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Impacts of Soil Health Practices on Hydrologic Processes

The rich, deep color of this soil indicates exactly what healthy soil looks like. Use of a diverse blend of crops, grasses, and cover crops creates a protective blanket that feeds and nurtures the soil. USDA-NRCS photo by Catherine Ulitsky.

Introduction

Research interest in soil health has grown in popularity in the past decade as scientists and producers alike seek to determine the best methods of soil management for optimizing crop production, ecosystem function, and biodiversity. The USDA-NRCS (United States Department of Agriculture Natural Resources Conservation Service) defines soil health as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans." This includes the capacity of the soil to filter contaminants, cycle nutrients, provide physical support for infrastructure and habitats, and regulate water movement.

Many approaches have been suggested for quantifying soil health, and often those techniques rely on measurements of chemical (Bünemann et al. 2018), physical (Haruna et al. 2020), or biological (Fierer et al. 2021) soil properties, or in some instances a combination of those properties (Singer and Ewing 2012). A growing number of scientists have acknowledged the need for a more comprehensive, integrated, and quantifiable approach to measuring soil health (Rinot et al. 2019; Lehmann et al. 2020).

While many measurements of the impacts of soil health are somewhat new, soil and water conservation practices that enhance soil health have been recognized and promoted for decades. In agricultural systems, the primary methods of increasing soil health involve minimizing disturbance by using no-tillage or reduced-tillage, maximizing biodiversity of both macro- and micro-organisms, maximizing soil cover using cover crops or plant residues, and maximizing the amount of living roots within the soil (USDA-NRCS 2016; 2023).

Benefits of increasing soil health in agricultural systems can generally fall into three categories: (1) increased water infiltration and storage, (2) greater crop yields, resilience, and food security, and (3) reducing greenhouse gas emissions to lessen climate impacts of agriculture. Often when summaries of soil health

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are documented, emphasis is given to the second and third categories above, with little attention paid to changes in the larger hydrologic cycle resulting from the implementation of soil health practices. This paper seeks to address this knowledge gap, summarize pertinent literature regarding the impacts of soil health practices on different components of the hydrologic cycle, and provide clear evidence and guidelines for policy- and decision-makers regarding the impacts of soil health practices on the hydrologic cycle.

Soil Health Impacts on Water Quantity in the Soil-Water-Atmosphere Interface

The adoption of management practices that promote soil health, including the use of cover crops and no-tillage or low-tillage, can have a significant impact on the hydrology of agricultural soils. These impacts include greater infiltration (Stewart et al. 2018) and soil water storage (Hudson 1994), along with reduced runoff (Langdale et al. 1991) and erosion (Olson et al. 2014). When implemented at the watershed scale, such practices can drastically improve the quality of surface and groundwater supplies (Zimnicki et al. 2020).

Indicators often used to quantify soil health include soil organic matter (SOM) content, microbial activity, porosity, water stable aggregates, and water and nutrient use efficiency (Hatfield et al. 2017). Soil water availability is one of the primary determinants of crop productivity and profitability. Hudson (1994) performed one of the first comprehensive assessments using the Natural Resources Conservation Service (NRCS) soil survey database to show there was a positive linear relationship between SOM and water holding capacity, with the degree of impact of SOM dependent upon the soil texture class (Figure 1). This relationship is expected because SOM has a relatively high water retention capacity because of its typically low bulk density and its high porosity and water absorption capacity (Pignatello 1998). The positive relationship found between SOM and soil water holding capacity was not region-specific, as data from soils in Florida, Iowa, Wisconsin, Minnesota, and Kansas were used for the analysis, demonstrating the positive impacts of SOM incorporation across most of the food-producing regions of the United States.

However, in terms of water dynamics in the soil-plant-atmosphere continuum, the effect of soil health practices on the hydrologic cycle cannot be drawn with a simple linear relationship because of feedback among the practices that simultaneously affect both soil health and soil water dynamics. For example, infiltration has been shown to increase in soils with higher aggregate stability but can also increase as a result of no-tillage or strip-tillage operations or the use of cover crops, both practices which increase aggregate stability and incorporate surface residue cover that prevents incoming rainfall from directly impacting the soil surface. Thus, in many cases it can be difficult to disentangle the effects of implemented sol health practices on the soil water balance.

Water dynamics in the soil profile are affected by a combination of factors associated with soil health practices. For example, the presence of cover crops has been shown to increase the infiltration rate and reduce soil water evaporation which leads to more water being stored in the upper soil profile (Franzlubbers 2002; Govaerts et al. 2007). Soils that are tilled and left bare are subjected to direct impact by raindrops and high soil water evaporation rates (Sauer et al. 1996; Burgess et al. 2014). Water in the soil-plant-atmosphere continuum can be removed from the soil profile either by transpiration, where water is taken up via plant roots and evaporated from the leaf surface, or through evaporation, where water is lost from the soil surface or plant surfaces without ever moving through the plant. Water within the soil profile is

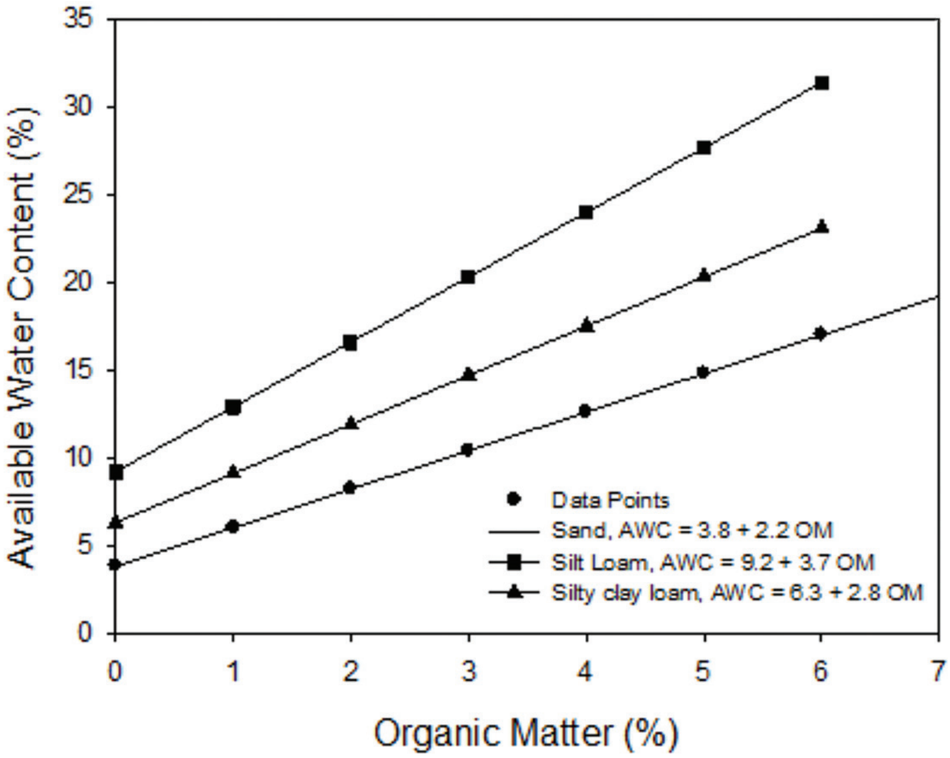

Figure 1. Available water content as a function of soil organic matter content. Values are based on linear relationships derived by Hudson (1994) based on measured data from soils of different textures. The equations used to estimate shown values are given in the figure legend.

more effectively removed by transpiration because roots extract water from the entire root zone while soil evaporation is typically confined only to the upper layer of the soil. Soil water evaporation, transport, and storage are influenced by the effects of soil health practices on soil water retention and storage, as well as soil structure.

