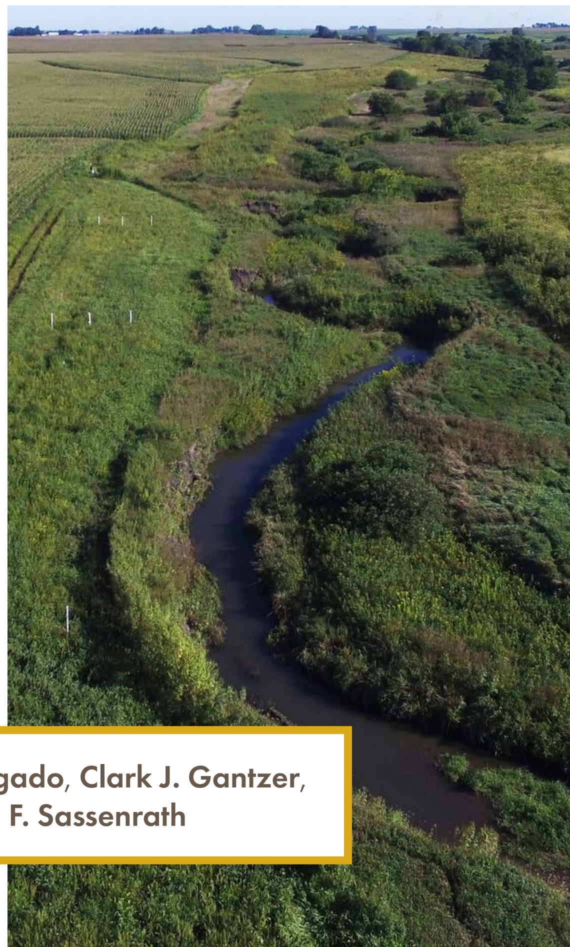
# SOIL AND WATER CONSERVATION

## A Celebration of 75 Years



Edited by **Jorge A. Delgado**, **Clark J. Gantzer**, and **Gretchen F. Sassenrath**

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SOIL AND WATER CONSERVATION SOCIETY®

Soil and Water Conservation Society
945 SW Ankeny Road, Ankeny, IA 50023
www.swcs.org



Project Manager and Copy Editor: Annie Binder

Designer: Jody Thompson

Cover photos: Upper left—Wind-devastated farmland during the Dust Bowl, Kansas, USDA NRCS photo. Upper right—Hugh Hammond Bennett (right), first Chief of the Soil Conservation Service, USDA NRCS photo. Lower left—Landowner and FAMU farm management specialist inspect strawberries grown as U-Pick operation, Campbellton, Florida, USDA NRCS photo by Bob Nichols. Lower right—Post-installation saturated buffer, Story County, Iowa, USDA NRCS/SWCS photo by Lynn Betts.

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The Soil and Water Conservation Society is a nonprofit scientific and professional organization that fosters the science and art of natural resource management to achieve sustainability. The Society's members promote and practice an ethic that recognizes the interdependence of people and their environment.

Justice, Equity, Diversity, and Inclusion: SWCS seeks diverse voices, actively listens, engages in dialogue, thinks critically, and takes meaningful action toward creating institutions and systems that serve and value people equally.

# Contents

# Foreword

It is an honor to bring you *Soil and Water Conservation: A Celebration of 75 Years* and serve as staff during our organization's 75$^{th}$ anniversary. This year has given us, as an organization, the opportunity to reflect on how we started, where have been, and where we are now.

When we first discussed plans to commemorate the 75$^{th}$ anniversary of the Soil and Water Conservation Society (SWCS), leadership had three goals: (1) to celebrate the work and accomplishments of conservation professionals, (2) to celebrate achievements of the Society, and (3) to provide a thoughtful dialogue on the future of conservation. During our 74th annual conference in Pittsburgh, the *Journal of Soil and Water Conservation* editorial board enthusiastically supported these ambitions and formed a committee to develop a collection of essays that would reflect on the state of conservation science and practice. The efforts of three dedicated editors and long-time SWCS members—Jorge A. Delgado, Clark J. Gantzer, and Gretchen F. Sassenrath—as well as dozens of expert authors and reviewers have resulted in an exceptional publication that more than achieves our goals.

Authors were given the formidable task of describing their areas of work in soil and water conservation, challenges of the past, progress in the last 75 years, and future goals and opportunities. In addition to 20 chapters with a conservation science and research focus, 9 chapters providing a "Practitioner's Perspective" highlight on-the-ground experiences through current projects, case studies, and practice implementation. While the chapters serve as introductions to complex and critical topics, many authors have included thorough references and resources for readers wishing to learn more.

Reviewing the important solutions presented in this collection, we ask the question: Could our organization's founder, Hugh Hammond Bennett, have ever anticipated the developments of the past 75 years—modeling, remote sensing, tools and partnerships made possible through an increasingly globalized world—or the complexity of the challenges that conservationists face today under pressures of a changing climate and growing populations? Could Bennett have imagined the dynamic assortment of conservation professionals that SWCS has assembled 75 years later? Would he have predicted their many contributions that have created a promising future for agriculture, the environment, and society? This collection, completed in just over a year, is a testament to the passion that our members and partners have for sharing their knowledge and communicating their work to a broad audience.

In exploring the past 75 years of human relationships to agriculture and the environment, conservation efforts, and our organization through these pages, a coherent story emerges: the devastation of the Dust Bowl; developments in fertilizer, crop, and equipment technology; the environmental movement of the 1960s and 1970s; shifts in policy and funding; effects of a changing climate; and renewed attention to soil health. Most evident to us, however, are the many diverse individuals and organizations whose contributions have had a role in advancing our understanding of soil and water conservation. It is their efforts that we mark in this collection and their commitment to stewardship that we seek to sustain. We must continue to learn from one another, find opportunities for partnership and collaboration, and share the conservation story. It is this community of conservation professionals who work tirelessly to understand, protect, and improve our natural resources that was at the center of the conservation movement 75 years ago, just as it is today.

**Clare Lindahl**
CEO, Soil and Water Conservation Society

**Annie Binder**
Director of Publications, Soil and Water Conservation Society

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We also wish to give special thanks to all the book chapter authors, whose contributions contributed to a high-quality product and whose timely composition and revision of the chapters helped keep the project on schedule.

Finally, we wish to express our deep appreciation of all the reviewers for each chapter, whose recommendations contributed to the improvement of the book.

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# Dedication

The 20th century was an era of tremendous challenges related to soil and water conservation. A few examples that readily come to mind are those of the early 1930s, such as the Dust Bowl and agricultural systems with depleted nutrient balances that reduced yields, as well as high erosion rates that degraded soil and water resources.

During this challenging time, policymakers, the private industry, and other conservationists worked together to find solutions and develop policies and best management practices. Through their efforts, a new approach to conservation agriculture emerged that contributed to a golden era in soil and water conservation. One of the key figures of this era was Hugh Hammond Bennett, a founding member of the Soil and Water Conservation Society and the first chief of the US Department of Agriculture's Soil Conservation Service (known today as the Natural Resources Conservation Service).

Global population growth had created an urgent need to increase agricultural productivity to feed the world by the 1950s, and the aforementioned groups, with plant breeders and soil fertility and nutrient managers, worked to develop a new response. The era of the Green Revolution and more intensive agriculture significantly increased yields and helped to feed people around the world. One of the great leaders of this time was Norman Borlaug, the "father of the Green Revolution," who received the Nobel Peace Prize in 1970.

In the last few decades, great new challenges have emerged, driven by a changing climate with extreme weather events, the ever-present need to continue to increase agricultural productivity to feed the growing human population, and losses of nutrients from agricultural systems that have impacted water quality, among other challenges. A new approach was needed and called for a similar team of professionals such as those that contributed to the golden era of soil and water conservation in the 1930s and the Green Revolution in the 1950s and 1960s. In the 1970s and 1980s, we started to use geographic information systems (GIS) and computers in agriculture, and by the 1990s and 2000s, we were increasingly using global positioning systems

(GPS), GIS, remote sensing, and modeling to apply precision agriculture and precision conservation in the present era of smart agriculture.

The next 75 years will likely witness a new era of modeling, genetic and bioengineering, microbiology, machine learning, artificial intelligence, robotics, drones, and other scientific and technological advances for soil and water conservation.

Each of these eras—past, present, and future—are distinct in their challenges, successes, lessons learned, and opportunities. This book aims to honor and thank all those personnel who contributed to the soil and water conservation success stories of the past, to celebrate those working tirelessly to tackle the challenges of the present day, and inspire those who will contribute to future achievements in the emerging era of machine learning, artificial intelligence, robotics, and genetic and bioengineering to protect soil and water resources for agricultural systems and increase the health of soils, crops, and animal systems. In addition, this book is dedicated to all the professionals of these past, present, and future eras working to conserve soil and water resources in natural systems, such as foresters, biologists, ecologists, and the many other professionals whose work also contributes to conservation of the biosphere.

# 1

# The Soil and Water Conservation Society: The Society's Beginning

*Clark J. Gantzer and Stephen H. Anderson*

The Soil and Water Conservation Society (SWCS) has provided excellent leadership in conservation over the past 75 years. As this special collection of essays celebrates progress made and identifies challenges of today, it is important to keep in mind the goals and achievements of SWCS founders and members. This effort traces the Society's beginning and the successes of its work "to foster the science and art of natural resource conservation" during its first 50 years. Discussions on the initial organization, annual meetings, business, Society leadership, and the *Journal of Soil and Water Conservation* (JSWC) are included, focusing on publications and published testimonies that have been a leading means by which the Society has advanced soil and water conservation.

The focuses of the earlier work of the Society continue today. As Wayne Pritchard, the first executive secretary of the Soil Conservation Society of America (SCSA; later renamed in the 1980s to the Soil and Water Conservation Society), stated in 1984, the real key to the future is the work and planning of landowners and farmers (Browning et al. 1984).

## Before the Formation of the Society

In the early 1900s, recognition of the need for an inventory of soils led to the establishment of the US Department of Agriculture (USDA) State Agricultural Experiment Station cooperative soil survey. The survey documented the variation in soils and the need for different soil management techniques to increase productivity and to control erosion.

**Clark J. Gantzer** is an emeritus professor of soil and water conservation, and **Stephen H. Anderson** is a professor of soil physics, in the School of Natural Resources at the University of Missouri, Columbia, Missouri.

The formation of the SWCS could not have occurred without the leadership of Hugh Hammond Bennett, who has since been called the father of soil conservation. Bennett studied geology and chemistry, and graduated from the University of North Carolina in the spring of 1903 (Cook and Lawrence 2015). Bennett said that it was an accident that caused him to take a job with the Bureau of Soils. His assignment was work on soil classification and mapping and observation of soil productivity. Bennett and Bill McClendon of South Carolina introduced the term "sheet erosion," in contrast to rill and gully erosion, which had been the usual field clues for identifying soil erosion problems (figure 1).

**Figure 1**

**Bennett's sheet erosion. Photo by C.M. Woodruff.**

Amazingly in 1909, Milton Whitney, Chief of the Bureau of Soils, argued that the soil was of inexhaustible and permanent fertility: "The soil is the one indestructible, immutable asset that the Nation possesses. It is the one resource that cannot be exhausted; that cannot be used up." Bennett angrily reacted to Whitney's statement, saying, "I didn't know so much costly misinformation could be put into a single brief sentence" (Cook and Lawrence 2015).

In 1914, F.E. Duley and M.F. Miller at the University of Missouri, established the first experiment plots to measure factors affecting runoff and erosion (Gantzer et al. 2018). In 1928, Bennett included results from these plots in his circular *Soil Erosion—A National Menace* (Bennett and Chapline 1928). In 1939, Bennett indicated that publication was critical in securing public and political attention to soil erosion (Bennett 1939). The importance of erosion was also highlighted by Walter Lowdermilk's report *Conquest of the Land Through 7,000 Years*, which contained erosion studies Lowdermilk made around the world between 1938 and 1939 (Lowdermilk 1953).

In 1929, due to his friendship to Arthur B. Conner, director of the Texas Experiment Station who argued that "protecting the soil that supports the citizenship protects the nation," Bennett was invited to testify before Congressman Buchanan's subcommittee and secured an amendment attached to the 1929 appropriation for the Department of Agriculture authorizing $160,000 over four years for soil erosion research. Bennett used the earlier Missouri erosion plot design for the first 10 USDA erosion experiment stations nationwide. This money was to be used "to investigate the causes of soil erosion and the possibility of increasing the absorption of rainfall by the soil" (Gantzer et al. 2018). Astonishingly, the loss of nutrients from erosion was greater than expected and was often greater than that by removal from crops. Nitrogen (N) loss was especially noted since it is found largely in the surface soil, which is most easily removed through erosion.

The dust storms of the 1930s accelerated nationwide soil erosion programs. The first great dust storm occurred on May 11, 1934, and blew soil from the Great Plains to Washington, DC. Bennett used this disaster to alert Congress and the nation to the need to protect farmland, and by lobbying Congress, helped to enact Public Law 46, which established the Soil Conservation Service (SCS) in 1935. Bennett's biography provides additional information about his important historical role as the first chief of the SCS as well as the founder of the SWCS who "started and organized—for conservation of our natural resources and for a better agriculture." Bennett dramatized the critical need of soil and water to politicians, and then formulated soil and water conservation practices and pressed forward to translate theory into action on the land (Brink 1951).

Another early leader in US conservation was Aldo Leopold, who introduced the idea of "environmental ethics" and appreciated comprehensive farm conservation through demonstration projects that extended land husbandry to include wildlife. This concept agreed with Bennett's belief that each acre on a farm or ranch should be "used for and treated in accordance with its capabilities" (Leopold 1949; Cohee 1987). In 1933 Leopold worked to integrate wildlife management into the nation's first soil conservation watershed demonstration, the Coon Creek project in Wisconsin (Cohee 1987; Meine 1987).

## The Society's Inception in the 1940s

The Society's inception was in 1941 when Bennett, Ralph H. Musser, A.E. McClymonds, and J.H. Christ proposed founding an organization titled "The American Society of Soil and Water Conservation." In a 1943 meeting in Washington, DC, Musser stated, "An organization of this kind should be worthy of the people interested in work in soil and water conservation, and it should be the medium of expression of the people of this profession."

The name of the organization, "Soil Conservation Association of America," was introduced in the Society's first publication of *Notes and Activities* in April of 1945. During a meeting that year, Bennett suggested a change in the name to "Soil and Water Conservation Association of America;" however, the membership voted to change the name to "Soil Conservation Society of America" (SCSA) (Pritchard 1956).

The first SCSA chapter meeting was held in 1945 and included a keynote presentation focused on "Upstream Measures as They Relate to Flood Control." In 1946 the first issue of the JSWC was printed. In 1949 the Journal published a Society statement on "National Land Policy" that said, "All lands should be used in a manner which will insure its continued and permanent maximum productivity and values . . . In a great measure, our natural economy, our democratic process and our national security are dependent on the future conservation and use of our basic natural resources" (Pritchard 1965). The fourth annual meeting of the Society was in St. Louis, Missouri, and proceedings were reported by national press, including *The New York Times*. Additionally in these early years, A. Dams published a highly cited paper, "Loss of Topsoil Reduces Crop Yields" (Pritchard 1956).

## Soil Conservation Society of America in the 1950s

The Society's effort to educate the public about soil and water was advanced by the publication of the booklet *Down the River* (1951). Over 200,000 copies were printed. It presented the causes of erosion and described methods of conserving both soil and water for a lay audience. In 1951 C.C. Taylor's article "Conservation: A Social and Moral Problem" was selected as the outstanding Journal article.

In January of 1952 the Society's first full-time office opened. The JSWC increased from a quarterly to bimonthly publication, and the article "Soil, the Substance of Things Hoped For" by Firman E. Bear was awarded the outstanding article of the year. In 1953, the eighth annual meeting was held in Colorado Springs, Colorado. A committee was established to determine the meaning of the term "soil conservation," and international soil conservation activity was facilitated with production of the article "A Soil Erosion Survey of Latin America" in the JSWC with cooperation of the Conservation Foundation and the Food and Agriculture Organization of the United Nations.

In 1955 an educational cartoon booklet, *The Story of Land—Its Use and Misuse*, was published (figure 2). Over 435,000 copies were sold by year's end. Ralph H. Musser testified for H.R. 8914, entitled the Farm Conservation Civil Defense Act of

**Figure 2**

***The Story of the Land.***

1956, writing, "I am pleased to see the stress placed on the conservation of our natural resources, particularly soil, water, forestry, and wildlife." Wayne Pritchard wrote, "Your proposal to combine conservation and a farm program with a civil defense program is a new approach to the total problem that needs to be accomplished. . . . the problem of conservation is a complicated one, and one in which we need to use many incentives because the urban citizen is dependent upon those who manage the agricultural land."

In 1957, the Society's annual meeting emphasized urban and rural land planning, and Douglas E. Wade became the first full-time editor of the Journal. Asheville, North Carolina, hosted the 1958 annual meeting with a theme of "Land and Water for Tomorrow's Living." There were a total of 1,139 attendees.

**Figure 3**

**US Postal Service commemorative stamp.**


In 1959, the annual meeting was held in Rapid City, South Dakota. A meeting highlight was the issue of a US Postal Service commemorative stamp honoring conservation and illustrating the importance of soil conservation measures, like contour plowing and the planting of cover crops (figure 3). Through arrangement with cartoonist Hank Ketcham, a cartoon publication, *Dennis the Menace and Dirt* (figure 4), was produced (Pritchard 1965).

The federal Soil Bank Program (authorized by the Soil Bank Act, P.L. 84-540, Title I) of the late 1950s and early 1960s paid farmers to retire land from production for 10 years. It was the predecessor of the Conservation Reserve Program (CRP), where the government bought back submarginal land to reduce the need for the government to support overproduction.

**Figure 4**

***Dennis the Menace and Dirt.***


### Soil Conservation Society of America in the 1960s

The 1960s introduced environmental events, including the book *Silent Spring* by Rachel Carson (1962), which addressed the danger of excessive use of pesticides; the Wilderness Act of 1964; and the federal Water Quality Act of 1965. These issues related to land use were of concern to the Society. To address them, SCSA published a 1960s position statement on "Land Use: Choices and Challenges." It stated:

> National legislation has been directed toward certain types of land such as parks, wilderness areas, wetlands, and surface-mined lands. . . . However, the United States has not been able to develop and adopt an over-all land use policy to help decisionmakers establish priorities when conflicts regarding land use occur. The nation needs to identify the importance of its productive agricultural land and develop ways to settle conflicts among competing private interests and protect the public interest . . . improved conservation measures must be considered now to help insure an adequate land resource base for the future. (Baum 1981)

The theme of the 1960 annual meeting in Ontario was "New Technologies in Land Resource Management." This marked the first annual meeting to be held in Canada and was attended by 1,256 people. Other 1960s topics included "Land Use: Changing Agriculture" and "Conservation—Key to World Peace." In 1965 a speech on "National Forest Wilderness" was delivered at the annual meeting by Associate Chief of the Forest Service Greeley (Frome 1975; Pritchard 1965).

Conservation work focused on the causes of lost soil productivity, and the JSWC published many papers on this topic. Peterson published "The Relation of Soil Fertility to Soil Erosion" (1964), Heilman and Thomas reported on "Land Leveling Can Adversely Affect Soil Fertility" (1961), and Eck and Ford wrote about "Restoring Productivity on Exposed Subsoils" (1962). Shrader et al. published an important paper on "Applying Erosion Control Principles" in 1963. Development of the Universal Soil Loss Equation for advancing and designing erosion control systems was published by Wischmeier and Smith (1965).

Additional important SCSA outreach activities in the 1960s included the *Soil and Water Conservation Glossary* published in Spanish in cooperation with the US Agency for International Development. In 1964 a popular booklet, *Making a Home for Wildlife*, was introduced at the 19th annual meeting. Also in 1964, *Focus on Resource Conservation* included articles on "Outdoor Recreation—Its Impact Today," "Policy in Land Management—A Symposium," and "Using and Managing Our Water Resources." The first scholarships offered by the Society were established during the 1960s.

## Soil Conservation Society of America in the 1970s

The 1970s ushered in the environmental movement. On January 1, the National Environmental Policy Act was installed. Senator Gaylord Nelson initiated the first Earth Day, an environmental teach-in, on April 22, 1970, and the US Environmental Protection Agency was founded later that year. The Federal Water Pollution Control Act amendments of 1972 (Clean Water Act), the Safe Drinking Water Act of 1974, and the Resource Conservation and Recovery Act (1976)—all landmark laws—were approved. The Surface Mining Control and Reclamation Act of 1977, regulating strip mining, and the Soil and Water Resources Conservation Act of 1977 were enacted and were also of profound interest to the Society.

Concern about excessive soil erosion increased. In 1977, average erosion rates in the United States exceeded 11 Mg ha$^{-1}$ y$^{-1}$ (5 tn ac$^{-1}$ yr$^{-1}$) for all row crops produced in the Southeast. In many counties, erosion rates exceeded 112 Mg ha$^{-1}$ (50 tn ac$^{-1}$) on corn and soybean land. For conventional tillage, average erosion was 21.5 Mg ha$^{-1}$ y$^{-1}$ (9.6 tn ac$^{-1}$ yr$^{-1}$); for chisel-plowing, soil loss was 8.7 Mg ha$^{-1}$ y$^{-1}$ (3.9 tn ac$^{-1}$ yr$^{-1}$); and for no-tillage, just 6.5 Mg ha$^{-1}$ y$^{-1}$ (2.9 tn ac$^{-1}$ yr$^{-1}$). A prescription to address the excessive erosion on sloping row crops must have sizeable increases in sod crops in the rotation, contouring and terracing, or growing of winter cover crops to control erosion (Larson 1981).

The prestige and distinction of the Society was greatly advanced by quality journal articles. The Journal published many papers, including Narayanan and Swanson's (1972) "Estimating Trade-Offs Between Sedimentation and Farm Income," Anderson et al.'s (1975) "Perspectives on Agricultural Land Policy," Lyles's (1975) "Possible Effects of Wind Erosion on Soil Productivity," Allen et al.'s (1977) "Conservation Tillage and Energy," and Burwell et al.'s (1977) "Nitrogen and Phosphorus Movement from Agricultural Watersheds." Foster edited *Soil Erosion: Prediction and Control* (1977), and "Soil Erosion Effects on Soil Productivity: A Research Perspective" was published by the National Soil Erosion-Soil Productivity Research Planning Committee (1981). The advances promoted by the Society in the 1970s ushered in important work on topics including improved tillage, the use of cover crops, and the off-site cost of soil and water loss from the land.

## Soil Conservation Society of America and Soil and Water Conservation Society in the 1980s

In the 1980s, Society policy statements and annual meetings advanced conservation science and policymaking. In the late 1980s, programming turned to research-oriented special projects. The first of these was a three-year field evaluation of USDA's implementation of conservation programs in the 1985 Food Security Act (farm bill), national mail surveys of CRP contract-holders, and a series of focus groups on the Wetlands Reserve Program. The Society worked hard in developing information for the 1985 farm bill (Berg and Gray

1984; Cook 1984). Conservation policy was greatly affected through the farm bill CRP and Conservation Compliance Programs.

In 1987 the Society's name was changed from "Soil Conservation Society of America" to "Soil and Water Conservation Society." The change was made to (1) broaden the Society's appeal by adding "water" to the name, (2) re-emphasize soil conservation, and (3) remove "of America" to highlight and promote international conservation.

The JSWC continued publishing excellent papers, including the Mannering and Fenster (1983) and Myers (1983) papers on conservation tillage, an article by Rodale (1984) on "Alternative Agriculture," "Evolution of the Universal Soil Loss Equation" by Meyer (1984), and an important paper on "The Off-Site Costs of Erosion" by Clark (1985). The decade was capped by a SWCS cosponsored conference on cover crops that resulted in a publication, *Cover Crops for Clean Water* (Hargrove 1991).

## SWCS Membership

The business of the Society is largely conducted through membership. The multidisciplinary, multi-institutional membership remains a major strength of the organization. At the Society's inception, it was not the intention to create an organization exclusively for USDA SCS (now Natural Resources Conservation Service) employees, but rather to create a scientific organization to foster soil conservation and represent individuals in government, academia, and business working professionally in soil conservation (Schnepf 2005).

In 1965 the Society had about 10,000 members, of which about two-thirds were SCS employees. Membership peaked around 1977 at about 15,000. It has been on a declining trend ever since. In 2019 membership is about 2,500, and the percentage of Natural Resources Conservation Service employees within the Society's membership has dropped to below a third. Reasons for the decline in membership are many. In the past, membership was important for one's resumé, and becoming an officer, council member, or even a committee chairman, with good performance, helped in promotion. Initial correlation between Society membership and membership across federal conservation agencies was greater than between the Society membership and the SCS members. That relation shifted beginning in the late 1970s when the Society narrowed its program focus more toward private land conservation instead of on both public and private lands generally and agricultural conservation issues specifically. The deceasing trend might have been accelerated by a change in the Society's interests. Historically these included both public and private land issues that interested members from the US Forest Service, Bureau of Land Management, and other public land agencies. Ethical issues of federal employee involvement in scientific and professional organizations also likely added to decreased membership (Schnepf 2005).

In 2020 the Society has 93 local chapters and 25 student chapters. The Society is a strong supporter of student chapters. One example of these is the University of Missouri student chapter in Columbia, Missouri. It has been active for 25 years and sponsors soil and water conservation activities throughout the academic year. Student club members have traveled and participated in the annual meetings, and past student club leaders have gone on to careers in soil and water conservation.

## SWCS Successes

There are many ways SWCS influences conservation. While much has been accomplished in 75 years of the organization, many concerns, including erosion, nonpoint source pollution, eutrophication and hypoxia of water, and flooding, remain. The need for conservation and environmental protection has not decreased (Cohee 1995). However, key to the future conservation work is improved planning for landowners and farmers, and the application of soil and water conservation practices on the land and water (Browning et al. 1984). Annual meetings have shown clearly that the Society can provide a venue for presenting and discussing the latest in conservation science and policy and offer professional development opportunities for membership. The SWCS collaborates with many conservation organizations, government, university, nonprofit partners, and industries to advance soil and water conservation.

Chapters offer members opportunities to advance local soil and water conservation. In 2020 considerable potential exists for the Society to advance its mission through special projects to influence and communicate conservation and to advance public policy in and beyond the United States.

The JSWC remains a great success for the Society and is one of the most important natural resource conservation forums published since 1946. As the Society's flagship publication, the multidisciplinary journal of natural resource conservation research, practice, policy, and perspectives is distributed to over 3,000 individuals and libraries worldwide. The current issues contain two sections (A Section and Research Section) designed to engage a diverse readership: a front A Section contains features, perspectives, and articles on practices; and the Research Section contains peer-reviewed applied research papers. The online journal provides access to JSWC issues back to 1981. In 2018, the JSWC had an impact factor (reflecting the yearly average number of citations) of 2.258 and ranked 14 of 34 titles in the "soil science" category, and 27 of 90 titles in "water resources."

This review of the early years of SWCS history touches on a few of the many accomplishments of the organization, including the presence of the annual meeting and high quality journal and the continued support of chapters and members that help promote soil and water conservation around the world.

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# 2

# Advancing Climate Change Mitigation in Agriculture while Meeting Global Sustainable Development Goals

*Rattan Lal*

Ever since its inception in 1945, the United Nations has addressed international issues of cultural, educational, economic, and human wellbeing through a series of initiatives that have evolved over time. The most recent of these initiatives is that of the Sustainable Development Goals (SDGs), launched in 2015. Of the 17 SDGs, 8 are strongly dependent on the judicious management of soil processes and their properties. However, many countries are not on track to accomplish these goals, and they also have the problems of soil and water degradation. An effective conservation of soil and water resources, restoration of degraded soils, adoption of conservation agriculture, and recarbonization of soil and vegetation are critical to advancing SDGs. Complementary to SDGs are initiatives, including the "4 per Thousand," to enhance sequestration of carbon (C) in soil for food and climate.

Global human population (in millions) was 200, 275, 450, 500, and 700 in the years 1, 1000, 1500, 1650 and 1750 AD, respectively. The population increased rapidly and was (in billions) 1.0, 1.2, 1.6, 2.0, 2.55, 3.0, 4.0, 6.0, 7.0 and 7.77 in the years 1804, 1850, 1900, 1927, 1950, 1960, 1975, 1999, 2011, and 2019, respectively (Rosenberg 2019). The world population (in billions) is projected to be 8, 9, 10, and 11.2 by 2025, 2043, 2083, and 2100, respectively (UN 2017, 2019).

**Rattan Lal** is a distinguished university professor of soil science and is the director of the Carbon Management and Sequestration Center, The Ohio State University, Columbus, Ohio.

