Linking Soil and Watershed Health to In-Field and Edge-of-Field Water Management

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STAC Publication 21-002

About the Scientific and Technical Advisory Committee

The Scientific and Technical Advisory Committee (STAC) provides scientific and technical guidance to the Chesapeake Bay Program (CBP) to restore and protect the Chesapeake Bay. Since its creation in December 1984, STAC has enhanced scientific communication and outreach throughout the Chesapeake Bay Watershed and beyond. STAC provides scientific and technical advice in various ways, including (1) technical reports and papers, (2) discussion groups, (3) assistance in organizing merit reviews of CBP programs and projects, (4) technical workshops, and (5) interaction between STAC members and the CBP. Through professional and academic contacts and organizational networks of its members, STAC ensures close cooperation among and between the various research institutions and management agencies represented in the watershed. For additional information about STAC, please visit the STAC website at http://www.chesapeake.org/stac.

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Cover graphic: Regional examples of drainage infrastructure designed to move excess water off as quickly as possible or lower water table conditions.

STAC Administrative Support Provided by:

Chesapeake Research Consortium, Inc.
645 Contees Wharf Road
Edgewater, MD 21037
Telephone: 410-798-1283
Fax: 410-798-0816
http://www.chesapeake.org

Workshop Steering Committee:

Kathy Boomer (Chair), Foundation for Food and Agriculture Research
Chris Brosch, Delaware Department of Agriculture
Amy Collick, University Maryland Eastern Shore
Matt Ehrhart, Stroud Water Research Center
Jane Frankenberger, Purdue University
Jason Hubbart, Institute of Water Security and Science, West Virginia University
Amy Jacobs, The Nature Conservancy
Annabelle Harvey, CRC / STAC Coordinator
Megan Cole, CRC / STAC Coordinator

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Michael Castellano, Iowa State University
Richard Cooke, Illinois University
Christopher Craft, Indiana University
Laura Johnson, Heidelberg University
Eileen Kladivko, Purdue University
Rattan Lal, The Ohio State University
Chandra Madramootoo, McGill University
Steven Mirsky, USDA-ARS, MD
Donald Rosenberry, USGS, Boulder, CO
Keith Schilling, University of Iowa
Ken Staver, University of Maryland
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Executive Summary

Improving soil health has gained traction within the farming community because of its importance to long-term crop production and watershed health. To date, management focuses on in-field crop management practices such as reducing tillage, following 4R nutrient stewardship guidelines, and maximizing vegetative cover throughout the year. Guidelines do not address agricultural water management, despite that soil moisture primarily drives underlying soil health processes. In January 2020, STAC partnered with the Foundation for Food and Agriculture Research, West Virginia University's Institute of Water Security and Science, The Nature Conservancy, and the Transforming Drainage partnership and convened experts to explore the *importance of agricultural water management to achieving soil and watershed restoration goals*.

Findings: Despite a solid conceptual basis, few studies have explored how artificial drainage contributes to soil degradation. This oversight could short-circuit the popular soil health movement and ultimately result in a lost opportunity to advance watershed restoration. Modern conservation drainage practices can mitigate these concerns, but the linkage between soil health and advanced water management practices requires validation, and adoption rates remain a challenge. **Based on the workshop discussions, the following recommendations emerged:**

To the Agricultural Community and Stakeholders:

- Recognize conservation agricultural water management is an opportunity to advance soil and watershed restoration goals on artificially drained lands while supporting enhanced crop production.
- Understand advanced water management, including the integration of in-field, edge-of-field, and edge-of-stream practices, requires precision installations customized to field conditions and planned farm operations.
- Share barriers to adopting conservation practices to improve technical assistance financial support.

To the CBP STAC and Broader Research Community:

- Pursue interdisciplinary collaborations to improve management effects on interactions among soil, water, plant, and microbiological realms across hydro-climatic gradients.
- Advance drainage engineering designs to maximize benefits while minimizing costs.
- Develop modeling tools to provide credible, field-based recommendations for agricultural water management under a range of climate conditions and inform field experiments.
- Promote integrated field research using common conceptual frameworks, sampling techniques, and data platforms to facilitate system reviews and meta-analyses.

To the Chesapeake Bay Program:

- Recognize the importance of soil health and water management on agricultural lands to a thriving Chesapeake Bay ecosystem and meeting the CBP's restoration goals.
- Address impacts from artificial drainage and increased hydrologic connectivity between source areas and regional waters by promoting the adoption of conservation drainage in both tiled and ditched systems, including but not limited to controlled drainage, naturalized waterways (e.g., grass waterways and riparian buffers), and targeted wetland restoration.

Workshop Overview

Despite mounting urgency to promote sustainable agriculture and restore regional waters, research in field hydrology has declined (Burt, T. P., McDonnell, 2015); and the linkages between agricultural water management and its effect on soil health, groundwater supply, and regional water quality remain uncertain. Soil scientists increasingly understand ties between crop yields, soil carbon content, microbiota health, and soil moisture based on experimental plot studies, but they have had limited opportunity to explore how landscape setting and artificial drainage influence these interactions. There also is increasing awareness regarding the impacts of artificial drainage on water supply, flood risk, and water quality. However, we know less about how in-field and edge-of-field water management affects these broader concerns through soil health effects. Shallow groundwater dynamics may impose significant constraints on biogeochemical processes within the soil-plant biome and the fate and transport of agrochemicals to downstream waters, suggesting that water table management presents an overlooked opportunity to meet multiple stakeholder concerns. Understanding these linkages is essential to developing precision conservation guidance (i.e., field-scale information regarding optimal practice designs and location) needed to address stakeholder concerns and meet restoration goals under changing climate conditions. Additionally, the adoption of conservation water management technology remains limited. In January 2020, technical experts in agronomy, soil science, hydrology, and agricultural engineering convened at West Virginia University's Institute of Water Security and Science to explore how agricultural water management can advance soil health and watershed restoration.

Workshop Objectives

- Facilitate cross-disciplinary discussions among researchers and field experts committed to advancing soil health and water management at the field and watershed scale.
- Identify critical information gaps that limit the capacity to provide advanced water management guidance and implementation across diverse landscapes and under changing climate conditions.
- Spark collaborations to address critical information gaps.

Introduction

Soil health, broadly defined as the continuous capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans (USDA-NRCS 2020), is essential to our agricultural and natural ecosystems (Lal, 2016). Healthy soils support diverse, abundant microbial communities that enhance plant production and desirable biophysical outcomes, including enhanced soil carbon sequestration, reduced greenhouse gas emissions, and reduced water quality impacts. Thus, the United Nation's 2030 development goals identify soil health as a critical driver of economic prosperity and world peace (Lal, 2016). Despite the growing global awareness, the soil health concept remains mostly overlooked in watershed management. For example, the Chesapeake Bay Program does not have a soil health goal to parallel the focus on sustainable fisheries, despite that food security represents critical challenges to the Bay community and its economy. Further, it is essential to highlight that soil health management and sustainable agriculture include many of the same practices prescribed for watershed restoration.

The disconnect between soil and watershed management likely reflects limitations in our current knowledge of the multi-scaled processes affecting field-to-watershed fate and transport dynamics. Even the functional definition of soil health remains unsettled, and a pragmatic definition continues to challenge management prescriptions. Soil organic carbon (SOC) represents a primary indicator, with a standard threshold of 2% considered essential to sustaining optimal soil health (Lal, 2016), although there is much discussion about critical factors essential to healthy soil function (Table 1). Critically, there remains no integrated understanding of how these attributes interact to regulate the processes or activity rates underlying soil health. Perhaps most challenging to manage soil management, the current target does not fully consider natural variability in soil conditions along hydro-climatic gradients.

Table 1. Soil health indicators (Soil Health Institute, https://soilhealthinstitute.org/). Soil organic carbon is considered the most reliable indicator.

Chemical	Physical	Biological
Cation Exchange Capacity	Water Holding Capacity	Crop Yield
Electrical Conductivity	Bulk Density	Nitrogen Mineralization
Nitrogen	Infiltration Rate	***Organic Carbon***
Micronutrients	Erosion Rating	Carbon Mineralization
pH	Penetration Resistance	
Phosphorus	Texture	
Potassium	Water Stable Aggregation	

Soil degradation is associated with the mid-20th century transition from perennial to annual cropping systems, increased tillage, and intensive fertilizer applications. Thus, the soil health movement focuses on crop management practices that minimize disturbance (e.g., limited tillage and planting cover crops) and maximize biodiversity, soil cover, and living root densities (Figure 1; USDA 2020). However, the current soil health movement may overlook another transformation during the Green Revolution that could short-circuit the success of current practice recommendations: agricultural drainage. While drainage is a necessary management practice to support efficient crop production and a secure food supply, over-drainage may threaten the resiliency of our agricultural systems. Drainage benefits must balance with costs to agroecosystem function (Strock, 2018; Strock *et al.*, 2010).

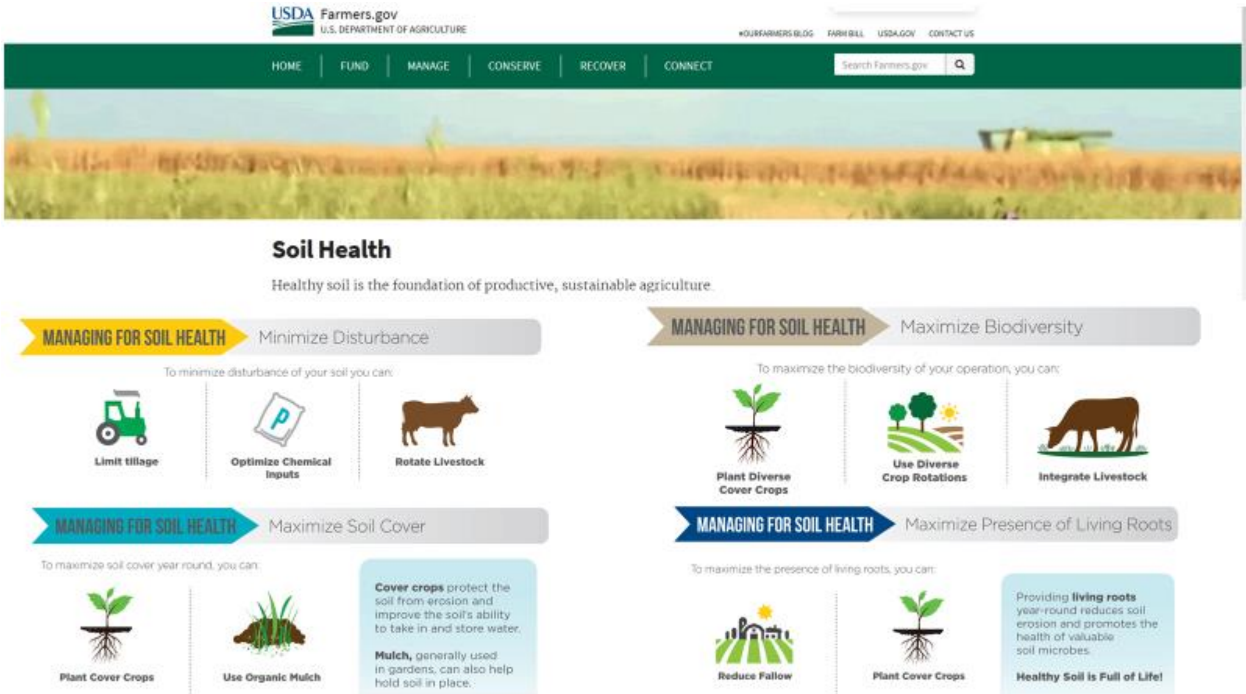


Figure 1. USDA summary of recommended soil health practices (https://www.farmers.gov/conserve/soil-health, accessed 1/15/2020). Prescribed practices focus on crop and soil management.

Extensive hydrologic alterations have wholly altered the distribution of near-surface ground- and surface-waters that naturally control plant species distribution and primary production (Fan *et al.*, 2017; Wohl *et al.*, 2017). In the US, more than 30 percent of the agricultural lands including croplands across the Chesapeake Bay watershed are drained artificially (Blann *et al.*, 2009), (Figure 2). The 2017 US agricultural survey estimates 56 million acres with tile drainage, increasing nearly 14% since 2012 (NASS, 2017). An additional 20 million acres are drained by open ditches (Christensen et al., 2017). As a result of these hydrologic alterations, river network lengths have increased by hundreds of thousands of kilometers (Bricker *et al.*, 2004; Buchanan *et al.*, 2013; Schilling *et al.*, 2008; Smith *et al.*, 2018; Wohl *et al.*, 2017); and watershed water residence times have decreased exponentially, from hundreds of years to less than two (Table 2; presented by Schilling). The potential loss of terrestrial water storage is staggering as well, especially as weather patterns shift to more sporadic, high intensity storms with intervening periods of drought (Hayhoe *et al.*, 2018). The product of the US drained area and typical drainage depth of more than one meter (3 to 4 ft) below the land surface suggests a loss of more than 300 km^3 of terrestrial water storage, equivalent to 65% of Lake Erie's volume. Because most prime agricultural lands occur where the water table fluctuates within 2 m near the land surface (Fan *et al.*, 2007, 2013), unchecked artificial drainage and the consequent loss of terrestrial water storage under changing climate conditions likely represents a global threat to food production and agricultural sustainability, as well as the integrity of our regional waterways.