Rainfall Impact

During rainfall, the energy of falling raindrops is transferred to the soil surface. The effect of rainfall intensity and the impact on soil stability, bulk density, and infiltration rate directly depends upon soil cover (Vaezi et al. 2017). For example, high amounts of cover protect the soil surface from raindrop impact, while bare soil is directly exposed to the energy of falling raindrops, which can detach soil particles from the bulk soil matrix and leave them susceptible to erosion. In addition to the destruction of soil structure by raindrop impact, rainwater can also penetrate the pore spaces within aggregates, destroying their structure from the inside out by increasing internal pore pressure (Wacha et al. 2018). The destruction of soil structure releases fine soil particles (i.e., clay) that begin to accumulate in pore spaces. The clogging of pore spaces restricts water flow (and air movement) through the soil column, prompting ponding and runoff conditions to develop (Hatfield et al. 2017). The detached soil particles are then carried by flowing water and redistributed downslope (Kinnell 2005). Management practices that promote soil health can directly affect the water dynamics of the soil by increasing the strength of soil aggregates, making them less susceptible to breakdown and erosion. A long-term study in the U.S. Midwest found surface aggregates (0–10 cm) under no-till management had 2.6 times more stability and 22% more soil organic carbon than conventional soils (Kumar et al. 2014).

Infiltration

Before water can be used by plants, stored in the soil profile, or transported to deeper depths it must enter, or infiltrate into, the soil. Infiltration rates are governed primarily by the texture and structure of the soil, the amount of water already in the soil, and the integrity of the pore spaces, which have been shown to be dependent on the size distribution and stability of aggregates within the soil profile. Typically, soil infiltration rates increase as sand content increases and as bulk density decreases (Basset et al. 2023). Aggregate stability and infiltration rates serve as indicators for retention and mobility of water and nutrients in the soil, and for the soil's suitability as a habitat for microorganisms (Doran 2002). Studies have shown that increasing SOM content improves both aggregate stability and infiltration rates (Karmi et al. 2012; Kumar et al. 2014; Lal 2016). In degraded soils, weak aggregate fractions collapse due to rainfall impact and begin to clog pore spaces and restrict infiltration. This results in highly unstable microclimatic conditions for soil microorganisms, which causes biological activity to plummet, further degrading soil health (Hatfield et al. 2017). Alternatively, soil aggregate stability has been reported to be more than 34% higher in no-till systems than in moldboard plow systems (Bottinelli et al. 2017). Thus, soil health practices have potential to enhance infiltration and soil microbial activity.

The influence of soil health practices on soil properties such as infiltration also has potential to impact surface water hydrology. Some evidence exists demonstrating that enhancing soil health minimizes variability in streamflow levels, potentially minimizing flood risks, because of the increased infiltration rates and longer time until the initiation of surface runoff (Hou et al. 2023). This moderation of rainfall runoff, especially during extreme precipitation events, has potential to mitigate flooding downstream.

Water Storage and Distribution

The soil water budget can be represented by a simple balance of inputs, losses, and storage (Figure 2). Soil water storage can greatly influence water, energy, and biogeochemical cycles, with implications for soil-gas exchanges, evaporation, plant water use, and photosynthesis rates (Seneviratne et al. 2010).

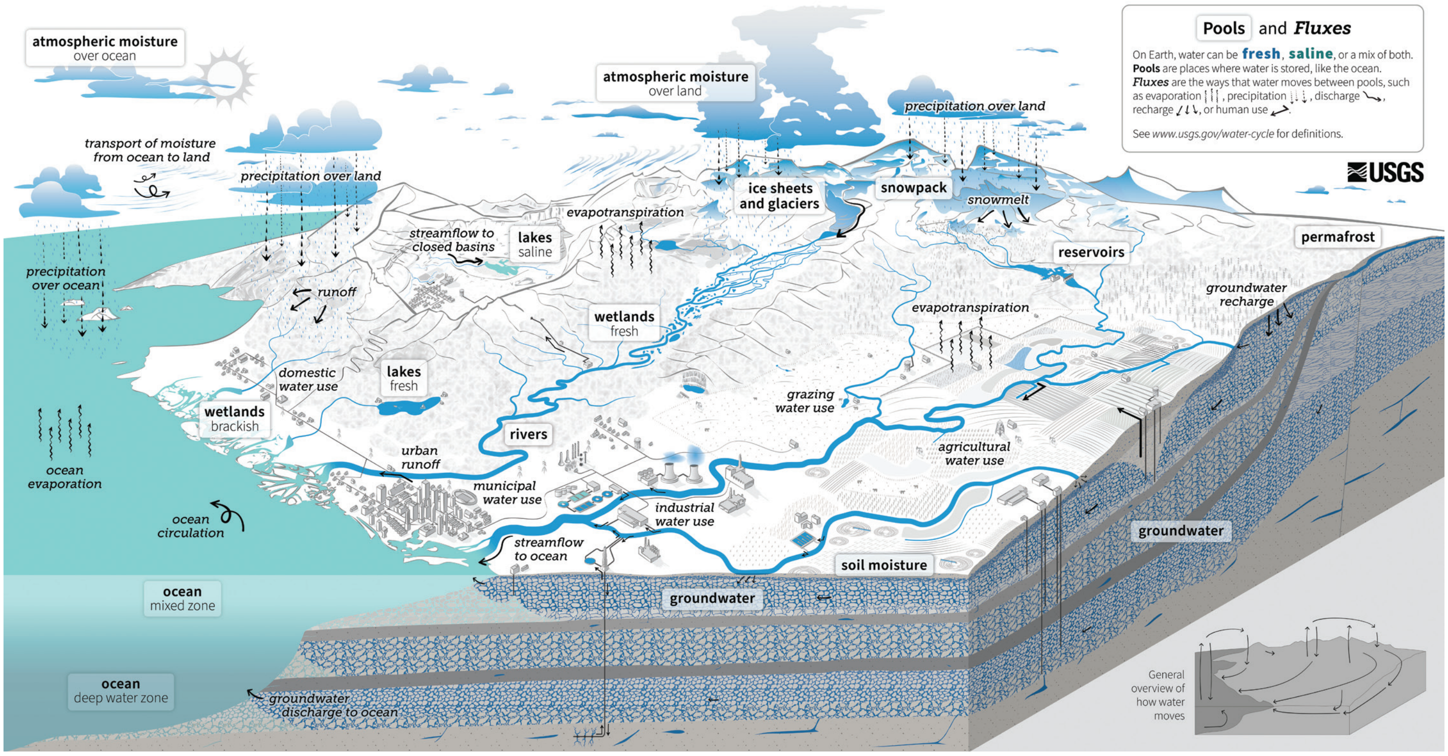

Figure 2. Earth's water cycle. Source: U.S. Geological Survey.

As mentioned previously, soil water storage is positively related to SOM content (Hudson 1994; Rawls et al. 2003; Figure 1) and an increase in infiltration rates will allow more water to penetrate into the soil volume with less runoff. Downward water movement through the soil profile will typically occur because of gravity if there are no restrictive layers. This movement of water will be enhanced when there are channels (e.g., macropores), often formed by burrowing insects or decayed plant roots, in the soil for water to move and carry solutes (Gish and Jury 1983). These macropores can aid in moving water to deeper soil depths but may also be responsible for a lack of water near the surface and decreased contaminant filtration. Recent research supports this long-standing observation on the effect of plant roots on water and solute redistribution in the soil profile (Hafner et al. 2020; Cai et al. 2022).