The rate of increase in global food production has exceeded that of the population growth since 1960. World cereal production was 785 Mt (865 million tn) in 1962, 998 Mt (1,100 million tn) in 1970, and more than 3 Gt (3.31 billion tn) in 2017 (table 1). Whereas the world population increased by a factor of 2.48 between 1960 and 2017, the total cereal grain production increased by a factor of 4.05 over the same period (table 1). Consequently, the per capita cereal grain production increased from 241 kg (530 lb) in 1961 to 395 kg (869 lb; +64%) in 2017, with an overall increase by a factor of 1.64. Such an impressive gain in food production, however, has been realized with severe environmental consequences, such as warming of climate, degradation of soils, eutrophication of water, pollution of air, reduction of biodiversity, extinction of species, etc. Furthermore, nutritional quality of food may not necessarily improve with an increase in total grain production because the increase in atmospheric concentration of carbon dioxide ($CO_2$) may threaten human nutrition (Myers et al. 2014). Thus, future needs for food production must be reconciled with the necessity of improving the environment by adopting the food-energy-water-soil nexus approach because of their strong interconnectivity (Kopittke et al. 2019), and by making agriculture nutrition sensitive (Soares et al. 2019). Rather than expanding the land area under agriculture, large yield gaps must be abridged (Neumann et al. 2010; Foley et al. 2011; Tilman et al. 2011; Wu et

**Table 1**

**Total population, global cereal grain production, and the per capita grain production. The data on population is from Rosenberg (2019) and UN (2017), and that of cereal grain production is from the World Bank (2017).**

| Year | Population ($10^9$) | Cereal production ($10^6$ Mg) | Per capita production (kg) |
|---|---|---|---|
| 1961 | 3.05 | 736 | 241 |
| 1970 | 3.71 | 998 | 269 |
| 1975 | 4.00 | 1,202 | 301 |
| 1980 | 4.45 | 1,342 | 302 |
| 1985 | 4.85 | 1,613 | 333 |
| 1990 | 5.28 | 1,706 | 323 |
| 1995 | 5.70 | 1,885 | 331 |
| 2000 | 6.08 | 2,050 | 337 |
| 2005 | 6.50 | 2,250 | 346 |
| 2010 | 6.93 | 2,463 | 355 |
| 2015 | 7.36 | 2,859 | 388 |
| 2017 | 7.55 | 2,980 | 395 |

al. 2018) and land resources saved for nature conservancy (Lal 2016). These options are properly called "climate-smart agriculture" (Dinesh et al. 2018), or regenerative agriculture (Francis et al. 1986; Rhodes 2017).

There is already an adequate amount of global food production even for a total population of 10 billion. However, the causes of undernourishment of 821 million people globally (FAO et al. 2018, 2019) are those related to inadequate access to and distribution of food, political instability, and internal displacement and civil strife. Additionally, 2.1 billion people are prone to the epidemic of overweight and obesity, and 2 billion to micronutrient deficiency (Beal et al. 2017). Excessive food intake, insufficient physical activity (Hill and Peters 1998), and inappropriate diet (Caballero 2007) aggravate obesity. The increase in atmosphere $CO_2$ concentration may decrease protein content in rice, wheat, barley, and potato by 7.6%, 7.8%, 14.1% and 6.4%, respectively (Medek et al. 2017), which may contribute to malnutrition. There is the serious problem of food waste (Corrado et al. 2019), and 1.3 Gt (1.43 billion tn) of food is wasted annually (Depta 2018). The amount of food wasted could feed 2 billion people (Huber 2017).

Impressive progress in agronomic production has also perturbed the global C cycle with drastic increase in atmospheric concentration of $CO_2$, methane ($CH_4$), and nitrous oxide ($N_2O$) since 1750 (WMO 2019). The decoupling of the coupled cycling of water, C, nitrogen (N), phosphorus (P), and sulfur (S) has exacerbated environmental degradation.

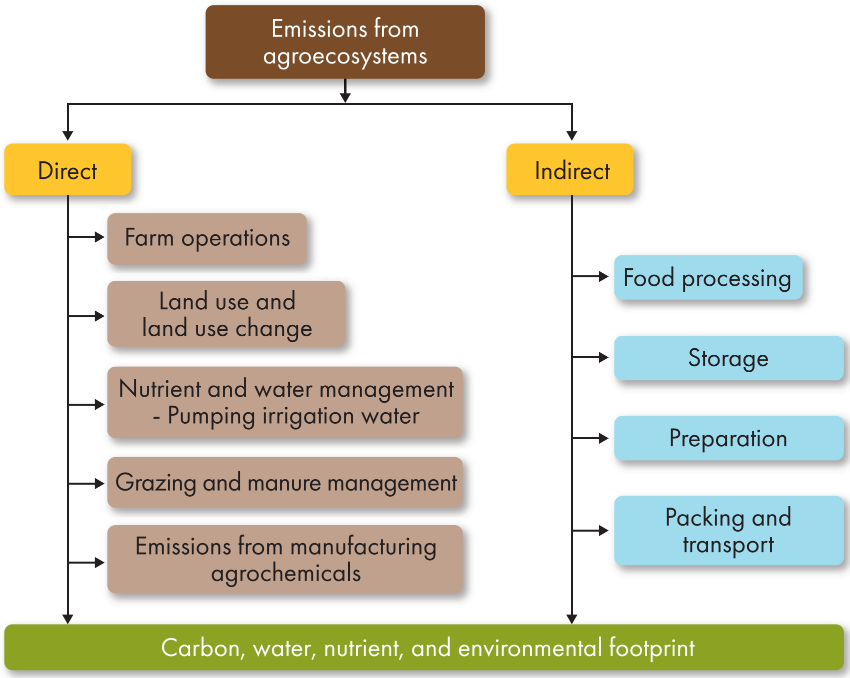
Thus, there is a strong need for a paradigm shift of adopting eco-effective measures of agriculture, which narrow the yield gap, produce more from less, increase food and nutritional security, and advance SDGs of the United Nations. Further, the need for recarbonization of depleted and degraded soils is also in accord with SDGs or the Agenda 2030 (UN 2015). Therefore, the objective of this chapter is to deliberate on the idea that global adoption of restorative and conservation-effective agriculture is critical to food and nutritional security, essential to advancing SDGs, and pertinent to meeting the ambition of climate change mitigation. The review is based on the hypothesis that restoration of depleted and degraded soils can sequester C while creating climate-resilient soils and agroecosystems, and advancing SDGs.

## Soil Degradation and the Anthropocene

The so-called "Anthropocene" began with the onset of settled agriculture about 10 to 12 millennia ago, accompanied by deforestation, biomass burning, soil tillage, and drainage of wetlands (Ruddiman 2003). Agriculture, especially extractive farming practices, created a negative ecosystem-C budget, depletion of ecosystem-C stocks, and emission of $CO_2$ and other greenhouse gases. Cultivation of rice (Sweeney and Mccouch 2007; Callaway 2014) and domestication of animals (Bollongino et al. 2012) caused emissions of $CH_4$. Production and use of synthetic fertilizers since the mid-20$^{th}$ century have been the major source of $N_2O$ (Smil 2001). Direct and indirect emissions from agroecosystems contribute about 30% of the total anthropogenic emissions expressed as $CO_2$ equivalent ($CO_2$ eq; figure 1).

**Figure 1**

**Direct and indirect sources of emissions.**




Conversion of natural landscapes to agroecosystems also exacerbated soil degradation by physical, chemical, and biological processes. Soil degradation by erosion affects as much as 1.1 Gha (2.72 billion ac) by water and 0.55 Gha (1.36 billion ac) by wind erosion (Oldeman 1994). Sediment transport into world rivers has increased from 14 Gt (15.43 billion tn) during the prehuman era to 36 Gt (39.7 billion tn) at present (Walling 2008, 2009). Expansion of land area equipped for irrigation in arid and semiarid regions increased risks of secondary salinization and depleted the groundwater level of aquifers around the world including the Indo-Gangetic Plains (Mukherjee et al. 2018), North China Plains (Yang et al. 2017), and the Ogallala of the US Great Plains (Terrell et al.

2002). Depletion of the soil organic C (SOC) stock in world soils is estimated at 133 to 135 Gt C (146.6 to 148.8 billion tn C) (Sanderman et al. 2017; Lal 2018). The negative nutrient budget in croplands of Africa, especially in sub-Saharan Africa (Kiboi et al. 2019), is the cause of low yield and poor nutritional quality of the food (Davidson et al. 2016). Land area vulnerable to diverse degradation processes covers 24% of the ice-free land (Bai et al. 2008) and affects as many as two billion people. Further, risks of soil degradation may be exacerbated by the present and projected climate change (Jiang et al. 2014).

## Sustainable Development Goals

Beginning with the report of the Brundtland Commission (World Commission on Environment and Development 1987), the United Nations has thus far focused on sustainable development through three consecutive development initiatives. The Agenda 21 was launched following the US Conference in Rio in 1992. The Millennium Development Goals, initiated in 2000, were built on the Agenda 21. The SDGs of 2015 comprise 17 specific focal points with numerous targets. The common themes connecting these three initiatives, improving the environment (i.e., climate, air, water, biota) and enhancing human wellbeing (i.e., food, equity, poverty, education), are strongly related to soil functionality and health, but especially to the accomplishments of some key SDGs.

SDGs closely related to soil processes include #1 (Ending Poverty), #2 (Zero Hunger), #6 (Clean Water and Sanitation), #13 (Climate Action), and #15 (Life on Land) (Bouma 2014, 2019; Bouma and Montanarella 2016; Hanjra et al. 2016; Keesstra et al. 2018; Lal et al. 2018a; Gil et al. 2019). If world soils are under threat (Montanarella et al. 2016), then SDGs are also under threat (Lal et al. 2018a). Indeed, 5 years into the 2030 Agenda, the world is not where it needs to be, and SDGs are also under increasing threat because of the COVID-19 pandemic and the rapidity of global warming. At the current rate of accomplishment, most SDGs may not be met within the next 10 years (Xu et al. 2020). There are several implications if SDGs are not met: poverty and hunger will perpetuate, human health and wellbeing will be jeopardized, water quality will degrade, aquatic life will be at risk, global warming will accelerate, and land degradation will be exacerbated. Therefore, improving and sustaining soil health is a high priority.

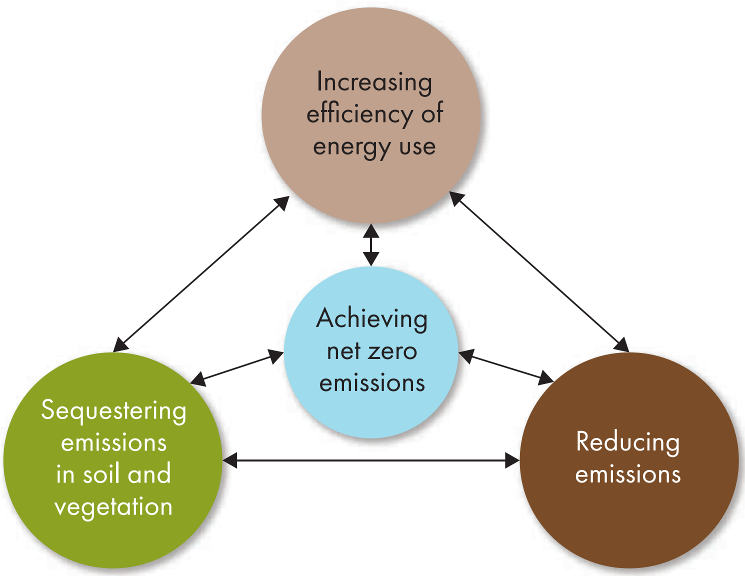
## Achieving Goals of Soil Carbon Sequestration

The COP 21 Climate Agreement of 2015 is a voluntary initiative to limit anthropogenic warming below 2.0°C (3.6°F) compared with the preindustrial levels, while also pursuing the options to limit the temperature increase to 1.5°C (2.7°F). In the meanwhile, the global mean temperature is increasing at the rate of 0.2°C ± 0.1°C (0.36°F ± 0.18°F) per decade, and it reached ~1°C (1.8°F) above the industrial levels in 2017 (Allen et al. 2018). With business as usual, the global mean temperature may reach 1.5°C as early as 2030 to 2050 (Allen et al. 2018). Achieving the ambitious target of limiting global warming to 1.5°C would imply achieving net zero greenhouse gas emissions by 2050 (IPCC 2018). However, there is still time to limit the global warming to 1.5°C by reducing anthropogenic emissions and sequestering atmospheric $CO_2$ in soil and vegetation (Lal et al. 2018b). Reduction in emissions from industry and travel because of the lockdown necessitated by the COVID-19 pandemic indicates that anthropogenic warming can be deaccelerated by judicious and timely action (Lal 2020a). The global land area adversely impacted is estimated at 4% (range of 2% to 7%) with warming of 1°C, 6.5% corresponding with warming of 1.5°C, and 13% (range of 8% to 20%) with the global warming of 2°C (Hoegh-Guldberg et al. 2019). The adverse effects of global warming on ecosystems are more severe for drylands than humid climates (Lal 2019c; Hoegh-Guldberg et al. 2019).

There are three strategies of achieving the net zero emission by 2050 (figure 2): (1) increasing efficiency by substituting low-C fuel sources (e.g., gas versus coal), (2) reducing emissions by implementing non-C fuel sources (i.e., wind, solar, hydro, geo, nuclear), and (3) sequestering emissions (e.g., terrestrial).

**Figure 2**

**Strategies to achieve net zero emissions from agroecosystems.**



## Agriculture and Soil as a Source of Greenhouse Gases

Since 1751, anthropogenic activities have emitted a total of 1.5 trillion t (1.65 trillion tn) of $CO_2$ (Friedlingstein et al. 2019), of which the United States has contributed 25% of the total (Ritchie and Roser 2019). In general, one-third of the total anthropogenic emissions are contributed by agriculture (Gilbert 2012). Therefore, adoption of improved agricultural practices (eco-effective techniques such as conservation agriculture) can reduce emissions and limit global warming (Thornton et al. 2018). Low-emission or no-emission agriculture should be the goal (Sà et al. 2017).

Soil is a source or sink of greenhouse gases depending on land use and management. Oertel et al. (2016) used an average rate of emission from all soils of 300 mg $CO_2$ eq $m^{-2}$ $h^{-1}$ (1,713 lb $CO_2$ eq $mi^{-2}$ $hr^{-1}$) or a global annual net soil emission of 350 Gt (385.8 billion tn) $CO_2$ eq. This is approximately equivalent to 21% of global soil C and N stocks. Total annual emissions from farm soils have been estimated at 68 to 77 Gt C (75.0 to 84.9 billion tn C) (Raich and Schlesinger 1992; Raich and Potter 1995), and at 98 Gt C (108 billion tn C) (Bahn et al. 2010). The Intergovernmental Panel on Climate Change estimated that 35% of $CO_2$, 42% of $CH_4$, 53% of $N_2O$, and 21% of nitric oxide (NO) of the total annual emissions are from soils (IPCC 2007). Globally, food is responsible for approximately one-quarter of greenhouse gas emissions (Poore and Nemecek 2018; Ritchie 2019). With more than 70 billion animals raised annually for human consumption (Arcipowska et al. 2019), meat production has strong implications for resource use and the environmental footprint.

## Reducing Emissions from Agricultural Soil and Managing Soil for Enhancing Its Capacity as a Sink of Atmospheric Carbon Dioxide

Emissions from the manufacture and application of agricultural chemicals (Lal 2004a) can be reduced by alternative approaches to managing soil fertility (e.g., biofertilizers and integrated nutrient management) and use of low-chemical or no-chemical pesticides (e.g., integrated pest management), and through enhancement and restoration of soil health that creates disease-suppressive soils (Mendes et al. 2011; Schlatter et al. 2017). Erosion-induced emissions and those from plow-based tillage can be reduced by conversion to conservation agriculture. A system-based conservation agriculture must be implemented in conjunction with crop residue mulch, incorporation of cover crops in the rotation cycle, use of complex cropping systems along with integrated nutrient management, use of perennial systems (Waldron et al. 2017; Gunathilaka et al. 2018), and integration of crops with trees and livestock (Lal 2015). These are pertinent options of land use and soil management for staying within the planetary boundaries (Heck et al. 2018). These are examples of eco-effective techniques (Czyżewski et al. 2018) because not all practices of sustainable intensification always produce the desired results (Mockshell and Kamanda 2018; Dicks et al. 2018).

Soils of agroecosystems are depleted of their antecedent SOC stocks. The soil-C sink capacity thus created can be filled by adoption of recommended management practices (RMPs), which create a positive ecosystem/soil C budget (Lal 2004b, 2010, 2018; Lal et al. 2018b). Conversion from a conventional tillage to conservation agriculture, along with the use of agroforestry, biochar, organic amendments, etc., can lead to SOC sequestration (Lal et al. 2018b). There is also a potential of sequestration of soil inorganic C as secondary carbonates and through leaching of bicarbonates in arid and semiarid climates (Lal 2019c).

The soil is a source of $CO_2$ if the net ecosystem exchange (NEE), the difference between photosynthesis and ecosystem (soil, vegetation, and biota) respiration, is positive, and a sink if it is negative. The objective of sustainable management of agricultural soils is to enhance their C sink capacity through a negative NEE. Increase in fertilizer use has increased agronomic productivity and improved access to food. It is estimated that N fertilizer supports 42% of all births over the last century (1910 to 2010) (Erisman et al. 2008; Ritchie 2017). As much as 30% to 50% of the yield increases may be attributed to fertilizers (Smil 2001; Stewart et al. 2005).

However, the magnitudes of NEE and net biome productivity are strongly affected by soil moisture regime (Zhao and Running 2010; Green et al. 2019). Drought stress, and loss of soil water in the subsoil, may be exacerbated by climate change (Feddema and Freire 2001). However, the plant available water capacity of the soil can be increased by restoring SOC concentration and sustaining it at the threshold level/range (Lal 2020b).

Low external inputs of organic or inorganic fertilizers have reduced productivity and decreased inputs of biomass C into soil. Aggravated soil degradation has diminished the SOC stocks and reduced agronomic productivity. Soil degradation caused by the severe depletion of SOC is a major problem in sub-Saharan Africa and South Asia, where there is a strong need to address environmental challenges by advancing SDGs (Omisore 2018). Predominant agricultural systems in sub-Saharan Africa and elsewhere in developing countries, based on extractive practices and poor management, contribute to the already serious problem of soil degradation and desertification. The goal is to strike the balance between attaining high agronomic yield and decreasing the environmental footprint of agroecosystems. Global cumulative potential of C sequestration (i.e., the maximum amount of $CO_2$ that can be transferred via photosynthesis into soil and biomass) in the terrestrial biosphere between 2020 and 2100, through adoption of eco-effective practices, is estimated at 155

Gt C (170.9 billion tn C, at the annual rate of 3.3 Gt [3.64 billion tn]) in the biomass compared with 178 Gt C (196.2 billion tn C, at the annual rate of 3.2 Gt [3.53 billion tn C]) for soil (Lal et al. 2018b). In addition, there exists a large potential of soil inorganic C sequestration in soils of arid regions (Groshans et al. 2018; Lal 2019c).

## Toward Low or Zero Emission Agriculture

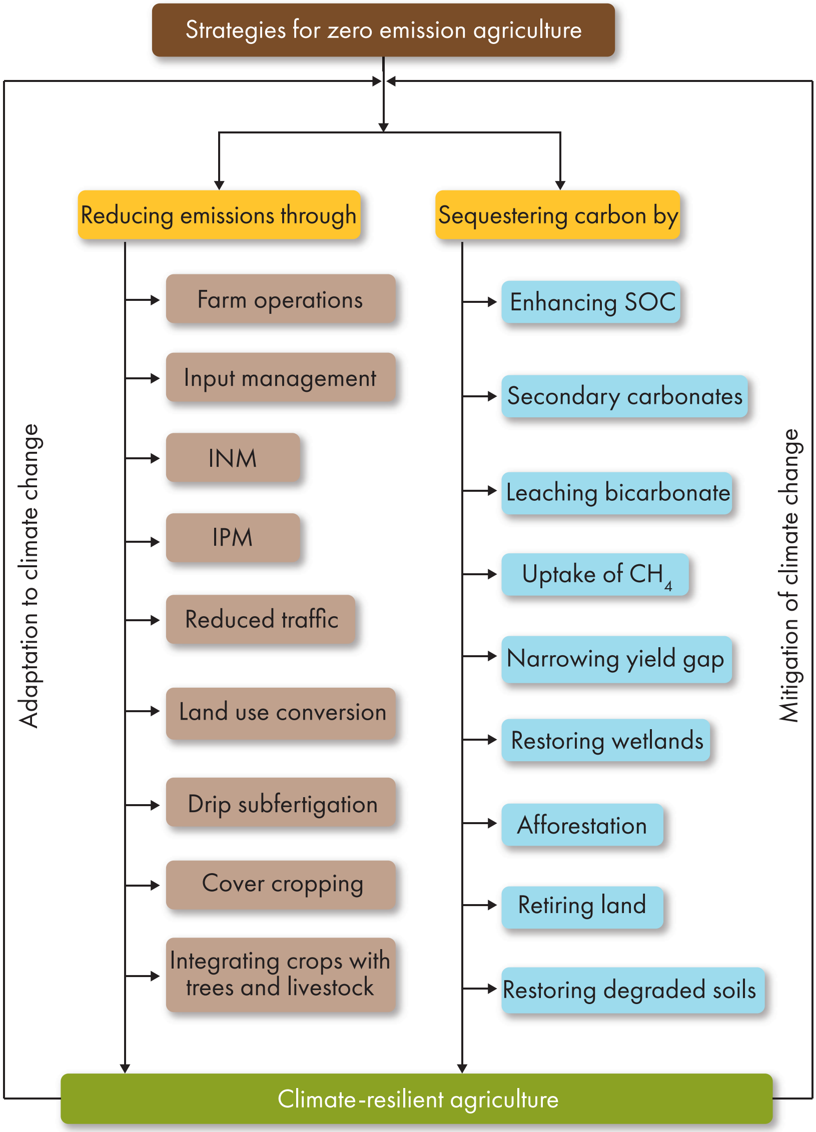
Rather than a problem, improved and science-based agriculture must be a solution to the environmental issues of the 21st century, including the changing climate, contaminated and depleted water resources, polluted air and enriched concentration of greenhouse gases, decreased biodiversity, and degraded landscapes. Important among technologies of achieving low or zero emission agriculture are those that reduce emissions by adopting energy-efficient options or those that are based on renewable sources of energy (figure 3). For South America, Sà et al. (2017) estimated that the terrestrial C sink capacity for adopting RMP-based agriculture is 8.24 Gt C (9.1 billion tn C) between 2016 and 2050. Sà and colleagues calculated that the ecosystem C payback time for RMP-based agriculture may be 50 to 188 years. It may be essential to use payments to incentivize land management for adopting RMPs and strengthening ecosystem services. Payments based on just and fair price of soil C (Lal 2014) may also promote the concept of Rights-of-Soil (Lal 2019a).

## Adopting Restorative/Regenerative Agriculture for Advancing Sustainable Development Goals

Adopting improved and restorative/regenerative agriculture is critical to advancing SDGs (Lal et al. 2018b) (figure 4). There is a strong need for adoption of "business unusual technologies" in agroecosystems to advance SDGs and achieve their mission by 2030 (table 2). Improving life on land is essential to achieving the goals of land degradation neutrality adopted by United Nations Convention to Combat Desertification (Lal et al. 2012b; Cowie et al. 2018). Public universities in developing countries can play an important role in advancing SDG #4 focused on education (O'Keeffe 2016). Sustainable management of wetlands can also advance some SDGs (Seifollahi-Aghmiuni et al. 2019), especially SDG #6. Several international initiatives have been launched to promote sequestration of atmospheric $CO_2$ in world soils. The "4 per Thousand" initiative launched at COP 21 in 2015 encourages farmers to voluntarily enhance SOC concentration in soil at an annual rate of 0.4% to 40 cm (16 in) depth (Chambers et al. 2016). Other initiatives providing region-specific RMPs include Adapting African Agriculture launched at COP 22 in 2016 (Lal 2019b), Global Soil Partnership/Inter-Governmental Panel on Soils (FAO and ITPS 2015), Global

**Figure 3**

**Approaches to making agriculture a solution to climate change.**




**Notes: INM = integrated nutrient management. IPM = integrated pest management. SOC = soil organic carbon. $CH_4$ = methane.**

Soil Week (Lal et al. 2012a, 2013), land degradation neutrality (Kust et al. 2017; Cowie et al. 2018), the pan-African Great Green Wall across Sahel (Goffner et al.

**Table 2**

**Strategies for mitigation of climate change through achievement of the Sustainable Development Goals or the Agenda 2030.**

| Specific goal | Specific strategies for mitigating climate change |
|---|---|
| #2 Zero Hunger | Land saving options, narrowing the yield gap, conservation agriculture, integrated nutrient management, improving use efficiency of inputs |
| #3 Good Health and Wellbeing | Nutrition-sensitive agriculture, improving soil health by carbon sequestration, enhancing quality of water and air by adopting improved systems |
| #6 Clean Water and Sanitation | Conservation agriculture, cover cropping, conservation-effective measures, reducing inputs of chemicals, agroforestry with establishment of contour hedges, drip subfertigation |
| #13 Climate Action | Carbon sequestration in soil and vegetation, producing more from less, integration of crops with trees and livestock |
| #15 Life on Land | Achieving land degradation neutrality, adopting diverse farming systems, restoring degraded soils |

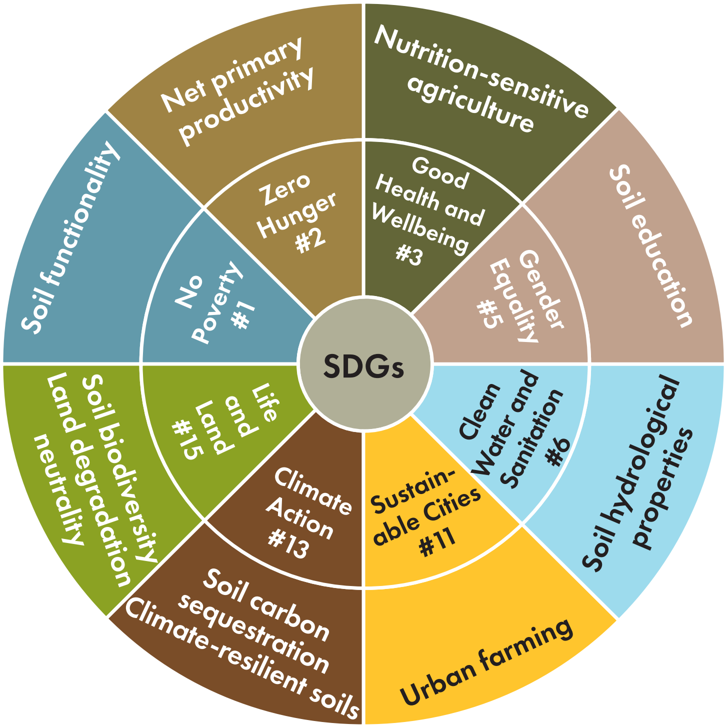
2019), and the Platform on Climate Action in Agriculture for Latin America at COP 25 in Madrid, Spain. Such international initiatives (figure 5), with effective systemic environmental governance (Gupta 2015; Williams et al. 2018; Scown et al. 2019) and political will, are needed to keep the SDGs on track, realistic, and effective (Deonandan and Mathers 2018).

People are the mirror image of the land on which they depend for their livelihood. When people are desperate, hungry, miserable, and suffering, they pass on their suffering to the land (Lal 2009). In turn, the land reciprocates and makes them even more miserable, and people and the land become entrapped in a series of overlapping vicious cycles that are difficult to break (Lal 2020a). It is this desperation and hopelessness that exacerbates the risks of political instability and civil strife and aggravates risks of pandemics (e.g., COVID-19) because of the increase in interactions between humans and the animal kingdom. There are numerous examples of this throughout human history that have resulted in the collapse of once-thriving civilizations (Diamond 2005; Montgomery 2007).

A viable entry point to break these overlapping vicious cycles (Lal 2020a) is the restoration of degraded/desertified soils to enhance their productivity and

**Figure 4**

**Meeting Sustainable Development Goals (SDGs) through soil conservation and restoration.**



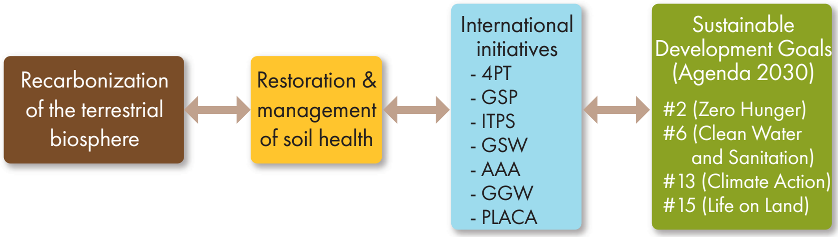

strengthen the provisioning of essential ecosystem services. Recarbonization of the depleted terrestrial biosphere (i.e., soil, vegetation) is a step in the right direction (Lal et al. 2012b).

