Soil Health and Water Quality

A whitepaper exploring the connection between soil health and water quality

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Background

This publication aims to offer agricultural educators a balanced approach to soil health when considering water quality issues. The principle of soil health underscores the functions of soils for plants and the environment, which are to provide a growing environment for plants to grow, recycle nutrients and organic materials, serve as a habitat for soil organisms, and purify and supply water. These functions are related to soil's biological, chemical and physical properties. Soil type, climate and management greatly influence soil properties, and therefore these factors also influence soil health and water quality. It is often difficult to specifically relate one single soil property to an outcome and function given the complexity and diversity of soil. Relating soil health to water quality is more difficult since a management practice that leads to better soil health might not necessarily result in better water quality. The context and set of specific conditions must be assessed for a given scenario in order to make soil health and water quality principles align. The purpose of this document is to provide background on soil health principles and management impacts on water quality.

Water Quality Concerns and Soils

Water is essential for plant and animal life. Similarly, soil is essential for life through many complex processes. Soil plays an important part in the water cycle by serving as a reservoir for plant water use, purifying water, and recycling nutrients. Soil's chemical, physical and biological properties affect these soil functions. Cation exchange capacity (CEC), nutrient content, organic matter, aggregation, soil infiltration, and biological activity affect the quality of water leaving a field through runoff and leaching or drainage. Agricultural management plays a vital role in soil health and water quality. Although management can be the primary factor affecting water quality, environmental factors (for example, rainfall amount and intensity, temperature, season, etc.) are also important.

The essential plant nutrients nitrogen and phosphorus are of great concern for human and aquatic health. Nitrogen is required for plant protein development and chlorophyll formation. The nitrogen cycle shows how complex soil processes

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and properties affect water quality (Figure 1). Nitrogen is added to the soil by fertilizers, manure, organic materials, crop residues, nitrogen fixation, and to a lesser amount, by atmospheric deposition. Organic nitrogen forms (e.g. manure and residues) must mineralize or convert into the inorganic nitrogen forms of ammonium and nitrate for plants to be able to utilize it. The mineralization process is mostly carried out by microbiological processes in the soil. This is an example of the connection between soil fertility and biology. In addition, during this mineralization process carbon in the organic material is consumed by the soil microbes as an energy source. Since the mineralization process is mediated by the soil biology, environmental factors such as temperature and moisture content greatly affect this process. This is one reason why it can be difficult to predict the plant availability of nitrogen from organic sources reliably year after year.

