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From the Dust Bowl to Precision Conservation

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Past Challenges

More than three-quarters of a century ago, the United States was at a crossroads as to how to manage lands to mitigate erosion. Hugh Hammond Bennett, the first chief of the US Department of Agriculture's Soil Conservation Service (USDA SCS) and often called "the father of soil conservation," once described erosion as a "national menace" because of the severe threat it presented to water quality, sustainability, and food security. In response to this threat, US Congress enacted legislation in 1935 that led to the establishment of the SCS; in 1994 the agency was renamed the USDA Natural Resources Conservation Service (NRCS) to better reflect the increased scope of the agency's work in conservation. The SCS/NRCS has worked to apply conservation on the ground in cooperation with other federal agencies (e.g., USDA Agricultural Research Service [ARS]), universities, farmers, the private industry, consultants, extension services, professional societies, and others since its establishment decades ago. Research was conducted by USDA ARS, universities, NRCS, and other peers to develop soil and water conservation practices and tools to facilitate the assessment of traditional management practices' effects on erosion and how conservation practices could be used to reduce erosion.

One of the great conservation success stories of the last 75 years was the development and application of conservation practices that reduced erosion rates across the United States, increased the sustainability of agricultural

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systems, and contributed to protection of water quality. Soil erosion of cropland in the United States declined by 43% from 1982 to 2007 (USDA NRCS 2010). Argabright et al. (1995) reported that from 1930 to 1992 the erosion rate for row crops in the northern Mississippi Valley Loess Hills decreased by about 42% to 58%. Another success was the significant increase in yield productivity around the world following the Green Revolution of the 1950s and 1960s, which significantly contributed to increased global food security. A substantial increase in the use of fertilizers, specifically nitrogen (N) fertilizers in the United States and other countries, was a key part of the Green Revolution. Development of fertilizers led to productivity gains that fed 3.5 billion people (Erisman et al. 2008), close to half of the current global human population at the time of this writing.

While there were many successes in the efforts to reduce erosion and protect water quality over the last 75 years in the United States, new challenges arose with the increased use of agrochemicals in the 1960s and 1970s. The increased use of fertilizers contributed to increased nutrient losses to water bodies, natural areas, and to the atmosphere. This change in management resulted in increased nutrient losses. Such losses could not only occur by the transport of soil particles carried away by erosion but also, in the case of elements like N, could occur by nitrate (NO_3-N) leaching via tiles or to groundwater, and through atmospheric loss pathways such as ammonia (NH_3) volatilization and nitrous oxide (N_2O-N) emissions.

These challenges were exacerbated with the increase of manure applications to agricultural fields, where in some cases the field sites changed from being sinks to sources (Sharpley et al. 1999, 2003). However, even with the successes of conservation practices in reducing erosion and improving the sustainability of agricultural systems over the last 75 years, challenges remain. While conservation practices such as no tillage can significantly reduce erosion, loss of nutrients to the environment is a persistent challenge in conservation. Improvements are critically needed to minimize water and air quality impacts by reducing leaching via tile drainage systems and NH_3 volatilization due to surface applications of urea on high pH soils or surface applications of manure (Delgado 2020a, 2020b).

Following the establishment of the SCS by Congress in 1935, the Federal Water Pollution Control Act (FWPCA) was established in 1948; together, these actions led to significant reductions in erosion losses. To address the challenges emerging from increased use of agrochemicals, the FWPCA was amended with the Federal Water Pollution Control Act Amendments of 1972, the Clean Water Act of 1977, and the Water Quality Act of 1987. These measures contributed to conservation of water quality alongside research and technological advances that improved water quality practices. Significant advances in development of best management practices, precision agriculture (Pierce and Nowak 1999), and precision conservation (Berry et al. 2003; Delgado and Berry 2008) have also contributed to water quality improvements.