## Conclusions

World soil, water, and other natural resources are adequate to meet rational and just needs of the current and projected population only if the current rate of degradation is curtailed and degraded soils are restored. The commendable progress made in enhancing agronomic production since the 1960s is also linked with large emission of greenhouse gases and the attendant global warming, eutrophication and depletion of water, degradation and depletion of soils, denudation of landscape, and mass extinction of species. While the quantity of grains produced is increased, nutritional quality (i.e., protein and micronutrients) may be adversely affected by soil degradation and global

**Figure 5**

**Recarbonization of soil and terrestrial biosphere through several international initiatives leading to achieving Sustainable Development Goals.**




**Notes: 4PT = 4 Per Thousand. GSP = Global Soil Partnership. ITPS = Intergovernmental Panel on Soils. GSW = Global Soil Week. AAA = Adaptation of African Agriculture. GGW = Great Green Wall. PLACA = Platform on Climate Action in Agriculture.**

warming. Strong threats to soil resources can also endanger SDGs, which are not on track to be accomplished by 2030. Thus, there is a strong need to reconcile the growing demands of the increasingly affluent human population with the necessity of restoring degraded soils and enhancing the environment through recarbonization of the biosphere in general and of the world soils in particular. Adopting the approach of food-energy-water-soil nexus through several international initiatives can keep SDGs on track. There is a need for a paradigm shift in adopting eco-effective measures for agriculture which can narrow the yield gap while restoring SOC stock and improving soil health.

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# 3

# Ecological Embeddedness, Agricultural "Modernization," and Land Use Change in the US Midwest: Past, Present, and Future

*J. Gordon Arbuckle Jr.*

In this essay, I examine how socio-technical and economic choices and changes have increasingly disembedded agricultural systems from their local ecologies and transformed agricultural land use and impacted soil and water conservation over the course of US history. I propose that the primary characteristic of land use change, and land degradation in particular, is a fundamental concept I term "agroecological disembeddedness." I begin with a definition and discussion of the concept of agroecological embeddedness. I then examine the history of North American agriculture up to mid-20th century, focusing primarily on what I consider to be the first major disembedding juncture, the "plow cultural revolution" that greatly disconnected agriculture from its agroecological foundations, and resultant impacts of that seismic shift in land use. The next section focuses on post-World War II fossil fuel–based technical and chemical "modernization," which further disembedded agriculture from its agroecological roots through the systematic promotion and spread of fossil fuel–based machinery, fertilizers, and agrochemicals that led to the current dominant model of agricultural land use: highly specialized, high-input, monoculture commodity production. The final section examines the rise of efforts to re-embed agriculture into its agroecological foundations, with a particular focus on soil health, and highlights the need for structural changes that promote diversity and regenerative agriculture.

**J. Gordon Arbuckle Jr.** is a professor of rural sociology at Iowa State University, Ames, Iowa.

The term "embeddedness," as used in reference to social-ecological systems, has its roots in economic sociology and the field that was once called "political economy." Most often traced to the work of Polanyi (1944) and later Granovetter (1985), embeddedness refers to economic activity that is integrated in and governed predominately by social and cultural relations and institutions, while disembedded economic activity is that which is governed and directed primarily by market forces. More recently, the concept of "ecological embeddedness" has been extended to include spatial and ecological dimensions of economic activity, especially in the realm of agro-food system studies, as agricultural production, perhaps more than any other economic activity, comprises both (agro)ecological and social dimensions (Jones and Tobin 2018). Agrifood scholarship such as Morris and Kirwan (2011) and Jones and Tobin (2018) has refined understanding of ecological embeddedness as a multilevel concept that includes landscape and farm ecologies, farm enterprises, farmers, processors, distributers, consumers, other actors within agrifood networks, and ecological benefits that different farming approaches might realize. However, for the purposes of this discussion of land use change I focus only on landscape and farm ecologies and the agroecological processes that farmers manage through farm enterprises. For this essay, I combine the political economic concept of embeddedness with the concept of agroecology as defined by Gliessman (2007): "…the application of ecological concepts and principles to the design and management of sustainable food systems." I use this lens of agroecological embeddedness to examine the trajectory of agricultural land use and soil and water conservation in what is now the United States, past, present, and future.

## Embedded Indigenous Agricultural Systems

Prior to European settler colonialism, indigenous agricultural systems were diverse and highly ecologically embedded. Indigenous peoples across North America practiced purposeful landscape management of grasslands, animal herds, and forest crops through use of fire, forest farming, and other management strategies (Mutel 2008; Mt. Pleasant 2015). Agriculture was led by the "three sisters" polycultures, with corn, squash, and beans providing excellent nutritional value while also maintaining soil fertility and managing pest and disease pressure. These were complemented by many other crops, including gourds, sunflowers, potatoes, and small native grains. By 1500, what is now the eastern and midwestern United States was dotted with agriculturally based villages with thriving village gardens as well as some large cities (Gallagher et al. 1985; Sasso 2003; Mutel 2008; Mt. Pleasant 2015).

As Schlebecker (1975) noted, many indigenous groups "…practiced a sophisticated and successful garden agriculture without plows." Indeed, native crop polycultures generally required little soil disturbance, allowing large quantities of food crops to be produced with low energy and time input and basic tools of wood, bone, and stone (Schlebecker 1975; Mt. Pleasant 2011, 2015). Early European settlers survived by adopting native agricultural practices, and corn and other native crops produced with little or no tillage were their principal food sources for at least a century. These cropping systems were well-adapted and "embedded" in local ecological conditions, and although they sometimes required conversion of forests, these changes in land use did not result in widespread soil degradation.

## The "Plow Cultural" Disembedding

While the native systems of corn, beans, squash, and other native crops production were generally embedded in local ecological conditions and thus had little ecological footprint (Sasso 2003; Mutel 2008; Mt. Pleasant 2015), introduced nonnative crops such as wheat and barley required "extravagant" expenditures of time and energy. Farmers could grow these crops at scale only "…if they used plows, harrows, rollers, and similar animal-drawn equipment…" and "clod crushers" and other equipment to further "pulverize" the land before seeding (Schlebecker 1975). However, because wheat had a higher commercial value, settlers were keen to produce it for local and European markets alike (Schlebecker 1975). As iron and then steel works developed, agricultural implement industries sprung up, and soon use of steel plows, harrows, cultivators, and similar machines to work the soil was common, and tillage became the norm (Schlebecker 1975; Cochrane 1993). Thus, as settler colonialism displaced native populations, so did plow-tilled methods of planting predominantly monoculture crops replace low- or no-till diverse, polycultural native agricultural systems.

The shift to "plow culture" over the course of the 19th century was viewed as an adaptive response both following and driving the transformation from a largely subsistence agriculture to a commercially oriented agriculture (Coughenour and Chamala 2000). Coughenour and Chamala (2000) note that this shift was radical in two respects: First, it ushered in "new and different… technical frames for preparing a seedbed, cultivating, and harvesting…the iron plow was the centerpost of a fundamentally different technical system of agriculture. Second…the adoption of plow culture was adaptive only if at the same time the farmer created a different farming system oriented to the market sale of crops and livestock products." In other words, the shift to market-based commercial farming systems was accompanied by a cultural shift that viewed iron plow tillage as a necessary means to increase labor productivity, allowing farmers to prepare more extensive seedbeds more quickly.

By the end of the century, "…the iron plow was adopted nearly everywhere" (Schlebecker 1975).

The impacts of this "plow cultural revolution" and widespread change in land use from no-till native systems to intensive tillage were swift and devastating, and ultimately maladaptive, however. By the late 1930s, on the heels of the Dust Bowl, the first nationwide appraisal of the condition of agricultural land found some 60% of croplands "either subject to continued erosion or is of such poor quality as not to return a satisfactory income to farmers…" and one-fourth or more of the original surface soil had been lost to erosion (Cooper et al. 1938). As Cooper et al. (1938) note in the seminal work *Soils and Men*, "A system of farming that keeps much of the land in continuous cultivation generally is a destructive system, since too often it does not provide for a return to the soil of much-needed humus and plant nutrients." Even in the most fertile regions of the United States, such as the Midwest's central Corn Belt and the Pacific Northwest's Palouse region, in many areas, tillage along with monocropping or short rotations had depleted soil organic matter and fertility, damaged soil structure, and led to declining yields (Cooper et al. 1938) that were far inferior to those of the native systems that had been displaced (Mt. Pleasant 2015).

## The Petrochemical Disembedding

The second major land use revolution in US agriculture, I argue, was driven by post-World War II shifts to a tripartite dependence on fossil fuels: mechanization powered by internal combustion engine, commercial fertilizers, and chemical pesticides. The impact of the advent of the fossil fuel-powered tractor on the reshaping of land use in the American agricultural landscape cannot be overemphasized. The vast increase in supply of farm power had two primary results. First, by replacing draft animals, tractors freed up some 40 million ha (100 million ac) of cropland that had been used to grow feed for work animals, and second, they provided the power required to till the acres that were shifted from pasture and hay production to row crops (Olmstead and Rhode 2001).

Despite the tillage transformation, however, prior to WWII most permanent crop production still required adherence to agroecological principles: extended rotations of diverse crops suppressed insects, weeds, and diseases and recycled and maintained organic matter. Biological diversity and rotations ensured modest but steady yields over time (Danbom 1997; Altieri 2000). The introduction of fossil fuel–derived fertilizers and chemical pest control disconnected crop production from the ecological processes that were once necessary, allowing a rapid transformation of agriculture to an even more specialized monocrop production of a handful of commodities. The ecological risks potentially associated with such a great ecological disembedding were attenuated by increasing reliance on agrochemicals while the economic risks were largely addressed through agricultural policies and programs. As Danbom (1997) articulated, "Farmers no longer needed to diversify carefully, rotate crops, or cooperate with neighbors to minimize their risks; thus, they imperiled the environment and contributed to community deterioration."

Indeed, post-WWII subsidized short-term risk minimization, whether through increased reliance on fossil fuels–based technology and agrochemicals or government programs, combined with overall increases in dependence on purchased inputs, had insidious side effects: it raised land values and tightened profit margins (Danbom 1997). This cost-price squeeze dynamic, along with rapidly changing technologies centered on increasing yields in specialized commodity production, led to overproduction and the "agricultural treadmill" effect that both spurred increases in farm size among operations that adopted new productivity-enhancing technologies, and hastened failure of farms that did not (Cochrane 1993). Simultaneously, monocrop specialization led to increasing pest and weed pressure and evolution of resistances to chemical controls and similar "pesticide treadmill" dynamics that required increases in chemical use over time (Gliessman 2007; Liebman et al. 2016).

## Diffusion of Innovations

It is important to recognize that these radical transformations in production processes, from regenerative systems embedded in local ecologies to productivist systems dependent on external, mostly nonrenewable inputs, were not a natural evolution. In reality, the transformations required substantial efforts by social and biophysical scientists and extension staff at land grant universities, in partnership with the growing agribusiness sector, and state and federal policies and programs centered on "modernizing" agriculture through systematic promotion of adoption and diffusion of new technologies. As the products of agricultural research became available in the post-WWII era, social science researchers, particularly rural sociologists, sought to (1) understand the processes through which farmers adopted new technologies, and (2) use that understanding to promote the widespread diffusion of those technologies (Buttel et al. 1990; Rogers 1995).

Starting with hybrid seed corn, as more chemical and mechanical technologies were developed, diffusion studies were conducted to inform their promotion, for example fertilizers (Beal et al. 1958a, 1958b; Beal and Bohlen 1958) and pesticides (Beal 1956; Beal and Rogers 1958). Research focused on communication, socioeconomic, and social-psychological predictors of technology adoption "was premised not only on understanding the spread of new technologies . . . but also, in general, took a promotional posture toward technological change" (Buttel et al. 1990). Thus, adoption-diffusion researchers generally were part of a larger promotional effort to bring "improved" technologies to farmers whose socioeconomic (i.e., age, education, income, farm size) and social-psychological (i.e., attitudes toward change) characteristics determined their relative "innovativeness" or "backwardness" in relation to new technologies or practices. Investigation of the diffusion of new agricultural technologies occupied hundreds of researchers and produced nearly a thousand publications from the 1940s through the early 1970s when there was a precipitous decline in the number of new diffusion studies, from nearly 20 per year to less than 5 (Rogers 1995).

The main driver behind the relative abandonment of diffusion studies among sociologists was a rising awareness of the negative environmental and social consequences caused by the innovations that they had helped to diffuse (Buttel et al. 1990; Rogers 1995). Criticisms leveled at rural sociologists as lackeys of a "land grant college complex" who placed agribusiness interests ahead of those of the public (Hightower 1978; Newby and Buttel 1980) hastened the demise of diffusion research as a central activity in the field. Nevertheless, the land grant university-agribusiness partnerships that focus research and extension predominantly on high-input, specialized commodity production continue (DeLonge et al. 2016), and their results are reflected in long-term trends, such as the decline in crop species diversity (Aguilar et al. 2015) and historical indifference or even antagonism from the land grant university research and extension establishment toward more agroecologically oriented production systems (National Research Council 1989; Coughenour and Chamala 2000; Duffin 2007).

## Toward a Return to Agroecological Embeddedness

As the brief discussion above indicates, the dominant trend over the last 75 years or so has been a disembedding of agriculture from local ecological processes, primarily through specialization in a handful of commodities undergirded by purchased inputs and government subsidies. And this has occurred, despite, as numerous chapters in this book describe, enormous efforts by the soil and water conservation community to address the negative impacts of the productivist model of agriculture on soils, water bodies, and wildlife habitat. That said, there is a deepening research base showing that specialization, monoculture, and lack of crop diversity are the root causes of our soil and water degradation problems (Hatfield et al. 2009; Hunt et al. 2019) and an increasing recognition that a return to diverse, ecologically embedded systems is the pathway to a truly sustainable agriculture (Gliessman 2016).

So how do we return to an ecologically embedded agriculture? I believe that a renewed commitment to soils and soil health is the cornerstone. As numerous authors in this book so eloquently state, healthy living soil is the ecological basis for a sustainable agriculture. The emphasis that the USDA Natural Resources Conservation Service has placed on soil health in their outreach strategies has resonated with farmers (Arbuckle 2017), many of whom see soil health management as key to increasing the resilience of their operations in a time of increasing weather extremes related to climate change (Roesch-Mcnally et al. 2018). Farmers are learning to pay attention to their soils and evaluate how different management practices can lead to improved or degraded soil health. This, in turn, can lead to longer-term thinking that allows farmers to see past the short-term return-on-investment mentality that specialized commodity production tends to privilege and motivates work toward more resilient, embedded systems that rely less on purchased inputs (Roesch-Mcnally et al. 2018), systems that are becoming known as "regenerative agriculture" (Gosnell et al. 2019).

While a renewed commitment to agroecological principles with soil health as a primary goal is a promising pathway to agricultural sustainability, the vast majority of farmers, however, are not on that path. Indeed, some argue that our dominant productivist agricultural production systems are more decoupled and disembedded than ever, are becoming less resilient to the impacts of climate change, and soil and water degradation are getting worse rather than better (Hamilton et al. 2020). Increasingly, such critiques hold that the voluntary approach that has been the compliance mechanism underlying the soil and water conservation programs and policies of the last 75+ years is woefully insufficient (Rundquist and Cox 2016). Invariably, calls for change emphasize that the policies and programs that shape the behaviors of farmers, agricultural researchers, agribusiness firms, and soil and water conservationists need to challenge the status quo. Indeed, because agricultural and environmental policies and programs set the structural boundaries of what is possible or not in our food system (e.g., shape markets), they must be reoriented to re-embed agriculture ecologically (and socially, for that matter). This is particularly important for farmers, who may understand the potential social, economic, and ecological benefits of transitioning to diversified systems that rely less on purchased inputs and more on agroecological processes, but perceive strong market and other structural barriers to change (Arbuckle 2015, 2017).

In 2009, Wes Jackson and Wendell Berry, two of the most influential thinkers in the realm of agriculture, published an op-ed titled "A 50-Year

Farm Bill" (Jackson and Berry 2009). The visionary proposal, which was developed through a series of meetings nationwide with farmers and farmer groups, outlined a "gradual systemic change in agriculture" (Jackson and Kirschenmann 2009) that would re-embed agricultural systems ecologically and socially through perennialization and increased diversity. A decade on, research-based evidence increasingly shows that diverse agricultural systems that incorporate perennials and continuous living cover are superior to specialized monocultures in terms of productivity, nutrient cycling, disease and pest management, habitat provision, soil health, and other metrics (Patel-Weynand et al. 2017; Schulte et al. 2017; Leandro et al. 2018; Hunt et al. 2019; Weisberger et al. 2019), yet we still have farm policies that privilege the status quo of specialized production of few commodity crops.

The evidence is clear that because the current dominant production systems rely on tillage that degrades soils, fossil fuel-based fertilizers that degrade water quality and contribute to greenhouse gas concentrations, and agricultural chemicals that harm biota and are increasingly ineffective as resistances mount, they are vulnerable and untenable over the long term. The evidence is also clear that the path to truly sustainable agriculture is through re-embedding agricultural systems in local ecologies. We need a policy pathway, such as a 50-Year Farm Bill, to move us decisively toward that goal.

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# 4

# Social Understandings and Expectations: Agricultural Management and Conservation of Soil and Water Resources in the United States

*Lois Wright Morton*

Social understandings of humans, their relationships with the land, and how they value and manage soil and water resources are built on the sciences of sociology, anthropology, political science, psychology, and economics. The "sociological imagination," of C. Wright Mills views the social nature of humans and their daily experiences from many perspectives and attempts to reconcile the two abstract concepts of the individual and society so as to see what *is* real and what *could become* real (Mills 1959; Crossman 2020). As we look at soil and water conservation challenges over the decades, seeing what is real—increased agricultural productivity concurrent with increased soil erosion, water degradation, and compromised ecosystem integrity—provides necessary feedback for changing the social narrative to what could become real—healthy soils, quality water, and resilient ecosystems alongside improved agricultural productivity and profitability.

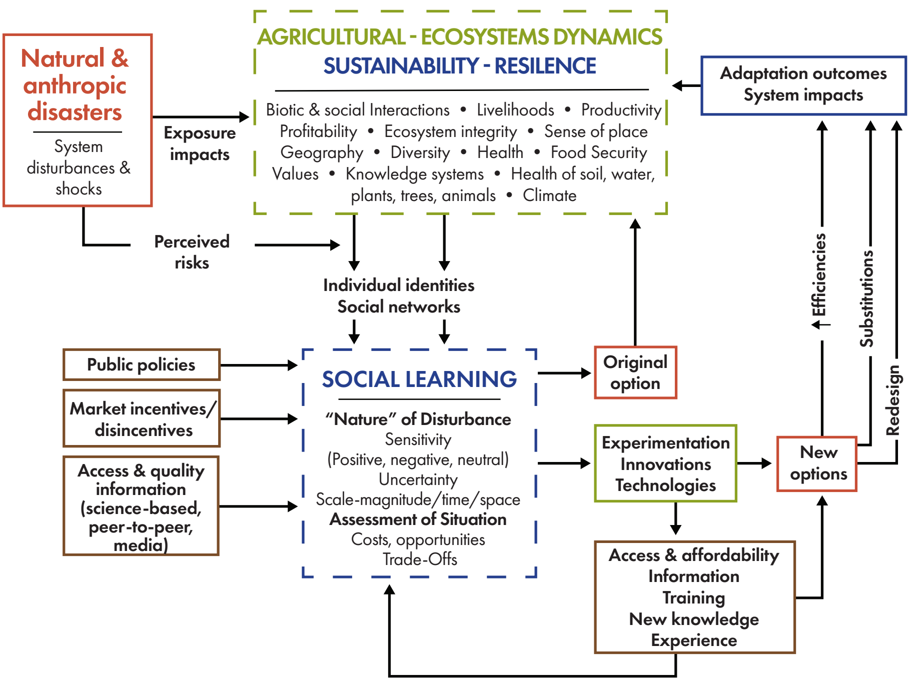
Social understandings of agriculture are built on analyses of historical and current events as well as future expectations. Human narratives are drawn from individual knowledge and experiences, values, social norms, and worldviews in the context of social and economic structures and environmental conditions.

**Lois Wright Morton** is professor emeritus in the Department of Sociology, College of Agriculture and Life Sciences, Iowa State University, Ames, Iowa.

The transitions from farming to raise one's own food and clothing to a commercial enterprise with the purpose of securing a profit and livelihood to the sustainable coproduction of productivity, livelihoods, and ecosystem integrity are phenomena that have transformed land management over the history of the United States (Warren 1913; USDA 1948; Chapin III et al. 2009; Hatfield and Morton 2013; Olson et al. 2017). Social-economic-environmental transitions and transformations are often catalyzed by natural and anthropic disasters—system disturbance and shocks that alter agricultural systems; human learning, beliefs, perceptions, and behaviors; and the ecosystem itself (figure 1). The ruined livelihoods and soil erosion crisis from which the Soil and Water Conservation Society was born began with a major system disturbance, a natural climate event—drought—fueled by anthropic farming practices that compromised the ecology and productivity of the Great Plains of the United

**Figure 1**

**Agricultural-ecosystem relationships are dynamic, nonlinear, and continuously changing over time and space. Human capacities for social learning are influenced by perceived risks from natural and anthropic system disturbances and the internal and external resources available to experiment, innovate, find new options, and adapt in ways that lead to desired sustainability and resilience outcomes in agricultural-ecosystems.**



States and brought disaster. Today the 1930s Dust Bowl serves as a historical reference point and catalyst for how soil, water, and agricultural ecosystems are viewed, valued, and managed by humans and society.

## The Farmer and Production Agriculture

One primary function of soil has dominated human history: its capacity to grow plants for food, clothing, and energy. Suitability of the soil to perform crop production has influenced US settlement patterns, the price of land, soil classification and functional uses, and farm management education (Warren 1913; Hatfield and Morton 2013; Olson and Morton 2016). The science of managing the soil and the training of farmers to increase practical agricultural knowledge and skills were the genesis of the land grant university system funded by Morrill Acts of 1862 and 1890. The University of Illinois at Urbana–Champaign dedicated Davenport Hall on May 21, 1901, with President Andrew S. Draper's quote inscribed over the front of the building, "The wealth of Illinois is in her soil and her strength lies in its intelligent development." The classic college Bailey series textbook, *Soils, Their Properties and Management*, published in 1909 and used at The Ohio State University, links soil formation to food production before launching into 764 pages of soil formation, structure, moisture control, acidity, amendments, tillage, and irrigation. The editor explains, the "debris of rock and plant residue that has accumulated through the centuries of struggle is the arable soil from which man obtains his bread" (Lyon et al. 1909).

Turn-of-the-century agricultural education curricula were designed to move farming from subsistence to a profitable occupation, a commercial business enterprise that generated surplus products for off-farm sales. The preface of the 1913 Bailey series on *Farm Management* describes the course as, "the science of the organization and management of a farm enterprise for the purpose of securing the greatest continuous profit" (Warren 1913). The first chapter of the textbook poses the question, "Shall I be a farmer?" It then elaborates on the personal characteristics desirable for a successful farmer: business man, mechanic, naturalist, and skilled laborer; and states clearly this is not an occupation for inefficient people (Warren 1913). These early themes, the farm as a business that makes a profit and the need for the farmer to be a naturalist who by observation of plants, animals, and the land acquires experiential knowledge and combines it with scientific investigation, run deeply through modern US agriculture.

Fifty years later, in the preface to the United States Department of Agriculture's *Grass, The Yearbook of Agriculture 1948*, Secretary of Agriculture Clinton Anderson reaffirmed the importance of the farm as a profitable livelihood: "To the farmer, security means year-to-year and generation-to-generation assurance that he can use his land as it should be used, free from fear of boom or bust; that he will have a fair market for the products of his soil and toil; and that he will get the amenities that he earns. So that he can serve community and country" (USDA 1948).

Although focusing on farm profitability, Secretary Anderson observed, it is time to give less emphasis "…to commodities likely to produce surpluses and instead direct more attention to practices designed to sustain the productivity of our soils" (USDA 1948). Thus, the *Grass Yearbook* served as a public marker for peacetime achievements in agricultural production post-World War II *and* an acknowledgement of the "extraordinary burden on the land" that cultivated crops place on soil and water resources. The authors called for a more balanced agriculture or permanence in farming systems through land use practices that revolve around a diversity of grasses, legumes, and livestock farming.

The concept of "permanence in farming systems" was a precursor to the language of "sustainability" and the increasingly urgent calls from scientists, practitioners, and farmers of the necessity to learn from the past and to use grass as a tool against floods, to guard water supplies, and replenish soils. It would be many years before "sustainability" in agricultural production systems became a central research concept that biophysical and social scientists attempted to measure. The General Assembly of the United Nations in 1983 created the World Commission on the Environment and Development and raised global awareness of critical food security and environmental issues associated with population growth, poverty, gender inequity, and wealth distribution that limit economic and social development (WCED 1987). Known as the Brundtland Report (1987), the Commission documented past successes and failures, defined sustainable development, and called for international cooperation and policies to address sustainability that rebalance the "interlocking crises" of human-ecosystem relationships in agriculture, energy, and trade sectors with environment, social, and economic concerns (WCED 1987).

Despite this report, many farmers, agricultural industries, and their value chains continued to view sustainability as a novel, unresolved, and contested concept. It was not until 2010 and the National Academy of Sciences volume, *Towards Sustainable Agricultural Systems in the 21st Century*, that the parameters of sustainable agriculture (human food, feed, fiber, and energy; environmental quality and the resource base; economic viability of agriculture; and quality of life for farmers, farm workers, and society) were again explicitly delineated (NRC 2010) and received broader acceptance by the US agricultural sector.

The framing of farming as an occupation; cyclical natural and anthropic conditions; rare system disturbances and disasters and their interactions and impacts on productivity, soil, water, and other ecosystem resources; and the modernization of US agriculture are the scaffolding that social scientists use to decode and make sense of when, how, and why farmers manage and adapt (or not) to changing conditions. Areas of research encompass individual perspectives, values, social identities, and decision making and structural and institutional arrangements that affect public policies and programs, markets, and incentives/disincentives that influence land use priorities and practices. Farmer interviews and surveys of cropping systems—perceptions of how to best manage soil and water resources—date back to the late 1970s (Davis 1977; Batie 1982; Nowak 1983, 1987; van Es 1984; Swanson et al. 1986; Kraft et al. 1989; Romig et al. 1995; Walter 1997; Coughenour and Chamala 2000). While the social sciences are increasingly funded to investigate, hypothesize, test, and reformulate models that might describe, explore, and explain agricultural-ecosystem complexity, gaps in our knowledge remain.

## Social Science Research on Agriculture and Conservation

Since the establishment of the federal Soil Conservation Service in the 1930s, efforts that encourage landowners to adopt soil conservation practices on privately owned agricultural lands have been an ongoing challenge (USDA 1948; Hatfield and Morton 2013; Prokopy et al. 2019). Social science research on patterns of human behaviors, social relations, language, societies and cultures, values, and beliefs encompass a wide variety of qualitative and quantitative methodologies ranging from ethnographic (long-term field work), historical, comparative, and empirical study by observation, interviews, experimentation, systematic analyses, and cross-sectional and longitudinal survey work. The Rural Sociological Society, founded in 1937, initiated and continues to conduct research examining rural life and livelihoods, agriculture and food systems, soil and water conservation, environmental conditions, community and organizational structures, demography, and adoption and diffusion of technologies.

Agricultural research on soil and water conservation practices in the 1950s and 1960s established the effectiveness of a variety of new technologies. Conservation tillage (no-till, strip-till, ridge-till, zone-till, mulch-till, deep tillage, and seasonal residue management) continues to be accepted as an effective method for reduction of cropland soil erosion by wind and water (Reeder and Westermann 2006) and for storage, retention, and sequestration of soil organic carbon (Olson and Al-Kaisi 2015). However, documented research on the scientific effectiveness of conservation practices does not necessarily translate into landowner implementation of these technologies. There was (and is today) a need to understand what farmers are thinking, how they view and value conservation, and factors that influence decisions to move (or not) to different systems of land management.

In the 1950s, rural sociologist C. Milton Coughenour became one of the first to explore why farmers continued their "plow culture" of planting crops in a finely tilled seedbed rather than planting crops in untilled or minimally tilled ground. He and other sociologists developed and tested theories of decision making, the processes of diffusion of new agricultural innovations, and the role of "change" agents in the sociocultural revolution in cropping agriculture (Coughenour and Chamala 2000). They discovered that this new agriculture represented new knowledge and understandings of soils, the environment, the biology and ecology of plants and pests, and their interactions—and that new learning needed to take place for farmers to change their current system (Coughenour and Chamala 2000). No-till cropping systems were found on 37% of US cropland in 1998, and an almost identical rate (37.5%) was found in 2012 in the upper Midwest Corn Belt, despite significant public federal and state dollars invested in technical assistance and financial cost sharing (Comito et al. 2012; Morton et al. 2015).