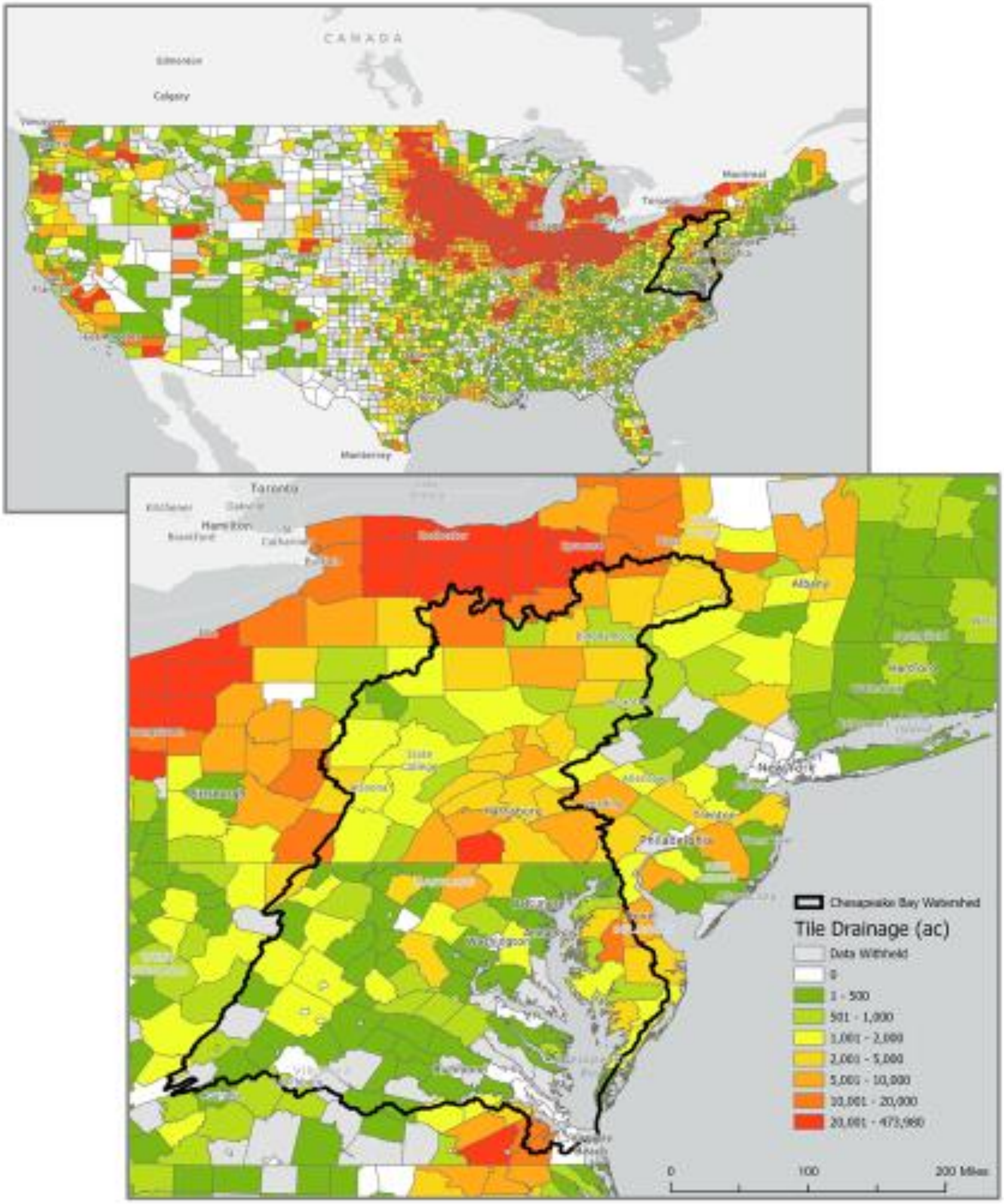


Figure 2. Tile drainage acres reported in the 2017 US Census of Agriculture across the conterminous US and the Chesapeake Bay watershed. While the most intensive installations occur in the Upper Mississippi and Great Lakes basins, artificial drainage has significantly altered the hydrologic landscape throughout all US agricultural regions, including most of the Chesapeake Bay watershed.

Table 2. Effects of artificial tile drainage on watershed flows and characteristics in Central Iowa HUC 12 basins (presented by K. Schilling).

Drainage Intensity	Mean travel time (years)	Drainage density (m-1)	Mean Flow Length (m)
High	1.07±1.28	0.039	23.6±21.4
Medium	2.64±2.88	0.010	55.5±42.7
Low	5.57±5.27	0.0047	110±82.4
Perennial network	82.5±88	0.0006	1,527±1215
Pre-settlement	181.6±134	0.00015	9,311±8197

The full impacts of these massive hydrologic alterations have yet to be determined. The most direct and well-documented effect has been the loss of nearly 60% of our nation's wetlands (Zedler, 2003). More recent studies highlight more erosive storm flows, increased hydrologic connectivity between fields and waterways, and altered stream flow regimes, all of which contribute to the excess nutrients, sediment, and bacteria delivered episodically to downstream waters. The massive hydrological shifts also exacerbate drought sensitivity (Blann *et al.*, 2009). We know less about the broadscale effects that conventional water management may impose more pervasively on soil health due to terrestrial water storage loss. Conventional drainage management likely has contributed significantly to the loss of more than 25 percent loss of soil carbon stocks across our agricultural lands (Sanderman *et al.*, 2018). Despite that soil moisture and soil-water chemistry drive crop production, carbon and nutrient dynamics, and greenhouse gas emissions (Castellano *et al.*, 2019), linkages between soil health and water management remain understudied.

To explore the importance of agricultural water management to soil and watershed health, the CBP STAC partnered with the Foundation of Food and Agriculture Research, West Virginia University's Institute of Water Security and Science, the Transforming Drainage project, and The Nature Conservancy to convene experts in soil and water sciences. Soil microbiologists and biogeochemists, field hydrologists, watershed modelers, and agricultural engineers evaluated the potential for improved shallow groundwater management to benefit sustainable agriculture and watershed restoration through improved soil health. The discussions focused on the humid US, including the Chesapeake Bay, Mississippi, and Great Lakes watersheds. The meeting included short talks and break-out discussions within each discipline to share cutting-edge insights and suggest cross-disciplinary bridges. Participant contributions were captured through guided notes (see Appendix D).

Emerging Workshop Themes

Conservation Drainage has Advanced Significantly, but Implementation Remains Low

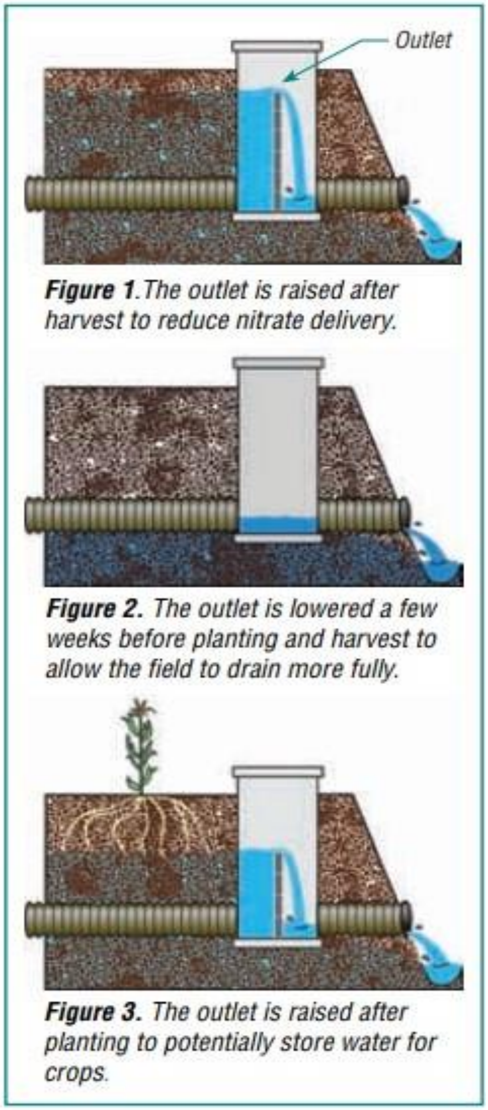
Drainage guidelines have evolved significantly to address water quality concerns. Strock and others (2011) provide an excellent comparison of conventional versus conservation drainage principles developed to address watershed concerns:

Conventional drainage reduces the risk of damage due to waterlogging and enhances trafficability. Drainage networks typically include an array of underground tiles and field ditches (i.e., drainage leads) that efficiently convey water to main lines that connect with adjacent river systems. Since the 1970s, tiles are constructed of perforated plastic pipe up to 60 cm (24 inches) diameter, typically installed 100 to 160 cm below the land surface and spaced 10 to 30 m apart, depending on soil permeability and cropping system. Design guidelines focus on a static groundwater level below the plant rooting zone. A well-designed drainage system can lower the water table to the target depth 24 to 48 hours after a rainfall event.

Conservation drainage refers to an integrated set of agricultural water management strategies, including controlled drainage, edge-of-field filters, and edge-of-stream practices, designed to address water quality concerns and crop production, trafficability, and waterlogging risk. Rather than setting the outflow elevation based on the average maximum depth of crops throughout the growing season, the water table is managed dynamically throughout the growing season (Figure 3a). Maximizing the water table elevation within the soil profile relative to crop constraints limits drainage of nutrient-enriched waters, facilitates plant uptake, and enhances denitrification (Bryant *et al.*, 2019). First-order strategies focus on reducing drainage density by increasing drainage spacing and reducing drainage depth (Christianson *et al.*, 2016). More sophisticated installations provide the capacity to manage water table conditions on a seasonal basis using drainage control structures. During the dormant season and after fertilizer applications, control structure gates are raised within 15 to 30 cm of the soil surface. In the spring, gates are removed or lowered to provide field access and reduce the risk of seedings lost to waterlogging. Once seedlings establish, operators can again raise control structures to increase groundwater storage and reduce vulnerability to drought conditions; then lower the structures as needed to maintain plant-available water without saturating the deepening root zone. Researchers continue to investigate how much drainage is required to maximize crop production (Figure 3b; Strock 2018), given crop root plasticity (Fan *et al.*, 2017).

The distribution of control structure installations in a field presents additional opportunities to manage water table conditions throughout the growing season. More structures distributed throughout a network, rather than a single water control outlet structure, allow broader influence on water table conditions (Figure 3c). Automatic structures increase the capacity to manage the field conditions in response to weather conditions. Operators can maximize water table control by subdividing fields into water management zones based on natural flow patterns. Multiple outlets preserve the more natural distribution of ephemeral channels, limiting concentrated flow that increases erosion and bypasses natural filters.

A)



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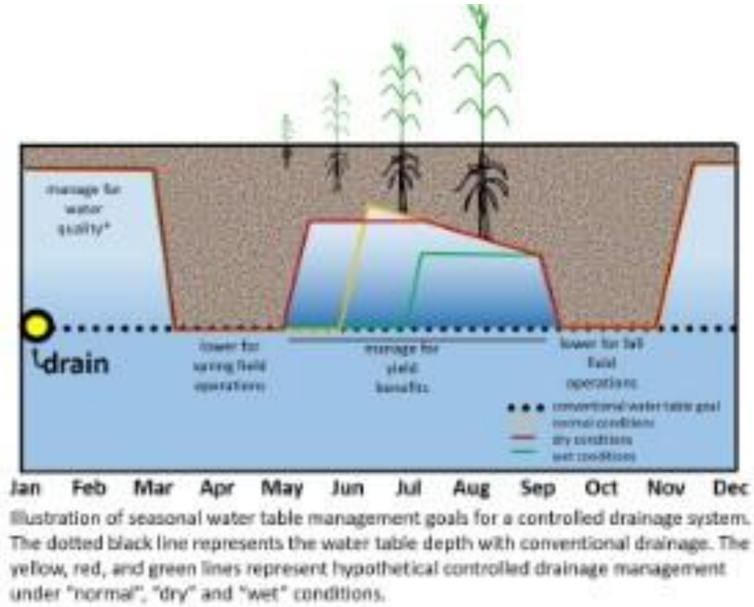

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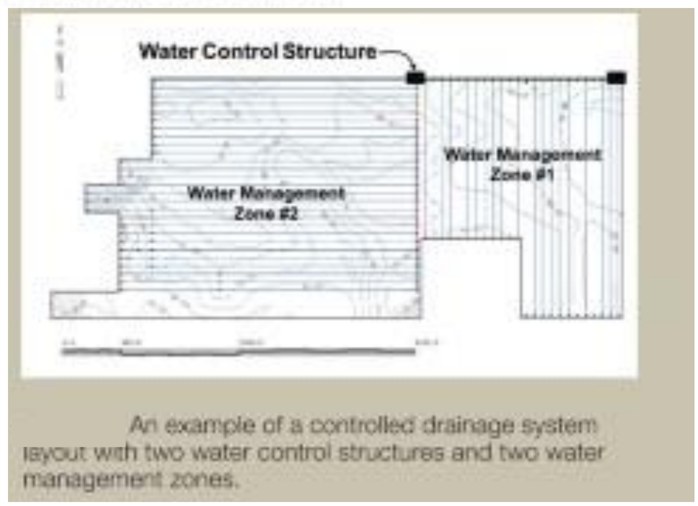

Figure 3. Conservation drainage techniques include A) inline outlets distributed through a drainage network, b) imposing dynamic water table conditions that more closely mimic natural hydroperiod conditions, and c) dividing fields into management zones, ideally based on natural drainage patterns.

Conservation practices sequenced along hydrologic flow paths can increase terrestrial water storage and natural filter processes more effectively than randomly placed practices or grid-based practices across a field, thereby maximizing targeted benefits. Practices and combinations of practices vary widely in design, costs, and benefits. More highly engineered and expensive practices like woodchip bioreactors (Figure 4) provide excellent nitrogen reduction benefits but do not address exacerbated storm flow concerns or habitat. In contrast, natural filters diffuse concentrated flow, thus reducing storm discharge and providing water quality benefits but may require taking more land out of production. These practices include saturated buffers (Figure 5; NRCS Conservation Practice Standard 605) and other vegetated treatment areas such as two-stage ditches (NRCS Conservation Practice 582)(Speir *et al.*, 2020), level spreaders (NRCS Conservation Practice Standard 632)(Sweeney and Newbold, 2014), and wetlands (NRCS Conservation Practice Standard 657, 658, 659). Restored and created wetlands and water recycling ponds can sequester nutrients and sediment and potentially hold water for irrigation (Figure 6). Stacking these practices provides the most significant and most reliable benefits under more variable weather conditions, which is likely to occur with climate change. For example, an integrated drainage system that includes shallower drains with wider spaces, connected to a saturated buffer, that borders a a two-stage ditch, provides a three-tier system for reducing peak flows and increasing natural filtration. The combination of practices reduces risks to flooding but also drought susceptibility. Strategic design and placement (i.e., precision conservation), however, is essential for success (Strock *et al.*, 2010).