Groundwater Recharge

Groundwater systems are an important source of water globally and contribute to baseflow in streams, rivers, and lakes (Hughes et al. 2021). Groundwater recharge occurs when rainfall infiltrates into the soil and moves downward through various pore spaces and pathways to the water table (Scanlon et al. 2005). Recharge is promoted when the input of water exceeds water losses (e.g., pumping for irrigation, evapotranspiration, etc.) and the soil profile's storage capacity, similar to surface runoff occurring when rainfall inputs exceed the infiltration rate. Soil health practices have generally been shown to have a positive effect on the infiltration rate and soil water storage, though in some studies the opposite was true. For example, Lipiec and colleagues (2006) found that no-tillage plots had lower porosity (0–20 cm depth) and therefore a lower soil water storage capacity, as well as lower infiltration rates than plots undergoing conventional tillage. This was primarily attributed by the breaking up of soil structure by tillage, which resulted in a lower bulk density and higher porosity in the conventionally tilled fields.

Further, observed changes in soil aggregate stability and SOM content are typically limited to the uppermost layers of the soil (e.g., the top 20 cm or 8 inches) and may not have significant impacts on water storage or transport at deeper depths typically considered when studying groundwater recharge (So et al. 2009). Given that water must travel deep into the subsurface to reach groundwater reservoirs, the amount of time required to see measurable changes in groundwater recharge due to soil health practices is on the order of decades to centuries. Because of this, and the relatively recent development of soil health concepts, little research currently exists on this topic, and it is not clear whether increases in soil water content near the surface due to soil health practices lead to increases in groundwater recharge.

Soil Health and Soil Water Interactions

Improving soil health has generally been shown to have a positive impact on soil attributes that directly affect soil water dynamics. Increases in SOM generally increase soil water holding capacity and soil aggregate stability, but the effect on soil water cannot be examined without an understanding of the practices (e.g., reduced tillage, cover crops, crop residue management, or manure additions) that caused the change in soil health. Even in arid and semi-arid regions, when changes in SOM are often not observed, soil physical and hydraulic properties typically improve under no-tillage as compared to conventional tillage due to a decrease in mechanical disturbance (Benjamin et al. 2008). Additionally, an increased supply of roots from cover crops coupled with the absence of mechanized tillage can also improve soil water infiltration, storage, and use by the crop (Mobius-Clune et al. 2008; Lal 2016). The combination of conservation tillage and residue cover has also been shown to improve both crop yields and crop water use efficiency (Jin et al. 2009).

Surface Water and Groundwater Pollution by Agricultural Chemicals

Soils act as a reservoir of plant-essential nutrients and chemicals, and often the movement of those chemicals from the soil profile into the surrounding environment is a major concern. If not taken up by plants, nutrient and chemical transport can occur vertically through leaching into subsurface layers or horizontally through surface or subsurface runoff (Ghadiri and Rose 1991; Wyatt et al. 2019). Leaching is governed by the solubility of the chemical in water and the speed at which water moves through the soil profile (Palis et al 1990; Wyatt et al. 2019). Surface water pollution is related to the solubility of the chemical in water, the attachment (sorption) of the chemical to soil particles (Moorman et al. 1999), and the water flow (i.e., depth and velocity) and sediment (i.e., size and concentration) characteristics (Palis et al. 1990). These chemical transport processes occur primarily in association with precipitation events. Therefore, chemical transport fluctuates throughout the year based on management practices, plant water uptake, and climatic conditions. Management practices associated with improving soil health have been shown to improve infiltration rates and water retention in the soil profile, both of which directly impact water budgets and reduce runoff and erosion (Mobius-Clune et al. 2008; Wacha et al. 2022).

Surface Water Quality Impacts from Soil Health Practices

There is continued concern about the impacts of agricultural production on the siltation of ponds, lakes, and reservoirs and the reduced capacity of these water bodies to store water (Papanicolaou and Barkdoll 2011). As an example, DeNoyelles and Jakubauskas (2008) found after surveying reservoirs in Kansas that more than 40% of the capacity of some reservoirs had been lost due to sediment transport by erosion from upstream and its subsequent deposition in reservoirs. In this context, both soil particles themselves and the chemicals they carry with them (and release in surface water bodies) are considered to be water pollutants. In fact, soil eroded from the land surface and introduced into surface waterways is the number one pollutant of surface waters in the United States (US EPA 2023). The transport of soil particles and the chemicals they carry from agricultural fields poses a significant risk to surface water quality.

Soil health practices can minimize off-site soil and nutrient transport in a number of ways. Enhancing soil health can increase aggregate stability, infiltration, and soil water storage, reducing the amount of surface runoff and erosion from agricultural lands. Another effective method of reducing the likelihood of soil particle detachment and transport is increasing surface residue or growing cover crops to protect the soil surface from raindrop impact and erosion (Kinnell 2005). Reduction in the off-site transport of soil particles reduces the potential for surface water contamination from nutrients or chemicals that are attached to soil particles. For example, phosphorus is often attached to soil particles and the detachment and mobilization of these particles can lead to excessive nutrient levels in nearby streams, lakes, and rivers (Penn et al. 2014; Wyatt et al. 2019). Similarly, herbicides and pesticides attached to soil particles can be transported from agricultural fields to nearby water bodies during runoff events. A comprehensive 2006 water quality survey of 186 streams in the United States showed that pesticides or their degraded components, which indicate significant past and present pollution of these water sources, impacted all the tested water bodies (USGS 2006). A more recent study found that at least 50% of tested surface waters contained levels of pesticide capable of causing negative human or aquatic species health impacts (Stackpoole et al. 2021). The adoption of management practices that promote soil health can significantly reduce the potential for soil and contaminants to move offsite.

Groundwater Quality Impacts of Soil Health Practices

It has often been assumed that increasing the soil's infiltration rate can lead to increased leaching through the soil profile and potentially increase groundwater contamination (Pitt et al. 2023), though research has yet to confirm this assumption. Soil health practices can increase infiltration rates, modify the ability of the soil to retain water, and increase the water holding capacity near the soil surface. These practices are also linked to an increase in soil biological activity, which in turn increases nutrient cycling (Aslam et al. 1999; Lehman et al. 2015). The result is a decrease in soluble nutrients in the free water moving through the soil profile (Hatfield et al. 2017). Likewise, increased biological activity facilitates the breakdown of harmful chemicals in the soil to further decrease potential groundwater pollution. Observations of nitrate-nitrogen in subsurface drainage tile lines in fields under enhanced soil health practices showed nutrient levels that were less than 25% of those found in conventional tillage systems (Fredericks and Peterson, personal communication 2022). In other work, Bawa and colleagues (2021) observed that the combination of cover crops with no-till reduced nitrate leaching by approximately 20% because of the cover crop uptake of nitrogen and improved soil health. An increased supply of SOM can also improve water quality, alter nitrate availability to plants, and reduce nitrate leaching (Nolan and Hitt 2006). Overall, research shows that soil health practices have potential to positively impact the quality of water flowing to groundwater reservoirs.