Changes in agricultural practices to address impaired water resources from field and off-farm nitrogen and phosphorus runoff into neighboring streams have similarly been elusive despite high profile hypoxia research, US Environmental Protection Agency impaired water designations, and media reporting (Comito et al. 2012). Ribaudo and Gottlieb (2011) report about 35% of all US crop acres receiving nitrogen follow all the best management practices to reduce off-field nitrogen losses. This means almost two-thirds of fertilized crop acres are *not* being managed as effectively as they could be to reduce water impairments.

Renewed research on cover crops is finding this practice addresses a multitude of agriculture-ecological management needs: reducing soil erosion, retaining soil organic carbon, reducing water runoff, and absorbing excess crop nutrients. The Sustainable Agriculture Research and Education–Conservation Technology Information Center recently reported that cover crop acreage doubled from 2011 to 2016 (Basche and Roesch-McNally 2017). This is promising, but farmer adoption of cover crops remains low. The 2012 Census of Agriculture reports cover crop acreage on only 3.2% of US harvested cropland, and a 2012 survey of Midwest corn-soybean farmers finds only 6% of acreage planted to cover crops (Morton et al. 2015). **The need to understand social and human factors within agricultural-ecosystem dynamics has never been greater. There is a need for both theory and data to theorize, develop, and**

**test models that better represent the complexity of human-natural relationships in agriculture.**

Public and private organizations and labs, including the land grant universities and USDA Agricultural Research Service, have invested heavily in agricultural, climate, and biophysical sciences to increase knowledge about soil, water, crop physiology, hybridization, insects and disease, crop management, weed control, engineering, and innovations in equipment and other technologies. However, it was not until the early 2000s that federal government grant opportunities emphasized inter- and transdisciplinary science proposals that integrate social sciences with the agricultural biophysical sciences to address coupled human-natural agricultural systems (Prokopy 2011; Eigenbrode et al. 2014).

Simultaneously during this period, ecological scientists accelerated efforts to establish principles of the earth's ecosystems and began to construct system models that included humans and their societies (Jackson et al. 2010; Miller et al. 2012). Halle and Fattorini (2004), in *Advances in Restoration Ecology*, write, "…restoring lost systems must include humans; otherwise, the restored habitats will soon be lost again, since the very reason for the initial loss has not changed…" Humans are the "black box" that social scientists are working at unpacking (McCown 2005; Dunlap 2008). Halle and Fattorini (2004) call for human-natural systems conceptual frameworks that recognize human learning as part of the system. Further, they note that lack of good theory hinders the capacity of scientists to solve system-specific problems.

## What Do We Know about Adoption of Agricultural Conservation Practices?

Social scientists use three approaches—qualitative, quantitative, and mixed methods—to develop and test theories about human behavior, social relations, and structures in agriculture. Depending on the questions of interest, prior evidence, and the complexity of human-natural systems under investigation, both inductive (observational, hypothesis-free) and deductive (standard hypothesizing) approaches are utilized.

Prokopy (2011) elaborates the uses of these approaches and their complementarity in mixed research design in the *Journal of Soil and Water Conservation* (JSWC) paper "Agricultural Human Dimension Research: The Role of Qualitative Research Methods." Inductive approaches can identify emerging concepts and events, help define research questions and relevant hypotheses, and ground-truth models that may be statistically significant but not realistically represent the phenomena that exist (Ranjan et al. 2019). A variety of paradigms, including interpretivism, phenomenology, and constructivism, utilize qualitative data such as interviews, observations, and archival materials.

"Meaning" is considered by many social scientists as socially constructed by individuals and their societies. Thus, qualitative data are particularly useful in decoding language, shared meanings, and the multiple belief systems and realities held by humans.

Deductive research, represented by hypothesis testing using quantitative methods such as surveys, seeks to uncover key variables or factors that significantly influence or predict specific outcomes. Survey methodologies have been used to examine farmer and landowner attitudes and opinions; production practices and conservation behaviors; motivations for how lands are managed; perceptions of soil and water management; farmer decision making; and how farmer identities influence soil and water conservation practices (Dillman 2000; Lubell et al. 2013; Arbuckle et al. 2015, 2017; Weber and McCann 2015; Morton et al. 2017).

The JSWC has published two classic papers that summarize the quantitative social science literature of the last 35 years on adoption of agricultural conservation practices (Prokopy et al. 2008; Prokopy et al. 2019). These papers identify several key trends that are critical for benchmarking current knowledge and guiding future social science research. Both 2008 and 2019 analyses reveal that "few independent variables have a consistent statistically significant relationship with adoption" of agricultural conservation practices (Prokopy et al. 2019). Further, in the 2019 review of 92 studies, more than three-quarters of the variables hypothesized were not statistically significant. Those factors most frequently reported significant and positively associated with adoption of conservation practices were self-identified stewardship ethic, attitudes toward the environment, awareness of a program (and positive attitudes towards the specific program), previous adoption of new practices, seeking and using information, erodible lands, larger farm size, higher levels of income and formal education, expectations of positive yields, and marketing arrangements (Prokopy et al. 2019).

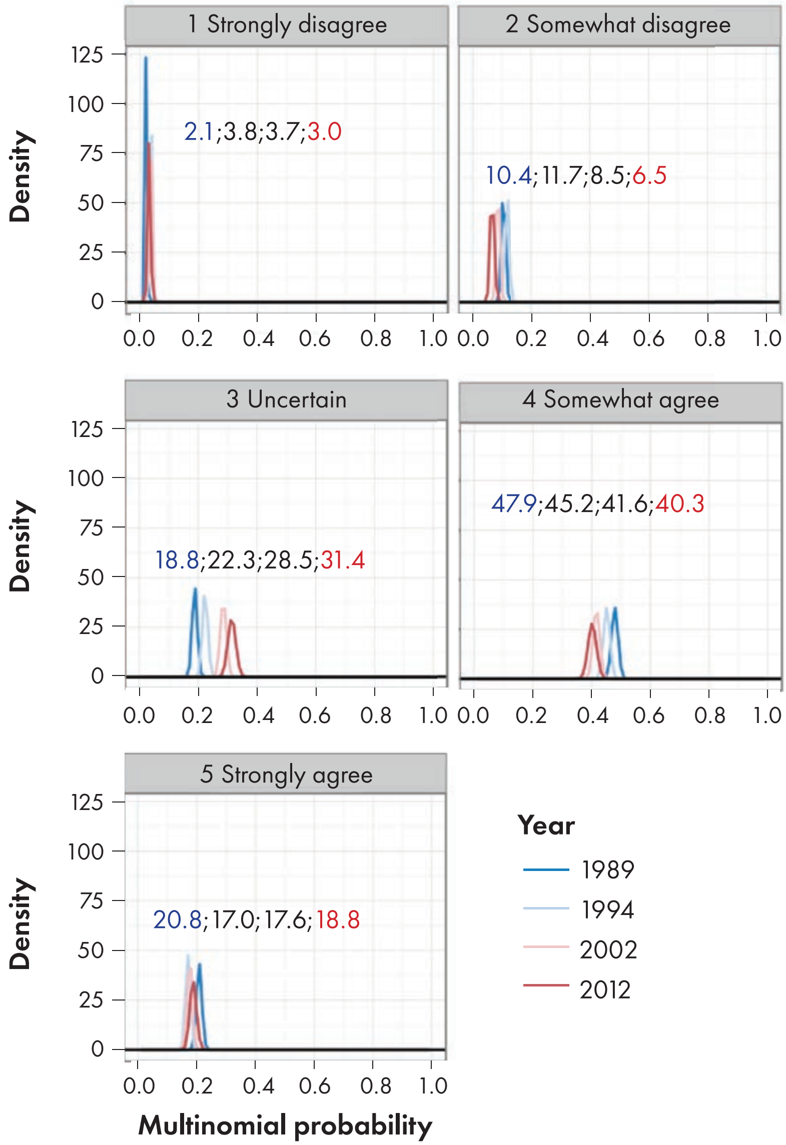
Although a number of studies applied current social science theories (e.g., attitudes toward behaviors, theory of planned behavior, values-beliefs-norms, and adoption-diffusion of innovations) to develop and test hypotheses, one-third did not use any theory in their research (Prokopy et al. 2019). More critical is that current theories are rather narrow in scope and do not represent well the complexity of individual and structural factors within human-natural systems relationships.

## Looking Toward the Future

Farmers are increasingly uncertain about whether increased use of sustainable farming practices will help maintain natural resources, such as soil and water (figure 2). Although surveys of Iowa farmers show most farmers over

## Figure 2

**Farmer uncertainty in the belief that, "increased use of sustainable farming practices would help maintain our natural resources" (1989 to 2012) has almost doubled over a 23-year period. Data below are from the Iowa Farmer and Rural Life Poll longitudinal survey asking whether farmers "strongly disagree, somewhat disagree, are uncertain, somewhat agree, or strongly agree" with this statement. Adapted from Morton et al. (2013), including unpublished 2012 data.**



a 23 year period agreed or strongly agreed that sustainable farming practices would help maintain our natural resources (Morton et al. 2013), an increasing number seem uncertain: 18.8% of farmers in 1989 were likely to be uncertain; by 2002, 28.5% were likely to be uncertain; and by 2012, almost one-third were likely to be uncertain.

What does this increasing uncertainty mean for the future of soil and water conservation in agricultural systems? Does increasing uncertainty suggest that new experiences with increasingly variable and extreme weather events, or accelerated rates of on-farm soil erosion, and/or disruptions in markets are shifting perceptions of sustainable farming practices and their effectiveness? Farmers have always made decisions in highly insecure and unstable conditions (Nieuwoudt 1972) and face many kinds of risk: production risks, price risks, and technology risks (Hamsa and Veerabhadrappa 2017). Public policies, insurance products, and expert advice have traditionally depended on economic measures of risk and complex models that estimate risk and probabilities of outcomes. These have been critical tools in helping farmers manage risk. Risk can be measured, but the uncertainties that drive risk cannot be measured or estimated. No amount of mathematics or technical adjustments change the fact that we are not able to know with certainty the future (Davidson 2010; Taleb 2014; Hamsa and Veerahadrappa 2017).

Are the uncertainties increasing in ways and at rates that make it more difficult for farmers to assess risk, evaluate their options, and make decisions? According to the Fourth National Climate Assessment, "The earth's climate is now changing faster than at any point in the history of modern civilization," and change is projected to intensify in the future (US NCA 2018). Rising temperatures, extreme heat, drought, wildfire on rangelands, and heavy downpours are expected to occur more frequently and increasingly disrupt US agricultural productivity (US NCA 2018). Climate is not the only uncertainty disrupting agriculture. The 2019 to 2020 coronavirus pandemic up-ended agricultural markets, food distribution systems, and food security in the United States and worldwide, leading to chaotic, unpredictable chain reactions (Torero 2020). Nature is nonlinear. The odds and impacts of rare events cannot be accurately computed due to lack of sufficient prior data, e.g., we have more data on 5 year floods than on 100 or 500 year floods (Taleb 2014), and we've never had a global pandemic of this magnitude before (Torero 2020).

Increasing natural and anthropic disasters and rates of system disturbance and shocks are exposing agriculture, soil, water, and Earth's ecological systems to unprecedented system-wide uncertainties (figure 1) (US NCA 2018). There is a need to better understand human internal perceptions of these events and external factors, such as social networks, public policies, market incentives, and access to science-based as well as peer-to-peer information, that influence the social meanings assigned to uncertainties and associated risks. What are the social learning processes that farmers are using to deal with uncertainty and make decisions? What factors dominate reevaluation of current practices and willingness to seek new options to address uncertainties and perceived risks? How are they deciding to hold steady (stick with original options) or adapt by increasing efficiencies, substituting technologies and practices and/or redesigning their farm systems (Morton et al. 2015; Pretty 2018)? When uncertainty is large in the system, is this an opportunity for innovation and learning to occur and a willingness to change? Or does the uncertainty at some threshold paralyze decision making and become a barrier to change and innovation?

Cultivated ecosystems cover more than 25% of the earth's land surface and "as much as six times more water is held in reservoirs than flows in natural river channels" (Walker and Salt 2006). Although climate change is one of the most prominent threats to our planet, water scarcity, poor water quality, degraded dryland and loss of wetland ecosystems, and overharvesting of marine fisheries already compromise the earth's ecosystems. Addressing changing climates, food security, commodity transport and national security associated with river and lake navigation, and water quality and supply will require new knowledge and new approaches to managing soil and water resources. **Key attributes of the future will be episodic change, unpredictability, increased uncertainty, conflicting social values and interests about land and water uses, and contested views about managing the earth's resources** (Holling 1996; Taleb 2014; Olson and Morton 2016; Pretty 2018).

Two concepts, sustainability and resilience, are front and center as humans reimagine their futures and seek solutions. Resilience assumes that change will occur and that biophysical and human systems will attempt to adapt. If successful, the system has resilience. "The measurement of resilience is the magnitude of the disturbance that can be absorbed before the system changes it structure... (Holling 1996)." What is the magnitude of disturbance an agricultural ecosystem can endure before it tips over into a different kind of system? Should resilience always be the goal or should we be embracing randomness, uncertainty, and volatility (Davidson 2010)? (This has been termed "antifragility." Taleb [2014] defines antifragile as being "beyond" resilience and robustness. Resilient means resistant to shocks and stays the same. Antifragile is the property of change in all natural and complex systems that have survived and thrived under conditions of randomness and uncertainty.) What roles will humans play in slowing or accelerating change and/or adapting to new conditions? These are human-society questions that can only be answered when biophysical and social sciences integrate knowledge, theories, and data in the search for new knowledge and solutions.

There is an urgent need for new models of human-natural systems and the integration of sciences with many kinds of disciplinary knowledge along with practitioners', landowners', and managers' experiences and knowledge. Figure 1 illustrates a conceptual framework that places human social learning as a key variable in responding to the uncertainties of system shocks and disturbances and capacities to experiment and evaluate technologies, innovate, and adopt new ways of thinking to find new options that could improve the resilience of agricultural-ecosystems and sustain soil and water resources into the future.

Agriculture should not be viewed as a "threat" to soil and water resources but rather a sector of human activity that is essential, whose future practices humans can shape (Kareiva 2011). The research society choses to invest in is value driven. If scientists, farmers, consumers, agribusiness, and governing agencies are to move toward a multifunctional agriculture that provides individual and societal benefits, we must talk with each other to learn what we value; we must together negotiate goals and actions that sustain society and increase capacities to thrive under the unexpected and future uncertainties.

## Resources to Learn More

- The Farmer's Decision: Balancing Successful Agriculture Production with Environment Quality. 2005. Edited by Jerry Hatfield. Ankeny, IA: Soil and Water Conservation Society.
- Resilience Thinking: Sustaining Ecosystems and People in a Changing World. 2006. Brian Walker and David Salt. Washington DC: Island Press.

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# 5

# A History of Economic Research on Soil Conservation Incentives

*Steven Wallander, Daniel Hellerstein, and Maria Bowman*

**Soil conservation is a physical and technological problem, as well as economic, and it is essential that the interrelationships between these two aspects be clearly seen. The physical specialist needs to understand the economic implications of physical changes just as the economist needs to understand the physical factors which underlie the problem.**

**— Arthur C. Bunce, 1942, *The Economics of Soil Conservation***

Do farmers undertake "enough" soil conservation efforts? If not, why? The tools of economics are designed to help policymakers and conservation planners answer both of those questions. With these tools, economists define and measure the private and public benefits and costs that influence choices of soil conservation activities. In this chapter, we review the history of these tools. Based on scientific advances in our knowledge of soil processes, hydrology, water chemistry, and other areas, economists have improved our understanding of how the incentives to undertake immediate soil conservation actions are related to current costs, future on-field benefits, and future off-field benefits. A variety of policy options are available if these incentives are not properly aligned, but every policy option faces its own set of complex incentives.

Soil conservation economics cannot be summarized by a single value for soil. Like soil itself, the value of soil conservation practices are highly variable.

**Steven Wallander** and **Daniel Hellerstein** are economists with the USDA Economic Research Service, Washington, DC. **Maria Bowman** is lead scientist for the Soil Health Partnership, National Corn Growers Association, Chesterfield, Missouri.

Spatial and temporal variation are tremendously important, especially for economic analysis of conservation policy. Other variation in the value of soil, particularly around the multiple benefits that come from conserving soil, is often the primary focus of soil conservation economists.

## The Early Foundations: Environmental Externalities

Most of the tools that economists currently use—dynamic optimization models, partial equilibrium models, econometrics, game theory, risk aversion models, and market and nonmarket valuation methods—were developed within the past 50 to 75 years. The idea of environmental externalities, which is the framework for applying these economic tools to analysis of soil conservation, has much earlier origins.

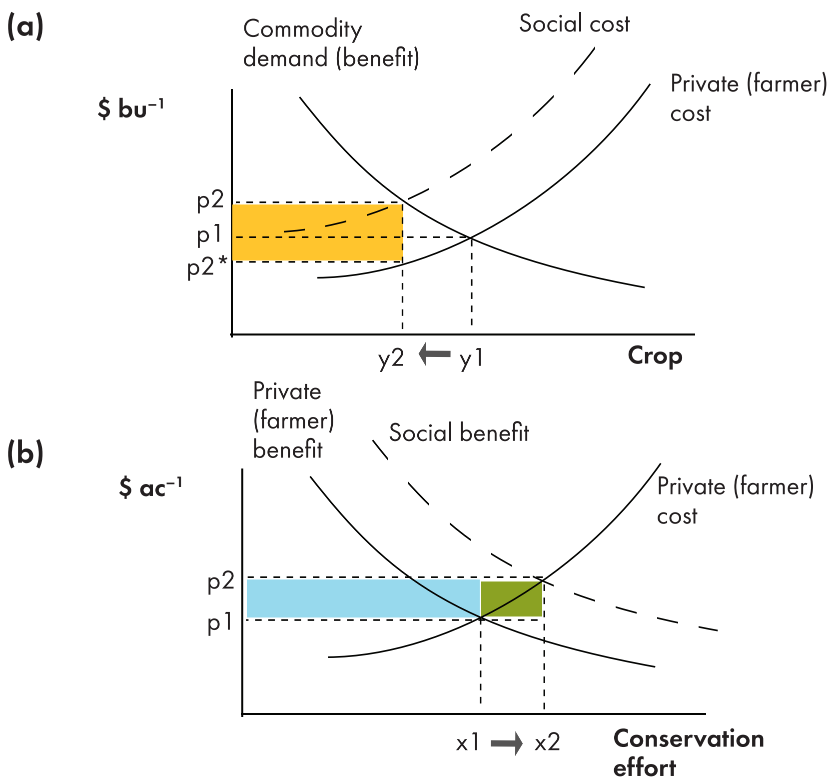
Concern over the potentially detrimental impact of agricultural production on neighboring individuals was noted as far back as the late 1700s by the Marquis de Condorcet, as detailed in Sandmo (2015). Condorcet argued that a sufficiently negative impact could justify restrictions on where agricultural production can occur, making perhaps the earliest proposal for rural zoning.

By the late 1800s, economists had developed the core mathematical system of demand and supply curves. Modeling market incentives in this way allowed economists to explore the implications of changes in marginal benefits (demand) and marginal costs (supply). In this framework, the observed allocation of any good (e.g., cars, electricity, corn, or doctors) is an equilibrium outcome captured in both quantity and price for that good. Changes in many other factors (e.g., policies, income, or other prices) can shift either the demand or the supply curve leading to a new equilibrium. Fitting the "good" of soil conservation into this framework required a number of additional developments in the field.

Pigou (1920) incorporated the issues raised by Condorcet and others into this supply and demand framework by conceptualizing pollution as an "externality." In Pigou's treatment, the negative impacts of pollution are costs imposed on the damaged parties and, most importantly, are not reflected in the production decisions of the polluting firms. In other words, firms make decisions on how much output to produce based on their costs, but those costs do not include disposing of or abating their pollution. Pigou's model is an enormously important tool for economists because it provides the theory on which to identify the equilibrium associated with a baseline in which some costs, such as the off-site impacts of conventional agricultural production, are ignored by markets, and also to identify the optimum allocation of resources that would occur if policy could fully "internalize" all of the costs and benefits of pollution abatement (figure 1a). The important feature of externalities is

**Figure 1**

**Two models of soil conservation as an externality: (a) Pigou's model where negative impacts of crop production are an external cost in crop production; and (b) an impure public good model where the social benefits of soil conservation get added to the private farmer benefits.**




**Notes: Under (a), Pigou's model of pollution as an external cost within the market for a production output, internalizing the social costs of crop production will lead to a decrease from the initial equilibrium (y1) to the social optimum (y2). This change can occur with a Pigouvian tax on crop production of p2 – p2*, which increases the price that consumers pay from p1 to p2 and decreases the price that producers receive from p1 to p2*. The tax generates revenue of y2(p2 – p2*) shown as the yellow box. Under (b), an impure public good model of soil conservation effort, the private benefits and costs to farmers lead to an equilibrium amount of conservation effort of x1. Incorporating the public benefits through a subsidy of p2 – p1 on all conservation efforts increases the amount of total effort to x2. The subsidy costs x2(p2 – p1). The portion shown as the green box is the revenue that goes to the "additional" increase conservation effort. The portion of that cost shown as the blue box is payments to conservation effort that would have been undertaken without the subsidy based only on the private benefits, which is called "nonadditional" spending.**

that they represent a form of market failure because the costs associated with pollution will remain external to market decisions without some sort of policy response. Essentially, the model says that some activity, in this example crop production, causes a certain amount external damages, and taking those into account would lead to less of that activity. Although rarely implemented as an actual policy, the use of a tax equal to the marginal value of external damages would be effective at reducing the total amount of the polluting activity. While policy tools other than taxes can also be used, this modeling framework only provides specific policy insights if external costs can be appropriately modeled through use of damage functions. For example, a damage function for coal-fired electricity generation would map the megawatts of electricity generated from coal-fired plants into a dollar value of damages.

Pigou's framework eventually became a cornerstone of environmental economics, but it took a long time. Initially, within the subtopic of the economics of soil conservation, many economists remained skeptical that there could be significant externalities associated with poor soil management practices, arguing that most of the benefits of soil conservation accrued on the farm (Ciriacy-Wantrup 1947). The focus on the private on-farm benefits of soil conservation did ultimately contribute to increased efforts of soil conservation as agronomists and farmers learned more about the link between their management decisions and outcomes such as long-run productivity. However, alongside this on-farm focus, the public off-farm benefits of soil conservation also began to play a major role in both policy and in the study of soil conservation economics.

Bunce (1942) directly attempted to incorporate Pigou into soil conservation economics, but he argued that the main externality involved was increased flooding due to more rapid runoff and higher downstream peak flows from more poorly managed soils. Most of Bunce's analysis was focused on specifying the drivers of erosion, which he viewed as representing a permanent loss of productive capacity, and of depletion of soil nutrients, which he viewed as replaceable with other inputs (such as fertilizer). On the issue of erosion, Bunce focused on the role of commodity markets in driving the rapid expansion of cropland in the 1910s and 1930s. For both erosion and nutrient depletion, he outlined the factors that can influence the on-farm benefits of investing in conservation efforts: interest rates, cash crop rotation, specific soil characteristics, land ownership and tenure relationship, and even education levels. Much of the research at this point, though, was theoretical and somewhat heuristic, lacking detailed mathematical structure. In part, this reflected the fact that the relationships between soil characteristics, crop yields, and nutrient requirements were not precise enough to support detailed economic models.

The early attention to on-farm benefits was consistent with the belief that a lack of information and limited sources for education were the primary reasons for insufficient soil conservation efforts. The creation of the Agricultural Extension Service in the 1914 Smith-Lever Act was an effort to address this issue. A greater focus on the difference between the private and public benefits of soil conservation would come in the 1970s and 1980s. The full implications of these different benefits, particularly in the context of voluntary conservation programs, received much greater attention in the 1990s and 2000s (Segerson 2013).

## Recent History: Targeting Conservation Using Public Net Benefits

Modeling environmental externalities in soil conservation was initially difficult. Not surprisingly, the details of how environmental systems convey, filter, and concentrate pollution have significant implications for the economics. Pigou's model simply asserts that certain production activities—such as farming—impose external costs. Future research would have to specify the mechanism through which these costs are imposed and figure out how to measure these costs.

As the physical sciences revealed the mechanisms behind different types of pollution—the nutrient cycle, water chemistry, hydrology, hydrogeomorphology, the carbon cycle, and climatology—economics followed along. Economists were concerned that simple descriptions of environmental externalities, such as Garrett Hardin's idea of the "commons," were not adequate descriptions of all types of pollution (Hardin 1968). In response, during the 1960s and 1970s economists developed a framework for characterizing different types of "goods."

The two most commonly studied goods within this framework are private goods and public goods. Private goods, such as agricultural commodities, can only be used by one person at a time. They are both "excludable" and "rival." Public goods, such as clean air and water, can be enjoyed by anyone and everyone simultaneously.

The challenge of soil conservation, from an economic perspective, is that it has elements of both private and public goods. The on-field benefits, such as productivity, are generally private goods that benefit a single user, the farmer. The off-field benefits, such as abatement of pollution in runoff, are generally public goods that benefit many users, such as everyone downstream in the watershed (Clark 1985). To address situations where a private good, such as the benefit of soil productivity to a farmer, is supplied jointly with a public good, such as the benefit of reduced nutrient losses to streams and lakes, economists define the joint good as an impure public good, which allows for better empirical models of the concepts raised by Bunce and Ciriacy-Wantrup.

To reconfigure Pigou's model based on the idea of impure public goods, we define the equilibrium in terms of soil conservation activity (figure 1b). Based on the private benefits and costs, a certain amount of soil conservation (x1) will occur at the baseline per acre cost (p1). Reaching the optimum soil conservation based on both the private and public benefits and the private costs requires a subsidy equal to the marginal public benefits of soil conservation, which increases the total amount of conservation provided (x2). While this model resembles current conservation programs, which use government payments to change the marginal incentives for soil conservation, it also requires detailed knowledge about the public and private benefits of soil conservation. Importantly, public benefits are added vertically to the private benefits due to the nonexcludable nature of public goods. The same is true when looking at public costs in the Pigou version of the model.

Estimating the value of soil conservation is complicated by two issues: the complex biophysical links between conservation practices and productivity, and the time-lags involved in seeing the benefits of good soil management or the costs of bad soil management. A common approach by economists is to use "revealed preference" valuation techniques that use observed data on decisions made by people, such as landowners or farmers or ranchers, to estimate their perceived net benefits of alternative choices (Hansen and Ribaudo 2008). Adopting these estimation tools assumes that farmers understand the links between soil health and farm profits in a way that gets captured in land markets.

For example, hedonic models statistically analyze land prices or cropland rental rates to estimate the value of a marginal ("small") improvement in some parameter of soil quality (Palmquist and Danielson 1989). While these studies support the Ciracy-Wintraup idea that farmers understand and incorporate the value of soil conservation into their decisions, a positive hedonic price on soil quality does not rule out the existence of potentially significant externalities. In an alternative approach, some studies simulate the returns to soil conservation using agronomic models of predicted changes in soil characteristics under alternative management approaches to a model of expected net revenue (Colacicco et al. 1989). More recent versions of both structural and revealed preference models include models that estimate the value of risk management benefits from healthier soils (Williams et al. 2016).

Public goods are more difficult to value, but many involve water quality (Holmes 1988). These models require hydrological and chemical models that link on-field conservation efforts to some sort of public good. The economic challenge is putting a dollar value on the marginal improvements in the public good that result from a change in conservation practices. Revealed preference approaches are also common here, although in this case it is the public, not farmers, whose market decisions reveal the extent to which they value water quality or air quality or some other good. For example, by examining where people choose to go for vacation or recreation trips, travel cost models can estimate the impact of water quality on recreational benefits. Hedonic analysis can estimate the impact of water quality on property values. When revealed preference approaches cannot be used, economists often turn to other methods. These include stated preference approaches, which use a survey that is structured to elicit values based on hypothetical choices. Programming tools, another approach, mathematically simulate the underlying choice problem and often include damage function analysis of outcomes such as the impact on water storage and treatment. An additional approach is averting cost analysis, which works for many public health–related benefits (Hansen and Ribaudo 2008). More recent efforts also examine the benefits of soil carbon sequestration (Bradford et al. 2019).