Although conservation drainage guidelines have advanced considerably, workshop participants agreed that practice adoption remains abysmally low, likely less than five percent, for several reasons. Dring and others (2016) found that the most common disincentive to controlled drainage adoption was the increased on-farm labor required to operate control structures, followed by concerns about the lack of extension services to support the practice the cost of control structures and installation. Lack of awareness and topographic constraints were also commonly cited as disincentives to adoption. Further, farmers may be aware that practice performance varies widely, especially concerning TP and sediment loss (Figure 7; Table 3)(Bryant *et al.*, 2019; Christianson *et al.*, 2018), and thus have concerns about the return on their investment.

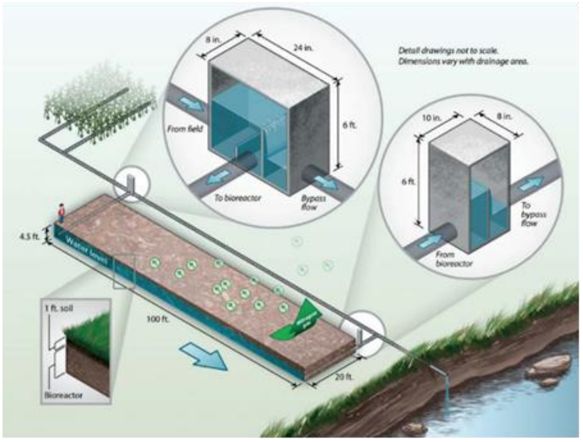

Figure 4. Woodchip bioreactors reduce nitrogen loads by up to 25 g N m^{-3} d^{-1}, by intercepting nitrate-enriched drainage discharge and providing labile carbon to denitrifying bacteria (Christianson and Helms 2011).

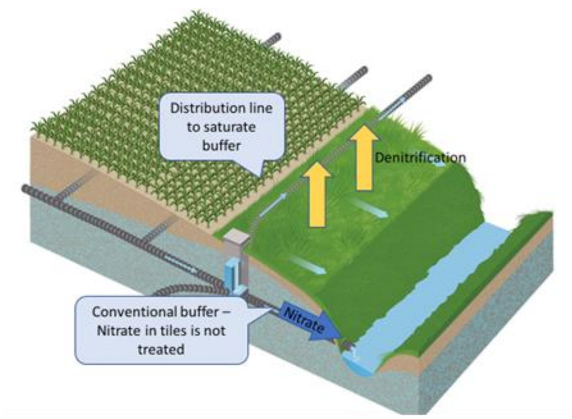

Figure 5. Saturated buffers (diagrammed to the left) and level lip spreaders diffuse concentrated flow across wetland habitat, thus allowing natural filter processes, including denitrification and sediment deposition, to reduce downstream loads. From Transforming Drainage (https://transformingdrainage.org/practices/saturated-buffers/, accessed 9/15/2020.

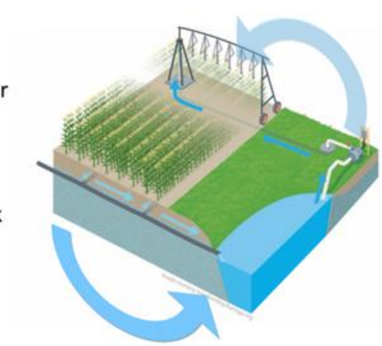

Figure 6. Vegetated retention ponds, sometimes referred to as drainage water recycling, can provide benefits like wetlands and provide a source of irrigation water during droughts. From Transforming Drainage (https://transformingdrainage.org/practices/saturated-buffers/, accessed 9/15/2020.

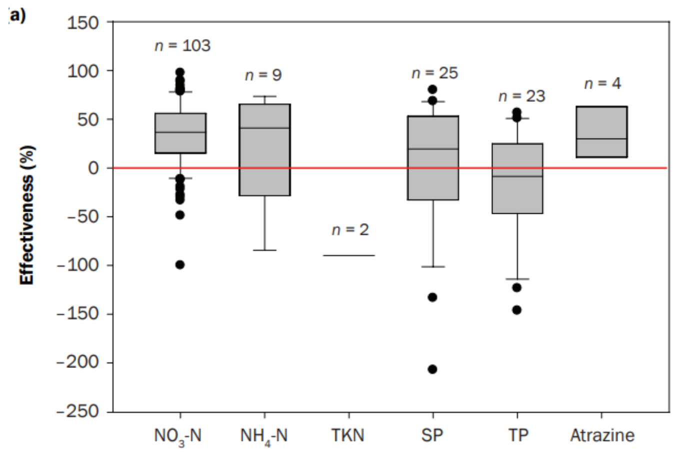

Figure 7. Practice effectiveness of drainage water management in tile drain for nitrate (NO3-N), ammonium (NH4-N), total Kjehldahl nitrogen (TKN), total N(TN), soluble phosphorus (SP), total P (TP), and atrazine. Solid red bar represents 0% effectiveness From Smith et al., 2019

Table 3. Conservation drainage practice effectiveness for retention of total nitrogen (TN), total phosphorus (TP), and total suspended sediment (TSS) as determined by the USEPA Chesapeake Bay Program expert panels.

BMP (NRCS Practice Code)	Reference	TN Retention Efficiency %	TP Retention Efficiency %	TSS Retention Efficiency %
Water Control Structures (587)	Bryant et al 2019	0	0	0
Drainage Water Management (554)	Bryant et al 2019	30	0	0
Saturated Buffers (604)	Bryant et al 2019	20	0	0
Two-Stage Ditches (582)	Bryant et al 2019	-	-	-
Wetland Restoration (657, 658, 659)	Mason et al 2016	42	40	31
Denitrifying Bioreactors (605)	Bryant et al 2019	20	0	0

Effects of Field Water Management on Soil Health Remains a Critical Knowledge Gap

Expansive drainage networks have lowered the water table below the plant rooting zone throughout most humid US agricultural regions, where SOC stock losses also range between 30 to 50 percent (Sanderman *et al.*, 2018). Groundwater may impose an important bottom-up control on soil carbon pools in arable soils (Castellano, Archontoulis, Helmers, Poffenbarger, & Six, 2019; Strock, 2018); however, few have explicitly investigated the linkages between soil health and agricultural water management.

The interconnected pathways and processes discovered in wetlands ecology at the field and watershed scale may provide essential insights to understanding these linkages. The source(s) of waters supplied to a field (e.g., precipitation vs. groundwater) determine the timing, duration, magnitude, and frequency of soil water content changes. Changes in water source intensity also regulate hydro-chemical conditions. The resulting combination of soil moisture, pH, and redox conditions regulate the soil microbial activity, thus controlling decomposition rates and soil carbon sequestration (Figure 8), nutrient mineralization and release, denitrification, greenhouse gas emission rates, and ultimately, plant diversity and productivity (Jungkunst and Fiedler, 2007; Richardson and Vepraskas, 2001). While the constant saturation in wetland soils results in significantly higher SOC content, the same biogeochemical processes likely regulate SOC content on arable lands. Wetland ecologists also continue to explore the geography of wetland ecosystem functions within and among different landscape settings. There is a deep awareness that no two wetlands (fields) are the same and that variation in ecosystem function reflects the combination of constraints imposed by the hydrogeologic setting (Winter, 1999), topographic position (e.g., Brinson, 1993; Rosgen, 1994), and the extent of hydrologic alteration (Johnston *et al.*, 2009; Mason et al. 2016). Similar paradigms likely apply to agricultural systems (Borch *et al.*, 2010; Clague *et al.*, 2019).

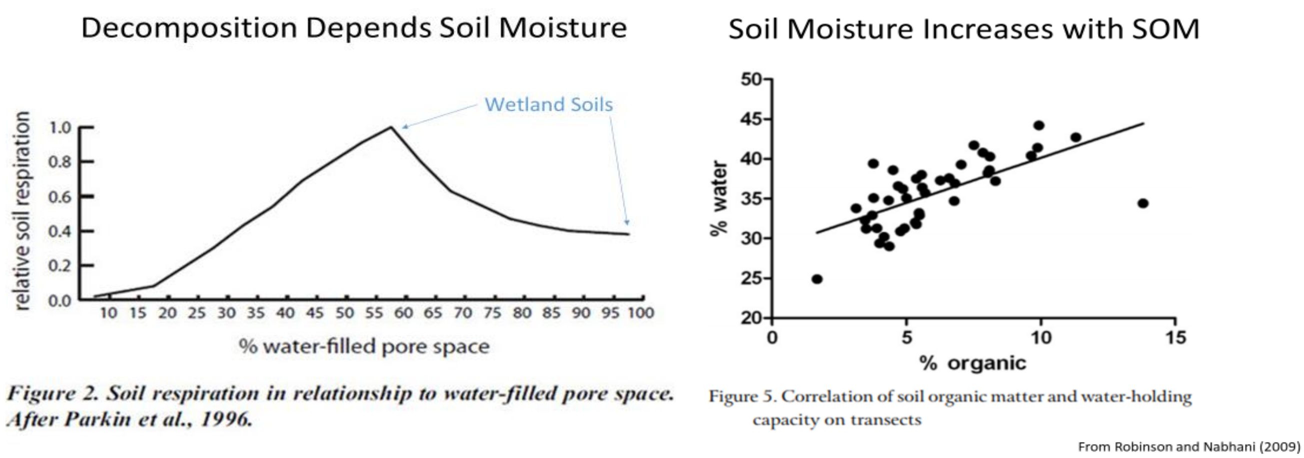

Figure 8. A) Soil respiration, which is an indicator of decomposition activity, depends upon soil moisture, indicated by water filled pore space (from Parkin et al 1996). B) Soil organic matter in increases with soil moisture content (from Robinson and Nabhani 2009).

Adapting field methods from other disciplines can help inform our understanding of biophysical processes across arable landscapes. Much of the existing agricultural research to investigate management effects compares homogenized experimental plots laid out randomly to limit background “nuisance” or “noise” (i.e., randomized block design). However, background (environmental or hydrologic) field gradients likely represent vital drivers affecting the biophysical processes related to soil health and productivity. Few agronomic studies systematically explore how agricultural practices perform in various hydrogeomorphic settings. Using hypothesis-based approaches to field sampling (Burt, T. P., McDonnell, 2015; Vereecken *et al.*, 2015) together with novel adaptations of sampling approaches used in contaminant hydrogeology (Hem, 1985; Rosenberry, 2010) and soil biogeochemistry (Maltby 2009) could advance our understanding of soil health variability across hydroclimatic and geomorphic gradients (Brantley *et al.*, 2016), and thus our understanding of where and when conservation practices can advance our management goals.

Advanced Agricultural Water Management Requires Integrated Strategies

Conservation drainage practices, including a suite of in-field, edge-of-field, and edge-of-stream practices designed to increase terrestrial water storage while accommodating cropping requirements, are needed to meet our water quality and habitat goals under changing climate conditions. Practices sequenced along a hydrologic flow path can maximize water storage and water quality benefits. In addition, a more integrated approach to drainage and irrigation is essential to maximizing progress toward sustainability and restoration goals. As an innovative example, irrigation waters supplied through tile infrastructure (i.e., sub-irrigation) can reduce greenhouse gas emissions (Crézé and Madramootoo, 2019). Conservation planning and incentives should promote fully integrated approaches to water management to advance environmental and farmer concerns more effectively.

Information Gaps and Research Needs

The following information gaps and research opportunities emerged from the workshop discussions:

Soil and Field Hydrology

The importance of soil moisture to soil health processes highlights a need to understand better the interaction of top-down (i.e., precipitation- and temperature-driven) versus bottom-up (groundwater-driven) controls on water exchange through the plant rooting zone (Rodriguez-Iturbe, D'Odorico, Laio, Ridolfi, & Tamea, 2007). Despite advances in biogeochemistry and microbiology that highlight a need to study environmental hydro-chemical fluxes, field hydrology has received less focus in recent decades (Burt, T. P., McDonnell, 2015). The few available interdisciplinary studies provide limited capacity to extrapolate field data across regional scales and predict how agricultural systems will respond to new land management strategies under changing climate conditions. Emerging technology, including simple, high-resolution modeling and monitoring tools, presents exciting opportunities to augment existing models and refine our understanding of these interconnected processes.

Effects of Groundwater and Regional Base Level on Field Hydrology

Understanding the broader hydrologic setting is essential to optimizing agricultural water management. Even "flat" landscapes typically have shallow hydrologic gradients that drive biogeochemical processes along flow paths. Hydraulic gradient ties strongly to the relative elevation of a receiving water body or base level (*sensu* Ashton, 2004), which also sets the lower level for erosion. While artificial structures can impose a temporary base level, the regional base level will strongly influence hydrologic fluxes through a field, especially during extreme events. Evaluating the regional hydrogeologic context also draws attention to various water sources' potential to influence soil chemistry (Böhlke, 2002). For example, the relative influence of rain versus groundwater supplied to the plant rooting zone controls ionic chemistry, pH, and redox conditions, key factors affecting the biogeochemical processes underlying soil health. To date, many agricultural studies focus primarily on the effects of precipitation and evapotranspiration, with little consideration to how additional hydrologic drivers can influence field conditions or hydrogeochemical fluxes through the soil zone (Vereecken *et al.*, 2015). Additionally, more research is needed to evaluate artificial drainage effects on groundwater systems (Smith *et al.*, 2018).

Effects of Drainage Management and Landscape Setting on Soil Hydrology

Land use patterns beyond crop management, including artificial drainage, influence hydrological connections through the soil zone and regional water supplies, yet few models applied to assess watershed conditions or target conservation practices capture these significant alterations.

The evolution of drainage systems in different physiographic regions indicates the critical ties between field drainage and hydrogeologic setting. For example, Schilling and others highlighted distinct patterns in tile drainage when they compared systems in young versus ancient, glaciated landscapes in the Mississippi River basin. In younger, less dissected landscapes, tile drainage is installed more systematically across the landscape, parallel ("gridiron") or herringbone patterns. In older, more incised landscapes, "targeted" drainage is installed in pockets along existing zero-order channels. Similar patterns manifest in the Chesapeake Bay watershed's Outer Coastal Plain. In the lowlands, where farmers are most concerned with minimizing impacts from persistent, low-flow, and shallow water table conditions, gridded ditches are installed systematically across agricultural fields. Across inland areas with more topographic relief, drainage installations mainly shunt water downstream during storm events. These installation patterns reveal the tight linkages between function and design and landscape conditions, thus highlighting that water management prescriptions require consideration of the watershed position and the physiographic setting.