Fixen and West (2002) and Snyder and Bruulsema (2007) reported that corn yields across the United States had been increasing without increasing N fertilizer application rates to corn systems, contributing to much higher N use efficiencies. However, a national analysis conducted by Ribaudo et al. (2011) identified a need to improve N best management practices, since they found that only about one-third of cropland in the United States was implementing all three best N practices of using the best rate of application, best method of application, and best time of application. Failure to implement all N best management practices may contribute to higher N losses. In 2013, the US Government Accountability Office reported that even with the legislation enacted during the last 40 years to improve water quality, some water quality issues persist. The US Government Accountability Office (2013) referenced the US Environmental Protection Agency's findings that over 50% of the assessed waters in the nation did not meet the established standards for swimming, fishing, or drinking water, and that 67% of assessed lake acres and 53% of the assessed river miles were impaired water bodies. Nutrients, mainly N and phosphorus (P), are still negatively impacting US waters, and the water quality issues of the 1970s have yet to be resolved (USGAO 2013; USEPA 2016). These analyses strongly suggest that if we are to adequately reduce the impact of nutrients and improve water quality, we cannot commit the errors and oversights of the past (Delgado 2020a, 2020b).

Maintaining soil quality and soil health of agricultural systems is another challenge. Research has suggested that erosion affects soil productivity and that yields could be reduced by 4.3% to 26.6% per every 10 cm (3.9 in) of soil loss, depending on the methodology to assess soil erosion (Bakker et al. 2004). Erosion contributes to losses of fine particles, soil organic matter, and nutrients; and can lead to significant soil degradation that impacts soil health and yields, and to sediment loss that impairs reservoirs needed for flood control and water storage for cities. In the 1940s the T-value concept emerged as a way to assess the tolerable erosion rate that can sustain the productivity of a given soil. This concept was proposed and defined by Smith (1941) and Smith and Whitt (1948). Soil systems are quite complex, and Cox (2008) reported that we need to include an assessment of soil quality and other properties and not rely on the T-value alone. Agricultural practices that contribute to reduced soil organic carbon affect the quality of a soil (Doran and Jones 1996). Several scientists have reported that the T-values are not sustainable in the long run, especially if the rate of loss is higher than the rate of soil formation (Johnson 1987; Montgomery 2007).

Delgado et al. (2013) reported that since T-values are not adequate as a guide to soil conservation because they do not account for productivity, soil quality, and soil health, we should move to a new approach that not only considers the impacts of erosion rate but accounts for the chemical, physical, biological, and ecological impacts. They suggested a framework that accounts for both short and long-term impacts on productivity, profitability, and soil (e.g., soil quality, soil health, soil ecology, and soil organic matter), as soil health and soil organic matter are key to adapt to climate change and the off-site effects of erosion (e.g., impacts to water bodies and sedimentation).

Agricultural systems have traditionally been managed using uniform conservation practices across fields. As new technologies emerged over the last three to four decades, we began developing methodologies that were instrumental in the assessment of the spatial variability of erosion and flows across fields. These new technologies contributed to the development of new and improved practices that increased the effectiveness of conservation efforts. The development of geographic information systems (GIS) technology in the 1970s and rapid expansion of its use in the 1980s and 1990s, together with the development and proliferation of personal computers in the last two decades of the 20th century, contributed to the development, use, and application of modeling efforts by scientists and conservation practitioners that could assess spatial and temporal variability.

Even before new precision farming and precision conservation techniques were developed, there were efforts to manage spatial variability using traditional soil survey maps across the field for soil and water conservation (Gardner 1957). From the 1920s to early 1930s, soil surveys began to incorporate the use of aerial photography (Gardner 1957), which is a classic example of how we started delineating the spatial variability across agricultural fields in the United States, planting the seed for future precision farming and precision conservation efforts. Without the availability of GIS, global positioning systems (GPS), and other modern tools, we started identifying spatial variability of soils across the landscape using mapping techniques, and this information was being made available to conservationists, nutrient managers, consultants, and others.