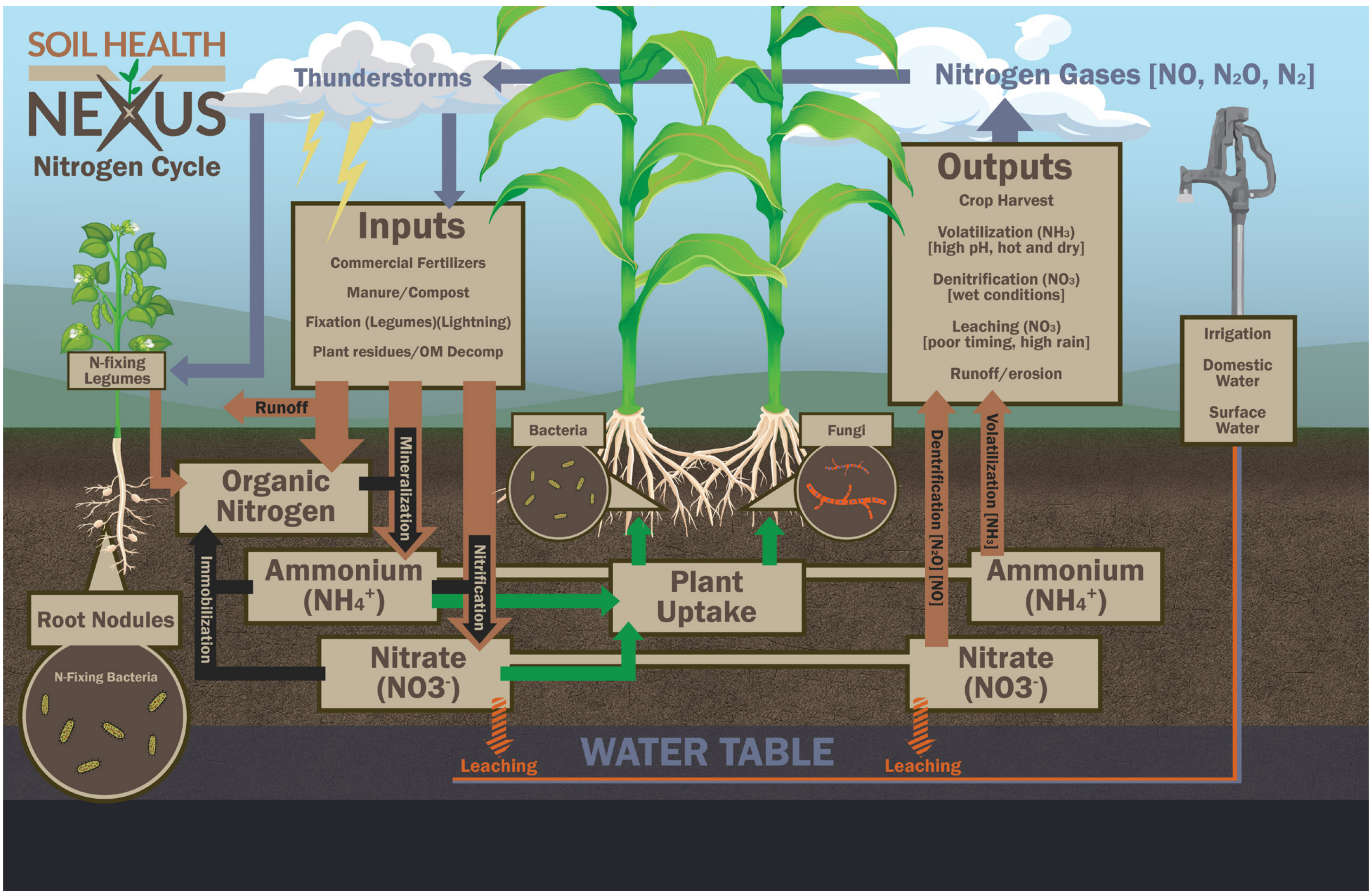

Figure 1. Visual depiction of the nitrogen cycle in the soil

Inorganic nitrogen forms of ammonium and nitrate are dissolved in the soil water (in solution) but interact with the soil differently. Nitrogen is primarily taken up by plants from soil in the form of nitrate. Since ammonium is a positively charged ion (NH4+) it can interact with the negative charges of soil particles, called the Cation Exchange Capacity (CEC), and become bound to soil particles. Nitrate is a negatively charged ion (NO3-), and because of this is repelled from soil particle surfaces, meaning that nitrate remains in solution and is available for the plant. Nitrate can also be taken up by soil microorganisms for their growth from the soil solution, making it unavailable to plants until those microbes die and decompose (mineralizing organic nitrogen). When not taken up by plants or microbes, the nitrate can leach out of the root zone and into groundwater. Nitrate concentrations in drinking water greater than ten parts per million

(0.001%) can lead to poor oxygen transport in the blood system of infants and stomach cancer in adults. Soil health influences nitrogen cycling in soil in various ways. First, since mineralization and immobilization processes are driven by soil biology, improving biological activity can have a positive impact on nitrogen availability to crops. Nitrate leaching from soil with a high nitrogen mineralization potential (rapid conversion of organic to inorganic nitrogen) occurs under the right temperature, moisture, and crop conditions. However, this risk is low relative to the leaching risk from nitrogen fertilizer applications. Using the concepts of soil biology to our advantage can be useful for nitrogen management.