Connecting Climate Change to Soil Health

Broadly, climate change refers to long-term shifts in temperatures and weather patterns (United Nations 2023). Many changes have occurred to the Earth's climate in the past, but recent climate change— characterized by the observed increase in global average temperature driven by human activities that have occurred since the Industrial Revolution— is more fast-paced and extreme than any seen in the past. Relative to the long-term average global temperature from 1951–1980, average global temperatures have increased by nearly 1.0 °C (1.8 °F) (Figure 3, NASA 2023). This increase in global average temperatures has a number of causes, including increasing greenhouse gas concentrations (such as carbon dioxide [CO_2] and methane [CH_4]) in Earth's atmosphere due to the extraction and burning of fossil fuels (such as coal, oil, and natural gas), wildfires, and natural processes like volcanic eruptions. By far, human sources of greenhouse gases are the largest contributor, increasing the amount of CO_2 in the atmosphere globally by 50% since the beginning of the Industrial Revolution in the 18th century (NASA 2023). This human-induced increase in CO_2 is greater than the natural increase observed at the end of the last ice age 20,000 years ago (Figure 4, NASA 2023), and its effects on Earth's hydrologic cycle are already being observed.

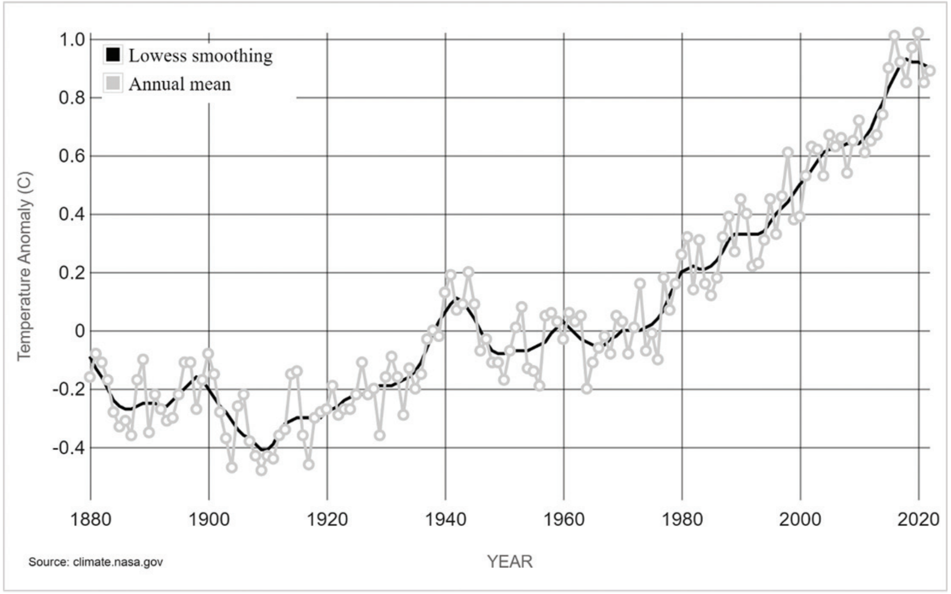

Figure 3. Annual mean global temperatures from 1880-2022. Gray line and markers indicate individual years, black line indicates smoothed trendline based on a five-year moving average. Source: NASA Goddard Institute for Space Studies.

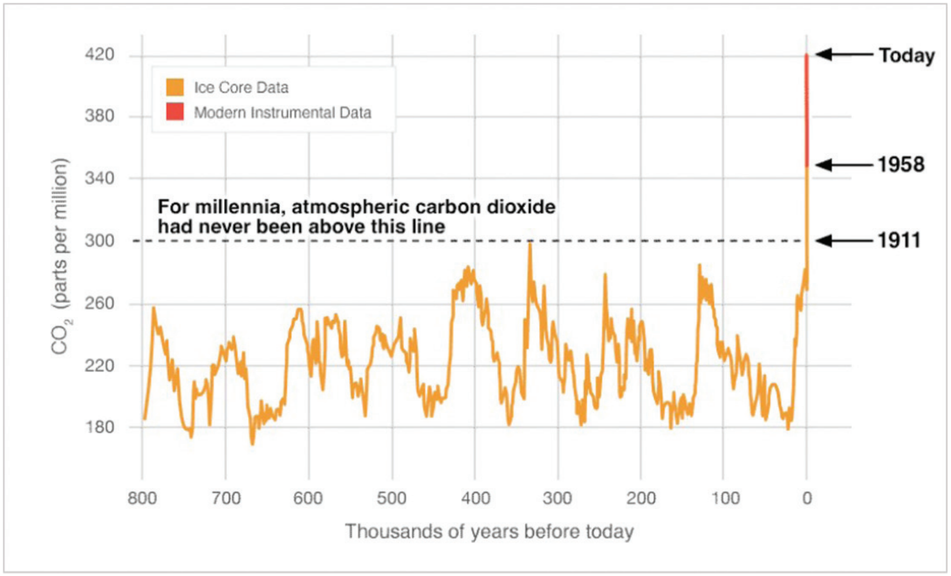

Figure 4. Estimated and measured CO_2 concentrations in Earth's atmosphere from 800,000 years ago to the present. Data before 1958 are estimated based on concentrations of atmospheric gases trapped in ice cores. Source: National Atmospheric and Oceanic Administration (NOAA).

Impacts of Climate Change on Hydrological Cycle

Climate change affects all components of the hydrological cycle. It has been shown to be increasing evapotranspiration (Liu et al. 2021), precipitation intensity and variability (Konapala et al. 2020), and surface runoff (Dai et al. 2018) while simultaneously decreasing soil water storage (Dai et al. 2018) and groundwater recharge (Al Atawneh et al. 2021). Increasing atmospheric temperatures are leading to increased water loss from the land surface via evapotranspiration, leading to less water availability in soils and surface water bodies. At the same time, a warmer atmosphere is able to hold a greater amount of water vapor, resulting in an increased intensity of precipitation events. Together, this results in more frequent and intense extreme events, including floods and droughts, with severe adverse effects on food production, the global economy, and human well-being. In fact, the number of extreme natural disasters in the United States is increasing (Figure 5), with subsequent increasing economic, ecologic, and societal consequences. Simply put, global climate change is increasing the occurrence of drought and decreasing soil