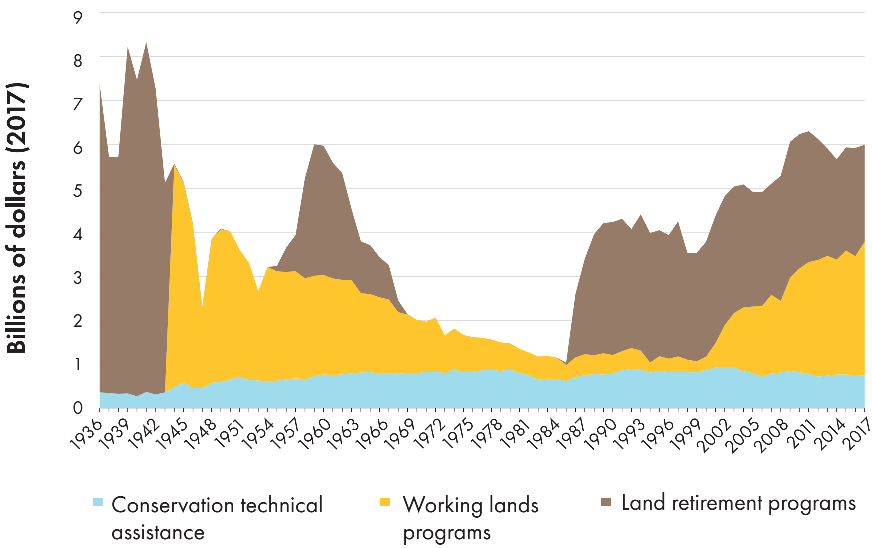
Beyond valuation of the public and private benefits, economic tools involve models of how different policies adjust the incentives for soil conservation. Financial incentives through subsidies for abatement activities, typically through conservation program contract payments and cost share, are common. In contrast, the regulatory approach suggested by Condorcet and output taxes suggested by Pigou are rarely used. Markets for environmental services, such as water quality trading efforts, are a combination of a regulatory approach and the financial incentives approach. The financial incentives in this setting are payments to unregulated individuals, often farmers, to provide an environmental service such as reduced nutrient runoff, which then reduces the regulatory requirement placed on another entity, often water treatment plants or industrial polluters. While various pilots for conservation trading platforms have developed, they are rarely sustained at large scale (Ribaudo et al. 2010).

For any of these policy tools, spatial variation in both the public and private benefits of soil conservation is a critical driver of actual economic outcomes. For at least the past 50 years, economists have studied the implications of different targeting approaches. Targeted policies direct either financial incentives or regulation toward those fields and farmers that will have the highest net public benefits. Early calls for targeting based on soil erosion involved the Conservation Reserve Program (CRP) (Ogg et al. 1982). Importantly, targeting cannot occur without underlying biophysical and economic data. The development of the Natural Resource Inventory provided the basis for understanding regional differences in erosion (Schnepf and Flanagan 2016). The development of parcel-specific measures of soil erodibility based on the

Soil Survey Geographic Database data allowed for targeting of both CRP and conservation compliance provisions (Claassen 2004), both of which targeted highly erodible land. Prior land retirement programs were similar in scale, in inflation-adjusted spending to CRP (figure 2). While the farm economic crisis

**Figure 2**

**Changes over time in three main types of US Department of Agriculture financial incentives for soil conservation: conservation technical assistance; land retirement of highly erodible land (such as the Conservation Reserve Program); and working lands cost share (such as the Environmental Quality Incentives Program and the Conservation Stewardship Program).**




**Updated from Pavelis et al. (2011) using data from US Department of Agriculture Office of Budget and Program Analysis and inflation adjustment to 2017 dollars with nondefense expenditures and gross investment index from the Bureau of Economic Analysis.**

of the 1980s provided a similar motivation for land retirement to earlier crises, particularly the Dust Bowl and Great Depression, targeting made CRP fundamentally different from the earlier programs (Hellerstein 2017). By focusing on higher benefit land, CRP combined a desire for farm support with an effort to correct an environmental externality, the underprovision of what is now referred to commonly as environmental services. However, the Environmental Benefits Index and other targeting mechanisms often are unclear on the distinction between private and public benefits (McConnell 1983). An important aspect of any targeting effort is that they typically impose transaction costs on both program managers and potential participants (Claassen et al. 2008).

Targeting has major implications for the behavior of participants in voluntary conservation programs, whether the land retirement programs described above or for working lands programs, which encourage conservation practice adoption on land that is in active agricultural production. Economists are particularly focused on two issues: whether some portion of program payments is going to participants who would have adopted the conservation practices anyway; and whether any changes in conservation practice adoption leads to compensating behavior (Segerson 2013). The possibility of payments going to conservation practices that would have occurred without payment, which economists call "nonadditionality," is evident in the model shown in figure 1b. For example, working land programs have provided considerable financial assistance for the adoption of no-till production; however, much of the increase in no-till adoption occurred prior to the large increase in working lands programs in the 2002 Farm Act. Other key incentives for no-till adoption include the conservation compliance provisions in the 1986 Farm Act (Claassen 2004) and the adoption of herbicide-tolerant crops, which are much more compatible with a no-till system (Fernandez-Cornejo et al. 2012) (figure 3).

## Future Directions: Program Design, Experiments, and Soil Health

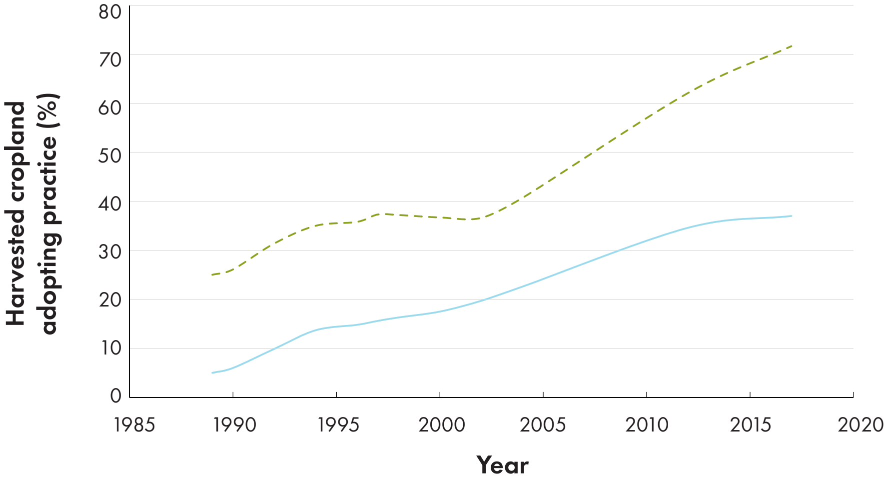
From the early 1940s until well into the 1990s, economists were focused on broad policy questions built largely on theoretical models. Economists tended to ask questions like, How do subsidies for pollution abatement compare to a tax on pollution? Increasingly, economists are focusing on finer details, the sort of policy questions that occupy many program design discussions. One of the seminal calls for this is for economists to work more as "plumbers" in the policy research process, focusing on how to implement a policy rather than the policy itself (Duflo 2017). Within soil conservation, this trend is likely to progress by leading to research that focuses on detailed aspects of conservation auction design (Whitten et al. 2017) and conservation contract structure.

Another major shift in economics is the move toward experimental methods that can answer targeted policy effectiveness questions (Ferraro and Hanauer 2014). When implemented within actual programs, these "field" experiments reveal how seemingly simple decisions, such as sending enrollment reminder letters, can have significant impacts on program outcomes (Wallander et al. 2017).

A third important trend for the future of the soil conservation economics is how economic models will have to adjust to the idea of soil health. In contrast to soil conservation, which largely focuses on the impact of conservation

**Figure 3**

**Trends and major change in incentives for no-till adoption (solid blue line) and conservation adoption (dashed green line) inclusive of no-till based on Economic Research Service Agricultural Resources and Environmental Indicators data (1985), Conservation Technology Information Center data (1990 to 2004), and USDA Census of Agriculture (2012 and 2017).**




**1985:** Farm Act introduces conservation compliance rules

**1996:** Farm Act creates Environmental Quality Incentives Program (EQIP)

**2002 to 2004:** Farm Act quadruples funding for EQIP

**2007:** Herbicide tolerant seed adoption hits 50% for corn

behavior on reducing negative outcomes, the shift toward soil health in policy and science in the United States emphasizes the positive impacts of managing for soil health on soil structure and function, productivity, and environmental outcomes. In part, the growing interest in soil health, which both reflects advancing science and a reframing of traditional issues, is an example of the importance of framing effects, the idea that the language used to talk about an issue can influence behavior (Stevens 2018). Another challenge is the growing recognition that soil conservation practices result in multiple private and public goods. The interaction between these is complex and can lead to competing policy recommendations (Bowman 2018; Bradford et al. 2019).

## Conclusion

Prior to the 1940s, the most important tools for soil conservation economics were theoretical models that recognized the importance of environmental externalities. This development mirrored the early developments in soil science. Over the past 75 years, economics tools have again followed the soil science in recognizing the complex and dynamic nature of soil conservation. On the economics side, this has involved developing tools that capture both on-farm, private benefits and costs, and off-farm, public benefits of soil conservation. Spatial variation in these costs and benefits means that targeting, based on biophysical and economic data, is a critical focus point for economic tools. The future of soil conservation economics is largely centered around the complexity of the policy tools required to move toward better soil conservation outcomes.

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### Disclaimer

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### Resources to Learn More

- USDA Economic Research Service, Environmental Quality. https://www.ers.usda.gov/topics/natural-resources-environment/environmental-quality/
- USDA Economic Research Service Report on Agri-Environmental Indicators. https://www.ers.usda.gov/publications/pub-details/?pubid=93025
- USDA Natural Resources Conservation Service Resources Conservation Act Reports. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/rca/
- Soil Health Partnership. https://www.soilhealthpartnership.org/
- Soil Health Institute. https://soilhealthinstitute.org/
- Center for Behavioral and Experimental Agri-environmental Research (CBEAR). http://centerbear.org/

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# 6

Practitioner's Perspective

# Ecosystem Services Markets Conceived and Designed for US Agriculture

*Debbie Reed*

For the last few decades, a patchwork of compliance and voluntary ecosystem service (ES) markets have operated throughout the United States, targeting different pollutants, from different sources, at varying geospatial scales. Existing markets have never addressed agricultural pollutants in a comprehensive way that is amenable to working agricultural lands. Agricultural production accounts for 8.4% of US greenhouse gas (GHG) emissions (USEPA 2019); is the largest identified source of impairments for rivers and streams (USEPA 2020) and the second largest identified source for lakes, reservoirs, and ponds; and accounts for approximately 80% of consumptive water use (USDA ERS 2020).

Agriculture has not been well covered by ES markets for three primary reasons. These markets treat agricultural sources the same as point sources of pollution. They lack a systems approach capable of comprehensively addressing GHG, water quality, water use, and other ecological challenges on working landscapes. Disparate markets and piecemeal approaches have lacked programmatic investments to integrate technologically advanced data collection, monitoring, reporting, and verification (MRV) capabilities. For several reasons, agricultural producers have been reluctant or unable to participate in ES markets. However, the Ecosystem Services Market Consortium (ESMC), a member-based organization formed in 2019, is designed to incentivize and scale outcomes-based environmental performance across the sector.

**Debbie Reed** is executive director of the Ecosystem Services Markets Consortium (ESMC), Falls Church, Virginia.

The ESMC is launching a national-scale, voluntary, private trading market conceived of and designed for the agricultural sector. ESMC's market was designed based on lessons from past private and public ES market initiatives. Private ES markets are supported by past legislative and policy actions. Section 2709 of the 2008 Farm Bill authorized the US Department of Agriculture (USDA) to "facilitate the participation of farmers, ranchers, and forest landowners in emerging environmental markets." A later USDA Natural Resources Conservation Service policy position allows "all returns to agricultural producers from the sale of environmental credits generated by the adoption of conservation practices, whether or not they are paid for in total or part by USDA conservation programs, accrue to them solely" (Kling and Secchi 2011).

ESMC provides quantified, salable credits representing improvements in soil carbon (C) sequestration, GHG mitigation, water quality impacts, and water use efficiency. Additional attributes such as biodiversity and habitat conservation will be added in 2022 or later. ESMCs innovations include a systems approach to track agricultural impacts, technological development, reduced transaction costs, seamless connections between credit supply and heterogeneous market demand, and market rules that facilitate producer participation while ensuring the integrity of environmental improvements. ESMC's systems approach centers around economic and environmental sustainability and resiliency, tying each to improvements in GHG, water quality, and water use performance. The ability to stack assets based on systems improvements and advanced technology utilization are reducing transaction of credit quantification, monitoring, reporting, verification, and sales. Reduced transaction costs will increase producer profits and thus the incentive to participate.

Both voluntary and compliance markets are governed by rules specifying which entities can generate credits, how, and under what conditions. Conventional market definitions of permanence and additionality used in existing GHG markets are not suited to dynamic, working farms and ranches, but are rather designed for static, more controllable systems like energy production or wastewater treatment facilities. By requiring that projects provision ES in permanence (variably defined as 40 to 100 years) (UNFCC 2014), markets effectively disqualify agricultural producers whose environmental performance changes with climatic variation and fluctuates according to annual crop selection, tillage, and fertilization decisions.

Such vast time horizons do not correspond with producer's planning timelines, ability to manage risk, and status as price-takers in the food and beverage supply chain. For C assets, ESMC sets 20-year permanence requirements for two 10-year enrollment periods, corresponding to the length of time required to build soil C levels to the point of near saturation (West et al. 2013). Water quality and use efficiency assets do not require permanence, because their benefits are not permanent. By relying upon soil C testing and modeling, ESMC's outcomes-based, practice-agnostic approach allows each participant to generate credits how they see fit. In other words, ESMC does not require adoption of a practice or certain practices, but instead allow producers to adopt beneficial practices most likely to enhance outcomes for their systems in their geographies. ESMC's hybrid asset quantification approach combines soil sampling and modeling based on individual producer actions.

Practice-neutrality and a 20-year enrollment horizon reduce the barriers to entry for producers, regardless of management style or size, and allows producers the flexibility they need to make critical management decisions in response to market signals and resource needs.

A revised vision of additionality is also a central feature of ESMCs market. Credits are deemed additional if they represent an environmental improvement that occurs compared to the baseline, which is the environmental status when a participant enrolls. Existing ES markets for agriculture use baselines targeting adoption of specific practices, such that "early adopters" of these practices are typically disqualified from market participation. Markets with baselines corresponding to modest environmental performance might raise stewardship levels of the average producer, but then bring about a plateau past which no additional conservation adoption occurs. Conversely, a high-performance baseline could exclude the majority of producers by requiring significant improvements before they are even eligible to generate credits. Such has been the case with the US Environmental Protection Agency's historic policy on water quality trading, which requires producers to meet their load allocation identified in the watershed's total maximum daily load (TMDL) before generating credits (USEPA 2003). ESMC's approach redefines this issue by setting a baseline for each participant. Individualized baselines incentivize continuous improvement for each participant and have the potential to garner sector-wide participation and to scale outcomes.

ESMC is working with its partners and members to advance the state of science and develop new MRV technologies and platforms to improve asset quantification and verification. For instance, ESMC is making investments in in-field C testing technologies, remote sensing quantification and verification capabilities, and new data management platforms that reduce the transaction costs associated with ES credit generation. A traditional ES credit's value is comprised mostly of incurred transaction costs, meaning the producing entity receives a small portion of the actual credit value.

Remote sensing will allow ESMC to minimize transaction costs associated with MRV. Existing markets largely rely on multiple in-field site visits, often years after practices were changed. The MRV platform will allow producers to seamlessly upload data via application programming interfaces (APIs) from their preferred farm management and record keeping software. Producer data, governed by data privacy agreements, will populate the models, and modeling results tied to spatially explicit grids and rasters allow credit purchasers to track outcomes within their supply chains. Data on GHG mitigation, nutrient and sediment loading reductions, and water conservation can be aggregated for reporting at various spatial scales according to field, farm, watershed, sourcing area, or administrative boundaries.

ESMC's science-based, outcomes-based credits are underpinned by soil C field sampling and model quantification. As ESMC expands beyond its pilot regions, launching nationally in 2022 with a goal of touching 101 million ha (250 million ac) by 2030 and 263 million ha (650 million ac) by 2050, it will continue to advance the state of science by corroborating model results with ground observations from every region and production system. With scale, models become more accurate and testing and monitoring less expensive. ESMC's ambition and unique strategy lies in its approach to scale its program nationally and create a positive feedback loop between low transaction costs, high participation, and transparent, reliable ES assets.

The most underappreciated impediments to well-functioning ES markets are trust and user friendliness. There are vast literatures on market design, modeling techniques, and regulatory landscapes, but even the best designed market with the most accurate tools and ideal policy conditions cannot create impact at scale if producers do not participate. ESMC estimates the combined potential near-term demand for C and water quality credits at $13.9 billion, with C and water quality credits valued at $5.2 billion and $8.7 billion, respectively. To ensure farmer and rancher acceptance, ESMC has involved them in each step of its program design, development, and piloting.

ESMC makes use of existing networks of trust, and the program design facilitates relationships among farmers, between farmers and their advisors, or between farmers and their customers and market demand. Buyers, primarily corporate entities seeking to mitigate their supply chain impacts, and sellers, who are agricultural producers, are well represented in ESMC's governance, science, development, and deployment structure. The MRV platform will offer displays of only relevant data for each program participant. Producers can see their production data and results. Market administrators and verifiers will be able to quantify, monitor, and verify assets using producer data and external inputs, such as satellite imagery, soil test results, and weather and soil maps.

Buyers will be able to purchase credits and mitigate supply chain impacts without accessing the personally identifiable information of their suppliers. The platform will engender trust among all market participants; facilitate and mediate each transaction; and serve as the locus for credit generation, monitoring, reporting, and verification.

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# 7

# Soil and Water Conservation Society and the Farm Bill: A Historical Review

*Joseph W. Otto*

The US farm bill is a piece of legislation periodically passed by Congress that contains funding and programming guidelines for government assistance to and oversight of various elements of the agricultural sector. Though often identified by year, each of the 18 farm bills passed since 1933 (National Ag Law Center 2020) carries a different title (e.g., the Agriculture and Consumer Protection Act is colloquially known as the 1973 Farm Bill) and is a product of compromise between the many diverse subsets of the agricultural economy including commodity sales and exports, loans and credit, financial assistance and price supports, nutrition and food availability, and conservation of soil and water resources. This diverse set of interests increasingly included a large concentration in every sector of the agricultural economy. The increasing dominance of commodity-focused agribusiness groups in these discussions, however, has led to market protections and access for only a few crops, and fostered the rise of biocide resistance and invertebrate kills, such as the pollinator problem. Congress generally passes a new farm bill every five or six years to coincide with the expiration of certain elements of its predecessor, with the last bill passed in 2018. The farm bill's story indicates how Americans' perceptions of agricultural production and consumption have changed over time. It also reveals the balance that exists between the promotion of economic growth and the conservation of natural resources fundamental to a stable and resilient food supply. Much overlap occurs between a bill's tendencies to produce wealth and conserve resources, as both generally promote the welfare of the American people. It is within those overlapping, gray areas of agricultural

**Joseph W. Otto** is the historian for the Soil and Water Conservation Society, Ankeny, Iowa.

policy that change occurs from one farm bill to the next. Taken individually, each farm bill is a snapshot of a particular historical moment, with a bill's content the result of specific tensions among and between multiple people and groups having different, and at times contradictory, priorities, yet all staking a claim to the proverbial common ground of US agricultural policy.

This chapter provides a closer look at the role of the farm bill's origins and core elements, explores significant policy reforms after the Second World War, and takes a closer look at role of the Soil and Water Conservation Society (SWCS) to shape and guide farm bill policy since 1985.

## 1933 to 1949: Response to a Crisis

The expansion of conventional agriculture onto poor lands is currently impacting the loss of small farming on better lands, access to water rights, and urban sprawl, and is more generally caused by a developer-focus on land use and control measures (American Farmland Trust 2018). This modern-day situation was preceded by earlier crises that caused Congress to pass the first farm bill in 1933, in response to the Great Depression and the prolonged drought in the Midwest and Great Plains known as the Dust Bowl. The expansion of agriculture after World War I (1914 to 1918) coincided with high land values, access to credit, and favorable commodity prices. The impulse to produce more crops on more acres led growers to extend agriculture into environmentally sensitive areas of the North American grasslands that were unsuitable for farming. When a prolonged drought hit the Great Plains in the early- to mid-1930s, the loose, dry, and thin topsoil of western Kansas and the panhandles of Oklahoma, Texas, and Nebraska blew away with vigor, leaving behind empty fields, granaries, bank accounts, and stomachs. This self-inflicted environmental catastrophe caused a great deal of human suffering, dislocated many Americans and their families, and led one historian of the Dust Bowl to refer to the Great Plains as America's "cultural boneyard, where the evidence of bad judgement and misplaced schemes lie strewn about like bleached skulls" (Worster 2004). For the people who endured the Dust Bowl, stayed on the land, and continued to farm, recovery would take many years. This reestablishment coincided with a new, public presence of personnel, programming, monitoring, and financial support at the federal, state, and local levels of government in the form of soil conservation.

Conservation became the watchword and mode of action to avoid future food production crises akin to the Dust Bowl. For its part, the federal government responded by increasing its role in conserving the nation's soil resources. In 1933, Congress created a support wing of the US Department of Agriculture (USDA) called the Soil Erosion Service. Two years later, this temporary entity was made permanent and renamed the Soil Conservation Service (SCS). Also in 1933, Congress passed the first farm bill. It declared a state of emergency caused by an increasing disparity between the value of farm and industrial commodities. The bill argued that the impact of low crop prices had "destroyed the purchasing power of farmers" and "burdened and obstructed the normal currents of commerce" to such a degree that it threatened the "national public interest" (Agricultural Adjustment Act of 1933). To remedy the problem of low commodity prices, the 1933 Farm Bill reduced the acreage of certain cash crops. For financial assistance, it authorized the sale of special bonds that gave farmers access to credit to help them avoid foreclosure. To raise the revenue needed to pay for acreage reductions, the 1933 Farm Bill included a processing tax on manufacturers, but this was later ruled unconstitutional by the Supreme Court (United States v. Butler 1936).

To legitimize financial assistance, Congress tied acreage reductions to soil conservation through the passage of a farm bill-adjacent act called the Soil Conservation and Domestic Allotment Act of 1936 (Helms 2012c). This act is not included in the USDA's official list of farm bills. However, it legitimized the 1933 Farm Bill by tying soil conservation to acreage reductions on certain cash crops deemed "soil depleting," created the chief financial support mechanism in the Agricultural Conservation Program, and was the predecessor to the 1938 Farm Bill, which contained amendatory language that added acreage allotments to the soil depleting cash crops (Agricultural Adjustment Act of 1938). The federal government thereafter began paying farmers a share of the overall cost of specific conservation practices. The 1938 bill stated that payments "based on soil-building or soil-conserving practices" were "divided in proportion to the extent which [the recipients] contribute to the carrying out of such practices," thus giving rise to the policy of "cost sharing" (Agricultural Adjustment Act of 1938). Although these actions did not reduce production as intended, they did satisfy the general welfare clause of the Constitution and thereby establish the enduring precedent of providing financial and technical assistance to farmers through farm bill legislation.

The fact that the central tenets of the farm bill were borne from a crisis is supported by the words of Hugh Hammond Bennett—pioneering soil conservationist, the first chief of the SCS, and founding member of the Soil Conservation Society of America (SCSA, the former name of SWCS). In his keynote address at the SCSA's first annual meeting in 1946, Bennett emphasized the relationship between soil conservation and national security. He told members that "…neither the world nor any nation can afford to lose any more productive land. Too many nations have much too little now…In some countries the danger line was crossed long before World War II" (Bennett 1946).

With the gun smoke of World War II still clouding the air, Bennett's words resonated with attendees who in the preceding decade likely witnessed first-hand tremendous suffering caused by farm failure, food scarcity, and the depravities of war. Soil conservation, it seemed, was the stabilizing force needed to protect the nation's natural resources and the people caring for them.

## 1954 to 1981: New Markets, New Concerns

The postwar recovery of global markets in the 1950s caused changes to the farm bill's reach and intent. At the end of the Second World War, US producers exported surplus commodities to war-torn nations desperately needing food. With foreign markets readily available, there was little need to address overproduction through additional acreage reductions. The recovery of European agriculture, however, gave rise to a new mode of farmer assistance—that of finding new markets for the growing surplus of products. The 1954 Farm Bill provided for the establishment of trade offices in foreign countries through the Foreign Agricultural Service (Agricultural Act of 1954). With market access diminishing, Congress moved beyond selling grain abroad to simply giving it away via the Food for Peace Program (Paarlberg 2013). The ramping up of Cold War tensions in the 1950s also likely fueled the search for new, democratic markets abroad. The loss of Cuba as a trading partner in 1959, for instance, left a sizable void in the US export market. Between 1956 and 1959, Cuba was the ninth leading destination for US agricultural exports, consisting mainly of rice, and was the second leading supplier of imports, consisting mainly of sugar (Zahniser et al. 2015). The search led to Asian nations such as Japan, South Korea, and South Vietnam (figure 1), where between 1960 and 1968 the annual value of agricultural exports increased by 92%, 163%, and 591%, respectively (Corley 1969). With an easing of Cold War tensions in the 1970s, the search for markets led to not-so-democratic nations as well. By 1976 the Soviet Union had become the second-largest foreign market for US agricultural products (Breedlove 1976).

On the domestic side, tensions of overproduction and conservation continued to dominate policy discussions. Similar to the original legislation, the farm bills of the 1950s were in response to twin crises of overproduction and drought, although the latter response was significantly diminished compared to the Dust Bowl years (Weiner et al. 2015). The 1956 Farm Bill addressed overproduction by establishing Soil Banks—a program to voluntarily retire land by "renting" it to the federal government. The Soil Bank program was twofold. For short-term reduction there was the Acreage Reserve Program (ARP), and for long-term reduction there was the Conservation Reserve Program (CRP). The ARP operated on an annual basis while the CRP ran for contracts of 3, 5, or 10 years. The ARP

**Figure 1**

**United States involvement in Vietnam in the 1960s included a nearly 600% increase in the importation of agricultural goods and enabled South Vietnamese farmers to purchase fertilizer and new, mechanized equipment for their operations. Photo credit: VA000826, Douglas Pike Photograph Collection, The Vietnam Center and Sam Johnson Vietnam Archive, Texas Tech University.**

targeted only leading cash crops and incentivized temporarily idling lands that would be cropped again. The CRP, on the other hand, had a broader incentive package. In addition to rental payments, an owner received cost-share for installing pasture, rangeland, forests, water impoundment, and marshlands. The CRP struggled to use its allotment in the first few years, as owners favored the higher paying and impermanent nature of the ARP. After 3 years, the ARP was discontinued, and the CRP rates raised to more appealing levels. By 1960, CRP enrollment jumped to 11.6 million ha (28.7 million ac), or about 6% of all cropland (Helms 2012b). With a resounding conservation success on their hands, the USDA faced new concerns about sustaining CRP enrollment acres beyond the initial lease period. A report from the 1963 *Yearbook of Agriculture* forecasted that "in the absence of continued payments for land diversion, it can be expected that the incentive to return lands to crop production will be great, unless profitable alternative uses…are developed" (Hill and Maier 1963). The final enrollment year for CRP was 1960, and the final year of payments was 1973. Following the expiration of these contracts, the CRP would itself be idled until the passage of the 1985 Farm Bill (Food Security Act of 1985).

For its part, the SCSA and its membership identified innovative conservation practices later included on the list of practices eligible for cost-share. Research on the benefits of no-till and reduced tillage practices appeared in the *Journal of Soil and Water Conservation* (JSWC) as early as 1961 (Hays 1961; Larson 1962). By the end of the decade, supporting research published in the JSWC found that "plowing was not necessary for good corn production" and that no-tillage was "extremely promising from the standpoint of soil and water conservation" (Harrold et al. 1967). Pioneering studies of alternative tillage practices published in the JSWC succeeded in opening the public's mind to reduced tillage and no-till farming. In 1973 the SCSA organized a National Conservation Tillage Conference. It was themed on "the use of surface vegetative residue in crop production for maintaining a quality environment" and attended by several hundred people (SWCS 1973). With firm backing from the SCSA and kindred organizations by 1973, the USDA made no-till and conservation tillage eligible for cost-share (Helms 2012c). The eligibility of no-till farming for cost-sharing resulted from conservation professionals studying the practice for a decade or more before building a consensus and effectively communicating its benefits to members of Congress and their agricultural constituencies.

## 1985 to 2018: Common Ground

With the SCS celebrating its 50th anniversary, the passage of the 1985 Farm Bill was a moment to reflect on conservation's past accomplishments. Speaking at a conservation tillage conference in the spring of 1984, SCSA CEO Walt Peechatka praised the accomplishments of the past 50 years yet urged conservationists of the difficult road ahead. With farmers still recovering from the prolonged farm crisis that saw prices drop and forced many farmers into dire economic straits, Peechatka noted that progress recently slowed could again be accelerated by the upcoming farm bill of 1985. A longstanding criticism of the farm bill was its lack of connectivity between supports for commodities and conservation practices. Peechatka called on the bill's framer to right this wrong by making participation in commodity support programs contingent on a grower's stewardship of soil and water resources (Peechatka 1984). Peechatka's words proved prophetic, as the 1985 Farm Bill contained provisions linking eligibility for financial assistance to certain conservation requirements. Producing crops on highly erodible lands or converted wetlands, for instance, made one ineligible for other benefits (Food Security Act of 1985).