The main water quality concern with phosphorus is loss in surface runoff. Both dissolved and particulate phosphorus are lost in runoff. While dissolved (soluble) phosphorus in runoff water leaving fields cannot be seen, particulate phosphorus can be seen as it travels attached to soil particles in runoff water. Both phosphorus forms can transform into bioavailable phosphorus, which can then cause algal blooms in streams and lakes. Algal blooms affect animal and human health in several ways. Algal growth can limit the amount of sunlight reaching a water body thereby affecting water temperature, that in turn affects plant and animal growth. Some algae produce toxins that sicken animals and humans if ingested, and in extreme cases cause death. When large amounts of algae die, its decomposition uses up the available dissolved oxygen in a system leaving none available for aquatic animals. This can result in large-scale fish kills.

How Does Soil Health Affect Water Quality?

The concept of water connectivity highlights the linkage of water on the planet through the water cycle (Figure 2). Rainfall water either infiltrates into the soil or runs off. Water may infiltrate quickly, reducing its interaction with plants and soil particles, or it may be retained for longer periods, where water-soluble nutrients are likely to be used by microbes and plants. High water infiltration capacity in soil will normally reduce runoff and erosion losses and thus should help improve surface water quality. However, where depth to bedrock is limited or tile drains are present, high infiltration rates equate to rapid delivery of nutrients to groundwater. This shows how a desirable soil trait in one place might not be the best in another field.

One of the three pillars of soil health is keeping soil chemical properties like pH, nitrogen and phosphorus. The pH of soil needs to be near neutral for crops to thrive. Similarly, nitrogen and phosphorus content in soil should be in a range that allows adequate plant availability. If nitrogen and phosphorus concentrations are greater than those needed to meet crop demands, the risk of losses to the environment are greatly increased. Soil organic pools in prairie-derived soils can provide between 18 to 250 pounds N per acre to corn, although all this nitrogen might not be crop available (Cassman et al., 2002). Although rare, soils with high organic matter content under the right environmental conditions can mineralize enough nitrogen to supply crop demand without additional nitrogen. In this situation, any nitrogen fertilizer applied would increase the risk of nitrate leaching since there would be an excess of nitrogen in the soil. The difficulty in managing nitrogen under field conditions comes from the complexity of predicting nitrogen mineralization because weather and soil conditions during the growing season are significant drivers (Stevens et al., 2005).

Taking the appropriate nitrogen credit when applying organic nitrogen sources like manures or compost is important. Nitrogen credits reduce the amount of additional nitrogen fertilizer to be applied to the crop and minimize the risk of nitrogen loss to the environment. Being extra careful to optimize and time nitrogen applications from organic and inorganic sources is important when dealing with soils with limited depth to bedrock and groundwater or in fields with tile drainage systems (Figure 3). Sandy soils