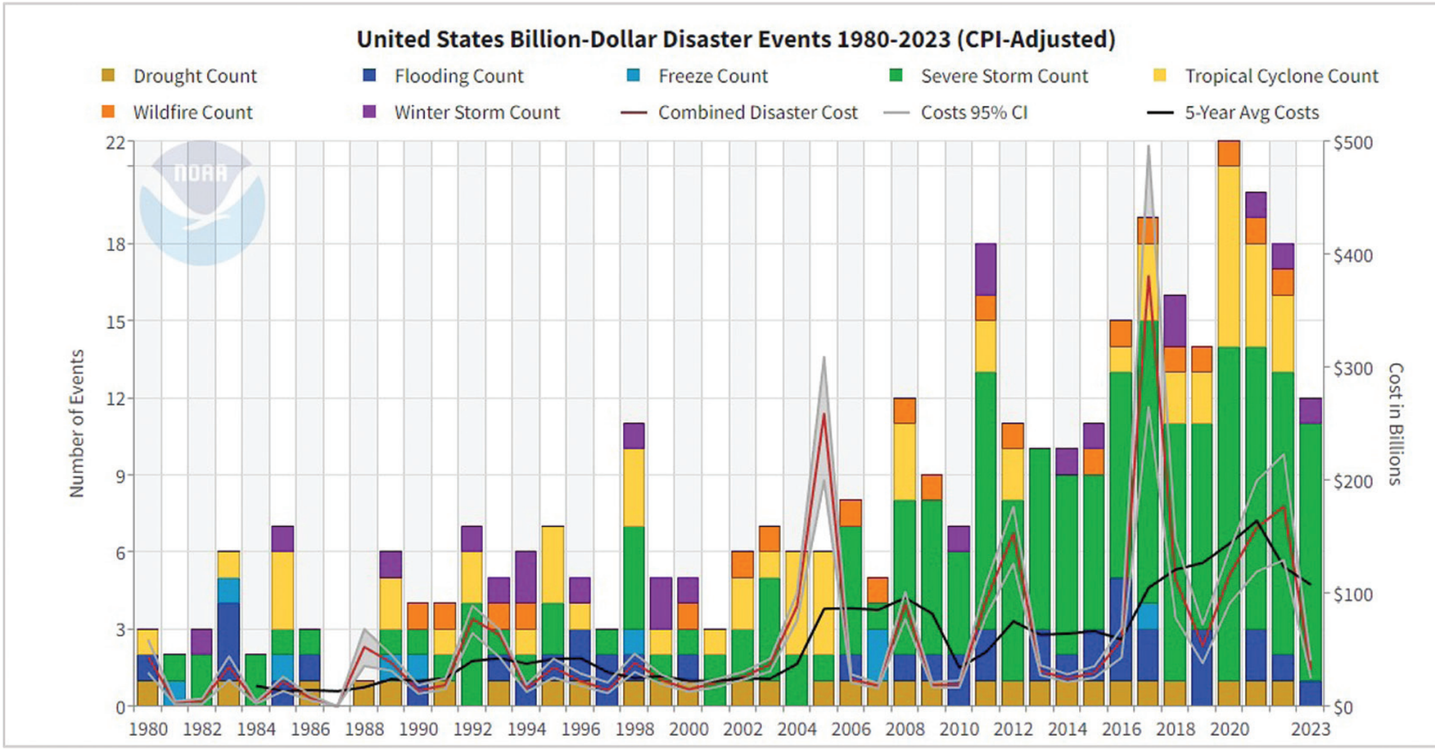

Figure 5. Number of billion-dollar natural disasters in the U.S. from 1980-2023. All values adjusted for inflation. Source: National Center for Environmental Information.

water storage in the root zone, which has negative implications for soil health and agricultural production.

Impacts of Climate Change on Agricultural Production

Soils are one of the largest reservoirs of fresh water on Earth, supporting ecosystems and food production globally. However, agricultural productivity is expected to be affected by increasing plant water use and evaporation from soil combined with more variable rainfall caused by climate change. Many areas globally may expect to see a decrease in agricultural productivity (Hussain et al. 2016; Schlenker and Roberts 2009), while other regions may see increases in productivity (Gregory and Marshall 2012; Potopova et al. 2017; Di Paola et al. 2018). Studies have indicated that yields of the world's three major crops—maize, wheat, and rice—are expected to decrease globally unless measures are taken to minimize climate change (Challinor et al. 2014). In the United States, it has been predicted that the resiliency of major crops will be reduced under future warming and that corn, soybean, and cotton yields will be reduced by 30–82%, depending on the severity of future warming (Schlenker and Roberts 2009; Ray et al. 2019). In addition to changes in water availability, expected threats to agricultural production due to climate change include increased pest pressure (Skendžić et al. 2021), increased occurrence of crop disease and frequency of outbreaks (Newbery et al. 2016; Velásquez et al. 2018), and increased heat stress for livestock (Lacetera 2018), among others. Global climate change poses a significant risk to future agricultural production.

In light of the potential threats of climate change to agricultural production, it is especially important to consider the potential positive impacts of soil health practices in mitigating these trends and preserving water in the soil. As mentioned previously, small increase in SOM content can enhance the soil's water storage capacity and minimize risks of agricultural drought while also improving the quality and quantity of food and strengthening other ecosystem services. For example, one acre-foot (0.12335 ha-m) of soil can hold an extra ~16,500 gallons (62,459.3 L) of plant available water for every 1% increase in soil organic matter (Gould 2015). For these reasons, restoration of SOM in degraded or depleted soils can improve the drought resiliency of both native (Zhao et al. 2023) and agricultural (Renwick et al. 2021) plant systems. Thus, it is increasingly important to incorporate soil health practices into agricultural management in light of climate change.

Role of Private Sector in Climate Change Adaptation and Mitigation

In addition to the actions of individual producers in implementing soil health practices, the private sector can play an important role in translating science of the hydrological cycle, soil health, and SOM dynamics into action by promoting nature-positive water use and soil health management practices, including carbon sequestration for adaptation to and mitigation of climate change. Payments for ecosystem services (e.g., clean water, water conservation, reducing runoff, and improving groundwater management) can promote the adoption of recommended management practices which conserve and enhance water resources and favorably moderate the hydrological cycle. This practice has been shown to have positive impacts on both ecosystems and social systems in Mexico, where beneficial land management activities such as controlling pests and promoting soil conservation increased by ~50% with payment (Alix-Garcia et al. 2018). The private sector can also enhance investment to support innovation in water resource conservation and management and improving water use efficiency in agroecosystems so that agricultural water use may be reduced.

Urban and Infrastructure Impacts on Hydrology

Historical landscape and infrastructure modifications, largely intended to improve land suitability for farming in the rural Midwestern United States, are responsible for a significant amount of erosion (Emerson 1971), loss of natural stream and riparian areas (Mattingly et al. 1993), and subsequent changes in hydrological flows in many areas (Urban et al. 2003). For example, the manipulation of natural river and stream systems in Illinois has been shown to be responsible for increased peak flows, increasing the potential for widespread flooding (White et al. 2003). Similarly, the replacement of natural flow paths with engineered drainage paths has led to increased occurrence of mass wasting and erosion, further increasing the environmental and economic costs associated with landscape manipulation (Simon and Rinaldi 2000). This alteration of natural flow paths opened up land for agricultural production but has also degraded many of the naturally fertile soils in the region. The implementation of soil health practices has potential to mitigate some of these effects, though research in this area is limited.

America's aging infrastructure is inadequate to handle current and projected extreme weather events. Every four years, the American Society of Civil Engineers (ASCE) generates an assessment of our nation's infrastructure. The ASCE's 2021 Report Card gives American infrastructure an overall grade of C- (an improvement from a D+ in 2017) and identifies important deficiencies in infrastructure designed to mitigate flood risks. Levees received a D grade. In the United States, approximately 17 million people are protected by levees and according to the U.S. Army Corp of Engineers (USACE), and $21B are needed to improve moderate to high-risk structures. Recent extreme weather events have made evident the weakness of some levee systems. For example, during the Missouri River and North Central flooding in 2019, 700 miles of levees were damaged (ASCE 2021). Furthermore, across the nation, many stormwater systems (D grade) are reaching the end of their design lives and are inadequate for addressing challenges related to urban flooding. The current funding amount needed to upgrade stormwater systems nationwide is estimated to be $8 billion (ASCE 2021). The traditional approach to managing stormwater in urban environments has relied on gray infrastructure (man-made water containment and transport systems such as ditches, sewer systems, etc.). However, in recent years green infrastructure and nature-based solutions in urban areas like rain gardens, bioswales, and green roofs have gained popularity (Berland et al. 2017; Diringer et al. 2020). This integration of urban land management and soil health principles has potential to reduce urban flooding and improve stormwater quality.

The U.S. Congress recently passed House Rule 3684 - Infrastructure Investment and Jobs Act, which will provide funding to modernize infrastructure across the nation. The act will provide a total of $1.2 trillion over the next ten years. Resources will be allocated towards various infrastructure projects like roads, bridges, water infrastructure, electric grid resiliency, ports, and waterways, among others. This historic investment is likely to produce significant improvements in America's infrastructure. However, funding through House Rule 3684 is lower than ASCE's estimated infrastructure investment gap of $2.59 trillion over the next ten years (ASCE 2021). It is likely that additional financial support will be necessary in the future in order to bring the U.S. water infrastructure up to date and increase public safety.