The 1985 Farm Bill's linkages between conservation and financial aid addressed the insinuation that price supports enabled poor soil stewardship. SCS Historian Douglas Helms identified the cause of this policy change to be in response to a growing disconnect between ethical land stewardship and market-driven management practices that emerged in the early 1970s. Motivated by relaxed conservation requirements, foreign market access, and a temporary price surge, growers plowed "from fencerow to fencerow" and severely threatened long-established conservation measures (Helms 2012a). With collateral damage to public resources and wildlife seemingly on the rise, a new coalition formed among established organizations such as the

SCSA, the Natural Resources Council of America, American Farmland Trust, and the National Association of Conservation Districts. Joining the coalition were kindred organizations such as the Izaak Walton League of America, the International Association of Fish and Wildlife Agencies, and the American Forestry Association. Support also came from environmental advocacy groups such as the Wildlife Society and the National Wildlife Federation (SWCS 1984). The emergence of a new, conservation-focused coalition brought additional voices and stakeholders to a farm subsidy conversation that has often favored large, wealthy operators over small farmers, the landscape, and the intrinsic ecological connections therein (Environmental Working Group 2020).

The 1996 Farm Bill followed a significant reorganization within the USDA. The SCS transitioned into the Natural Resources Conservation Service (NRCS), and the Agricultural Stabilization and Conservation Service became the Farm Service Agency (FSA). The NRCS came into existence with a new mandate to dispense financial assistance through the Environmental Quality Incentives Program (EQIP). Whereas the SCS had engaged only in conservation planning and technical assistance, personnel in the NRCS were challenged to strike a balance between the traditional and expanded roles. A balance became more elusive in the 21st century, as between 1996 and 2003 EQIP expenditures increased by 250% (Helms 2012c). With more obligations to dispense, review, and account for financial assistance programming, the NRCS has an arguably different identity than its SCS predecessor.

The SCSA also underwent an identity shift at this time. In response to members' calls to broaden its reach and mission, in 1987 the SCSA rebranded itself as the Soil and Water Conservation Society (SWCS). The Society's rebranding coincided with a new, supporting role in the framing of future farm bills. Following the renewal of the CRP in the 1985 Farm Bill, the SWCS collaborated with the SCS to survey CRP participants about their management intentions when the leases expired in 1995. The 1990 report gauged respondents' willingness to keep marginal lands out of production via easements, extended contracts, and reforestation (Nowak et al. 1990). The bleaker, follow-up survey in 1993 found that participants "now intend to return more of their acres to crop production and keep fewer acres in grass" (Osborn et al. 1993). SWCS's engagement in farm bill policy planning continued in 1994 with regional, issue-based forums. A key takeaway from the forums was a perceived lack of trust between agricultural, conservation, and environmental groups; yet, as the discussions unfolded, attendees found they shared more common ground than previously thought. Forum attendees' positive feedback on CRP foreshadowed its extension in 1996 and thereafter (SWCS 1995).

The Society's mediating presence abided in the 21st century. Ahead of the 2002 Farm Bill, SWCS reported a gradual shift in conservation planning. Whereas conservation traditionally served agriculture as a means to enhance production, in the last two decades its service role changed to "managing and mitigating its effects on the environment" (SWCS 2001). Feedback gathered at workshops in 2000 to 2001 led the Society to recommend 22 policy reforms to farm bill framers. A recommendation for the CRP was to deepen the applicant pool by eliminating cropping history requirements and allowing rangelands and pastures into the program. On management reforms it recommended expanding the authority of state technical committees to modify rules and funding allocations (SWCS 2001). The Society further identified the systemic problem of a conservation assistance gap. The demand for conservation assistance outstrips the supply of public funding, thereby opening a gap between people and groups who must compete for limited resources instead of forming coalitions on the proverbial common ground.

Between 1987 and 2007, the Society actively shaped farm bill policy by conducting surveys, hosting regional forums, and reporting on the myriad needs and wants of stakeholders. Cooperative agreements with the SCS/NRCS and financial support from charitable organizations enabled the Society to be a highly visible and recognized player in the debate. Ahead of the 2008 Farm Bill, the Society produced targeted reports on improving water quality in the Great Lakes basin, adjusting policies to the realities of climate change, and assessing farm bill technical assistance programs. The latter report found that the conservation assistance gap first identified in 2001 was widening due to reduced staffing at the NRCS and the FSA. The emergence of third party technical service providers addressed this problem somewhat, albeit unevenly across regions (SWCS and Environmental Defense 2007). Yet unexplored by the Society but arguably relevant to future farm bill discourse is the relationship between farm income, CRP enrollment rates, and the tributary role of marginal farmlands in the biofuels production boom of the early and mid-21st century (Hellerstein and Malcolm 2011).

## Chipping Away

On the eve of the passage of the 1985 Farm Bill, at the Society's 39th annual meeting, SCSA President Floyd Heft envisioned the conservation movement of the new millennium. He predicted reduced federal spending and sizable growth in state and local funding. He believed the next big management problem to be a response to highly visible, off-site damages caused by on-farm practices. He praised the possibility of at-scale, perennial row cropping as nothing short of revolutionary. Heft urged the Society to be cautiously optimistic, and that success would not come all at once, but "by continuing the chipping away process already begun" (Heft 1984). Chipping away aptly summarizes the Society's historic relationship with the farm bill. Since the beginning, the Society has recognized agriculture's importance to the welfare of the United States and around the world.

Out of this foundational ethos the Society chips away the excesses and inefficiencies that threaten the health of our soil and water resources. Through sound research and discussion, novel approaches become promising studies, which become innovative examples and best management practices. From JSWC research on conservation tillage in the 1970s to organic farming in the 1980s and carbon sequestration in the 2010s, the Society is an enduring pillar of support for conservation-friendly farm bill policies that will abide in the future (Hays 1961; Olson et al. 1981; Morgan et al. 2010).

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# 8

**Practitioner's Perspective**

# Protecting Ecosystems by Engaging Farmers in Water Quality Trading: Case Study from the Ohio River Basin

*Jessica Fox and Brian Brandt*

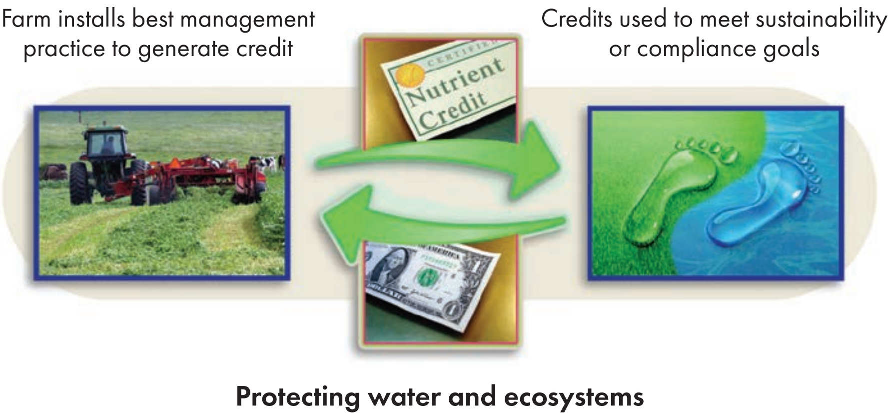
The Ohio River Basin Water Quality Trading Project is the world's largest water quality credit trading program. Focused on environmental impacts from diverse sources, the project has facilitated nontraditional collaborations to achieve a common commitment to improving water quality, as well as broader environmental benefits. The role of soil and water conservation districts (SWCDs) has been fundamental to the success of this groundbreaking effort. Federal and state government, power companies, farmers, and environmental organizations have also been engaged to guide the structure, implementation, and verification of the effort.

Winner of the United States Water Prize (2015), the project is the most recognized domestic program creating verified and registered credits to improve water quality. In addition to the water quality improvements, there are ancillary benefits such as the protection of pollinators and rare species, farm animal health, and soil health. In this brief overview, we summarize basic project elements relevant to agriculture, and discuss key lessons learned from working with farmers, SWCDs, the US Department of Agriculture Natural Resources Conservation Service (USDA NRCS), and state agricultural agencies to implement this effort.

**Jessica Fox** is senior technical executive at Electric Power Research Institute, Palo Alto, California. **Brian Brandt** is director of agricultural conservation innovations at American Farmland Trust, Worthington, Ohio.

**Figure 1**

**Graphical illustration of water quality trading.**




## Brief History of Water Quality Trading

Water quality trading (WQT) is an innovative, market-based approach to achieving sustainability and regulatory water quality goals in a cost-effective and ecologically effective way (figure 1). In order for credits from WQT programs to be eligible for meeting regulatory requirements, the programs must be consistent with the US Environmental Protection Agency's (EPA's) 2003 WQT Policy and 2007 WQT Toolkit for Permit Writers, which provide guidance to states, interstate agencies, and tribes on how to implement trading that is consistent with the United States Clean Water Act. Nearly two decades after EPA's original WQT Policy, the approach continues to attract interest; however, practitioners are still working to make their programs successful—particularly in the absence of regulatory drivers that incentivize active engagement from credit buyers. In recent years, there has been contemplation of the role that voluntary buyers needing to meet corporate sustainability goals (beyond compliance obligations) may play in mobilizing WQT programs. Currently, there are approximately 20 WQT programs in the United States with the credit transaction activity varying greatly between programs (USEPA 2019). Until the Ohio River Basin Water Quality Trading Project, there were no multistate WQT programs where everyone agreed to the same rules, which allows credits to be traded according to ecologically relevant watershed units crossing state lines, versus following jurisdictional or political boundaries.

### Ohio River Basin Water Quality Trading Project Overview

In the Ohio River Basin Water Quality Trading Project, water quality credits are created through the installation of best management practices (BMPs) with private landowners in Ohio, Indiana, and Kentucky (http://wqt.epri.com). Since 2012, the project has generated more than 200,000 verified water quality credits from agricultural conservation practices from approximately 50 farms in these states. The project has been covered by the *The Wall Street Journal* (Peters 2014), National Public Radio (Grant 2017), *The Economist* (Blooming Horrible 2012), in US Congressional Testimony (Fox 2014), a US Government Accountability Office report (US GAO 2017), *National Geographic* (Sacleux 2019), and in various academic publications (Keller et al. 2014; Liu and Swallow 2016; Massakkers 2016). Backed by watershed modeling, on-the-ground project verification, and rigorous credit registration, the program is the most defensible and trackable WQT program in the world.

The project has made significant investments (more than $1 million) in the modeling and credit quantification protocols (Keller et al. 2014). The project team has evolved the methods as models have been improved and calibrated over the last eight years. We currently use three models to calculate how many pounds of nitrogen and phosphorous are generated from each installed conservation project: USDA's Nutrient Tracking Tool, EPA Region V Spreadsheet Tool for Estimating Pollutant Load (STEPL), and the fully mechanistic Watershed Analysis Risk Management Framework (WARMF). Documentation and tracking are done online using the rigorous IHS Markit Environmental Registry (figure 2), enabling anyone to view nonconfidential project records to confirm the legitimacy of every conservation practice, every pound of nutrient, and every transaction.

**Figure 2**

**IHS Markit Credit Registry projects page (partial data list showing).**

## Farmer Outreach

Because this project is so far-reaching and is the largest of its kind, it has been important to identify and engage a diversity of stakeholders to proactively identify and evaluate concerns. Among other activities, the project convened a series of listening sessions with farmers and SWCDs to identify potential barriers that might discourage participation, and to collect input on how to best structure the project (EPRI 2011a, 2011b). SWCDs were critical for identifying eligible farmers in their counties, advising which BMPs to fund, coordinating the timing of funding to avoid competition with or complement state and federal cost-share programs, and for executing landowner contracts. The project team also established a broader agriculture advisory committee of experts from American Farmland Trust, Ohio Farm Bureau, Kentucky Farm Bureau, Indiana Farm Bureau, National Dairy Producers, Kentucky Corn Growers Association, USDA NRCS, USDA Agricultural Research Service, Agricultural Retailers Association, Ohio Department of Agriculture, Indiana State Department of Agriculture, Kentucky Division of Conservation, individual farmers, and others. This engagement was ultimately critical to designing a novel trading program that worked for all stakeholders, including environmental groups.

After program structure concerns were addressed, SWCDs in the three states agreed to act as the contracting party in order to move funds from the Electric Power Research Institute (the project manager) to local landowners. SWCDs also supported robust outreach to announce funding opportunities and annual on-ground inspection of the practices. While funding for the conservation practices was provided by the Electric Power Research Institute, farmers contracted directly with their local SWCDs, with whom they generally already had relationships and mechanisms for submitting payment requests. Approximately $800,000 has been allocated to farmers since 2012, with funding remaining available as of this publication.

Farmers are contracted to install conservation practices meeting USDA NRCS performance standards that are known to reduce nutrient runoff. Examples of these practices include cover crops, heavy use protection areas (figure 3), cattle exclusion fencing, riparian buffers, and tree planting (NRCS practice codes 340, 561, 382, 391/393, 612, respectively). Some of the SWCDs identified interested farmers by looking at applications that were not funded—often due to lack of funds—by state and federal cost-share programs (e.g., Environmental Quality Incentives Program [EQIP], Conservation Reserve Enhancement Program [CREP], and Conservation Reserve Program [CRP]). Some of the unfunded projects met the requirements of the WQT program and could result in significant reduction of nutrient runoff to local waterways. All projects were required to be installed according to the relevant NRCS practice

**Figure 3**

**Before and after photos of installed heavy use protection area.**


standard, at a minimum. Nearly all the landowners who have applied for funding are small farmers producing corn, soy, wheat, beef, and milk.

### The Farmer Viewpoint

From the farmer viewpoint, it is a relatively straightforward process to secure funds. It is entirely voluntary to participate and apply for funding, and landowners select the conservation actions that make sense for their operations. The first step is to review any active requests for proposals that outline the funding opportunity and details about the application process. Second, the farmer completes a funding application and then, if accepted by the Electric Power Research Institute, enters into a two- to three-page contract with the local SWCD. Then the farmer installs the BMP following NRCS practice standards and provides receipts to the local SWCD, which triggers an installation inspection by SWCD personnel, followed by verification by state agricultural personnel. The final step is reimbursement based on payment terms in the contract.

The conservation practices implemented may have nominal impact on operation yields, while still having huge benefits to water quality. Typical practices include the use of cover crops, riparian buffer strips, cattle exclusion fencing to prevent erosion of natural waterways, milk house waste management systems, manure wetland treatment systems, and cattle heavy use areas that allow for effective manure storage and management. More recently, we began funding tree planting to restore forests, with a focus on marginal crop land to generate significant nutrient benefits (Keller and Fox 2019). Contracts with farmers range from 5 years for seasonal practices (e.g., cover crops) to 40 years for forest planting.

While there are many details involved in credit generation, calculation, and sale, farmers are largely protected from this process. They are not subject to the uncertainty of the marketplace for the sale of the credits. All credits are "owned" by the program administrator (currently the Electric Power Research Institute), and all profits or losses from credit transactions stay with the program administrator. There is no risk to the farmer that credits will not be sold; farmers are paid after on-site confirmation of BMP installation regardless of whether or when the credits generated from those practices are, in fact, transacted. Given the uncertainty of buyers and the nascent nature of environmental markets, the fact that farmers are paid based on successful installation of the BMPs has proven very protective of the farmer. From a farmer perspective, the project offers a privately funded, cost-share opportunity using a simple contract.

## Lessons

There has been significant learning since the memorialization of this multistate WQT program in 2012. We tend to categorize lessons from two perspectives: credit generation and credit sales. This chapter has been focused largely on credit generation and agriculture engagements, so we will focus on related key lessons.

One important lesson is also the most obvious: the process must work for farmers. The project supports a straightforward process with simple landowner contracts, engagement with trusted SWCD offices, and focus on practices that farmers want. The project adjusted and evolved as we heard from landowners about what worked and what didn't. Timely payments are critical, and the project has had to address a number of issues to ensure rapid payments. Producers are accustomed to business contracts that clearly state, "if you do this, then you get this." We provided a good option for cost-share funding that improved producer operations, as well as water quality and ecosystems.

An issue that was necessary to overcome was the project's pay-for-performance approach. Applications for funding were evaluated based on the cost-per-pound of nutrient reduction. The nutrient reductions were estimated using an edge-of-field model (USDA Nutrient Tracking Tool or the EPA Region 5 STEPL spreadsheet). The cost of the funding request was calculated by adding the total cost-share request from the landowner, the payment to the SWCDs for the service (capped at 10% of the total funding contracted through their office), plus the additional cost of any state agency support. Then, the dollars-per-pound of total nitrogen and total phosphorous were calculated (dollars per pound of nutrient). This is in contrast to typical state and federal cost-share programs that fund practices based on metrics such as hectares (acres) or linear meters (feet) of fence, versus kilograms (pounds) of nutrients reduced. It was challenging to communicate that we could provide more funding for 20 ha (50 ac) of cover crops compared to 40 ha (100 ac) because the nutrient reductions were better due to site slope, soil type, and proximity to a waterway. This communication became easier as we gained experience explaining the approach.

It was important that farmers "have some skin in the game." The requirement for cost-share was an effective approach that ensured landowners were serious about the efforts and increased confidence that the practices would be implemented and maintained properly. Cost-share requests can range from approximately 50% of project costs up to the allowable limit of 75% to 80%, depending on the specific funding opportunity. On average, cost-share requests are approximately 65% of total costs, which can make it difficult to receive funding if the landowner requests the maximum allowable under the funding notice.

Working via local SWCDs to contact and enroll producers was appropriate in many cases. However, not all counties had SWCD staff with the engineering, planning, and design expertise needed to implement or contract for projects. Some SWCD offices needed support from NRCS staff or the state agriculture agency to get projects contracted and installed. It has been important to stay flexible to alternative approaches to ensure BMPs are contracted and installed efficiently, which sometimes means a neighboring SWCD office manages contracts, the Electric Power Research Institute directly contracts with landowners, or technical service providers and state agency staff oversee installation of conservation actions.

The amount of effort required to communicate a new funding source and associated requirements has been significant. This outreach effort should not be underestimated in the future, and hopefully our efforts have paved the way for future programs. There is a lag time between communicating a funding opportunity and producers expressing interest. It is prudent to maintain a very similar funding opportunity for three to five years, allowing farmers to watch how the program worked out for their neighbors before choosing to apply themselves. If the funding details change too drastically or quickly (i.e., 5-year cover crops versus 40-year forest planting), investments in communicating the prior year are lost; farmers were not allowed enough time to decide to apply for funding before the program changed focus.

Finally, it is important to understand the value of "legacy" for the landowners in these voluntary conservation programs. Many landowners we funded wanted to implement the projects and just needed a source of support. The landowners participating expressed great appreciation for the funding, and they showed true commitment to the conservation efforts, as communicated in various video interviews (figure 4).

**Figure 4**

**Video interview of one participating landowner.**


## Future

Overall, the project has overcome many barriers as it formed ways to move money from large, private funders all the way to small, rural farmers through a series of thoughtful contracts. Farmers seem happy to engage in this project and have expressed appreciation for the funding. We are proud of the positive environmental benefits that the installed practices have generated, including biodiversity, carbon sequestration, soil health, farmer wellbeing, and of course, nutrients (more than 90,700 kg [200,000 lb] of nitrogen and phosphorous avoided to date).

However, going forward it will be critical to sell enough credits to continue funding conservation practices and relieve reliance on various public and private grants that are currently necessary to keep the overall project running. To this end, in 2019, we announced a collaboration with First Climate, who added the water quality credits to their broader carbon credit offering to both domestic and international corporate clients. This created a science-based option for those seeking to mitigate supply chain impacts and meet personal environmental footprint goals, as well as larger corporate targets and permit compliance obligations. We have also aligned our credits with various sustainability programs and disclosures, including the Global Reporting Initiative, CDP, United National Sustainable Development Goals, and CEO Water Mandate. With these developments and the strong interest from EPA for applying credits towards compliance obligations under the Clean Water Act, we are optimistic that we will sell credits and continue funding conservation practices with farmers. We are very grateful for the ongoing collaborations with SWCDs and other agricultural agencies, all of which will be important for the continued success of this project.

## Acknowledgement

We would like to express appreciation for the farmers, local SWCDs, and state agency staff in Ohio, Indiana, and Kentucky who work on a daily basis to make this project successful.

## Resource to Learn More

- Ohio River Basin Water Quality Trading Project. http://wqt.epri.com

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# 9

# Water Availability for Agriculture in the United States

*Teferi Tsegaye, Daniel Moriasi, Ray Bryant, David Bosch, Martin Locke, Philip Heilman, David Goodrich, Kevin King, Fred Pierson, Anthony Buda, Merrin Macrae, and Pete Kleinman*

Water availability is essential to the sustainability of modern society and has long been a central focus of conservation activities in the United States and associated conservation science. According to the US Geological Survey (USGS) Report to Congress, water availability is a function of water quantity, water quality, and the structures, laws, regulations, and economic factors that control its use (Norton and Groat 2002). The major sources of water that

**Teferi Tsegaye** is the national program leader for water resources and coordinator of the Conservation Effects Assessment Project and Long-Term Agroecosystem Research Networks, USDA Agricultural Research Service (ARS), Beltsville, Maryland. **Daniel Moriasi** is a hydrologist, USDA ARS Grazinglands Research Laboratory, El Reno, Oklahoma. **Ray Bryant** is a soil scientist, USDA ARS Pasture Systems and Watershed Management Research Unit, University Park, Pennsylvania. **David Bosch** is a hydraulic engineer, USDA ARS Southeast Watershed Research Unit, Tifton, Georgia. **Martin Locke** is director, USDA ARS National Sedimentation Laboratory, Oxford, Mississippi. **Philip Heilman** is research leader and **David Goodrich** is a hydraulic engineer, USDA ARS Southwest Watershed Research Center, Tucson, Arizona. **Kevin King** is research leader, USDA ARS Soil Drainage Research, Columbus, Ohio. **Fred Pierson** is research leader, USDA ARS Watershed Management Research, Boise, Idaho. **Anthony Buda** is state resource conservationist, USDA ARS Pasture Systems and Watershed Management Research Unit, University Park, Pennsylvania. **Merrin Macrae** is a professor in the Department of Geography and Environmental Management, University of Waterloo, Waterloo, Ontario, Canada. **Pete Kleinman** is research leader, USDA ARS Pasture Systems and Watershed Management Research Unit, University Park, Pennsylvania.

are used by society—precipitation, surface water supplies, and groundwater aquifers—are influenced over the long-term by climate and in the short-term by precipitation and temperature distribution.

Agriculture is the largest user of water in the United States, with crop production comprising 95.4% of total national consumptive water use (Marston et al. 2018). Precipitation provides 86.5% of water use for crop production, while surface water and groundwater aquifers provide 5.9% and 7.6%, respectively. Irrigation for growing corn, hay, rice, wheat, soybeans, cotton, and almonds represents 47% of national surface water consumption and 75% of national groundwater consumption. However, a national, spatially detailed assessment of water use by all major sectors of the economy in the United States reveals tremendous spatial variability in surface water and groundwater consumption and identifies local areas of significant competition for these resources (figure 1). The category of "other crops" in

**Figure 1**

**Sector with the largest consumption of surface water and groundwater resources in each US county. Agriculture is the largest water user in 2,164 of the 3,143 counties. In other counties, service industries (354), thermoelectric power generation (289), manufacturing (234), and mining (102) are the dominant water users (Marston et al. 2018).**

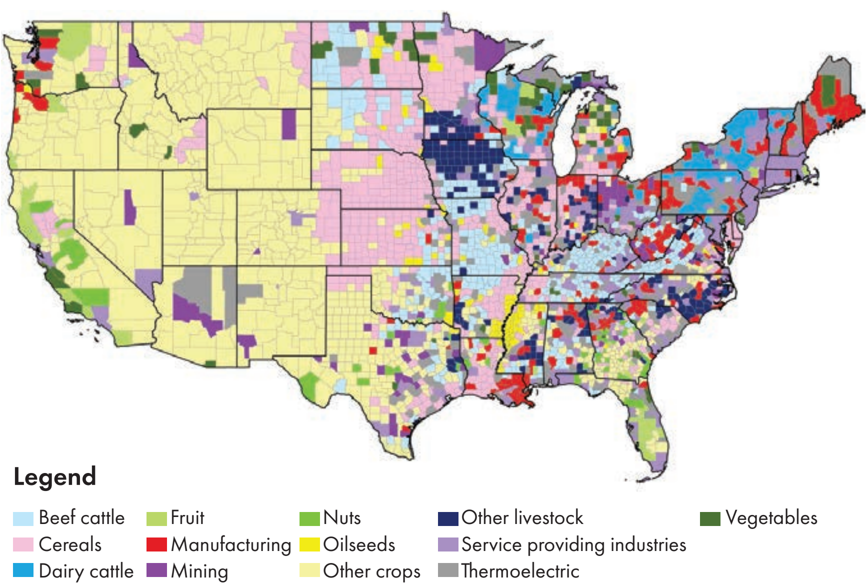

figure 1 (pale yellow) includes large areas of forest, rangeland, and desert in the western United States.

A patchwork of policies regulate water availability for agriculture in the United States. These range from the federal Clean Water Act (1972), which designates intended uses for different water sources and enforces action around protecting these uses, to state and local policies governing water resource rights and use (e.g., riparian versus prior appropriation). With over 30 federal agencies, boards, and commissions charged with overseeing the nation's water resources, there have been repeated calls to unify and simplify policies, all in the service of sustainable water use (Christian-Smith et al. 2011). These calls, along with incessant pressure to produce food, feed, fiber, and energy more efficiently, place a premium on understanding the diversity of water availability issues facing agriculture in the United States. This chapter reviews issues and challenges affecting water availability for agriculture in the Southeast and Southwest regions of the United States and in the Northeast, Midwestern, Great Plains, and Pacific Northwest regions of the United States and southern Canada. Research needed to address these issues and challenges is identified.

## Northeast

The Northeast, from the states of Pennsylvania, West Virginia, and Virginia to Maine and the southern parts of the Ontario, Quebec, and New Brunswick provinces, is blessed with abundant precipitation that supports a highly diverse (Aguilar et al. 2015), predominantly rain-fed agricultural industry that is vitally important to the economy and as a local food source for its inhabitants. Due to the Northeast's mountainous topography and expansive areas of marginal soils for agriculture, forest is the dominant land cover. Agriculture tends toward valley bottoms, on lake plains adjoining Lakes Erie, Ontario, and Champlain, and on the less steep topography near coastal areas. Dairy production in Pennsylvania, New York, Vermont, and southeastern Ontario, Quebec, and New Brunswick; beef production in the Virginias; and vegetable production in localized areas of New Brunswick, Maine, New York, New Jersey, and Virginia are major users of surface water and groundwater. Liquid manure management systems employed by dairy in the Northeast place especially high demands on surface water and groundwater resources. More importantly, water quality issues deriving from nutrient management associated with these agricultural enterprises affect the availability of water for other important uses, such as human consumption, fishing, and recreation. However, in most of the Northeast, overall consumption of surface water and groundwater resources by agriculture is minor compared to uses for service-providing industries, manufacturing, thermoelectric use, and mining (figure 1).

Given the limited footprint of agriculture in the Northeast compared with forests (by area) and urban sprawl (by intensity of resource consumption), factors affecting water availability for agriculture are often driven by nonagricultural priorities. For instance, providing an adequate public water supply for a large and growing urban population in the megalopolis that stretches from Washington, DC, to Boston is the foremost water availability concern in the Northeast. Water required for use as public water supply for this population exceeds that required to meet the needs of the population of the entire west coast by a third (Dieter et al. 2018). To illustrate the severity of concern for water availability for public consumption, consider water management in the Delaware River Basin, where three reservoirs, located in the headwaters, serve as public water supply for New York City and water drawn from near the mouth of the river serves as public water supply for Philadelphia. The Delaware River Basin Commission has the authority to declare a water supply emergency based on a drought or other condition that may cause a shortage of available water. The reservoirs may be forced to release water in order to maintain sufficient freshwater flow to keep saltwater from moving upstream and contaminating the Philadelphia water intake. The most severe drought emergency occurred in the 1960s, but drought emergencies were also declared in 1981, 1985, 1999, and 2001 (Delaware River Basin Commission 2019). Most major cities in the Northeast use surface waters as their municipal water source, but groundwater is locally important to many smaller towns and cities. Trenton, New Jersey, near to Philadelphia, relies on groundwater as its municipal water source, and the same saltwater encroachment that threatens Philadelphia's water source threatens the wells that tap Trenton's aquifer. Although much of Ontario receives drinking water from surface waters, many localized Canadian communities also rely on groundwater as their primary municipal water source.