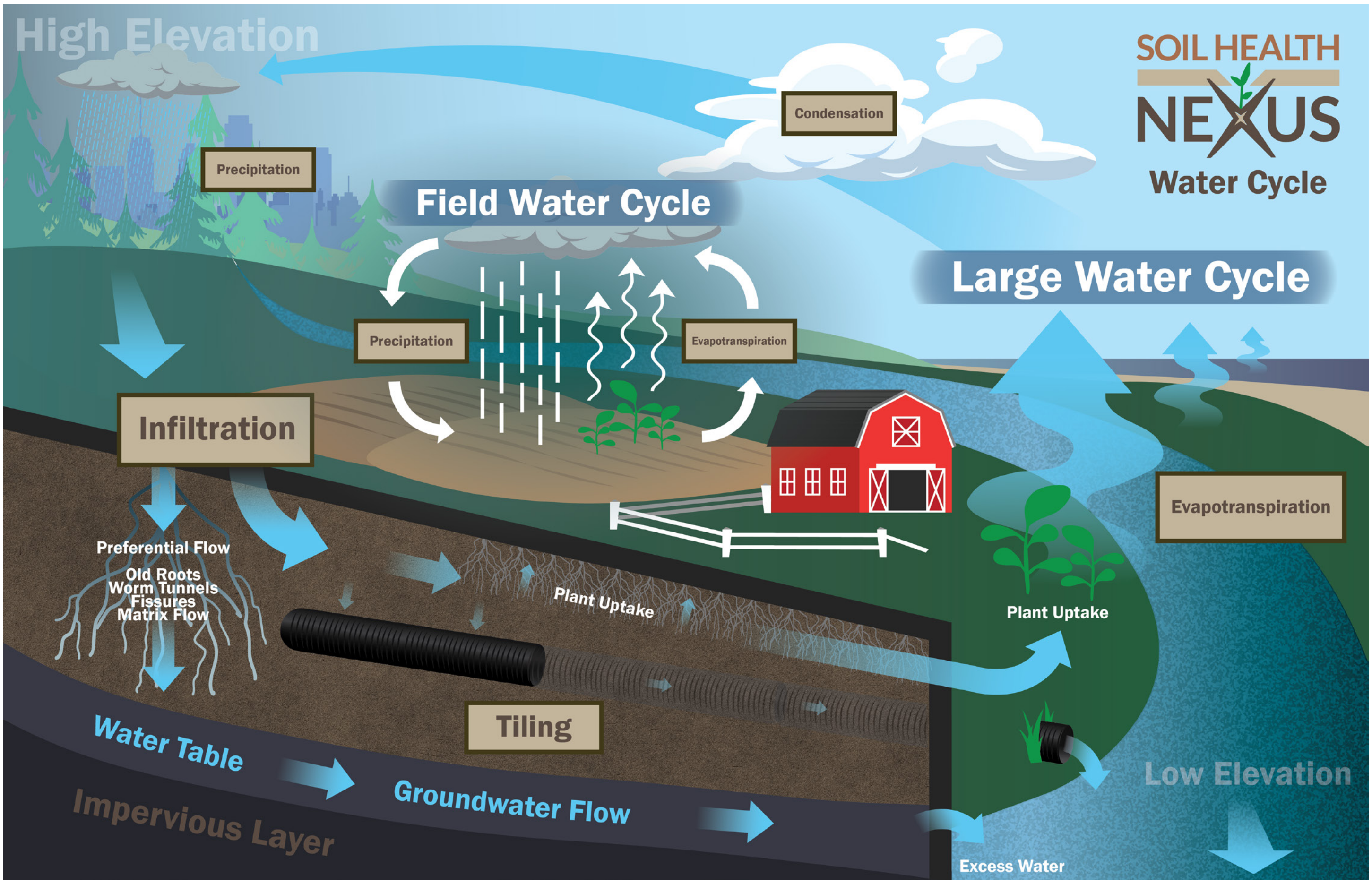

Figure 2. *Graphic illustration of the water cycle*

have a greater leaching capacity than other soil given their lower cation exchange capacity and relatively fast drainage capacity. However, clay rich and silty soils can have large pores (macro pores) that act as highways for water leaching to groundwater. Under these rapid transport scenarios, nitrogen, phosphorus and even pathogens can leach out of the soil and into water supplies creating serious human and animal health issues.

Soil and crop management practices affect soil health and water quality. Management practices that minimize soil disturbance and increase the amount of organic residue are mostly advantageous. However, no-tillage practices can result in more runoff and overall phosphorus losses from frozen soils in sloping fields relative to fall chiseling. This is a concern if the field receives manure applications during the winter, as in daily haul operations. The rough soil surface left after chiseling provides small depressions for water storage that remain largely intact as long as the soil is frozen, while the relatively smooth surface of no-tillage doesn't provide the water storage during the winter and early spring (Figure 4). A well-established high residue cover crop could also increase water storage in no-tillage systems, but may release dissolved phosphorus after either chemical or mechanical termination and periods of freezing (Duncan et al., 2019). Therefore, it is important to look at an entire system or situation to determine the potential water quality concerns and identify which soil health factors influence them (Table 1).