Another classic example of how variability was managed decades ago, before the emergence of precision farming and precision conservation, is grass waterways. During the 1930s and 1940s there was research on using grass waterways for channels (USDA SCS 1947; USDA NRCS 1996). Grass waterways were used by SCS/NRCS and embraced by farmers that installed these practices in areas of the fields where large flows would concentrate and contribute to the formation of gullies; in some cases there were counties with more than 90% of farmers using them (Berg and Gray 1984). Berg and Gray (1984) reported that grass waterways contributed to soil conservation but noted that other practices such as terraces, contour farming, and diversions should be used in conjunction with grass waterways. The national efforts of the SCS laid the foundation to managing the spatial and temporal variability of agricultural fields in the United States using tools available in the 1930s to 1970s. This was achieved through the development of tools such as soil surveys, which accounted for the spatial variability of the soil type across the field. Additionally, they used conservation practices such as contour farming and use of deviation ditches, grass waterways, and other practices that considered variabilities across the field (e.g., slope, and changes in slope across the landscape) so they could manage the flow of water to reduce erosion. It should be noted here that some of these practices, such as contour farming and terraces, were used thousands of years ago, but the SCS expanded the use of these practices using modern soil surveys to manage variability across the landscape.

The development of new technologies, such as GIS, modeling, remote sensing, and GPS, allowed intensive monitoring across the field in the 1990s. Development of these programs and the use of computers in agricultural equipment contributed to the development of precision agriculture (Pierce and Nowak 1999) and precision conservation (Berry et al. 2003; figure 1). Significant

Figure 1

Berry et al. (2003) reported that precision conservation should implement an approach where assessments could be conducted of the nutrient flows in and out of the field at the watershed and regional scales to determine how best to apply conservation practices for increased effectiveness. Reprinted from Berry et al. (2003).

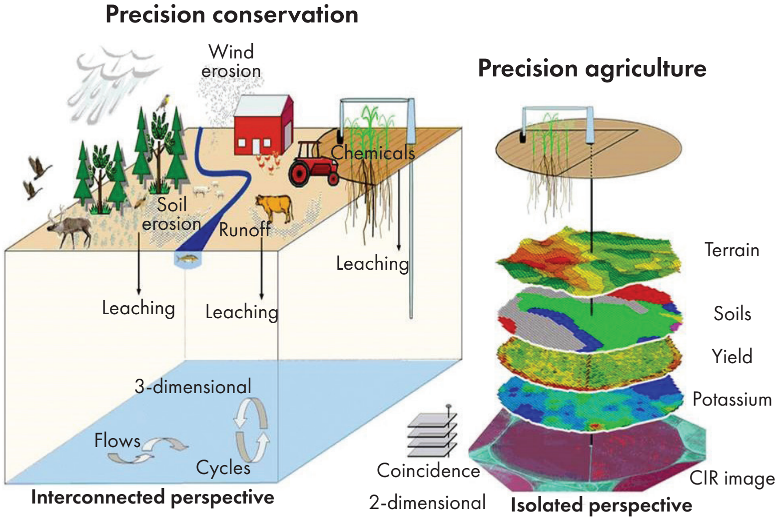
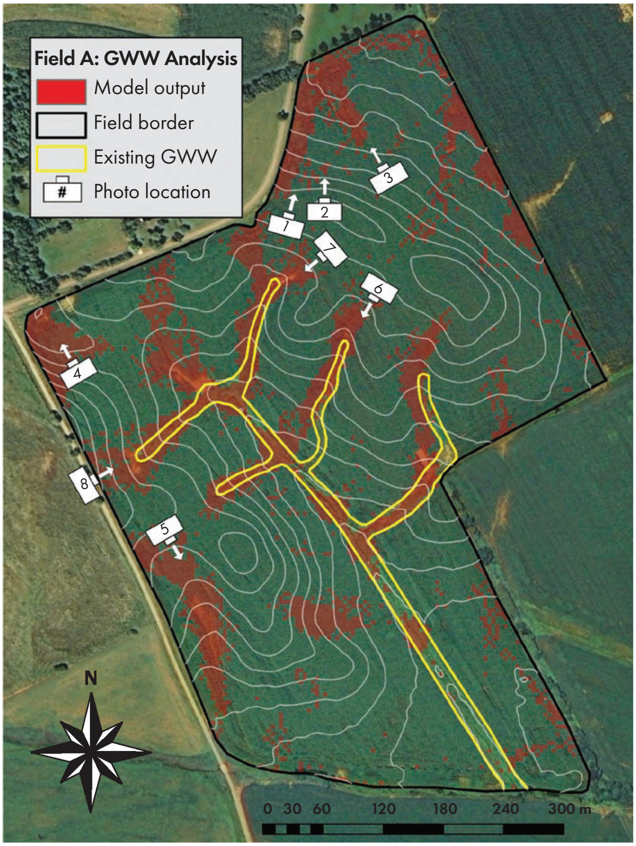