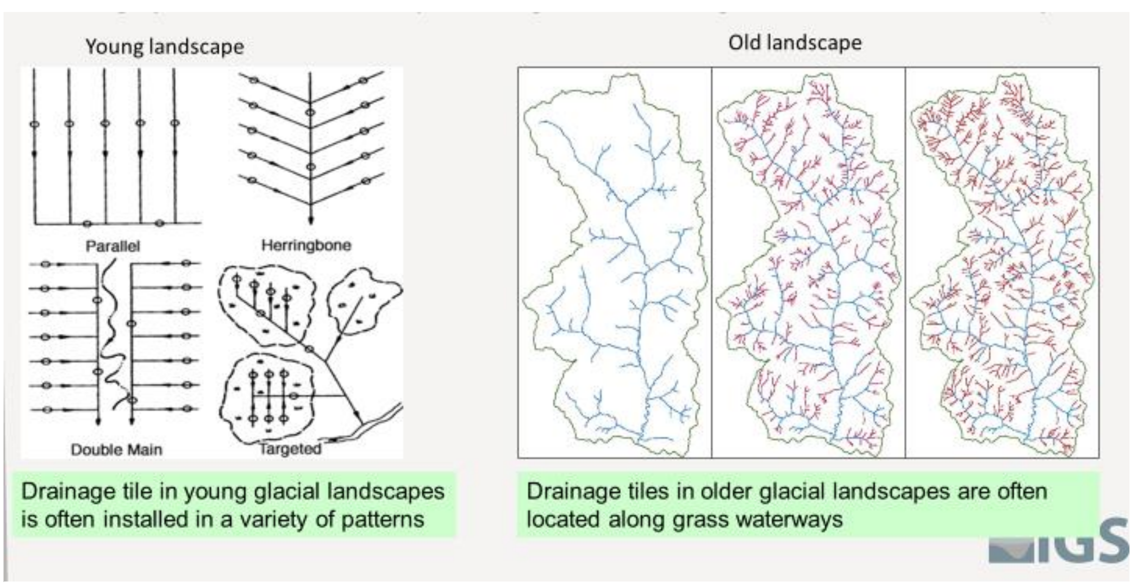

Figure 9. Drainage patterns in contrasting landscape settings of the Midwest (From Shilling et al 2015)

The spatial pattern and timing of hydrologic connection between a field and regional waterway continue to emerge as a critical driver of water quality concerns. For example, Ali and others (2019) observed that harmful algae blooms in Lake Winnipeg, Canada's third-largest freshwater lake, occurred when croplands were connected to regional waters by surface water flow in zero-and first-order waterways. Tile and drainage networks increase the likelihood and frequency of these hydrologic connections. Similar to observations in the Lake Erie basin (King *et al.*, 2015), investigators linked poor water quality to episodic pulses of excess dissolved phosphorus loads exacerbated by the artificially expanded stream network throughout a watershed. Results highlight the importance of strategically locating conservation drainage practices. Design guidelines developed over recent decades focus more on practice engineering. There remains an urgent need to reliably identify critical source areas and customize conservation practices to a wide range of arable landscape conditions (Kleinman et al., 2019). Tools like the Agricultural Conservation Planning Framework (ACPF; Tomer *et al.*, 2015) demonstrate a capacity to provide compelling, field-scaled data to identify candidate BMP sites, but prioritizing these opportunities remains a challenge.

Microbial Activity along Hydrologic Gradients

Soil health processes, including organic matter decomposition and nutrient mineralization, depend on a diverse soil microbial community regulated primarily by soil moisture and temperature (Moyano *et al.*, 2012) (Figure 10). Our limited knowledge of ties between soil microbial distributions and hydro-chemical gradients presents a significant challenge to soil health and watershed management. Genetic sequencing has revolutionized our capacity to characterize microbial composition, and advances in remote sensing and hydrologic modeling have improved the capacity to map soil moisture gradients. However, few studies have combined these technologies to evaluate the microbial activity and associated ecosystem functions systematically. Such cross-disciplinary studies are essential to advancing soil and watershed restoration goals.

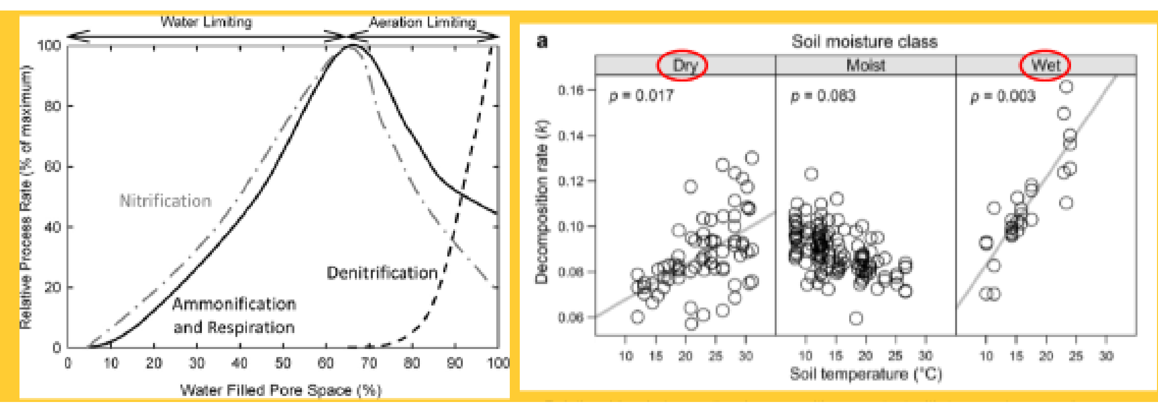

Figure 10. Left: Conceptual relationship between percent water filled pore space and relative biogeochemical processes rates (Stewart, adopted from Linn and Doran 1984 and Lohse et al 2009). Right: Observed decomposition rates related to temperature in dry, moist, and wet soils (from Petraglia et al. 2019)

Phosphorus Dynamics and Field Hydrology

Although artificial drainage increases nitrogen and phosphorus loads to downstream waters, conservation practice assessments have focused primarily on nitrogen reduction (Needelman *et al.*, 2007). However, excess phosphorus is also an urgent threat to impaired waters. For example, harmful algal blooms in Lake Erie, Lake Winnipeg, and the Chesapeake Bay linked to increasing dissolved phosphorus loads continue to threaten recreational access and public drinking supplies (Figure 11)(Ali and English, 2019; Bullerjahn *et al.*, 2016; Kleinman *et al.*, 2019). Further, USGS river monitoring data indicate dissolved phosphorus concentrations continue to increase over recent decades despite that advanced agricultural management has reduced soil erosion (Staver 2020). The source(s) of bioavailable phosphorus remains unclear. Much of the focus has been on no-till practices, which results in the accumulation of soluble phosphorus at the land surface that is more susceptible to transport during runoff events (Staver 2020). It is likely that chemical transformations along hydrologic flow paths connecting source areas to regional waterways also contribute significantly to water quality concerns (Kleinman *et al.*, 2019). Historically, artificial drainage was believed to limit P loads due to reduced erosion, but more recent research shows tiling increased dissolved P loads by nearly 50 percent, likely due to increasing macropore flow (King *et al.*, 2015). While we understand the mechanisms affecting phosphorus release, our ability to map transformation hotspots or hot moments and target conservation practices remains a critical need (Kleinman *et al.*, 2019; Staver 2020). A related challenge is a variability in practice performance (Staver 2020). We need to understand better how various agronomic and conservation practices may impact dissolved phosphorus loads in different soil types and landscape settings.

Greenhouse Gas Emissions and Soil Hydrology

Shallow water table dynamics influence greenhouse gas emissions, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), through its control on soil microbial activity and organic matter decomposition (Figure 12). Nitrous oxide emissions are especially concerning because annual emission rates have increased nearly 200 percent since the turn of the 20th century, and this gas is 300 times more potent than CO_2 (Bouwman *et al.*, 2013).

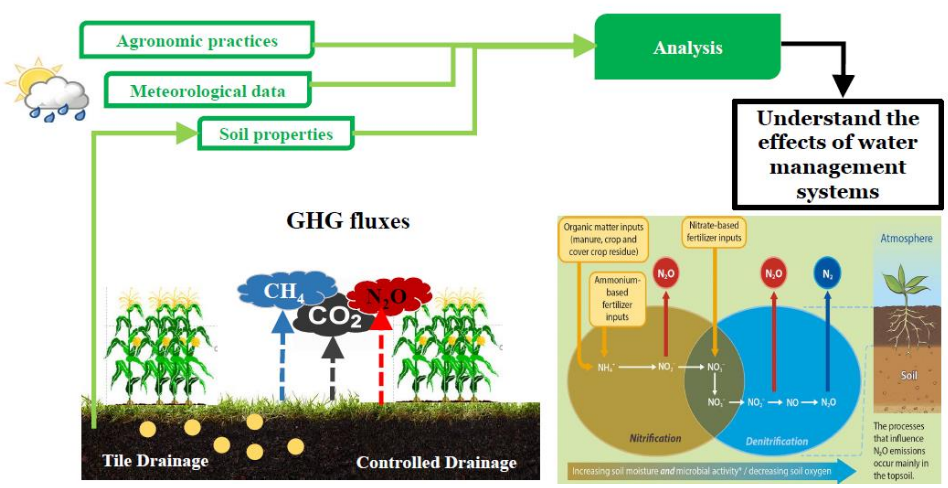

Figure 12 Conceptual diagram highlighting the potential effects of drainage management on soil microbial activity and greenhouse gas emissions. From Creze and Madramootoo, 2019.

Modern agriculture has increased GHG emissions significantly in part by altering underlying soil decomposition processes. These increases are attributed to excess fertilizer applications, conversion from perennial to annual crop systems, and degraded soil health. Water management, however, likely also plays an essential role by regulating the distribution of heterotrophic bacteria (Suriyavirun *et al.*, 2019). For example, a laboratory-based column study indicated that dewatering for 24 hours increased CO_2 emissions by more than 100% compared to shorter drawdown durations, likely due to elevated aerobic decomposition rates (Birgand et al.; Figure

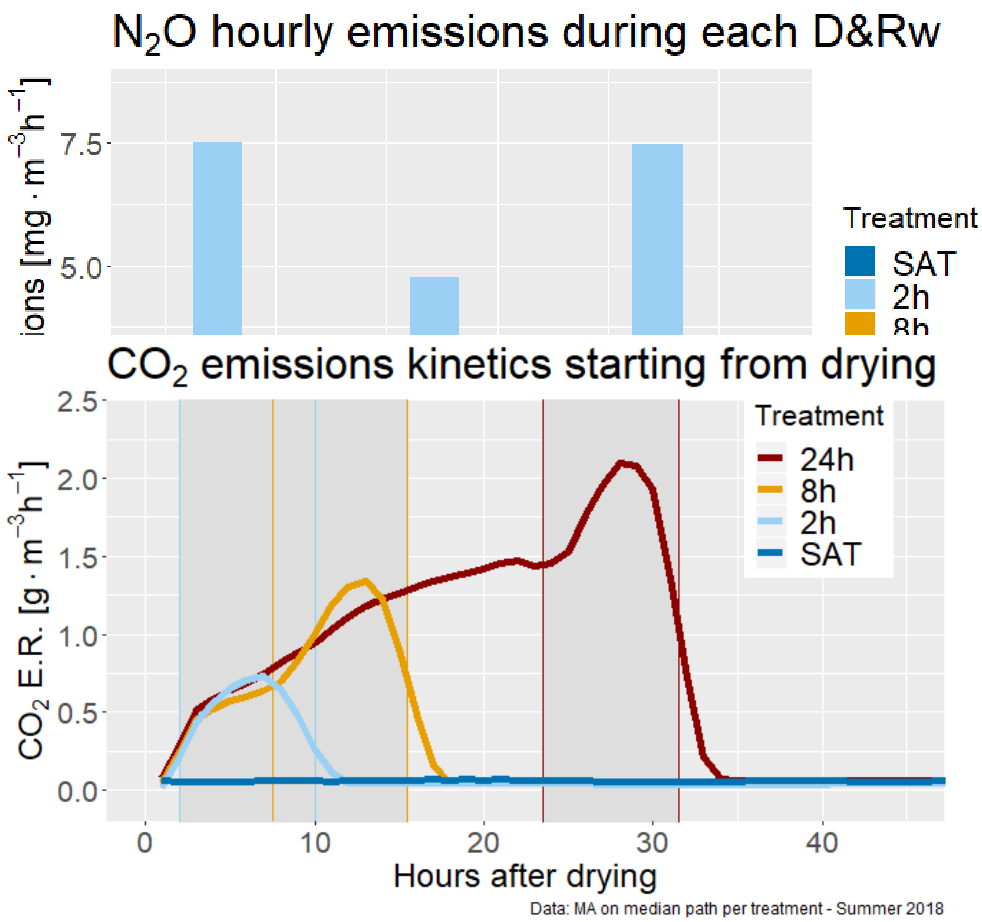

Figure 13. *Greenhouse gas emissions response to dewatering in a laboratory-based column study. Duration of drawdown conditions ranged from fully saturated (SAT) to 24 hours.* ***Top:*** *Observed soil carbon dioxide (CO_2) emissions.* ***Bottom:*** *Observe nitrous oxide (N_2O) emissions. Contributed by Brigand.*

13). Further, N_2O emissions were highest in soils with rapid rewetting cycles (every two hours) but lower under sustained saturation, which presumably allowed the complete cycling of denitrification to occur. Sub-irrigation field studies reinforce these findings. High water table conditions, established by filling tile systems, increased denitrification, reduced N_2O emissions, and limited NO_3 loss to downstream waters (Crézé and Madramootoo, 2019). The combination of laboratory and field studies indicates that water management plays an integral role in regulating soil microbial activity and GHG emissions. However, there remains much unknown regarding the distribution of soil microbes and their activity rates driving greenhouse gas emissions. Indeed, some studies suggest that drained agricultural lands reduce greenhouse gas emissions (Castellano *et al.*, 2019). Contrasting results indicate an urgent need to develop a more robust understanding of how carbon and nitrogen dynamics vary due to agricultural water management and changing weather patterns.