Figure 3. *Diagram of preferential flow and shallow depth to bedrock to illustrate greater leaching risk Photo: F. Arriaga*

Figure 4. *Rough soil surface with depression basins versus a smooth surface during frozen soil conditions on sloping land can help reduce phosphorus losses from erosion*

Water Quality Concern	Soil Health Indicator
SURFACE WATER	
Sediment	Runoff/Inflitration
Phosphorus	Aggregation
Nitrogen	Nutrient Cycling
GROUNDWATER	
Nitrogen	Drainage/water retention, nutrient cycling
Pesticides	Pesticide breakdown
Pathogens	Preferential flow

Table 1. *Water quality concern and possible soil health factors that can affect them*

Linking Soil Health to Water Quality

Soil health factors are important for crop production and a healthy environment. How a soil factor or condition will affect these can vary due to differences in landscape and time of the year. Table 2 presents major soil properties related to soil health and their relative effect on water quality. The effect of a given property on soil health and water quality will be different for different soil factors. Some properties have a "more is better" relationship, while others "less is better", and yet others follow a bell-shaped relationship where a maximum range is the target (Figure 5). Note that the optimal ranges for soil properties must balance the needs of crop production and water quality impacts.

Relating soil health to water quality is difficult given the interaction of soil, management and environmental factors, and that interactions can vary by soil type and region. Given these complexities, most of the scientific published work has focused on linking management practices to either water quality or to soil health, but not both at the same time. A conceptual framework developed by Zimnicki et al. (2020) recognizes that the connection between management practices and soil health, and between management and water quality in the scientific literature are well established (Figure 6). Still, we lack the capability to predict water quality outcomes at the watershed level from related soil health indicators. An example of this issue is the use of manure in agriculture to improve soil health. Choudhary et al. (1996) concluded in their review on the impact of swine manure on crop production and soil and water quality that manure application increased soil nutrient concentration and yields, but that excessive applications resulted in the leaching of nitrate, phosphorus and magnesium. Manure mismanagement can have negative impacts even though manures can help improve soil health by increasing plant nutrient contents, enhancing soil organic matter, promoting biological activity and improving soil physical condition. The availability of plant nutrients in manure, such as nitrogen, varies by animal species, management, type and weather factors making their specific contribution during a growing season challenging. An example of a simplified nitrogen contribution from manure is presented in Figure 7. Manures have organic and inorganic nitrogen forms. Inorganic nitrogen forms are more readily available for crop use, while organic nitrogen forms must be mineralized (Figure 1) for them to be available to crops. Soil biology has an active role during the mineralization process, and therefore environmental factors such as temperature and soil moisture affect mineralization. Also, not all nitrogen will be available the first year after manure is applied. Timing crop nitrogen needs and availability from manures should also be considered.

Soil health related property or process	Relative Effect on Water Quality Postive	Negative	Neutral	Notes
Aggregation, infiltration	XXX			Soil aggregation improves infiltration, thus reducing erosion risk.
Soil organic matter	XXX			Organic matter improves nutrient retention and soil aggregation.
Increased hydraulic conductivity	XXX	X	X	Greater hydraulic conductivity helps infiltration but can increase the risk of contaminants reaching drain tiles and groundwater in fractured or shallow depth to bedrock fields.
Breakdown of organic compounds (e.g. antibiotics, pesticides, N mineralization)	XXX	X	X	Organic compound breakdown in soil reduces the risk of leaching into groundwater but excessive N mineralization can result in greater leaching risks.
Increase on P availability (increase in soil P saturation)		XX	XXX	Increased P availability can lead to higher risk of P loss in runoff water and sediments.
Water holding capacity	XX	X	X	Generally greater water holding capacity helps soil absorb excess water but if water is retained for long periods of times it can lead to greater runoff and leaching risks.
Soil organic nitrogen content		XX	X	Greater soil organic N content can result in higher N mineralization thus an increased leaching risk; can be mitigated if N fertilization account for soil organic N.

