are treated (Bongiovanni and Lowenberg-DeBoer, 2000).

SWAT MAPS offer a practical way of improving the accuracy of measuring and tracking SOC over time. It gives a methodology to group similar soils together for measurement, balancing cost versus accuracy. Unlike methodology using satellite imagery and modelling, every SWAT MAP is ground-truthed and either organic matter or soil organic carbon can be 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.

Figure 10. Soil profiles (60 cm depth) from three SWAT zones demonstrating variable depth and amount of organic matter.

Protecting the Water

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, but also does not risk 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 can lead 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. A similar approach can be taken for nitrogen, allowing the proper rate of N to be applied to different areas based on available N in the soil, estimated mineralization of N in-season, and crop uptake requirements. Matching applied nitrogen rates with these parameters will limit the amount of available soil nitrate at any given time, reducing the chance of nitrate leaching, nitrate runoff, and N2O emission as previously discussed.

The data layers used to make SWAT MAPS also indicate water flow paths, location and size of watersheds, and water accumulation areas. With this information, a farm can identify high risk source areas of contamination to manage differently (Cornell University Cooperative Extension, 2021). This could include reducing nutrient application, avoiding manure application, variable rate irrigation (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. A SWAT MAP identifies the location of these high-risk areas so they can be targeted with greater precision.

Texture variation has a substantial effect on nitrogen losses such as leaching. Leaching of nitrates 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 courser 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 nitrogen use efficiency. The impact this practice has 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 soils' 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).

Soil water holding capacity is primarily based on soil texture – one of the properties incorporated into a SWAT MAP. A spatial map of these soil properties, as well as landscape position and water accumulation areas, can help guide VRI prescriptions with multiple benefits including:

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.**

Inclusion of soil moisture probes to monitor plant available water in the soil profile can further improve the accuracy of VRI, especially with the ability to produce a SWAT WATER map – a spatial soil water map that models the variability of soil water across a landscape (Figure 11).

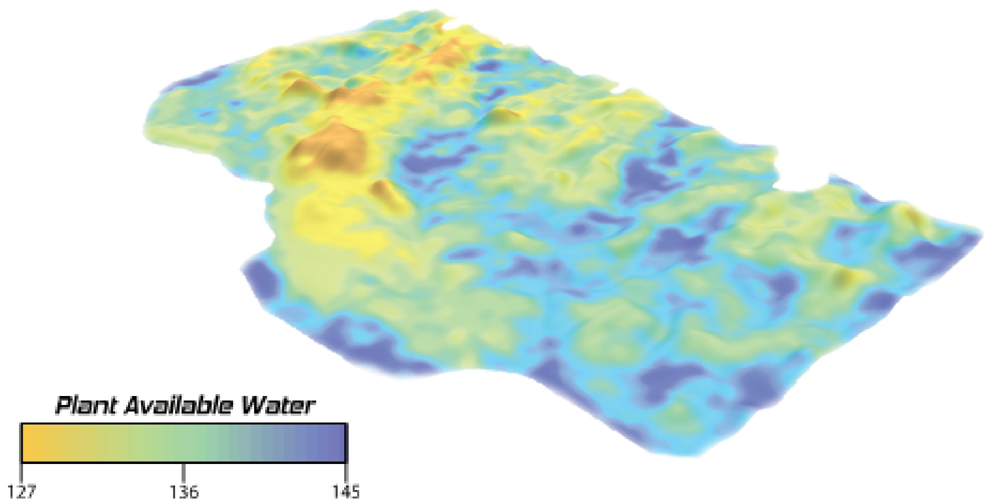


Figure 11. SWAT WATER map modelling available water in the soil profile.

SWAT MAPS allow farms to spatially apply several best practices at once to reduce nitrogen losses. A SWAT MAP considers 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 poor 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 course texture 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 variable rate irrigation technology to more accurately apply water based on water holding capacity 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.

Pesticides are another agricultural input that can cause environmental concern in water. 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 (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 water holding capacity, 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. 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. Variable rate herbicide application has potential in some landscapes that are variable enough to justify different rates based on soil type or weed population. 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.

Mapping of weeds and weed density also can reduce pesticide requirements utilizing variable rate technology. 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 12). 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. For example, 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 13). This simple on/off prescription reduced the applied amount by 54%, relative to treating the whole field.