Current and future changes in climate pose challenges for maintaining water availability in the Northeast (Tavernia et al. 2013). Changes in seasonal warming patterns, advances in high-spring streamflow, decreases in snow depth, extended growing seasons, and earlier bloom dates have already been observed (Hayhoe et al. 2007; Dupigny-Giroux et al. 2018). Moreover, shrinking snow cover, more frequent droughts, and extended low-flow periods in summer are predicted with climate warming. In coastal aquifers of the Northeast, saltwater intrusion poses a growing threat to drinking water supplies, as well as agricultural and industrial uses (Lall et al. 2018). These climate-driven challenges to maintaining adequate water supplies are further compounded by predictions of continued population growth in the Northeast (Jones and O'Neill 2013; US EPA 2019). Notably, the major metropolitan areas surrounding Boston, New York, Baltimore, and Philadelphia are projected to experience population increases of 20%, 11%, 12%, and 5%, respectively, by 2040 (Thomas 2016).

Although there has been a long history of irrigation in the region for high-value, specialty crops, this practice has been steadily growing over recent decades, including for agronomic crops and as a means of reusing wastewaters. Presently, about 7% of the Northeast's cropland is irrigated, with 67% of agricultural irrigation water sourced from groundwater (Dieter et al. 2018). In some cases, introducing irrigation may mitigate more frequent droughts that threaten yields of these high value crops, but only if water extraction does not compete with water needed for public water supplies. Heavily irrigated areas along the North Atlantic Coastal Plain, including the lower Delmarva Peninsula, have seen declining groundwater levels that are due in part to increases in irrigated areas (Russo and Lall 2017) as well as rising domestic consumption (Dong et al. 2019). Although a small number of farms in Ontario are irrigated, irrigation represents the greatest fraction (greater than 50%) of agricultural water use in the province (Ecologistics Limited 1993; de Loë et al. 2001), and in some cases, irrigation is used excessively (Bernier et al. 2010). In some areas of southwestern Ontario, groundwater is being withdrawn at a rate that exceeds natural recharge (Schellenberg and Piggott 1998). These trends bear careful watching, as irrigated areas are projected to expand with climate change throughout the Northeast (Sanderson 1993; Marshall et al. 2015).

Despite growing competition for surface water and groundwater between agricultural and nonagricultural sectors, competition that may be exacerbated with climate change, the most pressing research priorities related to water availability in the Northeast continue to undoubtedly involve water quality. The importance of water quality is evidenced by multistate and international programs to address problems in the Chesapeake Bay (Kleinman et al. 2019), Lake Champlain (Howland 2017), and Lake Ontario (Environment and Climate Change Canada and the US Environmental Protection Agency 2018). New and more effective strategies are needed for controlling sediment and nutrient losses from agricultural lands that threaten water quality and thereby limit water availability for commercial fishing and recreational use in the Chesapeake Bay, Lake Ontario, and Lake Champlain.

## Southeast

The climate of the Southeast (Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Tennessee following USGS definition) is a powerful driver of the region's agricultural economy. The region experiences generally mild temperatures and a relative abundance of sunshine and water resources, enabling a long and productive growing season. Most areas across the region receive an average of over 1,020 mm (40 in) of precipitation annually, which is typically sufficient to support a wide variety of crops (Kunkel et al. 2013).

Much of the Southeast tends to use less water from all sources as compared to other eastern states (Dieter et al. 2018). The use of irrigation in the Southeast has increased as farmers recognize its potential for improving yields and sustaining crops during periods of dry weather (Harrison 2001; Goklany 2002; Dukes et al. 2010). However, the proportion of water used in irrigation is generally low compared to other regions, with exceptions of Arkansas, Mississippi, and Florida. Competing interests between agriculture, conservation, recreation, and utilities makes appropriating limited water supplies difficult, especially in vulnerable basins where demand for water is high. Groundwater depletion is occurring in the Atlantic Coastal Plain in North Carolina, South Carolina, and Georgia; along the Gulf Coastal Lowlands of Alabama, Florida, and Louisiana; and in the Mississippi Embayment in Arkansas, Mississippi, and Louisiana (Konikow 2013; Kresse et al. 2014; Barlow and Clark 2011 ).

Changing climate is anticipated to have a major effect on water resources available for agriculture with significant implications for future crop production in the Southeast. The frequency and intensity of extreme heat and heavy precipitation events is rising (USGCRP 2017). These extremes could result in more frequent droughts of longer duration. Heavy precipitation events may lead to greater erosion and water loss in runoff, as opposed to infiltration and storage. Climate models predict increases of 40 to 50 days with temperature maximum over 32ºC (90ºF) in much of the Southeast (USGCRP 2017). Fall precipitation is decreasing in the Southeast, and the eastern half of the United States, including the Southeast, is experiencing the largest increases in extreme precipitation events (USGCRP 2017). Variable precipitation patterns strongly influence stream flow, which, in turn, impact riverine ecosystem integrity (physical aquatic habitat, water quality, connectivity, biota quantity, and diversity) (Anandhi et al. 2018). A survey of data from 1936 to 2016 determined that the greatest stream flows were in late spring, with the largest variability and the lowest flows in late summer to early fall (Anandhi et al. 2018). Other stressors to aquatic ecosystem sustainability over the past century include construction of impediments, such as weirs and dams, and changes in land use. Altering the natural flow of streams can negatively impact habitat and diversity in these systems. Some trends in water and land use in the Southeast that impact stream flow include the conversion of land from forest to agriculture during the early part of the 20th century, regeneration of forests during mid-20th century, increased irrigation, and increased urbanization in the latter portion of the 20th century and early 21st century (Anandhi et al. 2018; Massey et al. 2017; Yasarer et al. 2020).

Continued aquifer declines due to increased use of groundwater for irrigation, decreasing stream flow, increased periods of drought due to variability in precipitation patterns, decreased land available for crops, and extreme rainfall events are water resource challenges facing agriculture in the Southeast. Better water management through precision irrigation, implementation of conservation practices that increase soil water storage and decrease runoff, improvements in storage of stormflow, and development of more water efficient crops offer opportunities to mitigate the negative impacts of these patterns. Conservation practices that improve soil carbon present a win-win situation for agriculture, mitigating climate change while improving soil water storage. In addition, a better accounting of agricultural water use is critical to facing increasing urban, industrial, and environmental water demands.

## Midwest

The Midwest (Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, Wisconsin, and southern Ontario, Canada) sits adjacent to four of the Great Lakes and is blessed with an abundant supply of water resources. The unique combination of glacially derived soils and cool, humid climate in the Midwest make it one of the most intense and productive agricultural areas in the world, generating approximately 65% of the US corn and soybean production (Pryor et al. 2014; NOAA 2013) and about half of Canadian soy and corn production. In addition to its agricultural significance, the Midwest tourism industry depends heavily on the Great Lakes and its many miles of shoreline. Water supply for the 61 million people (20% of the US population) who call the Midwest home originates primarily from surface sources.

Annual precipitation across the Midwest varies from greater than 1,150 mm (45 in) along the Ohio River and Missouri to less than 625 mm (25 in) in northern Minnesota while snowfall depths range from approximately 25 mm (1 in) in the southern latitudes to greater than 5,000 mm (197 in) in the Upper Peninsula of Michigan (NOAA 2013). The precipitation distribution also varies across the region with greater precipitation generally in the spring and summer. Midwest agricultural production is dependent on this precipitation distribution. However, excess precipitation in the spring often leads to localized flooding and prevents field access for farming practices. Excess water in the spring is often removed through artificial surface or subsurface drainage

(Blann et al. 2009) to facilitate agricultural crop production and reduce localized flooding concerns. Between 18 and 28 million ha (45 and 70 million ac) of cropland in the Midwest benefits from subsurface tile drainage (Zucker and Brown 1998), with drainage intensity continuing to increase (Sugg 2007; Blann et al. 2009).

The Midwest has historically been plagued by extreme rainfall events leading to extensive flooding and loss of life. For example, the 1913 flood in Ohio resulted in greater than 450 deaths and approximately 40,000 homes lost or destroyed, and has been referred to as Ohio's greatest weather disaster. Following the Ohio 1913 flood, conservancy districts were established to develop plans for preventing and/or addressing future flooding. The 1993 Mississippi River flood forced the prolonged closure of roads, bridges, railroads, and river traffic, and the losses to agricultural production and personal property were catastrophic (NOAA 2013). Most Midwest floods result from extreme precipitation; however, spring snowmelt can also lead to localized flooding (Kunkel 2003).

The greatest current water availability related issue in the Midwest is not supply but quality, and this water quality impairment is in large part due to artificial subsurface tile drainage (David et al. 2010; Maccoux et al. 2016). Indeed, in 2014, the city of Toledo issued a "Do Not Use" drinking water warning due to toxins related to a harmful algal bloom in Lake Erie, and many other streams and watersheds within the Midwest have been listed as impaired. In Iowa, several lawsuits have been filed over water quality concerns and the role agriculture plays in water quality. In Flint, Michigan, a major water quality crisis that received national attention developed when thousands of residents were exposed to lead in their finished drinking water. Furthermore, the tourism industry has been negatively impacted from poor water quality as many beaches along the Great Lakes and inland water bodies are forced to issue periodic warnings regarding water quality and human contact. As shifts in local weather and climate occur, water quality concerns will be exacerbated (Pryor et al. 2014; Verma et al. 2015).

Climate shifts and climatic variability predictions for the Midwest suggests warmer and wetter winter and spring months, a greater frequency of intense storms throughout the year, and more severe and longer droughts in the summer (Takle and Hofstrand 2008; USGCRP 2009), taxing an already weak infrastructure and exacerbating future water quantity and quality concerns. Decreased precipitation in the summer suggests agricultural watersheds will be subjected to increased water withdrawals for irrigation purposes (Wuebbles and Hayhoe 2004) creating a major shift in water usage and putting pressure on surface water resources. If supplemental water is not available, increased growing season drought conditions will lead to a reduction in crop yields. Furthermore, nutrient loss and availability are expected to be impacted under these future climate scenarios (Robertson et al. 2013; Jarvie et al. 2013) and directly impact water quality. Projected increases in temperatures and humidity are expected to exacerbate air and water quality degradation, increasing public health risks (Pryor et al. 2014). As pressure to produce more food, feed, fiber, and fuel from our agricultural lands increases and climate shifts occur, it will be increasingly important to balance social, economic, and environmental concerns.

## Great Plains

The Great Plains, which covers parts of Canada and the United States, is usually a windy and periodically dry region. Here we discuss the Great Plains water resources in the United States that cover all or parts of Colorado, Kansas, Montana, Nebraska, North Dakota, Oklahoma, South Dakota, Texas, Wyoming, and southern parts of Manitoba and Saskatchewan, Canada. Water availability in this region is driven by climate and mainly irrigation water use (Council of Canadian Academies 2013; Wishart 2019). As with other regions of the country, climate is the largest driver of water availability, with precipitation accounting for all surface water and a significant portion of groundwater recharge. In general, rainfall and snowfall increase from west to east varying from 350 to more than 1,000 mm (14 to more than 40 in) annually and vary from one year to the next (Whishart 2019). The climate in the Great Plains is characterized by extended periods of dry and wet years (Garbrecht 2008). In the Northern Great Plains, soil moisture reserves are sustained by snowmelt and can therefore vary considerably from year to year (Pomeroy et al. 2005). In very dry years, widespread crop failure results, and in very wet years, flooding occurs, particularly around snowmelt, damaging agricultural infrastructure (Pomeroy et al. 2005). Temperature affects evapotranspiration rates during the growing periods and the length of the growing season, with number of frost-free days ranging from more than 200 days in the Southern Plains to less than 100 days in the Northern Plains (Wishart 2019). According to Zou et al. (2018), areas in the far northern Great Plains had increasing open-surface water body area for the 1984 to 2016 period while the southern Great Plains had a decreasing trend for the same period. Shook and Pomeroy (2012) have shown that the occurrence of multiday storms in summer is increasing across the Northern Plains, which has implications for increased flow in summer. These climate-driven divergent open-surface water body area trends have serious consequences for water resources, especially in the water-poor parts of the Great Plains.

Water resources comprise of both groundwater and surface water. Surface water sources include natural streams, lakes, manmade dams, and flood retarding reservoirs. In the Great Plains region, there are 80 large multiuse reservoirs with a total capacity of $2.8 \times 10^{10}$ $m^3$ (22.9 million ac-ft) of water (Wishart 2019). Also, there are thousands of smaller, headwaters flood control reservoirs implemented, especially in the southern Great Plains, as a result of the Watershed Protection and Flood Prevention Act of 1954 (Hanson et al. 2007; Hunt et al. 2011). Over time, these dams and reservoirs that were built several decades ago lose water storage capacity due to sediment that is eroded from overland, transported downstream, and deposited in the reservoir (Morris and Fan 1998; Moriasi et al. 2018; Randle et al. 2019). One of the consequences of continuous dam and reservoir sedimentation is the reduction in the reliability of surface water supply.

Irrigation withdrawal for crop production is the biggest user of water resources, especially in the southern Great Plains. Irrigation that was introduced to the region by the Spanish settlers before 1700 initially utilized surface water (Whishart 2019). However, surface water body area shrinkage due to climate change as well dam and reservoir sedimentation over time has led to huge groundwater extractions for irrigated agriculture, which furthers surface water body area shrinkage, especially in the southern Great Plains (Zou et al. 2018). The classic example of the effects of groundwater overexploitation on water resources is the Ogallala Aquifer, the largest aquifer in North America (McGuire 2014; Gowda et al. 2019). The Ogallala Aquifer underlies an area of 450,000 $km^2$ (175,000 $mi^2$) spanning parts of Texas, Oklahoma, Kansas, New Mexico, Colorado, Nebraska, Wyoming, and South Dakota, i.e., the High Plains Region. The irrigated area of the High Plains Region has significantly increased since 1949 when pumping began, which has led to declines in groundwater storage (McGuire 2014; Gowda et al. 2019).

As a result of the declines in both surface and groundwater resources, especially in the southern Great Plains, compounded by impacts anticipated with climate change, new management strategies will be needed to ensure that surface water (Randle et al. 2019) and groundwater (Gowda et al. 2019) resources can sustain food production and other water uses. Strategies that improve water use efficiency, such as by incorporating drip irrigation; adopting cropping systems that require less water; and utilizing management systems that improve efficient infiltration, storage, and use of precipitation so that supplemental irrigation requirements are reduced, must be developed. Many surface water bodies in the Great Plains, particularly Lake Winnipeg (Schindler et al. 2012), have been severely impacted by water quality issues resulting from agriculture, and the nutrient loads are especially difficult to control due to the climate of the region (Council of Canadian Academies 2013). Thus, improving water resource use efficiency also requires optimizing the selection and strategic placement of conservation practices on the landscape to reduce soil erosion and improve water quality, as well as utilizing improved nutrient management strategies that apply only what crops need for optimal crop production while reducing excess nutrients transported into surface water bodies or leached into groundwater. Research is required to improve understanding of key soil, hydrologic, and agroecosystem processes that control water quality and quantity, and support the development of tools and techniques to improve watershed integrity and related ecosystems services.

## Pacific Northwest

Water availability in the Pacific Northwest region of the United States (Washington, Oregon, Idaho, and northern California) and southern British Columbia, Canada, is highly dependent on winter mountain snowpacks. Snowfall in this region can represent between 50% to 70% of annual precipitation totals (Serreze et al. 1999), with maritime to intercontinental snowpacks in the different ecoregions across the Pacific Northwest (Trujillo and Molotch 2014). These vital natural water towers provide timely delivery of water, with further man-made reservoirs regulating water yields for ecological functions, energy generation, and water supply for human consumption and agriculture while simultaneously protecting from effects of droughts and floods.

The Pacific Northwest is generally warm and dry in the summer months and cool and wet in the winter months. However, due to complex interactions between the onshore jet stream and mountain topography, the Pacific Northwest can be further subdivided into a variety of smaller ecoregions. In coastal Washington, Oregon, and northern California, precipitation totals are the highest in the conterminous United States, with a significant portion of winter precipitation falling as snow. Further inland, the mountains of Idaho and eastern Oregon and Washington, along with southern British Columbia, Canada, are colder and exhibit a higher snow proportion of annual precipitation. These snowpacks then supply runoff to the Columbia River, the fourth largest US river basin by volume. To the south, the Columbia's largest tributary, the Snake River, flows across Idaho's large high desert southern plain and is crucial for much of the region's agriculture.

Regional annual mean temperatures over the last century have risen by approximately 1ºC (2ºF), with the majority of the increases occurring during winter snow accumulation months (Abatzoglou et al. 2014; Mote et al. 2014). Future climate scenarios depend on current and future greenhouse gas emissions, but overall paint a dark picture. Under current emissions scenarios, temperatures across the Pacific Northwest are projected to rise 4ºC to 10ºC (7ºF to 18ºF) by the end of the century (May et al. 2018; RMJOC-II 2018). At the same time, future precipitation trends are less certain due to uncertainties in the Global Climate Models that underpin the projections (Abatzoglou et al. 2014; Kormos et al. 2016), but many projections agree that precipitation will generally increase throughout the winter and decrease in summer months (Jiang et al. 2018; Shrestha et al. 2014). However, even the combination of warmer winter months and an unchanging precipitation scheme will result in decreases in the snow proportion of annual precipitation, reduced mountain snowpacks, and decreased summer streamflow (Mote et al. 2014). Mountain basins that rely on large snowpacks for streamflow production will be the most sensitive to warming temperatures because winter flows will increase, and the annual spring melt timing will come earlier. These changes to the regional water cycle will have dire consequences on agricultural production, hydroelectric energy production, reservoir operations for both flood and drought mitigation, aquatic ecology, and forest fire severity.

Across the Pacific Northwest, continued reduction and increased variations in western mountain snowpack storage of water will continue to drive competing demands for available surface water from agriculture, urban use, energy production, and environmental flow requirements. The use of groundwater to offset available streamflow will continue to increase the challenges of decreasing groundwater levels and the need to increase recharge potential. Enhanced snowpack water measurement and stream flow prediction technologies provide opportunities to improve reservoir management needed to offset periods of inadequate surface water availability and to allocate excess surface water for groundwater recharge during periods of high runoff. Improved crop water use efficiency, recovery of agricultural soil quality, and control of agricultural impacts on water quality all provide additional opportunities to offset regional water management issues by reducing agricultural impacts on water supplies.

### Southwest

The Southwest (Arizona, California, Colorado, Nevada, and New Mexico), naturally hot and dry, faces water supply shortages that will only worsen with time. John Wesley Powell, who led a boat expedition down the Colorado in 1869 and served as the second director of the USGS, famously said, "I tell you gentlemen you are piling up a heritage of conflict and litigation over water rights, for there is not enough water to supply the land" (Pitzer 2019). Powell argued in vain for sparse settlement designed around watersheds. Instead, with the help of significant federal investment in water management infrastructure, the Southwest developed irrigated agriculture, and later, large urban areas like San Diego, Los Angeles, Las Vegas, Phoenix, Tucson, Denver, and Albuquerque that expanded the region's population to 60 million. Most of the water used (three-quarters of the total in 2010 for all southwestern states except Colorado) goes to irrigated agriculture and intensive livestock production (Gonzales et al. 2018). Although only a small fraction of the Southwest's water is transferred though water markets, and such markets face a patchwork of legal and practical constraints, the role of water markets in the Southwest is expected to increase with water scarcity (Schwabe et al. 2020).

In addition to increasing demand from a growing population, the Southwest faces additional challenges to its water supply. Rising temperatures, in addition to decreased precipitation, result in "aridification," or a more permanent water shortage than is conveyed by the term drought: Colorado River flows from 2000 to 2014 were 19% below the 1906 to 1999 average because of reduced snowpack and increased evapotranspiration (Udall and Overpeck 2017). There is also a "structural deficit" in that the basis of the 1922 Colorado Compact and later agreements provided for the use of $9.3 \times 10^9$ $m^3$ (7.5 million ac-ft) on average over a 10-year period for both the upper (Wyoming, Colorado, New Mexico, and Utah) and lower (Arizona, California, and Nevada) basins, plus $1.9 \times 10^9$ $m^3$ (1.5 million ac-ft) to Mexico, exclusive of prior rights and evaporative demand from reservoirs. Unfortunately, tree-ring studies indicate that long-term flows at Lee Ferry may range between $1.6 \times 10^{10}$ to $1.8 \times 10^{10}$ $m^3$ (13 to 14.7 million ac-ft), rather than the $2.0 \times 10^{10}$ $m^3$ (16.4 million ac-ft) anticipated in the Colorado Compact (National Research Council 2007). The result is that Lake Mead is close to the 325 m (1,070 ft) elevation level that will trigger a shortage declaration on the lower Colorado River. At the first level of the shortage declaration, the drought contingency plan would result in a 25% to 40% reduction in surface water deliveries to Arizona. The reductions would almost entirely be borne by agriculture, with up to 40% of agricultural fields fallowed in Maricopa and Pinal counties. "The impact of fallowing land in Pinal County could result in more than $200 million in lost agricultural revenues, and job losses up to 6% of the workforce" (Bickel et al. 2018). In the near term this shortage could be offset by groundwater pumping. However, this is a short-term solution, as Thomas and Famiglietti (2019) report that groundwater, the buffer of last resort, is being depleted during periods of precipitation deficits. In summary, water supply, always a limiting factor in the Southwest, will become an even more binding constraint. Research is needed to improve water efficiency in irrigated agriculture, increase flexibility of livestock operations in the face of drought, assess the impact of declining flows on salinity in the Colorado River basin, expand the use of degraded and brackish waters, and better quantify water budgets and increase recharge in rural areas.

## Summary

The sustainability of agriculture in the United States is inexorably linked to the availability of water resources, although factors affecting water availability vary widely. Water availability for agriculture has historically been controlled by the water cycle, but, increasingly, quality of water resources as affected by agricultural practices restricts their availability for other important uses. Ensuring long-term water availability requires adaptation to changing climate, implementation of comprehensive conservation strategies, and an evolution of agricultural production systems. Fortunately, the United States is well positioned to meet critical research needs in support of ensuring water availability in the face of climate change. National research networks, such as the National Ecological Observatory Network, the Long-Term Ecological Research Network, and the Long-Term Agroecosystem Network, are organized to address local and regional research needs and extrapolate results to national scale. For more information related to the subject of water availability, readers are encouraged to read chapters in this book on the topics of water quality, irrigation, drainage, climate change, and modeling.

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# 10

Practitioner's Perspective

# Water Optimization through Applied Irrigation Research

*Matt Yost, Niel Allen, Warren Peterson, and Jody Gale*

Irrigation, insurance, and life often do not end up in the same sentence. Irrigation provides essential insurance, even the lifeblood on irrigated farms. During the past 75 years, irrigation has brought people and prosperity to rural areas throughout the world. Given adequate water resources, irrigation ensures water essential to economic production of high quality food, fuel, feed, and fiber in needed quantities. Agriculture has become the largest user of extracted or diverted water on the planet and, consequently, the forefront of efforts to conserve and optimize water use.

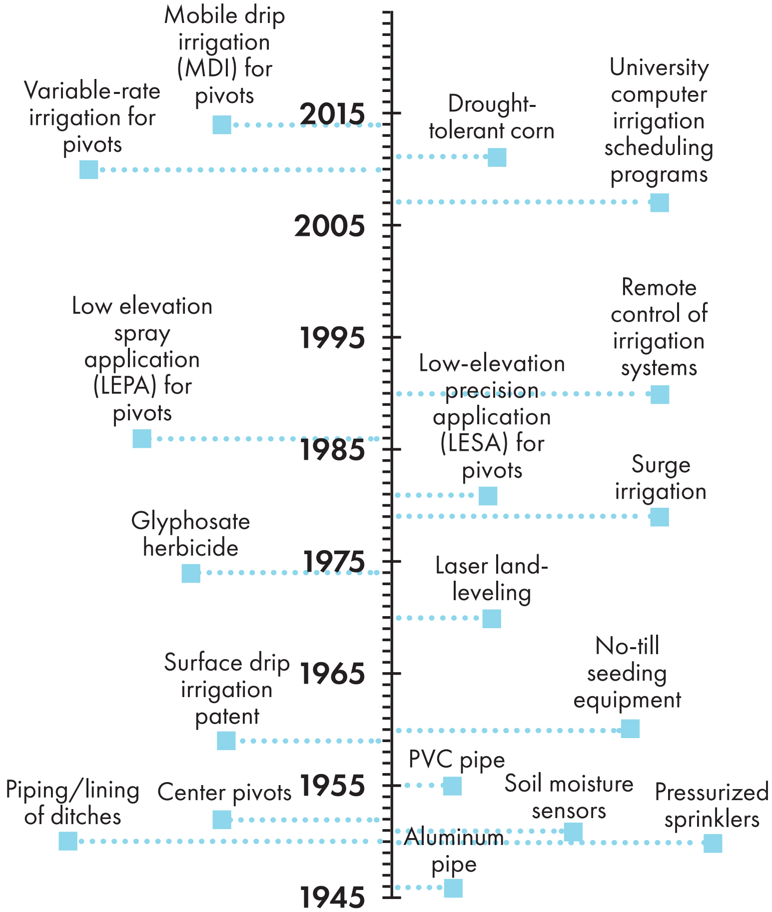
As competition for limited water resources increases across the world, water scarcity rises as a sustainability concern for irrigated agriculture. Rapid urban growth, increased food demands, groundwater depletion, soil and water salinity, and water supply shortages drive this competition. Competition will also increase due to projected climate trends toward less frequent, more variable, and different types (rainfall versus snow) of precipitation.

To address these water scarcity concerns, policymakers, scientists, engineers, practitioners, educators, farmers, and many others have and are working to optimize agricultural water use. Numerous technologies, developments, and policies have brought tremendous advancements in agricultural water optimization. For the sake of brevity, this article highlights only a few major changes of the last 75 years (figure 1) and a few needed efforts for the future. This discussion focuses on three central areas impacting water

**Matt Yost** is an agroclimate extension specialist and **Niel Allen** is an extension irrigation specialist, Utah State University, Logan, Utah. **Warren Peterson** (retired) was land and natural resources vice president, Farmland Reserve, Inc., Salt Lake City, Utah. **Jody Gale** is extension associate professor, Utah State Univeristy, Richfield, Utah.

**Figure 1**

**Timeline of some of the major advances in water conservation from 1945 to 2020. Dates for many technologies are when they were first widely commercially available, unless otherwise noted.**




optimization—irrigation, crop, and soil management—while acknowledging that complex interactions of these and other factors influence water optimization in agriculture.

## Irrigation Management

A comprehensive view of irrigation management begins from the point of first diversion through delivery to the field, continues to water application, and evapotranspiration (ET) through the crop, and ends with return flow and soil water storage. Major advancements in the first two areas are described briefly below.

***Diversion and Delivery to the Irrigation System.*** Artificial irrigation relies on diversion from surface and groundwater sources. Greater access to and utilization of groundwater has reduced losses incurred during surface water delivery. Lining and piping of delivery systems have also been a major water optimization advancement (Schaible and Aillery 2012). Lined ditches and piping catalyzed by developments of improved materials (concrete, polyvinyl chloride [PVC], high-density polyethylene [HDPE], etc.; figure 1) have greatly reduced water losses during delivery from diversion to the field. Other major advances in delivery systems include technologies to monitor and remotely control flow through headgates, valves, weirs, and other devices (Stubbs 2016). Planned diversions through water orders from developed irrigation institutions (Bretsen and Hill 2007) instead of set diversions have also reduced system losses.

***Application to the Crop.*** Irrigation has three major interacting components: method, amount, and timing. Surface irrigation systems efficiencies have benefited from advancements in laser-leveling, high-head, level basin irrigation, surge irrigation, and other related approaches (figure 1). One of the largest impacts in irrigation methods has been the development and widespread adoption of pressurized irrigation systems (USDA ERS 2019), namely center pivots and laterals. Massive transitions from gravity to pressurized irrigation systems have occurred, and still continue to occur, in the United States (USDA NASS 2018) and other countries. In many cases, this has enabled greater irrigation application uniformity and efficiency, and more precise and real-time control of irrigation. It has also significantly reduced farm labor requirements. In some cases, however, sprinkler systems have also increased evaporative losses, reduced return flows, and disrupted downstream water allocations (Grafton et al. 2018).

Center pivot technology rapidly advanced during the late 1990s and continues to date. Center pivots can now be remotely controlled and programmed to apply precise amounts of water throughout a field, enabling variable-rate irrigation approaches. To reduce evaporative losses and improve application uniformity, sprinkler systems, especially center pivots, have largely transitioned from sprinklers at high elevations (including on top of pivot) to mid- (~1.5 m [4.9 ft]) and low-elevation (0.5 m [1.6 ft]) systems. Most center pivots in the last two decades have utilized some form of mid-elevation spray application (MESA), but adoption of three more efficient pivot sprinkler technologies (low-elevation spray application [LESA], low-energy precision application [LEPA], and precision mobile drip irrigation [PMDI or MDI]

**Figure 2**

**Four pivot/linear irrigation packages including mid-elevation spray application (MESA), low-energy precision application (LEPA), low-elevation spray application (LESA), and mobile drip irrigation (MDI).**


systems; figure 2) is increasing as the industry, irrigators, and scientists have documented their benefits (Schneider et al. 2000; Peters et al. 2016; Kisekka et al. 2017). These advanced irrigation systems have been appealing because they can be installed on existing pivots at much lower investment costs than subsurface drip irrigation.