Crop Yields and Water Management

Drainage historically is considered essential to increasing crop yields because waterlogged soils restrict root growth, cause early leaf senescence and sterile florets, and increase disease susceptibility (Castellano *et al.*, 2019). However, conventional installations may lead to unintended, adverse outcomes. Many of the soil biogeochemical processes that enhance plant growth require high soil moisture conditions. Indeed, poorly drained soils where the water table intermittently intersects the plant rooting zone represent some of our most productive soils. Some investigations suggest that excess drainage may provide limited benefit to crop production (Castellano *et al.*, 2019; Figure 14), whereas controlled drainage can increase crop production (Delbecq *et al.*, 2012).

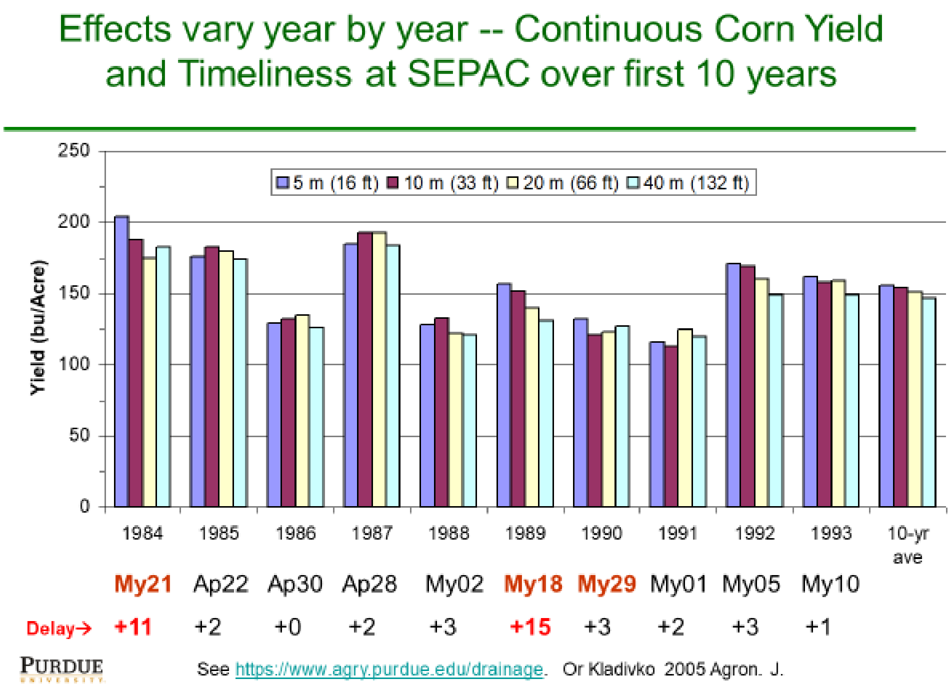

Figure 14. Interannual comparison of corn yields among fields with varying drainage intensities. Tile spacing ranged from 5 to 40 m. From Kladivko et al 2005.

Limited access to precision data, including continuous field sensors and high-resolution remote-sensing data, reveal uncertainties regarding crop yield response to agricultural water management. For example, Zipper and others (2015) linked more robust corn yields to low-lying areas where the water table is more likely to occur within the plant rooting zone and observed higher yields during wetter years (Figure 15), perhaps suggesting that nuanced shallow groundwater management could benefit crop production. These results are consistent with field studies indicating that nutrient uptake efficiencies increase with soil moisture (Strock, 2018). There is an urgent need to leverage precision yield data and high-resolution remote sensing data to evaluate management effects across different field conditions.

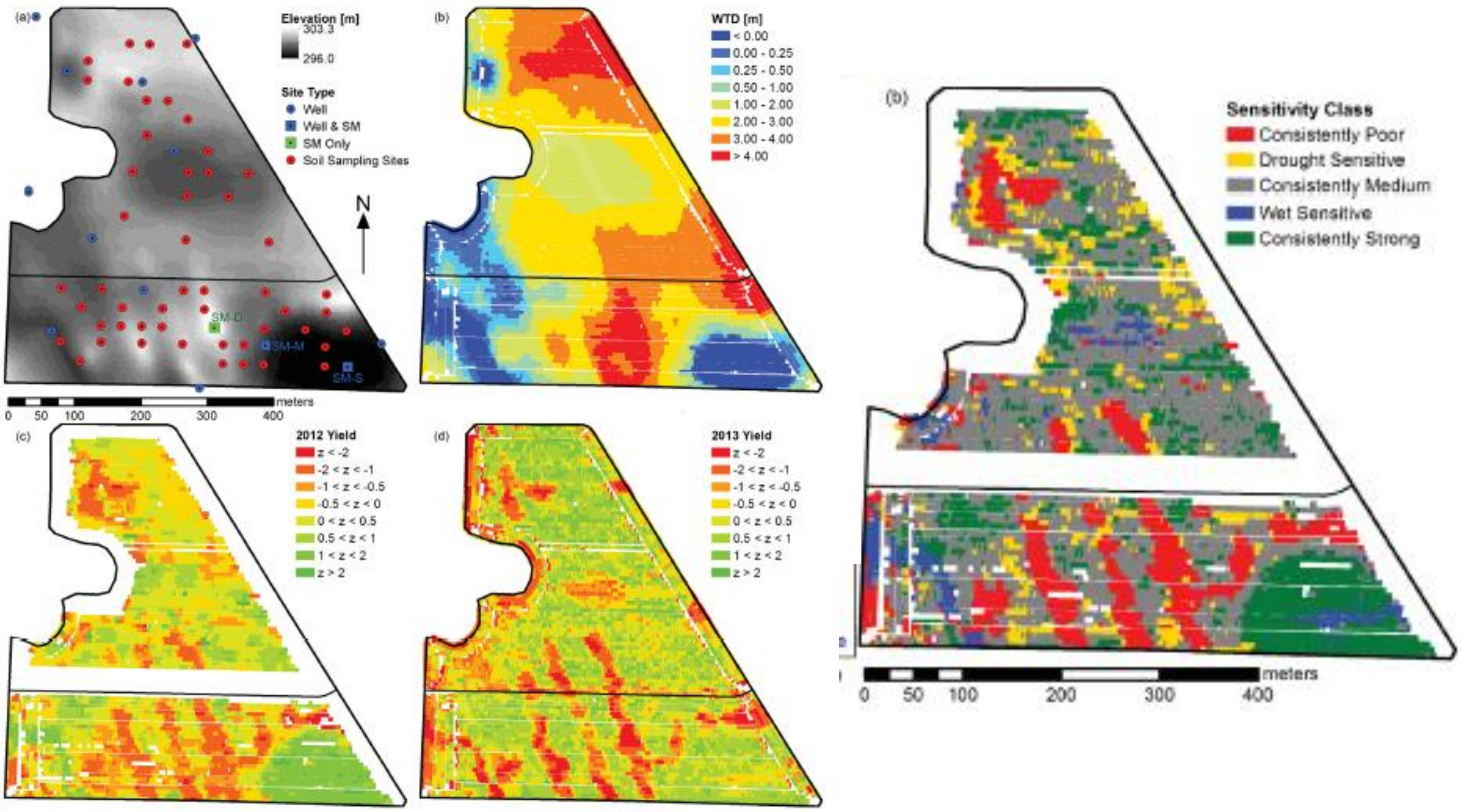

Figure 15. Crop yields reflect microtopography and variations in soil moisture and soil texture in a Yahara River Watershed corn field, WI. Top left: Field monitoring locations relative to field topography, using LiDAR-derived topography DEM data. Top-middle: High 7 day mean water table depth (WTD) Interpolated from field measures. Bottom left and middle left: normalized corn yields for 2012 and 2013, respectively. Right: A multi-variate, sensitivity analysis indicates yield sensitivity to shifting weather patterns. Consistently higher yields seemingly corresponded to wetter field depressions. From Zipper et al. 2015.

Stakeholder Engagement and BMP Implementation

While the workshop focused mainly on drainage management from a biophysical perspective, participants unanimously acknowledged that the existing technology in conservation drainage remains underutilized. Workshop participants estimated that less than 5 percent of ongoing tile installations use “smart” or “conservation” drainage practices. There is also a need to broaden the conversation around conservation practices in artificially drained systems, including infield crop management and soil health, drainage practices in ditches and tile systems, and edge-of-field practices, including wetlands and recycling pond systems.

Workshop Recommendations

To the Agricultural Community and Stakeholders

- ***Recognize that conservation drainage on drained lands in combination with edge-of-field filter practices and edge-of-stream wetland restoration is critical to sustainable agriculture and watershed restoration.*** The mantras, “Drainage is good” and “drainage pays,” should be considered carefully given their potential to promote conventional drainage installations that adversely affect soil and watershed health. While conventional drainage practices benefit crop production, they short-circuit processes that enhance soil and watershed health. Lowering the water table by 1 to 1.25 m below the plant-rooting zone represents a drastic change in shallow groundwater conditions that could significantly influence soil health processes. Instead of targeting a static water table elevation, operators should consider conservation drainage practices that partially restore a field system’s natural soil water regime and maximize terrestrial water storage. Reduced soil moisture in the shallow plant rooting zone likely limits soil carbon sequestration by enhancing decomposition. The integrated combination of controlled drainage, edge-of-field filter practices, and edge-of-stream wetland restoration is critical to managing soil health, increasing resiliency to extreme weather events, and improving downstream water quality while reducing flood risks.

- ***Understand advanced water management requires installations customized to field conditions and planned farm operations.*** A field’s location relative to the regional drainage network and frequency of hydrologic connectivity strongly influences infield soil water conditions and drainage patterns. Further, existing ditch networks require consideration when evaluating how best to implement advanced agricultural water management practices. The complex set of drivers likely require advanced technical service providers who can design the best combination of practices and designs, given a field’s location and operator concerns.

- ***Realize that sharing precision agricultural data presents exciting opportunities to inform drainage management, improve crop yields, and reduce losses.*** Sub-meter scaled precision agriculture data currently is used to inform fertilizer applications, and to a lesser extent, irrigation schedules. However, these data also have outstanding potential to improve agricultural water management. High-resolution (meter-scaled) remote sensing data can help identify areas that routinely have inadequate production or an elevated risk of excess nutrient loss, erosion, flooding, and drought and inform the design of conservation practices to provide a broader range of ecosystem services.

- ***Explore barriers and incentives for advancing the adoption of conservation practices.*** Conservation water management, including integrated controlled drainage, edge-of-field, and edge-of-stream practices, has been established as essential to effective field and watershed management. However, conservation practice adoption occurs on far less than 10 percent of US agricultural lands. Refining our understanding of where and how best to design integrated conservation practices is essential to building the farming community's confidence and willingness to adopt these practices. Meeting our collective restoration goals will require understanding the barriers to implementation and how best to support farmers through more effective outreach, technical assistance, and incentive programs.

To the CBP Science Technical Advisory Committee and Broader Research Community

- ***Pursue interdisciplinary collaborations to evaluate management effects on interactions among soil, water, plant, and microbiological realms across hydro-climatic gradients.*** To date, soil health research projects often take a randomized, experimental approach to investigate how a handful of indicators responds to a limited number of interventions (Stewart *et al.*, 2018). Few studies have investigated variability in soil health metrics along hydro-chemical gradients, despite that soil moisture, temperature, pH, and redox conditions impose a strong influence on the soil microbiome (Figure 16). Advancing our understanding requires diverse partnerships to establish a hypothesis-driven network of hydrological observatories across different climate regions (Vereecken *et al.*, 2015). Ideally, such a partnership also will leverage existing networks established to study hydrological fluxes across multiple scales. Compiled results are essential to improving controlled drainage prescriptions that can restore soil and watershed health while maintaining or improving yield under changing climate conditions.

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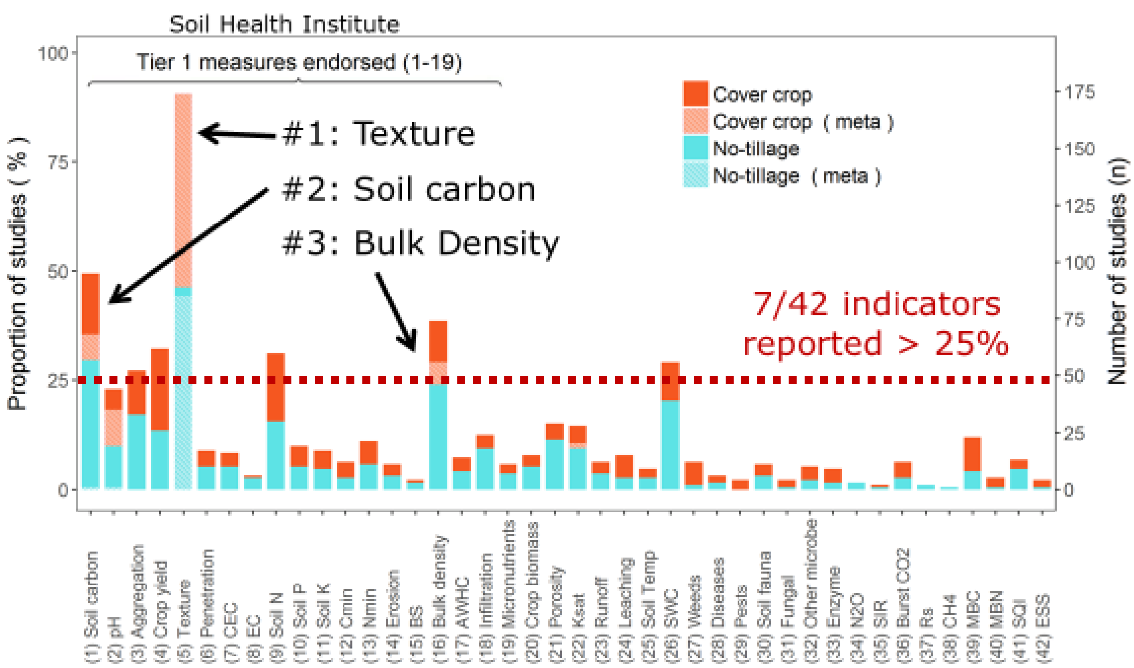

Figure 16. Review of peer-reviewed publications related to soil health indicators. Few publications focus on soil microbial activity or influence of soil fungi. (Stewart et al., 2018)

- ***Advance drainage engineering designs to address a broader set of concerns beyond yield and costs, to include increased terrestrial water storage and reduced downstream flood potential, increased soil carbon sequestration, and reduced nutrient loss and greenhouse gas emissions; and to address additional farmer concerns such as labor shortages.*** Innovative field equipment likely has an important role to play in advancing cost-effective strategies to improve soil and watershed health. For example, as technology costs decline, advances might include the combination of field sensors and robotic equipment, such as remote-controlled, multi-depth water control structures or tile network connectors, to enable more effective water zone management. Fine-tuning integration strategies of in-field, edge-of-field, and edge-of-stream practices also are essential to addressing soil and watershed health concerns while minimizing costs and risk to the landowner, who is concerned especially with impacts from extreme weather events. Finally, designing more effective conservation drainage installations requires more sophisticated consideration of the field setting. Advanced designs and practice prescriptions must better account for geography.