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 12. Example of SWAT CAM image using machine learning to process crop and weed leaf cover, as well as canola population.

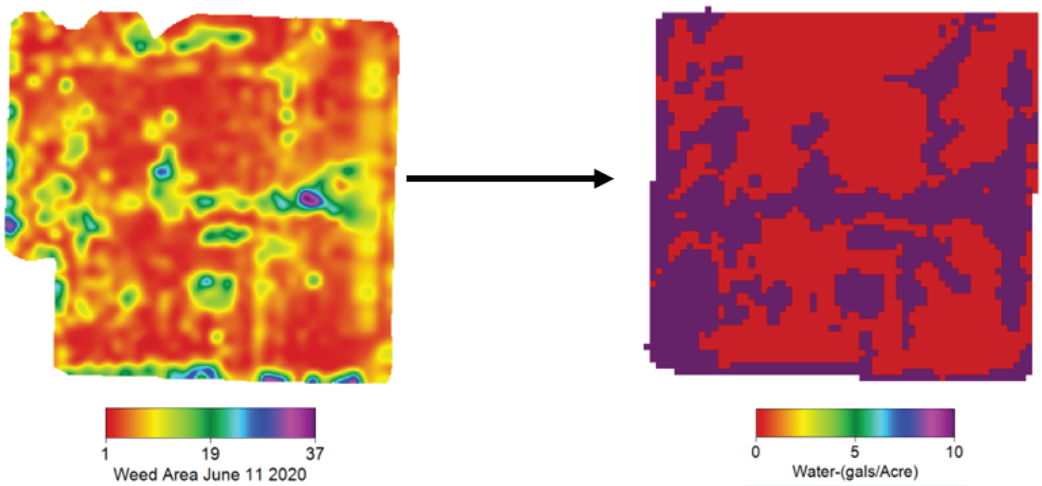


Figure 13. SWAT CAM map of weed leaf area (left) and the herbicide prescription derived from it (right).

A secondary 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. 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 problem weed species.

Protecting natural water bodies and aquifers from sources of agriculture pollution is a complex issue that is multi-faceted. 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.

Supporting Biodiversity

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 favor 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.

For 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. 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.

Historically, farms have been reluctant to surrender annual cash crop land to perennial forages or other species for several reasons.

Figure 14. Productive perennial grass hay mix growing in a flood prone sodic soil (SWAT zone 10) in SE Queensland, Australia.

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 irregular 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.

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, and 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).

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 15 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 16).

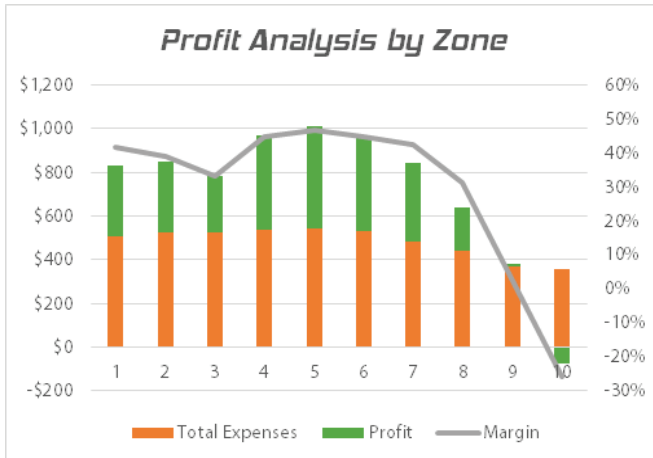


Figure 15. Example of an economic analysis by SWAT zone.

Summary

Agriculture faces many challenges with the environmental impact of growing food and the perception of its impact by the public, most of whom are far removed from where their food is grown. Data shows many sectors have improved greatly and will continue to improve, which will support continued research on advanced 4R nutrient stewardship and precision agriculture tools. 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 variable rate capable equipment, enhanced efficiency fertilizers, variable rate irrigation, and soil moisture probes, the future of environmentally sustainable agriculture is promising.

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Contact

Wes Anderson
Vice President, Agronomy
Croptimistic Technology Inc.
wes@swatmaps.com

swatmaps.com / @swatmaps