Figure 2

Aerial view of a production field indicating areas where the erosion runoff model has calculated a probability of erosion with values higher than 0.5 (shown in red), grassed waterways (GWWs), and locations of eroded areas that have been photographed. Reprinted from Luck et al. (2010).



advances in precision conservation in the 2000s and 2010s have enabled assessment of temporal and spatial variability and more effective installation of conservation practices (figure 2). Advances in the 2000s allowed conservationists to use logistic regression models to predict the spatial occurrence of soil erosion considering site-specific information to identify areas of the field where gullies could develop and accelerate erosion (Mueller et al. 2005). These precision conservation approaches to identify the best areas of the field to place grass waterways can increase the effectiveness of this conservation practice (Luck et al. 2010; Mueller et al. 2005; Pike et al. 2009; figure 2).

Current and Future Challenges

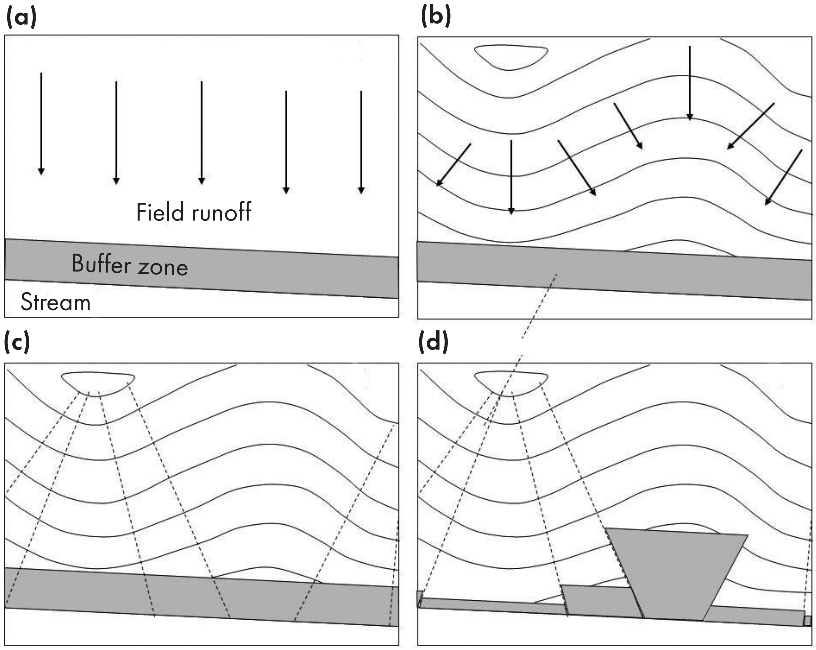
One of the greatest challenges of the 21st century will be adapting to a changing climate while increasing agricultural productivity to feed the growing global human population. A changing climate is contributing to droughts, floods, and intensive precipitation events that are impacting agricultural production (United Nations 2018; Trewin 2014; WMO 2019; Corlett 2014). Extreme weather events will increase erosion; for every 1% increase in total rainfall, the erosion rate increases by 1.7%, and even if the total precipitation remains unchanged, the rate of erosion may increase due to increased occurrence of more intense precipitation events (Nearing 2001; Nearing et al. 2004; Pruski and Nearing 2002a, 2002b). Conservation practices can play a role in adapting to these extreme weather events that are likely to accompany a changing climate (Delgado et al. 2011). Precision conservation can help identify the weather variability spatially and the locations across the fields where extreme flows will occur, and specific conservation practices can be applied to minimize the potential effects of this variability (Delgado et al. 2011).