Table 2. *Selected soil health related properties and their relative effect on water quality*

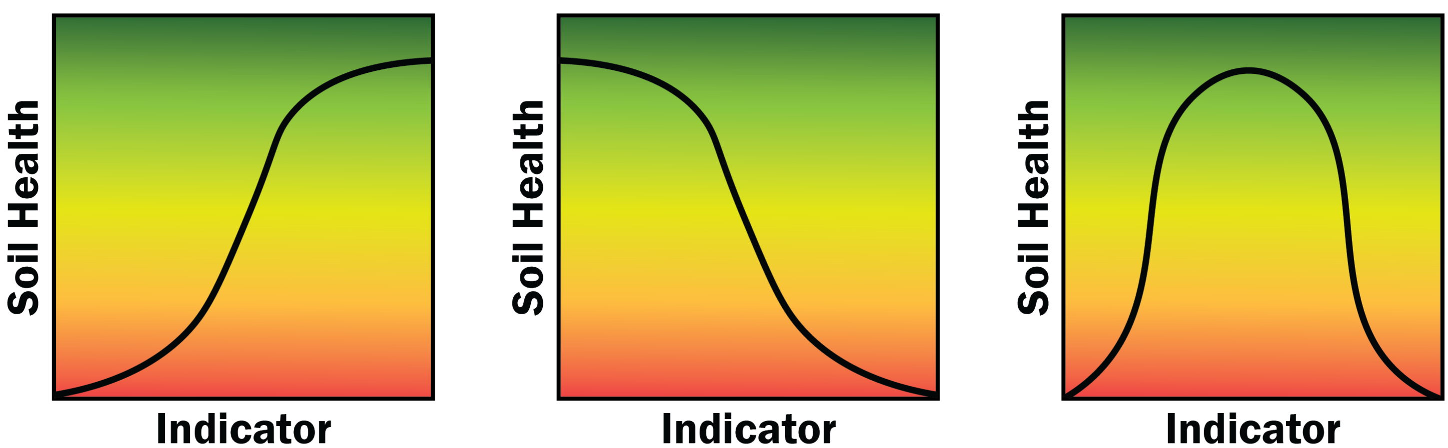

Figure 5. *Scoring function examples for soil properties (adapted from Andrews et al.)*