- ***Leverage modeling tools to provide field-based recommendations for agricultural water management and inform field experiments.*** The power of modeling tools to inform research priorities and provide a sampling framework remains underutilized. Too often, researchers and managers invest extensive resources into a single "best" model for scenario assessments and rarely assess model structures or use model predictions as a basis for designing a monitoring or research program. High-resolution models that pinpoint source areas or biogeochemical "hotspots" can be combined with precision field data to identify where monitoring or research can provide information critical to testing our understanding of system behavior in response to management actions.

- ***Promote collaborative field research, using common conceptual frameworks, sampling techniques, and data platforms to facilitate system reviews and meta-analyses.*** The Transforming Drainage project has established a database focused on the Midwestern US and North Carolina to centralize field data related to advanced water management. However, the database does not include research from large swaths of the country, including much of the USDA's Northern Crescent and Eastern Seaboard agricultural regions and the Chesapeake Bay watershed (Figure 17). Engaging farmers in developing this database, for example, by including them in the design, implementation, and monitoring of a project, may help address risk concerns and ultimately increase adoption.

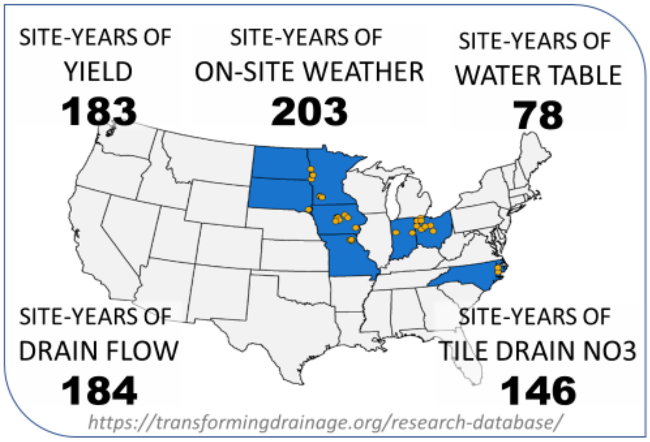

Figure 17. Areal coverage of the Transforming Drainage Database, which was constructed to facilitate multi-site comparisons. Additional coverage is needed to build an understanding how best to design conservation drainage, depending on field operations, location, and climate condition.

To the Chesapeake Bay Program and Other Watershed Management Agencies

- ***Recognize the importance of soil health and water management to meeting restoration goals.*** Improved soil health reduces erosion and nutrient transport to downstream waters, increases terrestrial water storage, increases resiliency to drought, reduces downstream flood risks, and reduces greenhouse gas emissions, in addition to not ensuring sustainable crop yields. These benefits are directly related to field and watershed hydrology, underscoring the need to integrate conservation drainage practices to address farmer concerns and meet our environmental goals more effectively. Further, *prescribed practices are <u>the same</u> as those recommended to tackle water quality concerns*. Soil health has traction with farmers, leading to more conservation practice adoption and farmers also understand the importance of water management to crop productivity. Most importantly, improving soil health is essential to a thriving agricultural system essential to the health of our watershed communities.

- ***Recognize the potential for conservation drainage, including the integrated combination of controlled drainage and edge-of-field filter practices, to improve regional water quality and provide a range of other ecosystem services.*** Extensive hydrologic alterations, including 100,000's miles of artificial drainage (tile and field ditches), have significantly altered river flow regimes. Further, tile installations continue to increase by more than 25% over the past ten years. The resulting increased storm flow contributes to excess nutrients and sediment delivered to downstream systems while also increasing flood and drought risks and degrading habitat conditions throughout our river corridors. Despite these vast impacts, however, advanced agricultural water management remains overlooked. The integrated combination of in-field, edge-of-field, and edge-of-stream practices, which together can increase terrestrial water storage, has the potential to address a wide range of concerns related to soil health, sustainable agriculture, and watershed restoration.

- ***Explicitly evaluate how hydrologic connectivity between fields and waterways imposed by artificial drainage influences downstream water quality and habitat conditions.*** It is increasingly evident that relatively small areas of a watershed impose a disproportionate impact on regional waters and that these impacts occur when such source areas have direct hydrologic connections to regional waterways. It is essential to map these concentrated flow channels and characterize channel flow regimes (i.e., frequency, duration, magnitude, and timing of flow) that influence land-water connections.

- ***Promote research projects that explore how agricultural water management can enhance both soil and watershed health.*** To date, watershed management focuses primarily on surface water and benefits to downstream users. Few consider how hydrologic alterations to the near-surface ground- and surface-water interactions affect infield soil health and ecosystem services. Mapping (modeling) hydro-biogeochemical fluxes within agricultural fields across a gradient of hydrogeologic settings and testing these predictions are essential to addressing farmer concerns related to conservation practice performance and ultimately better managing watersheds to ensure food and water security and climate resiliency.

Conclusions

Experts convened from across the humid US agreed that **advanced agricultural water management remains an overlooked and urgent opportunity to address the interrelated goals of healthy soils and watershed restoration**. Expansive networks of open ditches and tile drainage have extended our waterways by incredible lengths. While agricultural drainage provides benefits, adverse impacts of these micro-waterways are likely also significant. The resulting loss of terrestrial water storage and increased storm flow have demonstrably increased risks of erosion, flooding, and water impairment, as well as susceptibility to drought during (lower) baseflow conditions. However, the broadscale drainage installations likely have imposed an even more pernicious yet overlooked threat to the long-term sustainability of farm operations. The aggressive redistribution of soil moisture likely has increased organic matter decomposition and greenhouse gas emissions while reducing soil organic matter and enhancing nutrient release, likely contributing significantly to the more than 50 to 70% of soil organic carbon loss and chronic soil degradation across our agricultural systems. Thus, **the adoption of integrated conservation practices, including stacked combinations of controlled drainage, edge-of-field filter practices, and edge-of-stream water storage and water quality practices, could have significant on-site benefits to farmers as benefits to downstream users**. Despite the solid conceptual basis and empirical evidence to suggest these linkages, however, the effects of water management on soil health remain largely understudied. Advancing our understanding of how agricultural water management can control soil moisture regimes across geographies is essential to providing adequate technical support to advance soil health and watershed restoration under shifting weather patterns. Drainage practices must evolve to balance water retention, sustain healthy soil ecosystems, protect regional water supplies, and enhance climate resiliency.

Literature Cited

Ali, G. and C. English, 2019. Phytoplankton Blooms in Lake Winnipeg Linked to Selective Water-Gatekeeper Connectivity. Scientific Reports 9:1–10.

Blann, K.L., J.L. Anderson, G.R. Sands, and B. Vondracek, 2009. Effects of Agricultural Drainage on Aquatic Ecosystems: A Review. Critical Reviews in Environmental Science and Technology 39:909–1001.

Böhlke, J.K., 2002. Groundwater Recharge and Agricultural Contamination. Hydrogeology Journal 10:153–179.

Borch, T., R. Kretzschmar, A. Skappler, P. Van Cappellen, M. Ginder-Vogel, A. Voegelin, and K. Campbell, 2010. Biogeochemical Redox Processes and Their Impact on Contaminant Dynamics. Environmental Science and Technology 44:15–23.

Bouwman, A.F., A.H.W. Beusen, J. Griffioen, J.W. Van Groenigen, M.M. Hefting, O. Oenema, P.J.T.M. Van Puijenbroek, S. Seitzinger, C.P. Slomp, and E. Stehfest, 2013. Global Trends and Uncertainties in Terrestrial Denitrification and N2O Emissions. Philosophical Transactions of the Royal Society B: Biological Sciences 368. doi:10.1098/rstb.2013.0112.

Brantley, S.L., R.A. Dibiase, T.A. Russo, Y. Shi, H. Lin, K.J. Davis, M. Kaye, L. Hill, J. Kaye, D.M. Eissenstat, B. Hoagland, A.L. Dere, A.L. Neal, K.M. Brubaker, and D.K. Arthur, 2016. Designing a Suite of Measurements to Understand the Critical Zone. Earth Surface Dynamics 4:211–235.

Bricker, O.P., W.L. Newell, and N.S. Simon, 2004. Bog Iron Formation in the Nassawango Creek Watershed, Maryland, USA. Geo-Environment: Monitoring and Remedation of the Geological Environment IX:13–23.

Brinson, M.M., 1993. Changes in the Functioning of Wetlands along Environmental Gradients. Wetlands 13:65–74.

Bryant, R.B., A. Baldwin, B. Cahall, L.E. Christianson, D.B. Jaynes, C. Penn, and S. Schwartz, 2019. Best Management Practices for Agricultural Ditch Management in the Phase 6 Chesapeake Bay Watershed Model.

Buchanan, B.P., K. Falbo, R.L. Schneider, Z.M. Easton, and M.T. Walter, 2013. Hydrological Impact of Roadside Ditches in an Agricultural Watershed in Central New York: Implications for Non-Point Source Pollutant Transport. Hydrological Processes 27:2422–2437.

Bullerjahn, G.S., R.M. McKay, T.W. Davis, D.B. Baker, G.L. Boyer, L. V. D'Anglada, G.J. Doucette, J.C. Ho, E.G. Irwin, C.L. Kling, R.M. Kudela, R. Kurmayer, A.M. Michalak, J.D. Ortiz, T.G. Otten, H.W. Paerl, B. Qin, B.L. Sohngen, R.P. Stumpf, P.M. Visser, and S.W. Wilhelm, 2016. Global Solutions to Regional Problems: Collecting Global Expertise to Address the Problem of Harmful Cyanobacterial Blooms. A Lake Erie Case Study. Harmful Algae 54:223–238.

Burt, T. P., McDonnell, J.J., 2015. Whither Field Hydrology? The Need for Discovery Science and Outrageous Hydrological Hypotheses. Water Resources Research 51:5919–5928.

Castellano, M.J., S. V. Archontoulis, M.J. Helmers, H.J. Poffenbarger, and J. Six, 2019. Sustainable Intensification of Agricultural Drainage. Nature Sustainability 2019 2:10 2:914–921.

Christianson, R., L. Christianson, C. Wong, M. Helmers, G. McIsaac, D. Mulla, and M. McDonald, 2018. Beyond the Nutrient Strategies: Common Ground to Accelerate Agricultural Water Quality Improvement in the Upper Midwest. Journal of Environmental Management 206:1072–1080.

Christianson, L.E., J.R. Frankenberger, C. Hay, M.J. Helmers, and G.R. Sands, 2016. Ten Ways to Reduce Nitrogen Loads from Drained Cropland in the Midwest. doi:10.1057/978-1-349-95943-3_903.

Clague, J.C., R. Stenger, and U. Morgenstern, 2019. The Influence of Unsaturated Zone Drainage Status on Denitrification and the Redox Succession in Shallow Groundwater. Science of the Total Environment 660:1232–1244.

Crézé, C.M. and C.A. Madramootoo, 2019. Water Table Management and Fertilizer Application Impacts on CO2, N2O and CH4 Fluxes in a Corn Agro-Ecosystem. Nature Scientific Reports 9:1–13.

Delbecq, B.A., J.P. Brown, R.J.G.M. Florax, E.J. Kladivko, A.P. Nistor, and J.M. Lowenberg-DeBoer, 2012. The Impact of Drainage Water Management Technology on Corn Yields. Agronomy Journal 104:1100–1109.

Dring, C., J.F. Devlin, G. Boag, M.D. Sunohara, J. Fitzgibbon, E. Topp, and D.R. Lapen, 2016. Incentives and Disincentives Identified by Producers and Drainage Contractors/Experts on the Adoption of Controlled Tile Drainage in Eastern Ontario, Canada. Water Quality Research Journal of Canada 51:1–16.

Fan, Y., H. Li, and G. Miguez-Macho, 2013. Global Patterns of Groundwater Table Depth. Science 339:940–943.

Fan, Y., G. Miguez-Macho, E.G. Jobbágy, R.B. Jackson, and C. Otero-Casal, 2017. Hydrologic Regulation of Plant Rooting Depth. Proceedings of the National Academy of Sciences 114:10572–10577.

Fan, Y., G. Miguez-Macho, C.P. Weaver, R. Walko, and A. Robock, 2007. Incorporating Water Table Dynamics in Climate Modeling: 1. Water Table Observations and Equilibrium Water Table Simulations. Journal of Geophysical Research Atmospheres 112:1–17.

Hayhoe, K., D.. Wuebbles, D.R. Easterling, D.W. Fahey, S. Doherty, J. Kossin, W. Sweet, R. Vose, and M. Wehner, 2018. Our Changing Climate. D. R. Reidmiller, C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, and B. C. Stewart (Editors). Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. U.S. Global Change Research Program, Washington, DC, USA, pp. 72–144.

Johnston, C.A., J.B. Zedler, M.G. Tulbure, C.B. Frieswyk, B.L. Bedford, and L. Vaccaro, 2009. A Unifying Approach for Evaluating the Condition of Wetland Plant Communities and Identifying Related Stressors. Ecological Applications 19:1739–1757.

Jungkunst, H.F. and S. Fiedler, 2007. Latitudinal Differentiated Water Table Control of Carbon Dioxide, Methane and Nitrous Oxide Fluxes from Hydromorphic Soils: Feedbacks to Climate Change. Global Change Biology 13:2668–2683.

King, K.W., M.R. Williams, M.L. Macrae, N.R. Fausey, J. Frankenberger, D.R. Smith, P.J.A. Kleinman, and L.C. Brown, 2015. Phosphorus Transport in Agricultural Subsurface Drainage: A Review. Journal of Environment Quality 44:467.