The 4Rs (right fertilizer source at the right rate, at the right time, and in the right place) of nutrient management are an important approach to management that has contributed to increasing fertilizer use efficiency (Roberts 2007; Murrell et al. 2009). Delgado et al. (2016) expanded this concept to incorporate conservation management. They reported that the 4Rs are not enough to reduce the transport of nutrients across the watershed and that there is a need for an expanded approach that includes conservation, proposing the 7Rs for nutrient management and conservation, also known as precision agriculture and precision conservation, or the 4Rs of nutrient management and the 4Rs of conservation (Pierce and Novak 1999; Berry et al. 2003, 2005; Cox et al. 2005; Delgado et al. 2016, 2018, 2019). The 7Rs approach joins precision farming and precision conservation for the management of agricultural fields and natural areas. This new approach is also being called 4R+, where the plus signifies conservation (The Nature Conservancy 2020).

Advances of the last 30 years have made it possible to identify flow patterns across fields to increase the effectiveness of conservation practices (Mueller et al. 2005), or to design buffers in such a way that they can be tailored to manage the concentrated flows at specific locations of the fields (Dosskey et al. 2002, 2005, 2007, 2018; figure 3). Precision conservation can then be used to increase the effectiveness of conservation practices, such as the placement of wetlands, riparian buffers, bioreactors, and other practices (Delgado and Berry 2008). With the advanced technologies available today, we have computers in practically every vehicle cab that farmers are using to increase the effectiveness of conservation practices. The use of these systems can increase the effectiveness

Figure 3

Diagrams of crop-field runoff patterns, topographic contours, and alternative buffer designs: (a) uniform runoff flow to a uniform-width buffer; (b) nonuniform runoff flow to a uniform-width buffer; (c) nonuniform runoff areas and the corresponding uniform-width buffer locations to which they flow; (d) nonuniform runoff areas and the corresponding variable-width buffer areas to which they flow. Both (a) and (d) yield an approximately constant level of pollutant filtering along the entire length of the buffer. Reprinted from Dosskey et al. (2005).



of agricultural machinery, avoid overlap in application, and apply the right rate at the right place, which will reduce the overapplication of agrochemicals and also improve the profitability of best management practices (Fulton and Darr 2018). These practices can be used to increase yields and to manage tillage, fertilizers, and pesticides more effectively (Fulton and Darr 2018).

We have improved models that can be used to assess erosion spatially and identify the most susceptible areas of the landscape and where implementation of site-specific precision conservation practices may have the greatest effectiveness across the landscape (Ascough et al. 2018). Models available today can conduct simulations across watersheds and conduct reasonable assessments of nutrient transport (Yuan et al. 2018). There is potential to use these models to evaluate hot spots across watersheds and to implement conservation practices in these hot spots (Yuan et al. 2018). Ongoing advances in technologies such as high-resolution Light Detection and Ranging (LiDAR), high-resolution digital elevation maps (DEM), and real-time kinematic (RTK) GPS equipment can be used to improve the accuracy of placement and design of terraces (Bay et al. 2014; Thompson and Sudduth 2018). Additionally, WebTERLOC (web-based TERrace LOCation program), can be used to improve the design and precise placement of these conservation practices while reducing terrace lengths and construction costs by 15%, and contributing to lower erosion and control of gully formation (Thompson and Sudduth 2018).

For tile systems, yields can be increased by improving drainage management (Skaggs et al. 2012). We can potentially use GIS, GPS, DEM, and new software and/or technologies for better assessment of hydrology at a given site and improved design of drainage systems to improve water management considering spatial and temporal variability (Shedekar and Brown 2018). We will be able to connect management practices used at agricultural fields with natural areas surrounding the agricultural fields to better define the benefits to wildlife biology and agricultural economics (McConnell and Burger 2018). Using precision conservation methodologies, we can assess the impacts of crop residue on carbon sequestration across the landscape and its potential to improve soil health (Clay et al. 2018).