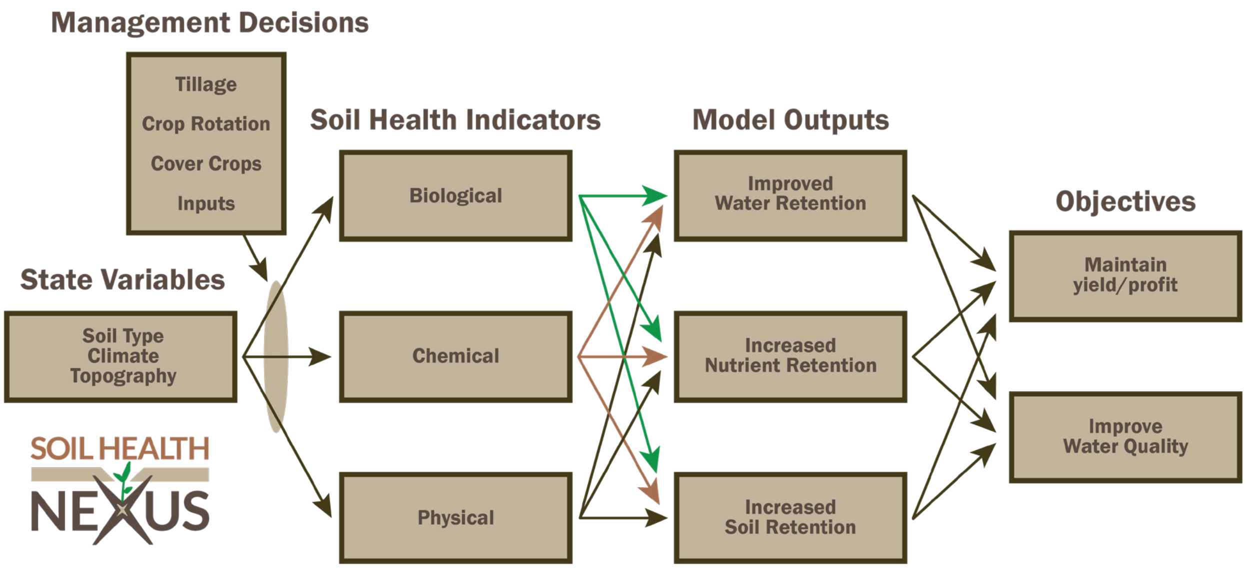

Figure 6. *Visual illustration of the complex links between management, soil health, and water quality. Arrows connecting indicators to outputs represent the largest knowledge gaps. Adapted from Zimnicki et al., 2020*

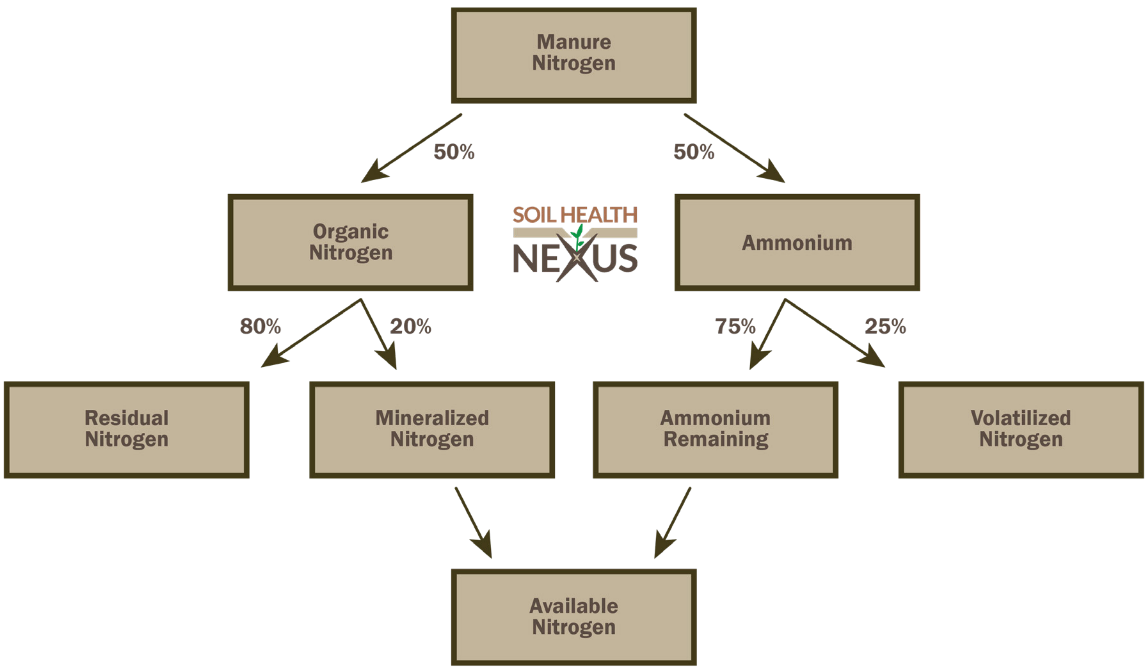

Figure 7. *Nitrogen contribution to crops from manures applied to soil. Adapted from Beauchamp, 1983*