Kleinman, P.J.A., R.M. Fanelli, R.M. Hirsch, A.R. Buda, Z.M. Easton, L.A. Wainger, C. Brosch, M. Lowenfish, A.S. Collick, A. Shirmohammadi, K. Boomer, J.A. Hubbart, R.B. Bryant, and G.W. Shenk, 2019. Phosphorus and the Chesapeake Bay: Lingering Issues and Emerging Concerns for Agriculture. doi:10.2134/jeq2019.03.0112.

Lal, R., 2016. Soil Health and Carbon Management. Food and Energy Security 5:212–222.

Moyano, F.E., N. Vasilyeva, L. Bouckaert, F. Cook, J. Craine, J. Curiel Yuste, A. Don, D. Epron, P. Formanek, A. Franzluebbers, U. Ilstedt, T. Kätterer, V. Orchard, M. Reichstein, A. Rey, L. Ruamps, J.A. Subke, I.K. Thomsen, and C. Chenu, 2012. The Moisture Response of Soil Heterotrophic Respiration: Interaction with Soil Properties. Biogeosciences 9:1173–1182.

Needelman, B.A., P.J.A. Kleinman, and A.L. Allen, 2007. Improved Management of Agricultural Drainage Ditches for Water Quality Protection : An Overview. Journal of Soil and Water Conservation 62:171–178.

Richardson, J.L. and M. Vepraskas, 2001. Wetland Soils. doi:10.1007/s00572-006-0064-7.

Rodriguez-Iturbe, I., P. D'Odorico, F. Laio, L. Ridolfi, and S. Tamea, 2007. Challenges in Humid Land Ecohydrology: Interactions of Water Table and Unsaturated Zone with Climate, Soil, and Vegetation. Water Resources Research 43:1–5.

Rosgen, D.L., 1994. A Classification of Natural Rivers. Catena 22:169–199.

Sanderman, J., T. Hengl, and G.J. Fiske, 2018. Erratum: Soil Carbon Debt of 12,000 Years of Human Land Use (Proc Natl Acad Sci USA (2018)114 (9575–9580) DOI: 10.1073/Pnas.1706103114). Proceedings of the

National Academy of Sciences of the United States of America 115:E1700.

Schilling, K.E., M.K. Jha, Y.-K. Zhang, P.W. Gassman, and C.F. Wolter, 2008. Impact of Land Use and Land Cover Change on the Water Balance of a Large Agricultural Watershed: Historical Effects and Future Directions. Water Resources Research 44:1–12.

Smith, E., T. Gillette, K. Blann, M. Coburn, B. Hoppie, and S. Rhees, 2018. Drain Tiles and Groundwater Resources: Understanding the Relations.

Speir, S.L., J.L. Tank, and U.H. Mahl, 2020. Quantifying Denitrification Following Floodplain Restoration via the Two-Stage Ditch in an Agricultural Watershed. Ecological Engineering 155:105945.

Stewart, R.D., J. Jian, A.J. Gyawali, W.E. Thomason, B.D. Badgley, M.S. Reiter, and M.S. Strickland, 2018. What We Talk about When We Talk about Soil Health. Agricultural & Environmental Letters 3:1–5.

Strock, J.S., 2018. Drainage Requirements to Maintain Soil Health. D. Reicosky (Editor). Managing Soil Health for Sustainable Agriculture Volume 2. Burleigh Dodds Science Publishing, Cambridge, UK, p. . doi:10.1201/9781351114585.

Strock, J.S., P.J.A. Kleinman, K.W. King, and J.A. Delgado, 2010. Drainage Water Management for Water Quality Protection. Journal of Soil and Water Conservation 65:131–136.

Suriyavirun, N., A.H. Krichels, A.D. Kent, and W.H. Yang, 2019. Microtopographic Differences in Soil Properties and Microbial Community Composition at the Field Scale. Soil Biology and Biochemistry 131:71–80.

Sweeney, B.W. and J.D. Newbold, 2014. Streamside Forest Buffer Width Needed to Protect Stream Water Quality, Habitat, and Organisms: A Literature Review. Journal of the American Water Resources Association 50:560–584.

Tomer, M.D., S.A. Porter, K.M.B. Boomer, D.E. James, J.A. Kostel, M.J. Helmers, T.M. Isenhart, and E. McLellan, 2015. Agricultural Conservation Planning Framework: 1. Developing Multipractice Watershed Planning Scenarios and Assessing Nutrient Reduction Potential. Journal of Environment Quality 44:754.

Vereecken, H., J.A. Huisman, H.J.H. Franssen, N. Bruggemann, H.R. Bogena, S. Kollet, M. Javaux, J. van der Kruk, and J. Vanderborght, 2015. Soil Hydrology: Recent Methodological Advances, Challenges, and Perspectives. Water Resources Research 10.1002/20:2616–2633.

Winter, T.C., 1999. Relation of Streams, Lakes, and Wetlands to Groundwater Flow Systems. Hydrogeology Journal 7:28–45.

Wohl, E., K.B. Lininger, and J. Baron, 2017. Anthropocene Land before Water : The Relative Temporal Sequence of Human Alteration of Freshwater Ecosystems in the Conterminous United States. Biochemical Pharmacology 18:27–46.

Zedler, J.B., 2003. Wetlands at Your Service: Reducing Impacts of Agriculture at the Watershed Scale. Frontiers in Ecology and the Environment 1:65–72.

Zipper, S.C., M.E. Soylu, E.G. Booth, and S.P. Loheide II, 2015. Untangling the Effects of Shallow Groundwater and Soil Texture as Drivers of Subfield-Scale Yield Variability. Water Resources Research 51:6338–6358.

Appendix A: Workshop Agenda

Linking Soil and Watershed Health to In-field and Edge-of-Field Water Management

January 23-24, 2020

Erickson Alumni Center, West Virginia University

Rationale: Despite mounting urgency to promote regenerative agriculture and protect regional waters, research in field hydrology has declined; and linkages between agricultural water management and its effect on soil health, water supply, and regional water quality remain uncertain. Soil scientists increasingly understand ties between crop yields, soil carbon content, microbiota health, and soil moisture based on experimental plot studies, but they have had limited opportunity to explore how landscape setting and artificial drainage influence these interactions. At the same time, there is increasing awareness regarding impacts of artificial drainage on water supply, flood risk, and riverine water quality. Less is known, however, about how in-field and edge-of-field water management affects these broader concerns through deleterious effects to soil health. Shallow groundwater dynamics may impose significant constraints on biogeochemical processes within the soil-plant biome and the fate and transport of agrochemicals to downstream waters, suggesting that water table management presents an overlooked opportunity to meet multiple stakeholder concerns. *This forum will convene technical experts in agronomy, soil science, hydrology, and agricultural engineering to explore how in-field and edge-of-field water management can advance regenerative agriculture and watershed health*.

Key discussion questions:

- Is there need and capacity for "Precision Drainage"?
- What (and where) are most promising opportunities to promote soil and watershed health?
- Likelihood of creating a win-win: Can shallow groundwater management enhance soil and watershed health, help tackle climate change, AND maximize crop yields?
- What stakeholder concerns might influence the adoption of advanced water management best management practices?

Workshop Objectives:

- Facilitate cross-disciplinary discussions among researchers and field experts committed to advancing regenerative agriculture and water security.
- Identify critical information gaps that limit capacity to provide water management guidance across diverse landscapes and under changing climate conditions.
- Spark collaborations to address critical information gaps.

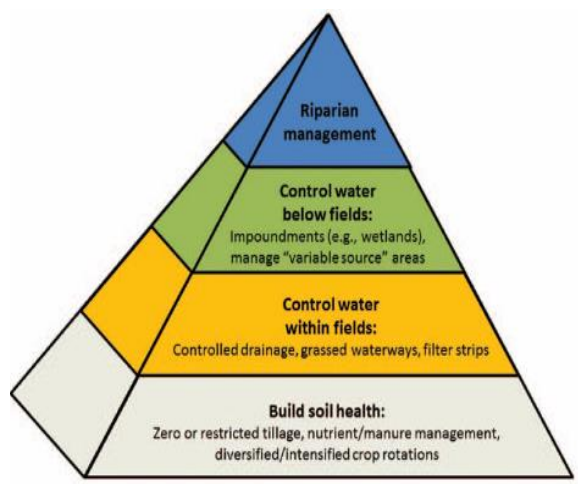

Figure 1**. From Tomer et al 2015: "Conservation practices in a watershed, conceptualized as a pyramid. Healthy agricultural soils will improve the effectiveness of practices placed within fields, below fields, and in riparian zones."* ***Soil health should form the base of watershed management. Understanding linkages across different spatial scales, from local fields to regional river systems, is critical to advancing soil health and watershed protection

Linking Soil and Watershed Health to In-field and Edge-of-Field Water Management

DAY 1:

8:30 Pre-Meeting Breakfast Mixer *(optional)*

9:30 Introductions and Overview *Kathy Boomer (FFAR), Sally Rockey (FFAR)*

10:00 Plenaries:
1) Overview of current research challenges in drainage management *Chandra Madramootoo (McGill);*
2) Soil health from a wetland biogeochemist's perspective *Chris Craft (Indiana University)*

11:20 Break

11:30 PANEL I - Soil Heath State of the Science and Understanding
What is our current understanding of soil health, and what are current research priorities?
Facilitator: Matt Erhardt (Stroud Research Center) Speakers: Rattan Lal (Ohio State), Ken Staver (University of Maryland), and Mark Tomer (USDA-ARS Ames, IA)

12:30 LUNCH (provided)

1:30 PANEL II - Soil Health, Soil Physics, and Hydrology in the Vadose Zone
How do vadose zone hydrodynamics influence soil moisture, biogeochemical processes, and microbial functions affecting soil health, nutrient cycling, and plant growth and what are the opportunities and challenges to model these relationships and interactions in a changing climate? How are biological processes related to soil health being characterized and how might these indicators vary based on hydrodynamic conditions across the landscape? How does agricultural management impact the soil environment in the vadose zone to influence nutrient use efficiency and other soil characteristics?
Facilitator: Amy Collick (University Maryland Eastern Shore) Speakers: Ryan Stewart (Virginia Tech), Brian Badgley (Virginia Tech), Michael Castellano (Iowa State University), Sotirios Archontoulis (Iowa State University), and Ray Bryant (USDA-ARS, State College, PA)

3:00 BREAK

3:30 PANEL III – Impacts of Drainage Water on In-field Soil Conditions and Watershed Hydrology. *How has field water management influenced local water table dynamics and saturated flow, as well as hydrologic connectivity throughout a watershed? How does location and climate conditions affect interactions between water table management and field or watershed conditions?*
Facilitator: Amy Jacobs (The Nature Conservancy) Speakers: Eileen Kladivko (Purdue University), Keith Schilling (University of Iowa), Laura Johnson (Heidelberg University), and Kathy Boomer (FFAR)

4:45 Day's Wrap-Up and Preview for Day 2

5:00 – 7:30

- Reception -

Linking Soil and Watershed Health to In-field and Edge-of-Field Water Management

DAY 2:

7:30 Breakfast Mixer

8:00 Introduction to Day 2 *(Kathy Boomer, FFAR)*

8:05 Plenary and Discussion: **Agronomy-Watershed linkages, advancing our understanding of where management action has the highest potential to reduce ecosystem and human risks through innovative research**. *Donald Rosenberry (USGS, Lakewood, CO)*

9:00 PANEL IV: Innovative Drainage Practices to Manage Shallow Water Tables. *What innovative practices have emerged to manage the water table in artificially drained land? How effective are they at reducing nutrient loads and improving crop yields? How does raising the water table influence soil biogeochemistry and soil health? How can we address the complex interactions between shallow water tables and soil health? Facilitator: Jason Hubbart (West Virginia University) Speakers: Jane Frankenberger (Purdue University), Richard Cook (University of Illinois), François Birgand (North Carolina State), and Jeff Strock (University of Minnesota)*

10:15 BREAK

10:30 PANEL V: Understanding the Broader Range of Concerns Related to Drainage Water Management *Facilitator: Amy Jacobs (TNC) Speakers: Steve Mirsky (USDA ARS, Beltsville MD), Samual Zipper (University of Kansas), Chandra Madramootoo (McGill University), and Genevieve Ali (University of Guelph).*

12:00 LUNCH (provided)

12:30 PANEL VI: Bridging the Sessions: Interactive Discussion to reflect upon the Need and Opportunities to Advance Field Water Management for Soil Health and Watershed Restoration. *Facilitator: Kathy Boomer (FFAR); Panel Members: Mark Tomer (USDA-ARS), Paul Wolfe (Walton Family Foundation), and Tom Bruulsema (IPNI, Canada)*

1:45 Workshop Summary, Outline of Next Steps

2:00 Adjourn

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Chesapeake Bay Program

Steering Committee: *Kathy Boomer (FFAR), Chris Brosch (DE Department of Agriculture), Meg Cole (STAC CRC), Amy Collick (UMES); Matt Erhardt (Stroud Research Center), Jane Frankenberger (Purdue University), Annabelle Harvey (STAC CRC), Jason Hubbart (WVU); Amy Jacobs (TNC), and Lindsay Thompson (Executive Director of the MD Association of Soil Conservation Districts, Maryland Grain Producers).*