In urban areas, soil health management can increase our nation's resilience to extreme weather events as well as provide agronomic and ecosystem benefits and should be an integral part of climate mitigation and adaptation plans. In urban environments, impervious surfaces such as concrete, asphalt, and roofs prevent water infiltration into soil entirely. Little to no water infiltration, along with an intensified water cycle and urban growth, increase both the potential for and human exposure to flooding (e.g., developing in flood-prone areas), and outdated infrastructure have created the conditions for significant flood damage in many regions of the world, including the United States.

Flooding is the natural hazard that represents the greatest threat to communities in the United States (NASEM 2019). Several natural and man-made factors influence the generation of floods. These include heavy rains, snowmelt and ice-jams, sea level rise and storm surges triggered by tropical storms or tsunamis, outdated infrastructure and structure failures like dam breaks and levee breaches, urbanization, deforestation, policy and planning decisions, and land-use practices that reduce infiltration such as soil disturbance and the use of heavy machinery that leads to soil compaction (Brody et al. 2011; Merz et al. 2021).

The societal and economic impacts of flooding are significant and are increasing because of climate change. The National Oceanic and Atmospheric Administration (NOAA) has maintained a list of the costliest weather and climate disasters since 1980. In recent years, flood-related events commonly appear at the top of the list (NOAA NCEI 2023). For example, Hurricane Ian (2022, $112.9B), Hurricane Ida (2021, $80.2B), Hurricane Laura (2020, $26.7B), Missouri River and North Central Flooding (2019, $12.7B), Hurricane Michael (2018, $29.5B), Hurricane Harvey (2017, $151.3B), and the Louisiana Flooding (2016, $12.6B), are major flood events that have had serious economic and social impacts in the past decade. The frequency of these billion-dollar disasters displays an upward trend. The U.S. experienced 119 events in the 2010s whereas only 59 billion-dollar di-

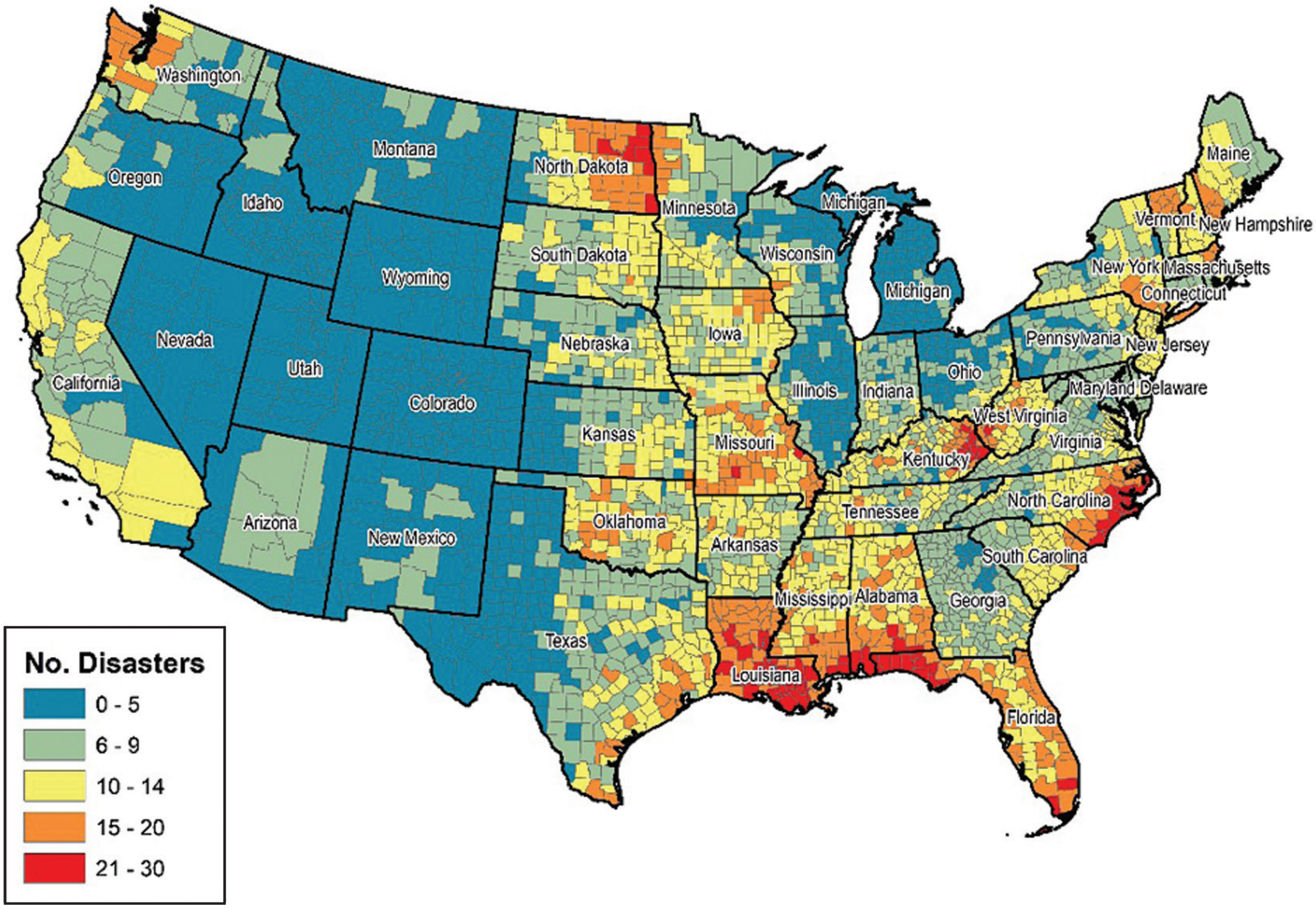

Figure 6. Number of flood-related Presidential Disaster Declarations by county (1989–2022). Raw data source: FEMA

sasters were recorded in the 2000s (Smith 2020).

Under the Stafford Act of 1988, the President of the United States can issue disaster declarations for regions impacted by catastrophic events. The Federal Emergency Management Administration (FEMA) distributes most of the federal assistance intended to help affected regions (Moss et al. 2009). Figure 6 was created with records obtained from FEMA and shows the number of times, on a per-county basis, that regions of the country received flood-related disaster declarations during 1989–2022. This figure illustrates how flooding in the United States is not limited to coastal counties, with many land-locked counties impacted by significant flood events, especially in the Midwest and Great Plains. In addition, it shows how pervasive major flooding is in some counties, with approximately 400 counties receiving 15 or more flood-related disaster declarations over the last three decades (e.g., on average, one every other year). Further, the information presented in Figure 6 represents only a subset of the flood events impacting communities in the United States, since less severe floods are not represented. A recent study by The Pew Charitable Trusts found that flooding occurs almost daily in the United States (Tompkins and Watts 2021). These floods vary in cause and impact, but nearly all have negative economic and social impacts.