Combining other management practices that improve soil health can be a good strategy to mitigate the environmental risks that can come from farming. Cover crops can improve soil health by promoting biological, chemical and physical properties, while they can help cycle nutrients and reduce losses to ground and surface water (Dabney and Delgado, 2001). However, they indicate that cover crops might not be suitable in all situations and are most suitable for warm areas with enough precipitation, and their benefits are affected by the amount of biomass produced. Table 3 includes cover crop advantages and disadvantages. A SARE technical bulletin (Myers et al., 2019) reported that cover crops are most likely to be economically successful when soil compaction or herbicide resistant weeds are an issue, when they are grazed, in transition to no-tillage, in dry conditions, or where they can replace high fertility costs (e.g. organic systems) or sequester nutrients in manure.

Advantages	Disadvantages
Reduce soil erosion	Additional costs
Increase residue cover	Planting timing presents labor issues
Can increase soil moisture in certain conditions (high amount of dead biomass rolled acts as mulch)	Can decrease soil moisture in certain conditions (when actively growing)
Increased water infiltration	May increase pest populations
Improve soil physical properties	May increase disease risk
Improve trafficability	Some species could cause allelopathy
Nutrient recycling	
Fix nitrogen (only legume cover crop)	
Weed control (large biomass amount needed)	
Increase beneficial insect populations	
Reduction of some crop diseases	
Increase mycorrhizae in crop	
Can be harvested as forage crops (double crop)	

Table 3. *Cover crop advantages and disadvantages (adapted from Dabney et al., 2001)*

Plant residues from cover or cash crops on the soil surface help reduce runoff and associated soil particle and nutrient losses. Organic carbon of crop residues left in fields help promote biological activity, improve soil aggregation and cation exchange capacity as they transform into soil organic matter. Tillage is the primary tool for crop residue management and has been widely shown to alter soil health and water quality. Infiltration rates and aggregation for a long-term no-tillage double cropping system were significantly greater than for a conventional tilled system (tandem disk 2 to 3 times per year to a depth of about 5 inches) with winter small grain production (Franzluebbers, 2002). Better infiltration rate and soil aggregation should result in lower runoff and erosion losses during non-frozen soil conditions. However, no-tillage might be at a disadvantage in sloping soils where greater runoff and nutrient losses have been reported during the frozen season when compared to fall chisel with spring finisher (Stock et al., 2019). Frozen water in soil pores restricts infiltration and drainage, which increases runoff. The risk for runoff is greater in sloping land, especially if the soil is frozen. As previously mentioned, under the scenario of sloping land during frozen soil conditions, performing a tillage operation that generates small depressions or basins that can store melt water will increase infiltration by providing a longer contact time between the water and soil surface (Figure 4). This is counter to soil health principles of minimizing soil disturbance, but water quality risks should be considered when making recommendations. Soil health concerns with tillage can be at least partially offset by using a reduced tillage approach with either less aggressive techniques or rotational tillage practices, and the use of cover crops and residue management. This should also be considered in tile drained fields where light tillage operations are recommended to break up macropore continuity and their direct connection to the tile lines before liquid manure applications to reduce the risk of phosphorus and pathogens losses in the tile line to surface streams (Cooley et al., 2013). Flexible tillage options such as strip-till, vertical tillage, and rotational tillage serve to prepare a seed bed, size crop residue, and incorporate manure and fertilizer while minimizing soil disturbance.

Closing Thoughts

Soil health is important for crop production and environmental sustainability. Improving soil properties and increasing overall system resiliency are needed for long-term sustainability. Similarly, water quality is important for human and environmental health. Often management systems that lead to better soil health result in a decreased risk to water quality. However, under some conditions management systems that are promoted for soil health benefits can result in an increased risk to water quality. It is important to recognize that what works in a field might not be the best option in another location. Specific conditions, factors and expected outcomes must be evaluated in order to develop recommendations that lead to improved soil health and water quality.

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