Appendix B: Workshop Participants

Name	Affiliation	Email
Debbie Absher	Sussex Conservation District	debbie.absher@de.nacdnet.net
James Adkins	University of Delaware	adkins@udel.edu
Tom Basden	WVU	TJBasden@mail.wvu.edu
Jason Beard	USDA	jared.beard@usda.gov
Isabella Bertani	CBP	ibertani@chesapeakebay.net
Gopal Bhatt	CBP	gopal.bhatt@psu.edu
Lisa Blazure	Stroud Water Research Center	lblazure@stroudcenter.org
Maria Bowman	Soil Health Partnership	soilhealth@ncga.com
Tom Bruulsema	IPNI Canada	tom.bruulsema@ipni.net
Peter Claggett	USGS	pclaggett@usgs.gov
Megan Cole	CRC	colem@chesapeake.org
Loretta Collins	CBP	lcollins@chesapeakebay.net
Mark Dubin	CBP	mdubin06@umd.edu
Paul Duncan	Anuvia Plant Nutrients	pduncan@anuvianutrients.com
Lisa Duriancik	NRCS, Beltsville	lisa.duriancik@usda.gov
Alex Echols	Cambell Foundation	aechols@campbellfoundation.org
Annabelle Harvey	CRC	harveya@chesapeake.org
Lauren Hershey	FFAR	lhershey@foundationfar.org
Cordelia Hiers	FFAR	chiers@foundationfar.org
Michael Jones	NRCS	michael.jones3@usda.gov
Elliott Kellner	WVU	elliott.kellner@mail.wvu.edu
David Kingsbury	NRCS	david.kingsbury@usda.gov
Alisha Mulkey	MDA	alisha.mulkey@maryland.gov
Christopher Neale	Daugherty Water for Food Global Institute (DWFI)	cneale@nebraska.edu
Jennifer Nelson	DE Assoc of Conservation Districts	jen.nelson@resourcesmartllc.com
Will Osterholz	ARS - Columbus	will.osterholz@ars.usda.gov
Diane Oviedo	Stroud Center	doviedo@stroudcenter.org
Chas Remley	USDA Kansas	chad.remley@usda.gov
Gary Shenk	CBP	gshenk@chesapeakebay.net
Jan Surface	USDA	jan.surface@usda.gov
Allison Thomson	Field to Market	athomson@fieldtomarket.org
Kristin Veum	ARS - Columbus	Kristen.Veum@ars.usda.gov
Paul Wolfe	Walton Family Foundation	pwolfe@wffmail.com
Isaac Wolford	NRCS	isaac.wolford@usda.gov

Appendix C: Speaker Abstracts

Lal, Rattan (The Ohio State University)

Soil Health and Its Management

The term soil quality is related to soil functions, or its capacity for provisioning of specific ecosystem services. In comparison, the term soil health refers to soil as a finite and dynamic living resource. As a living entity, soil health depends on activity and species diversity of fauna and flora, which in a healthy soil may weigh about 5 Mg/ha (metric ton= 1000 kg). Consequently, the health of soil, plants, animals, people and the ecosystem is inter-connected. Objectives and strategies of managing soil health change with the change in demands, aspirations, lifestyle and the societal values of each generation. Soil organic matter (SOM composing of ~50% of organic carbon), its quantity and quality, is a strong determinant of soil health through its effects on soil physical, chemical, biological and ecological properties, and interaction among them. There may be a threshold range of 3.5% to 4.5% of SOM content for temperate and 2.0 to 2.5% for tropical regions. The threshold value of SOM content depends on climate, clay content and mineralogy, land use and management. In addition to SOM content and relative proportion of diverse fractions (i.e., light, heavy), other indicators of soil health are related to soil properties (i.e. bulk density, texture, structure, water retention and transmission, pH, CEC, nutrient reserves, microbial biomass carbon, soil respiration). SOM content affects soil moisture regime and especially the plant available water capacity. Soils severely depleted of their SOM content (<0.5%) are prone to the drought/flood syndrome, have low agronomic productivity, and low use efficiency of inputs (i.e., fertilizers, water). Being the source of energy for soil fauna, SOM affects soil health by impacting soil biodiversity. Indeed, soil biota is the bioengine of the earth. Land use and management practices that can enhance soil health of agroecosystems include the use of improved plant/animal varieties and species characterized by high productivity and plants of a deep root system, conservation agriculture comprising of residue mulch and cover cropping along with complex rotations and integrated nutrient management, integration of crops with trees and livestock, and discriminate use of fertilizers and water as and when needed. The strategy is to restore and sustain SOM content to the threshold range that also creates disease suppressive soils. Soil health affects economic development through its impact on climate (mitigation, adaptation, stabilization), food (quantity, quality, safety), biodiversity (above and below ground, activity) and water resources (quality, quantity, renewability). Soil health also determines world peace and political stability through food and nutritional security, economic prosperity, and human wellbeing. Restoration and sustainable management of soil health is also essential to advancing some of the Sustainable Development Goals (SDGs) or the Agenda 2030 of the United Nations. SDGs specifically dependent on soil health are #1 (No Poverty), #2 (Zero Hunger), #6 (Clean Water and Sanitation), #13 (Climate Action) and #15 (Life on Land). The basic strategy of managing and sustaining soil health is of "producing more from less." Rather than expanding the land area under agriculture to meet the demands of growing and increasingly affluent world population, restoration of soil health can save land, water, and other natural resources for nature conservancy. Restoring and sustaining soil health is land-saving strategy.

Craft, Christopher (Indiana University)

Soil Health and Soil Quality: A Wetland Ecologist's Perspective

Wetland soils are characterized by periodic to continuous inundation or saturation that produce physical, chemical and nutritional properties that differ from terrestrial soils. Inundation and saturation dramatically slow decomposition of soil organic matter (SOM), promoting its accumulation and enrichment. Increased soil organic matter improves physical properties by increasing porosity, with resultant increases in water holding capacity, and air and water movement. SOM improves chemical properties by increasing cation exchange capacity that retains the essential elements, calcium, magnesium and potassium and it enriches soil fertility by building the nitrogen capital of the soil. SOM also enhances biological activity, from increased microbial activity to greater numbers of nematodes and earthworms. Inundation and saturation also promote a number of microbially-driven reducing reactions that do not occur in terrestrial soils where oxygen is abundant and aerobic respiration predominates. Denitrification is especially important as it converts nitrate, a eutrophication-causing nutrient to gaseous N2 that is returned to the atmosphere where it belongs. Edge-of-field practices such as wetland and riparian restoration can ameliorate eutrophication of downstream waters through processes such as denitrification, sedimentation and sorption of phosphorus, another nutrient that, in excess, can contribute to eutrophication. Because of its large edge area ratio, restoration of riparian areas is particularly effective for intercepting nutrients from agricultural fields before it enters aquatic ecosystems downstream. In-field water table management by maintaining water tables closer to the soil surface can improve soil by building organic matter and nitrogen while enhancing denitrification. Together, maintaining moist soils and building SOM can enhance soil health while reducing nutrient loads to vulnerable waters downstream.

Stewart, Ryan (Virginia Polytechnic Institute and State University)

Hydrologic Implications of Using Cover Crops to Build Soil Health

Soil health has emerged as an organizing concept for discussing effects of different management practices on soil properties and productivity. However, there still exists great uncertainty about to define and measure soil health. At the same time, changes in soil health have not been well linked to changes in hydrological processes such as overland flow, subsurface drainage and leaching, evapotranspiration and soil water storage, even as these interactions may change in landscapes with shallow water tables and active water table management. The research presented in this workshop presentation had three objectives: 1) identify soil health indicators that respond to cover crops over relatively short (1-3 year) timescales; 2) quantify how cover cropping affects the soil water balance across studies; and 3) assess whether water table depth influences soil health response to cover cropping. The work was based on a meta-analysis of soil health-related studies representing 350+ sites from across the globe and 5,900 unique data entries (compiled in a database called SoilHealthDB). The analyses presented here focused on identifying which and how frequently different soil health indicators were used, as well as the responsiveness of the indicators to cover crop usage. The responsiveness of individual indicators was then regressed against depth to permanent water table, with the latter data based on published global-scale models. The analysis revealed that of the 42 different soil health indicators reported in the peer-reviewed literature, only 13 changed by more than 10% over 1-3 years in response to cover crops. Three of the responsive terms represented hydrological processes, including infiltration (significant increase with cover crops in nearly all climates, soil types, and cropping systems), surface runoff (significant decrease in most climates and soil types), and subsurface drainage and leaching (significant decreases in all but monoculture soybean systems). Depth to permanent water table had significant positive correlations with cover crop-induced changes in several soil health indicators, including yield (greater yield response to cover crops in systems with deeper water tables), soil aggregation (greater increases in aggregate stability when using cover crops in deeper water table systems), and soil organic carbon (more carbon with cover crops in deeper water table soils). While these results need further exploration, they nonetheless point to the possibility that active water table management may be a way to improve soil health in certain cropping systems.

Schilling, Keith E. (Iowa Geological Survey, University of Iowa, Iowa City, Iowa)

Water Table Fluctuations in Tiled Glacial Landscapes

The US Midwest has been glaciated on numerous occasions during the last two million years, with the most recent glacial advance during Wisconsin Period occurring approximately 10,000 years ago. Recently glaciated (young) regions are dominated by areas of level terrain and poor surface drainage, whereas older glaciated regions that have been eroding for 500,000 years are dominated by hillslope terrain and dendritic surface water drainage patterns. Cropping intensity varies across the Midwest, but is much greater in the flatter, recently glaciated regions where the poor drainage has necessitated installation of widespread artificial drainage systems (tiles) to drain perennially or seasonally wet soils for crop production. Water tables in intensely tiled areas fluctuate according to seasonal climate patterns and increase in the spring with precipitation recharge and decrease in the mid-summer and fall due to less recharge and increased ET Water table depths in tiled areas often correspond to the tile depth of about 1 to 1.2 m below ground surface. Groundwater in tiled areas contributes to tile drainage flows and occasionally rises above the land surface and contributes to surface ponding. In contrast, water table levels in old, sloping landscapes are heavily dependent on landscape position. Water tables are deeper and exhibit greater seasonal fluctuation in upland landscape position compared to floodplain areas. More groundwater recharge occurs in floodplain areas compared to upland areas, and much less occurs in sideslope areas where surface runoff is greatest. Tile drainage in both old and young glacial terrain affects tile drainage patterns and groundwater travel times. In older glacial areas, tile drainage is often found in lowland drainageways following a dendritic patterns and groundwater travel times can be reduced by 50% with increased drainage intensity. In young glacial landscapes, tile drainage is often installed in patterns over entire fields, resulting in greatly reduced groundwater travel times. In one example from central Iowa, intense patterned tile drainage reduced the watershed-scale mean travel time to one year and the average groundwater flow length to about 20 m, the typical length of tile spacing in the basin.

Rosenberry, Donald (USGS, Denver, CO)

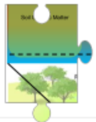
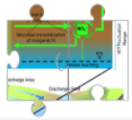
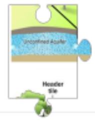
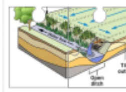
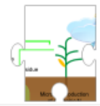
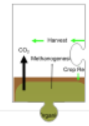
Potential hydrogeological controls on soil health and cropland productivity

Soil health refers to a carbon-rich, biologically diverse soil environment, which enhances crop growth and productivity. Recommended strategies to enhance soil health focus on “top down” practices including advanced tillage, crop and livestock rotations, and soil amendment schedules. Recommendations do not consider or address water management. Croplands require soil moisture that is ample but not excessive for maximum crop production. Many farmers install buried drainage pipe, commonly called tile drains, to remove excessive soil moisture and prevent waterlogging conditions that would otherwise wilt crops and substantially reduce yields. This management method works well during rainy periods or when the water table rises near the land surface , but is largely unrelated to hydrogeological processes. A “bottom up” management strategy that incorporates groundwater could be used to both increase yields and reduce release of nutrients to the surface-water drainage network. Spatial and temporal variability of groundwater recharge can either exacerbate waterlogging conditions, requiring a greater density of tile drains, or substantially reduce soil moisture when the water table lowers to well beyond the reach of plant roots. Increased understanding and consideration of processes related to groundwater recharge, flow, and the proximity of the water table to rooting depths could lead to better crop management and higher and more consistent yields. For example, turning off tile drains when not needed would allow greater recharge to underlying groundwater, which would allow the water table to rise and increase the duration of time when groundwater could provide soil moisture to crops via the capillary fringe and also increase groundwater storage that could be used during dry times. Alternately, creating a groundwater ridge along a surface-water drain could prevent sub-surface flow of water and nutrients from the croplands to adjacent or nearby streams or rivers, preserving water for use during dry periods and also reducing drainage of nutrient-laden groundwater into the surface-water network. Monitoring groundwater levels with shallow, inexpensive water-table wells installed in the field could be linked to automated valves installed in tile drains. When groundwater levels are high, tile drains could be programmed to automatically open, allowing excess water to drain from the field. When groundwater levels are lower than a programmed threshold, tile-drain valves could be automatically closed, allowing subsequent recharge events to infiltrate to the water table rather than being shunted out of the watershed. Determining the optimal water table regime to meet multiple objectives, including enhanced carbon-sequestration and improved water quality, as well as trafficability and crop yields, remains a critical challenge.

Zipper, Samuel C. (Kansas Geological Survey, University of Kansas)
Crop yield response to water table depth, soil texture, and weather variability

Water table depth (WTD), soil texture, and growing season weather conditions all play critical roles in determining agricultural yield; however, the interactions among these three variables have never been explored in a systematic way. Using a combination of field observations and biophysical modeling, we answer two questions: (1) under what conditions can a shallow water table provide a groundwater yield subsidy and/or penalty to corn production?; and (2) how do soil texture and growing season weather conditions influence the relationship between WTD and corn yield?. Subfield-scale yield patterns during a dry (2012) and wet (2013) growing season are used to identify sensitivity to weather. Areas of the field that are negatively impacted by wet growing seasons have the shallowest observed WTD (<1 m), while areas with consistently strong yield have intermediate WTD (1–3 m). Parts of the field that perform consistently poorly are characterized by deep WTD (>3 m) and coarse soil textures. Modeling results find that beneficial impacts of shallow groundwater are more common than negative impacts under the conditions studied, and that the optimum WTD is shallower in coarser soils. While groundwater yield subsidies have a higher frequency and magnitude in coarse-grained soils, the optimum WTD responds to growing season weather at a relatively constant rate across soil types. We conclude that soil texture defines a baseline upon which WTD and weather interact to determine overall yield. Our work has implications for water resource management, climate/land use change impacts on agricultural production, and precision agriculture.

Appendix D: Participant Prompts

	Soil Health 	Vadose Fluxes 	Field Hydrology 	Water Management 	Stakeholder Concerns 	Other Eco-Processes 
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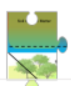
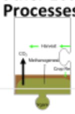
	Soil Health 	Vadose Fluxes 	Field Hydrology 	Water Management 	Stakeholder Concerns 	Other Eco-Processes 
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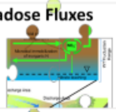
Vadose Fluxes 						
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