Given that many counties in the Upper Midwest, Kansas, Oklahoma, North Carolina, and along the Mississippi River have both large areas of cropland and a high number of flood-related disaster declarations (Figures 6 and 7), opportunities exist to achieve flood-reduction benefits through improvements in soil health that may increase infiltration and water retention in agricultural lands. River networks create upstream-downstream connectivity and the possibility for heavy precipitation events upstream to generate flooding in downstream communities, as was the case in the Missouri River and North Central flood in 2019, which impacted 14 million people and caused $6.2B in property damage (Figure 8; National Flood Services 2023). This connectivity also creates opportunities to develop infrastructure projects that deliver multiple environmental benefits, incentivize rural-urban and upstream-downstream dialogue, encourage sustainable development, and increase landscape resilience to extreme weather events. For example, improving soil health and infiltration in upstream agricultural fields can generate multiple ecosystem services on-site while also potentially reducing downstream

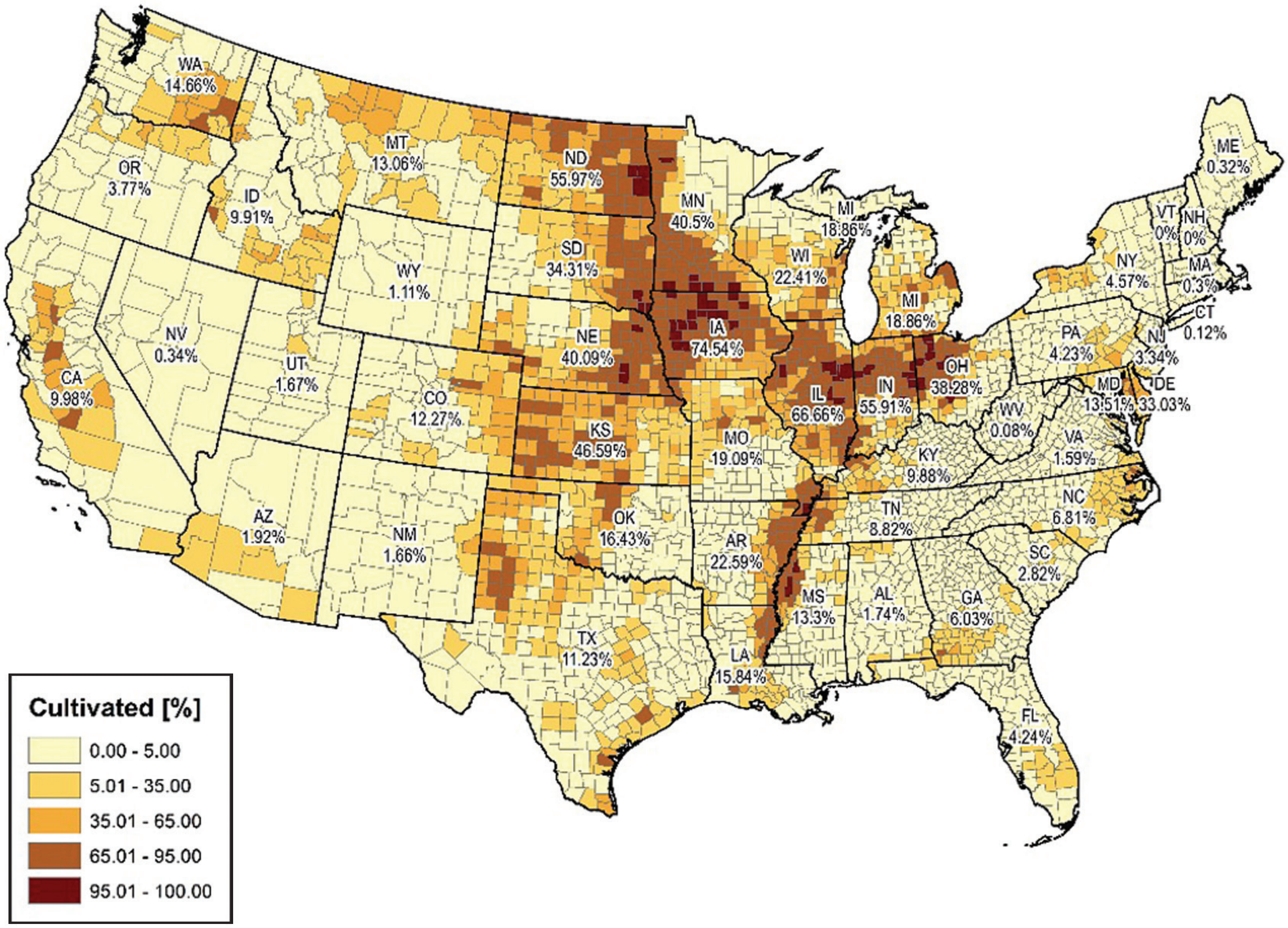

Figure 7. Percentage of land under cultivation by county. Raw data source: USDA.

flooding; the impacts of these practices may also become an important part of the community's plan to mitigate flood impacts (Sun et al. 2018; Turner et al. 2018).

Economic and Social Impacts

The interconnections of water, soil health, and societal well-being (including economics) are complex and multifaceted. Water, for instance, plays a crucial role in soil health by influencing its physical, chemical, and biological properties (Young et al. 2008; Sánchez-García et al. 2019). Excessive or insufficient water can accelerate soil erosion (Borrelli et al. 2017), limit plant (including crop) productivity, and modify microbial diversity and functioning (Kibblewhite et al. 2008). The health of the soil, in turn, affects human well-being through its contribution to more stable and nutritious food production (Brevik et al. 2012; Lal 2010; Piper and Kogel-Knaber 2017), cleaner air and water (Kibblewhite et al. 2016; Pardo et al. 2017), improved stability of green and built infrastructure (Smith and Chaney 2002) and decreased exposure to harmful chemicals (e.g., through lower reliance on agrichemicals like pesticides and fertilizers and remediation of existing chemicals in the soil; Franzleubbers et al. 2000).

Estimates of the cost of poor soil health on societal well-being (including economic well-being) can vary widely depending on how soil health and well-being are defined, the estimation approach applied, and spatial and temporal extent of the analysis. Several efforts, however, have attempted to quantify the impact of soil health on society by estimating economic impact. The cost of poor soil health on global food production, for example, has been estimated to range from \$15B to \$40B per year (Echeverría et al. 2016; Nkonya et al. 2016). Global estimates of the cost of soil salinization range from \$12.9B to \$27.3B per year in lost crop production and increased soil management costs (Munns et al. 2020; Noto et al. 2021). Berry and colleagues (2003) estimated the overall global cost of soil degradation on lost agricultural production, impacts to infrastructure, and reduced air and water quality at \$3T annually, or 3–5% of the global annual GDP. Liu and colleagues (2015) estimated that the cost of sedimentation to U.S. water treatment facilities alone is approximately \$1.5B

Figure 8. Flooding in Hamburg, Iowa in March 2019. Source: National Flood Network.

per year. It is important to note that these estimates are increasingly dated and subject to a high degree of uncertainty depending on the specific assumptions and data used. However, they highlight the magnitude of potential impact that improvements to soil health can have on societal well-being.

There are additional, harder-to-quantify social outcomes that are modified by soil health, such as recreation, tourism, and spiritual and religious practices (Contanza et al. 1997; Kibblewhite et al. 2008). Inland water bodies with toxic algae blooms, loss of cultural foods, and soil contamination that prevents food production are all negative impacts attributable at least in part to soil degradation. On the other hand, functional soils also support the broader social-ecological system's resilience to extreme weather events and other shocks (Birgé et al. 2016: Peters et al. 2015). Many conventional cropping management approaches, for instance, focus on practices that maximize short-term yields but may undermine longer-term stabilizing processes, like the soil's ability to maintain its structure and moisture storage capacity in the face of floods or drought.