Systems using these new precision conservation technologies could be used in emerging markets to trade ecosystem services. Delgado et al. (2008, 2010) developed the concept of the Nitrogen Trading Tool (NTT) in cooperation with NRCS. This tool uses the Nutrient Leaching and Economic Analysis Package (NLEAP) model and GIS to assess the effects of best management practices and conservation practices in reducing atmospheric (N_2O, NH_3), leaching and surface runoff losses. These savings (reductions in losses) could then be traded in air and quality markets (e.g., direct and indirect emissions of N_2O in carbon dioxide [CO_2-C] equivalents). The NTT was improved for use in trading in water quality markets by Saleh et al. (2011) and Saleh and Osei (2018) to assess not only reductions in N, but also P and sediment losses (savings) due to improved conservation practices. The initial ARS/NRCS NTT was expanded to a Nutrient (N, P, and sediment) Tracking Tool (NTT) using the NTT concept and framework developed by Delgado et al. (2008, 2010) and the Agricultural Policy/Environmental eXtender (APEX) model (Gassman et al. 2010) by Saleh and Osei (2018). This NTT, released by the USDA Office of Environmental Markets, is used across millions of acres as a water quality and quantity trading tool and for water quality/quantity assessment (Saleh and Osei 2018). NTT has been verified and is used in 33 states with the goal of being applied across the United States (Saleh, personal communication); the N trading tool concept will impact agricultural economics/markets nationwide.

For air quality markets, the COMET-Farm system (a web-based tool to evaluate potential carbon sequestration and greenhouse gas reductions from adopting NRCS conservation practices) can be used to assess potential reductions in emissions that could then be traded in such markets, and it considers spatial and temporal variability. The COMET-Farm is a state-of-the-art model that can evaluate the effects of precision conservation practices on CO_2, methane (CH_4), and N_2O emissions at the farm level (Paustian et al. 2018).

These recent advances in precision conservation are methodologies that can be used for precision regulation (Sassenrath and Delgado 2018), where voluntary approaches using conservation programs, such as the Environmental Quality Incentives Program, could be used to increase the effectiveness of conservation practices. The private industry is also using precision conservation on farms across the United States (Heartland Science and Technology Group 2017; Illinois Sustainable Ag Partnership 2018).

Conclusions

Soil and water conservation legislation passed by the US Congress over the past 75 years has contributed significantly to increasing soil and water conservation and the sustainability of agricultural systems in the United States. Federal agencies, such as NRCS and ARS, and universities, extension personnel, farmers, nonprofit organizations, consultants, and others working in conservation have contributed to increased conservation, reduced erosion, improved water quality, and sustainability. If we consider the impact that erosion has on productivity as described by Bakker et al. (2004), implementing soil and water conservation practices during the last 75 years has also contributed to the current crop yields across the nation. Legislation enacted in the last 75 years related to the conservation of soil and water as well as other conservation efforts over this period have contributed to increasing farmers' incomes while helping conserve the environment. With that said, the challenges of today are perhaps even greater than they were 75 years ago.

Enormous challenges lie ahead, and there is a need to develop creative, new solutions to confront a changing climate and its impacts on food security, soil productivity (yields), soil erosion, water quality and air quality. In addition to the climate change challenge, we still have the unresolved challenge of protecting water quality from nutrient losses from agricultural fields. We also have the challenge of anticipated further decreases in soil organic matter content and potential negative impacts to soil health due to agricultural intensification, even where rates of erosion have decreased. There is also the challenge of determining how to manage spatial and temporal variability to increase conservation effectiveness across the landscape. These challenges are related to soil productivity and must be addressed.

Future precision conservation technologies using machine learning and artificial intelligence techniques will make it possible to better manage the spatial and temporal variability. With these advances will come improvements in the development and application of precision conservation to target hot spots across watersheds. Additionally, recent advances in soil biology and next-generation fertilizers such as enhanced efficiency fertilizers with biostimulants are promising approaches with the potential to increase nutrient use efficiencies, reduce nutrient losses, and maintain or even improve soil health. The next 75 years offer promising opportunities to find solutions to the challenges of increasing productivity, improving soil health, and reducing nutrient losses across watersheds while minimizing erosion rates.

Emerging environmental markets are an area where precision conservation could potentially be applied to reduce the nutrient losses from hot spot areas across watersheds that may be contributing more significantly to greenhouse gas emissions and other nutrient flows from agricultural systems. Connecting the cultivated areas of the field with natural areas and using precision conservation could help wildlife and sustain both agricultural and natural systems while providing other sources of income to farmers that trade ecosystem services in air and water quality markets.

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