A well-known example of the consequences of lost stabilizing processes in ecosystems is the 1930s "Dust Bowl" desertification event in the Great Plains of the United States. In the decades leading up to the Dust Bowl, intensively plowed, shallow-rooted annual wheat cover replaced native perennial, deep-rooted, drought tolerant grassland species. While an exceptionally intense and long-lasting drought in the 1930s (Miao et al. 2007; Cook et al. 2009) was the proximate cause of the Dust Bowl, the ultimate driver of this event was the loss of stabilizing ecosystem processes that occurred when the native grassland vegetation was plowed under and replaced by annual crops (Rietkerk and van de Koppel 1997; Peters and Havstad 2006; Scheffer et al. 2001). Overall, 39 million hectares of U.S. topsoil were displaced because of wind erosion. The Dust Bowl is unfortunately far from the only example of the desertification following land conversion and poor cropland management practices. Only 40 years later, farmers in the Soviet Union plowed and planted 40 million hectares of grassland into wheat, 2.8 million of which were lost in a severe flash drought in the 1960s, plummeting millions of peasant farmers into destitution and starvation (Worster 2004).

One of the legacies of the Dust Bowl was a new social conception of soil as a precious resource to be managed for both agricultural production and resilience to extreme weather, pests, and other stressors (Birgé et al. 2016). A direct result of the Dust Bowl was the 1933 establish-

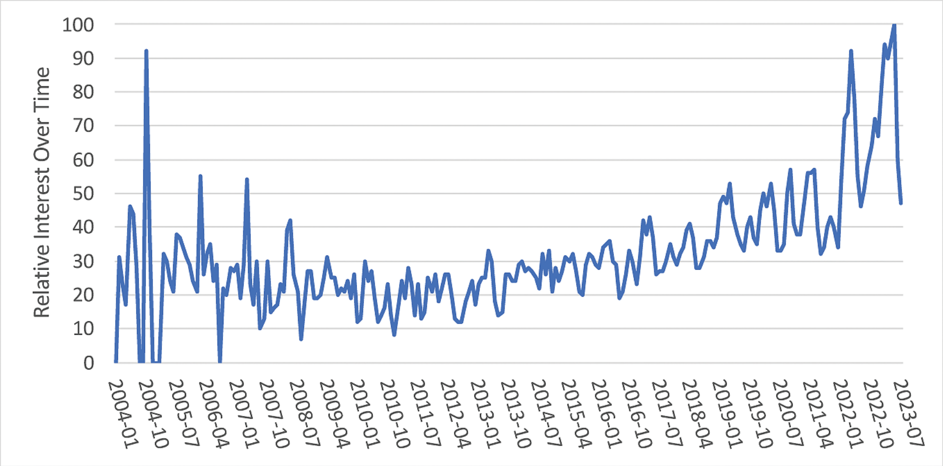

Figure 9. Relative use of the term "soil health" as a Google search term from 2004-present.

ment U.S. Soil Conservation Service, a precursor to today's NRCS whose annual budget as of 2023 is more than $5.2B. Civil society actors, from farmers to academics and NGOs, have also taken up the cause of soil health, increasing the popularity of the term among the public (Figure 9). In the past hundred years, farmers have been innovating on their own to improve the soil health of their land rather than relying strictly on researchers or government investment, even conducting scientific experiments on their operations – inviting academic and government researchers to join their studies in an about face from historic producer-scientist collaborations. Capitalizing on this leadership from farmers will require increasingly sophisticated science, policy/governance enabling conditions, and mechanisms to scale up private sector investment in soil health practices.

Many of the practices employed by farmers to restore function and resilience to their soil are derived from indigenous principles of agricultural management. In the Pre-Columbian era, sophisticated row crop agriculture systems supported large and complex societies across the North American continent for millennia (Graeber and Wengrow 2023). The cultivation of maize, beans, squash, and other row crops using techniques including intercropping, crop rotation, milpa (a system of clearing forest, intercropping complementary foods in that field for ~2 years, then allowing the land to return to forest), terracing, and advanced irrigation were widespread approaches that enabled indigenous cultures to thrive in diverse environments and weather and climatic variability (Mann 2005). These ancient systems of agricultural production principles are undergoing a modern revitalization in the modern Indigenous Food Sovereignty movement through an emphasis on ecological sustainability, cultural preservation, community empowerment, resilience, and knowledge exchange and through non-indigenous circles interested in concepts of agricultural management that restore ecological function and avoid resource exploitation (Altieri 2004). Indeed, many of society's solutions for our modern soil challenges may exist in the rich history and cultural legacy of indigenous conceptions of agriculture, which should be reflected in remediation efforts.

Implications for Policy and Decision Makers

Effective governance of complex natural resource systems requires a balance of stability and flexibility. Stability ensures predictability and consistency, while flexibility enables responsiveness and innovation in the face of new challenges (i.e., "adaptive governance" as described in Garmestani et al. 2019). Policies must also be grounded in legitimacy, fairness, cultural appropriateness, and the best available science (Craig et al. 2017).

In the context of water and soil governance for societal well-being, two approaches meet these requirements: creating new policy mechanisms or adjusting existing policies (Garmestani and Benson 2014). Here we explore the latter. The expansion and possible reapplication of existing policy, with an emphasis on integrating farmer and indigenous-led innovation and solutions, likely represents an underused resource for creating more reflexive, adaptive governance necessary for managing complex natural resources concerns (e.g., those that arise from the interconnections of water, soil health, and societal wellbeing) (van Bueren and ten Heuvelhof 2005; Garmestani and Benson 2014; Garmestani et al. 2019).

Examples of existing, relevant governance channels that can be used to address the impact of water and soil health on societal outcomes include multiple conservation programs administered by tribal programs, such as the Intertribal Agriculture Council (IAC); federal mechanisms via the USDA-NRCS including the Environmental Quality Incentive Program (EQIP), Conservation Reserve Program (CRP), and Conservation Stewardship Program (CSP); and various farmer groups such as the National Corn Growers Association. Other relevant programs designed to address more emergent natural resources challenges include the NRCS Regional Conservation Partnership Program (RCPP), which awards funding to non-federal entities to develop new conservation approaches adhering to a shared template with existing NRCS programs (e.g., EQIP). Similarly, the USDA Partnerships for Climate Smart Commodities program (also known as the Climate Smart Agriculture Initiative) recently committed $3.1B in support for 141 projects throughout the United States aimed at improving producer implementation of climate smart principles, including soil health practices. It is expected that this initiative will reach over 60,00 farms comprising more than 25 million acres of land in the United States and will be responsible for removing an estimated 60M metric tons of CO_2 from the atmosphere over the project period (USDA 2022). In all cases, an analysis of the program's strengths, weaknesses, opportunities, and threats (SWOT analysis) can assist policymakers and civil society in understanding how these efforts can be adjusted or reemphasized to better meet the complex challenges that arise from poor soil health and a changing hydrologic cycle.

Conclusion

Soil health practices have proven potential to improve ecosystem function by increasing water infiltration and soil storage and decreasing soil erosion and surface water pollution, while at the same time moderating negative impacts of flooding and drought. Beyond their use in agricultural production, the implementation of soil health practices in urban areas may also reduce flooding concerns both on-site and downstream, improve surface water and groundwater quality, and provide additional social and aesthetic benefits. The impact of soil health practices on the hydrologic cycle as a whole is less-studied than their impacts on agricultural production and greenhouse gas emissions, but existing data indicate that these hydrologic impacts have potential to be equally, if not more, important. Given the rapid recent and projected changes to Earth's hydrologic cycle due to climate change, understanding the influence of soil health practices on agricultural production, flooding, and drought resilience is likely to become increasingly important.

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