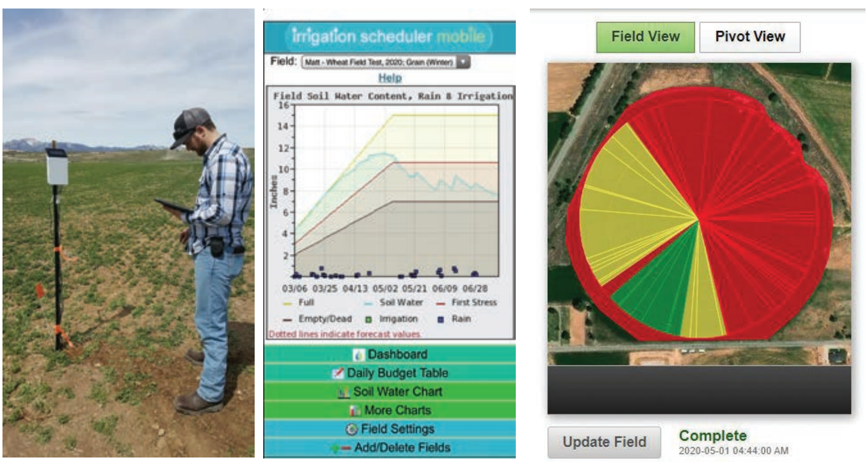
Subsurface drip irrigation equipment and techniques have also advanced greatly in the last 75 years. This irrigation method has among the highest potential irrigation application efficiency (upwards of 97%) but has been impractical for many operations due to large capital investments and logistical concerns (Neibling 1994; Amossen et al. 2011). Subsequently, its growth has been the greatest in high value crops.

Simple and inexpensive management methods have allowed irrigators to improve water management, such as modifying irrigation amounts and timing. Irrigation rates have easily been modified by changing flow rates, irrigation set lengths, nozzle size, and other methods. These adjustments match irrigation rates to soil intake rates, maximum soil water depletion between irrigations, and ET demand, which in turn reduces or prevents unnecessary runoff or other losses (Andales 2014). The approach has been adjusted to account for inadequate water supplies and has included various forms of deficit or partial irrigation (Lindenmayer et al. 2011; Putnam et al. 2017).

**Figure 3**

**Examples of advanced irrigation scheduling approaches: (a) soil moisture sensing system with telemetry, (b) weather station data used to estimate evapotranspiration and create irrigation schedule programs (e.g., Irrigation Scheduler developed by Washington State University), and (c) a commercial scheduling product called FieldNet Advisor developed by the Lindsay Corporation.**

(a) (b) (c)




Several methods developed to determine ideal irrigation schedules include the following:

- Monitoring soil moisture by hand using the "feel" method, or with a variety of soil moisture sensors (Maughan et al. 2015; figure 3).
- Irrigation scheduler systems that utilize weather data to estimate ET, calculate water balances, and recommend irrigation rates according to maximum allowable depletion (Leib et al. 2002).
- Canopy temperature sensors to detect crop water stress (Stockle and Dugas 1992).
- Commercial programs that utilize crop growth models, soil characteristics, and ET estimated from satellite or aerial imagery. In some cases, these programs have the ability to send prescriptions directly to pivot controls for autonomous irrigation.

Although adoption of advanced irrigation scheduling techniques has been slow in the United States (USDA NASS 2018), interest from irrigators has grown each year as more growers realize benefits associated with improved scheduling.

## Crop Management

Water optimization can be achieved when crops are better able to utilize water. This has occurred in many ways, but only three will be discussed here:

- Improved weed control has been a major advancement in crop management that has improved crop water utilization. Weeds often extract water in greater amounts per unit of dry matter than crops. Modern herbicides such as glyphosate have greatly reduced water competition from weeds for a large variety of crops.
- Improved crop varieties and hybrids have been another important advancement. The yield potential of most crop varieties has dramatically increased during the last 75 years. In tandem with yield increases, crop water use efficiencies have also improved. In some crops, advanced breeding and genetic techniques have led to more drought-tolerant varieties. Drought-tolerant corn hybrids such as AquaMax developed by DuPont Pioneer and DroughtGaurd developed by Monsanto are a couple of examples (McFadden et al. 2019).
- Alternative crops with lower and/or different timing of water requirements has been a third common advancement toward better water optimization. Alternative crop lists are lengthy, but some of the major gains in acreage have occurred with sorghum and related species, pearl millet, triticale and other various small grains, and some oilseeds like canola and safflower.

## Soil Management

Another approach to water optimization is improving the soil's ability to retain water and make it available to plants. While many management practices influence soil water dynamics, a few have shown promise across wide geographies. These include proper nutrient management; reduced or eliminated tillage; residue management (up to 25% to 40% improvements in water productivity [Hatfield et al. 2001]), and soil amendments with high carbon organic materials such as manure, compost, cover crops, and/or biochar to help increase soil organic matter and improve water holding capacity (Khaleel et al. 1981; Ali and Talukder 2008; Karhua et al. 2011; Hunter et al. 2017).

## Looking Forward

For the sake of brevity, this chapter has only scratched the surface of water optimization efforts during the last 75 years. Technology advancements of water delivery and application systems, coupled with irrigation, crop, and soil management have made large strides. Volumes have (Stubbs 2016; Nurzaman

2017) and could be written about the numerous policies, technologies, science, education, and adoption that have positively influenced water optimization.

Some of the major challenges going forward will be to discover, prioritize, and incentivize long-term economic and environmental ways to best optimize water use. Because it is impractical and unaffordable for all water-optimizing practices to be simultaneously implemented, advanced tools will be necessary to help farmers, policymakers, and other stakeholders identify the suites or combinations that produce the greatest water efficiencies. These tools and investments should be guided by ongoing and innovative long-term irrigation research, which is currently sparse or nonexistent compared to other agricultural research.

## Acknowledgements

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# 11

# Water Quality

*Jorge A. Delgado*

## Past Challenges

About 60% of an adult human's body weight is comprised of water, highlighting the critical importance of access to drinking water to survival. Across human history, civilizations have developed and flourished around water resources. Water has also been a source of conflict, both between countries and even within a given country where water disputes have occurred. Water is needed to grow the crops and forages that feed humans and livestock, and to sustain forests used for housing and other products. Water is also used as a transport mechanism for commerce and in aquaculture, which contributes to the overall food supply of the population. Water resources in the United States have been protected with policies to conserve water quality, a natural resource vital to national security.

In the 1930s and 1940s water quality policies, resources, and practices largely focused on erosion and flooding, but there was not a national policy on water quality. Not until the Federal Water Pollution Control Act (FWPCA) was enacted in 1948 was the concept of water quality brought to the forefront. The original, unamended FWPCA addressed water quality issues that were related to soil erosion, sedimentation, and flooding control. As new challenges and research emerged, there were changes in the FWPCA to address challenges that were due to chemical and agrochemical pollution. In the decades that followed, legislative amendments were implemented to address these challenges, namely the Federal Water Pollution Control Act Amendments of 1972, the Clean Water Act of 1977, and the Water Quality Act of 1987.

Although it was not until the 1970s that changes in policy were implemented to specifically address the nutrient issues related to water quality, the issue of

**Jorge A. Delgado** is a research soil scientist with the USDA Agricultural Research Service Soil Management and Sugar Beet Research Unit, Fort Collins, Colorado.

water quality was addressed when Congress acted in 1935 to authorize and direct the Secretary of Agriculture to establish the USDA Soil Conservation Service (SCS), which was later renamed with an amendment in 1994 as the Natural Resources Conservation Service (NRCS). The establishment of SCS (later NRCS) contributed to the improvement of water quality by creating an agency that led the effort to mitigate erosion, an action that also contributed to reducing the transport of agrochemicals to water bodies. This action, along with the FWPCA and later amendments, were key components of the 20th century efforts to protect water quality in the United States. Farm bills passed by Congress over the last 75 years have included water quality funding provisions that have contributed to programs and initiatives that have helped conserve water quality.

The challenges that the United States faced 75 years ago with soil erosion threatening the sustainability of agricultural systems, including the Dust Bowl era of the 1930s, were significantly mitigated as understanding of the soil erosion process improved and management practices reduced off-site transport of sediment, which was a major success for sustainability and food security in the United States. The SCS/NRCS addressed challenges related to sedimentation, which were impacting water quality and contributing to flooding problems, with the development and implementation of management practices to reduce erosion. Additionally, universities, extension services, private consultants, conservation practitioners, farmers, ranchers, and natural resource conservation organizations have been working with SCS/NRCS to implement conservation practices on the ground to reduce erosion and protect water quality. Professional societies have played an important role in bringing together experts in water quality. For example, the Soil and Water Conservation Society serves as a forum for soil and water conservation professionals to come together for discussion of water quality issues as well as policies related to water quality.

## Current and Future Challenges

There is no doubt that there have been success stories that have contributed to significant advances in water quality protection through reduction of erosion, and conservation practices implemented during the last 75 years to reduce erosion have also reduced transport of agrochemicals and nutrients to the environment. NRCS reported significant reduction of erosion rates in the 20th century (USDA NRCS 2010; Argabright et al. 1995). Erosion rates declined about 58% from the 1930s to 1992 in the northern Mississippi Valley Loess Hills (Argabright et al. 1995). The reduction of erosion rates during the golden era of soil and water conservation (1930s to 1980s) is one of the great conservation success stories of the 20th century, yet it often goes untold. If we extrapolate the data from USDA NRCS (2010) and Argabright et al. (1995), we can infer that the erosion rate was reduced across the entire United States by over 50%, with roughly 80% of this reduction occurring during the golden era of soil and water conservation and 20% of the reduction occurring from the 1980s to 1990s, contributing to conservation of water quality (year and erosion rates in mm $y^{-1}$ [in $yr^{-1}$]: 1930, 2.9 [0.11]; 1982, 0.77 [0.03]; 1992, 0.67 [0.03]; 2007, 0.51 [0.02]; 2020, 0.51 [0.02]). Yet significant water quality challenges remain, and there are biological, agrochemical, and other factors that are difficult to control. Excess nutrients can escape to the environment through different pathways, complicating efforts to control these losses. Losses of reactive nitrogen (N) and phosphorus (P) to the environment are a wicked problem, and this becomes particularly apparent when legacy P is considered. The water quality challenges of the 20th century were not completely resolved and indeed persisted, and may have even worsened by the end of the millennium.

The 21st century presents both familiar and new water quality challenges. Among the new challenges for water quality is the impact of rapid population growth that has occurred since 1946 in the United States and globally and the need to increase agricultural production to feed an additional 2.5 billion people by 2050. This has put pressure on agricultural systems to intensify production, including production of beef, poultry, pork, dairy products, and other agricultural products, which has contributed to some agricultural areas shifting from nutrient sinks to nutrient sources (Sharpley et al. 1999). Ribaudo et al. (2011) reported that over 90% of acres treated with manure in the United States were not using best N rate, best method of application, and/or best time of application. A changing climate with more frequent extreme weather events also threatens to increase erosion rates and the off-site transport of agrochemicals and nutrients to water bodies via surface runoff or leaching. Greater precipitation events can increase nitrate ($NO_3^-$) leaching through tiles and through the soil profile, potentially impacting groundwater. With legacy effects that continue to affect nutrient transport, these water quality challenges persist in the United States and other regions.

A new challenge is highlighted by recent reports of N contributing to increased microcystin concentrations via impacts to the cyanobacterial community. Guidelines established by the World Health Organization recommend that microcystin levels in drinking water not exceed 1.0 μg $L^{-1}$ (WHO 2011). In the United States, the US Environmental Protection Agency (EPA) has established a safe limit for children under six years old of only 0.3 μg $L^{-1}$ (USEPA 2015a). Microcystin contamination could compromise human health by contributing to gastroenteritis and liver and kidney damage.

It has been recently reported that nutrient losses could contribute to or exacerbate hypoxic zones and algae blooms that could increase microcystin levels

(Monchamp et al. 2014; Smith et al. 2018). Phosphorus losses can also contribute to hypoxic zones that impact water quality (e.g., Lake Erie) (International Joint Commission 2013). Besides negative environmental impacts caused by lower water quality, hypoxic zones and algae blooms negatively impact tourism and fishery industries as fish populations decrease and local communities are impacted by temporary closures of beaches, lakes, and other water bodies that serve as recreational areas.

Water quality affects water bodies across the United States, with economic impacts in the billions of dollars per year. For example, it is well established that soil erosion negatively impacts water quality. At the individual farm level, it is estimated that for every 10 cm (4 in) of soil lost via erosion there is approximately a 4.3% loss of productivity, and this loss of productivity will be greater for the next 10 cm of soils that get eroded (Bakker et al. 2004). Additionally, the value of the nutrients lost from a given field has a dollar value. The off-site impacts on water quality may be higher, especially the potential impacts to human health. Ribaudo et al. (2011) reported that the cost in the United States to remove $NO_3^-$ from drinking water supplies is $1.7 billion annually. Nitrates can significantly impact human health (Follett et al. 2010; Temkin et al. 2019). The EPA has reported that the safe limit of $NO_3^-$ in drinking water is 10 mg $NO_3$-N $L^{-1}$ (USEPA 2015a). Temkin et al. (2019) has recently suggested that lower concentrations of $NO_3$-N could have negative impacts on human health. Temkin et al. (2019) reported that a colorectal cancer risk of one in a million was associated with concentrations as low as 0.14 mg $NO_3$-N $L^{-1}$, with higher risk at higher concentrations. They also reported that close to 3,000 cases of low birth weight and about 2,300 to 12,500 cancer cases annually in the United States could be linked to $NO_3^-$ exposure. The economic cost of $NO_3$-N impacts on human health was reported by Temkin et al. (2019) to range from $250 million to $1.5 billion, with an additional cost of $1.3 to $6.5 billion when lost productivity is accounted for.

Delgado (2020) noted that while the use of N fertilizer has led to an abundant food supply, it has also resulted in increased N losses from agricultural systems to the environment. He also reported that although there are benefits to nutrient management, there will continue to be environmental damage unless the errors of the 20th century are avoided. The challenge of 21st century management is thus to avoid these errors to produce food for a population of 9.5. billion by 2050, while also adapting to the challenges of a changing climate, dwindling water resources, and the increased occurrence of extreme weather. Sustainable Precision Agriculture and Environment (SPAE, similar to the 7 Rs [Delgado et al. 2019]) can be used to help us adapt to a changing climate and reduce the off-site transport of nutrients to the environment.

## Current Status of Water Quality

Although there have been significant advances in water quality efforts, recent analyses of trends in water quality across the United States indicate that water bodies remain significantly impacted. For example, a recent EPA study reported that more than half of the nation's stream miles are negatively impacted (USEPA 2016). The EPA reported that the water quality of the nation's streams is significantly impacted by chemical stressors, overwhelmingly N and P with 41% and 46% content, respectively. Additionally, the US Geological Survey (USGS) has a website that tracks current levels of pollution for water quality, including levels of total P, total N, orthophosphate ($PO_4^{3-}$), and $NO_3^-$. Visitors to the site may graph the trends across the nation for these and many other parameters from 1972 to 2012; 1982 to 2012; 1992 to 2012; and 2002 to 2012 (USGS 2020b).

Across about 100 sites in the United States, total P exhibited an increasing trend from 2002 to 2012, while at about 120 sites, the P concentrations decreased, and for about 80 sites, the concentrations of P remained the same, suggesting an average of about 30% of sites with increasing total P concentrations (figure 1). For $NO_3^-$, about 100 sites exhibited increasing $NO_3^-$ concentrations from 2002 to 2012, and at about 70 sites, the concentrations of $NO_3^-$ remained the same, while about 150 sites experienced decreasing $NO_3^-$concentrations, suggesting an average of about 30% of sites with increasing total $NO_3^-$ concentrations (figure 2).

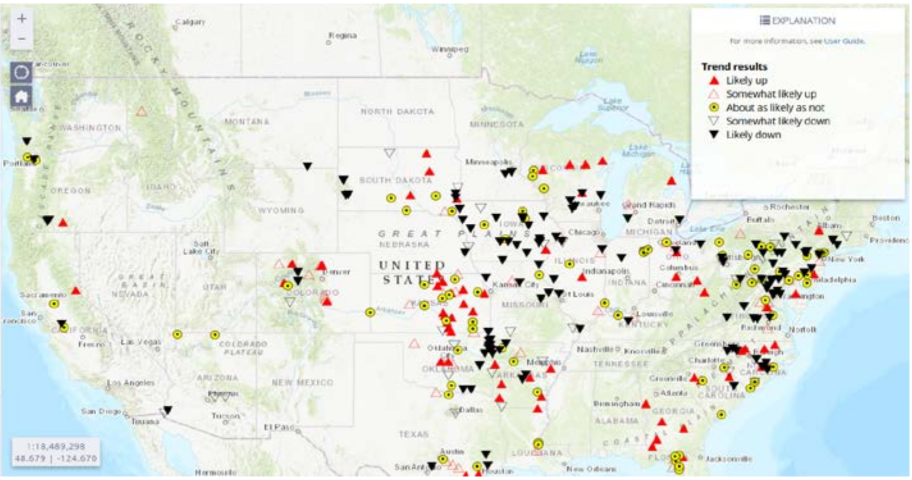
The trends in annual water quality load to the Gulf of Mexico may also be monitored through a USGS website (USGS 2020a). The five-year moving average of the yearly total P load increased from 1979 to 2019 (figure 3), and only in two years from 1997 to 2019 did the flows meet the goal of a 20% reduction from the 1980 to 1996 baseline in yearly total P load, with one of those years as low as 45% reduction (2006). The goal of a 20% reduction in total P has not been achieved during the last 13 years, and total normalized loads have not decreased since 1983. The year 2019 had the highest total annual P load of this 40-year period. The total dissolved $NO_3^-$ plus nitrite ($NO_2^-$) flow-normalized loads have not been reduced since 1979, and if anything, have slightly increased (figure 4). The year 2019 had the highest total $NO_3^-$ loads of the past four decades. The USGS data are in agreement with the EPA report that water quality in the United States is under stress, especially because of nutrient losses (mainly N and P). Other water quality measurements, such as trends in pesticides and algae (diatoms), are also available at the USGS website.

## Current Advances in Nutrient Management

The growing use of N fertilizer recommendations for different crops and soil types across the United States and the world played a key part in the Green

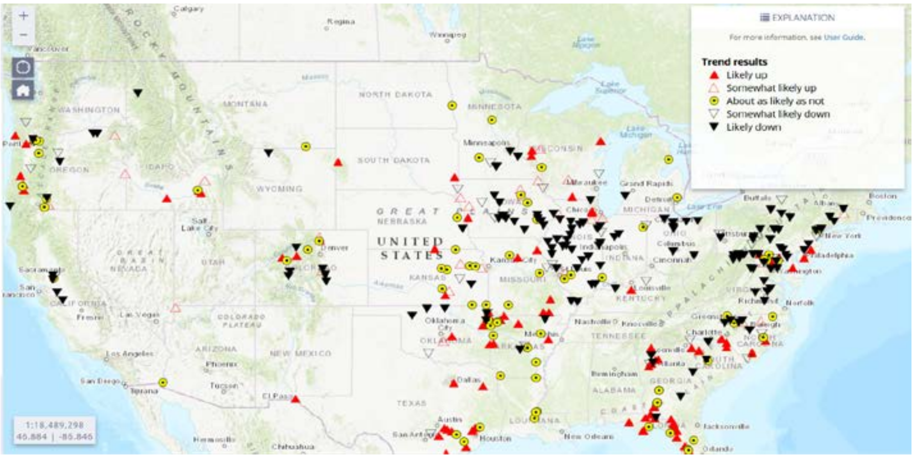
## Figure 1

**Trends in nutrient content (total phosphorous) of water from 2002 to 2012 across the United States (USGS 2020b). Red triangles indicate areas where phosphorus is likely up, while upside-down black triangles indicate where it is likely down.**



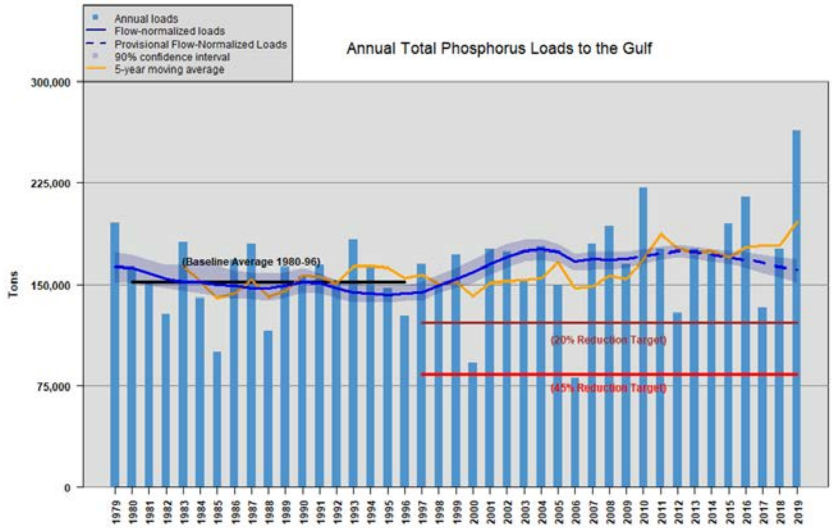

## Figure 2

**Trends in nutrient content (nitrate) of water from 2002 to 2012 across the United States (USGS 2020b). Red triangles indicate areas where nitrate is likely up, while upside-down black triangles indicate where it is likely down.**



## Figure 3

**Trends in yearly phosphorus loads to the Gulf of Mexico from 1979 to 2019 (USGS 2020a). Graph shows annual loads (bars) and reduction targets (red lines), as well as flow-normalized loads (solid blue line), 90% confidential interval (shaded area), and the five-year moving average (yellow line).**

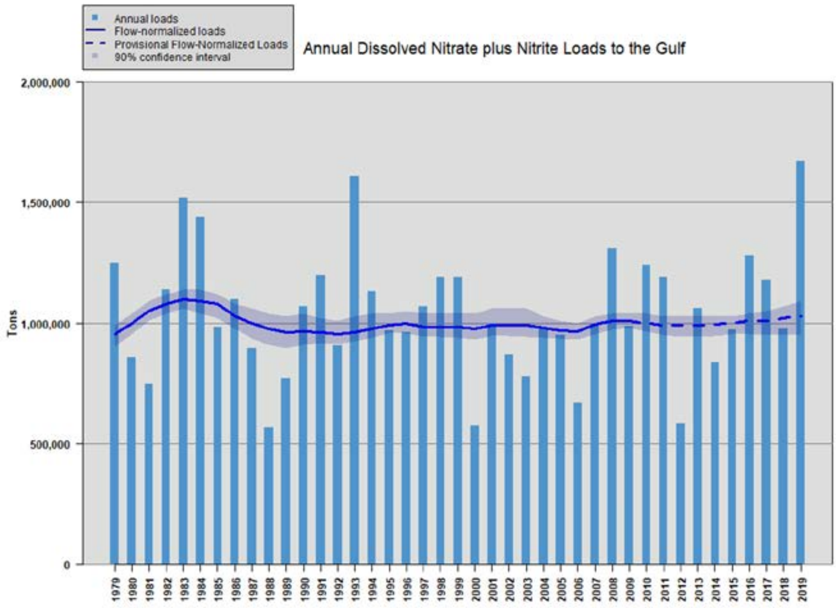



| Trend start period | Trend end year | Trend, in percent change | Lower 90% confidence interval | Upper 90% confidence interval | Trend attributed to changes in streamflow | Trend attributed to other changes in the watershed |
|---|---|---|---|---|---|---|
| 1980-1996 | 2019 | 7% | -5% | 17% | 1% | 6% |

Revolution in the 1950s and 1960s. The use of N fertilizer and other fertilizers increased greatly during this time (Cao et al. 2018). Although research about denitrification, ammonia ($NH_3$) volatilization, and leaching was being conducted by the 1960s, it was not until the implementation of amendments to the FWPCA in 1972 and the Clean Water Act amendments of 1977 that development of research and management practices that can be applied to reduce nutrient losses to the environment by these pathways was expanded. The goals of water protection and conservation of the Clean Water Act amendments stimulated this research and the transfer of these technologies and practices to address the increased losses of nutrients that were being observed at the time. Research during the second half of the past century improved our understanding of pathways for nutrient losses, and how to implement and apply best management practices and conservation practices on the ground to reduce the losses of nutrients from agricultural systems. Nutrient management was defined by Delgado and Lemunyon (2006) as “the science and art directed to link soil, crop,

**Figure 4**

**Trends in yearly dissolved nitrate plus nitrite loads to the Gulf of Mexico. Annual total loads to the Gulf from 1979 to 2019 (USGS 2020a). Graph shows annual loads (bars), as well as flow-normalized loads (solid blue line) and 90% confidential interval**




weather, and hydrologic factors with cultural, irrigation, and soil and water conservation practices to achieve the goals of optimizing nutrient use efficiency, yields, crop quality, and economic returns, while reducing off-site transport of nutrients that may impact the environment."

New technological trends at the end of the 20$^{th}$ century such as the proliferation of standalone personal computers in the 1980s facilitated the development and use of computer tools and simulation models to evaluate nutrient management practices. The development and expansion of geographic information systems (GIS) in the 1990s facilitated the assessment of nutrient management spatially across the landscape. Field applications of remote sensing for nutrient management, such as various indices (e.g., normalized difference vegetation index [NDVI], nitrogen reflectance index [NRI]) and global positioning systems (GPS), came to be used more extensively in agriculture during this time and were becoming nutrient management assessment tools during the 1990s, paving the way for the development of the concept and application of precision agriculture, which made it possible to better assess the temporal and spatial distribution of sources, sinks, and pathways for nutrients. New developments in agricultural engineering and computer systems allowed users to apply variable rates of nutrients across the landscape in a given field to match maps of nutrient rate recommendations that were designed to match the observed yield variability at the same field with new yield monitoring equipment that had GPS and computer software mounted on harvesting equipment.

These new developments enable users to apply site-specific approaches to nutrient management on the ground. Precision conservation, conceived and developed in the early 2000s, considered nutrient sources and sinks and pathways for losses and transport from fields to natural areas surrounding the fields. By the 2010s, the rise of open access databases and cloud technologies started enabling the potential application of machine learning and artificial intelligence for assessment of nutrient management. Applications of robotics and drones in agriculture were emerging. Universities, the private industry, government organizations, professional organizations, consultants, farmers, and ranchers began implementing these technologies to maximize yields and increase the use efficiency of inputs while reducing the losses of nutrients to the environment. A new generation of nutrient managers and conservation practitioners were being trained at the time to apply these new technologies that differed from the traditional nutrient management approaches of five or six decades ago.

Machine learning and artificial intelligence, big data, cloud storage technologies, and handheld field devices such as smartphones and tablets have provided crucial support to nutrient management research in the application of new technologies (e.g., the rise of personal computers, the Internet, simulation models, GIS, GPS, remote sensing, precision farming, precision conservation, the cloud, drones, robotics, new agricultural equipment) at a field level. The rapid advances of the past 30 to 40 years have meant that nutrient managers and conservation practitioners have had to adapt to keep pace.

Similarly, the traditional development of best management practices that was integrating these new management technologies also was expanded during the last three to four decades to integrate some of the new findings from research. Some of the principles of nutrient management for reduction in $NO_3^-$ leaching were published by Meisinger and Delgado in the *Journal of Soil and Water Conservation* in 2002. They reported that $NO_3^-$ leaching losses from N fertilizer applied to common grain-production systems typically could range from 10% to 30%. Meisinger and Delgado reported that management can be a viable approach to reducing $NO_3^-$ leaching losses and that it is important to know the soil-crop-hydrologic cycle and apply the proper N rate and in sync with the crop demand by splitting N applications at planting and during the growing season. They reported that cropping systems could be used as management tools by rotating shallow-rooted crops with deeper-rooted crops that increase the use of soil resources. They also reported that rotations with deeper-rooted crops could be used as scavenger crops and recover residual soil $NO_3^-$ from the soil profile. Additionally, they reported adding cover crops to the rotations could also help scavenge residual soil $NO_3^-$ from the soil profile.

Meisinger and Delgado (2002) additionally recommended that adding a legume to the rotation of grain cropping systems will reduce the need for N fertilizers and increase N cycling. There is a need to manage ecosystems, and tillage equipment and improved management practices, such as use of nitrification inhibitors, controlled release fertilizers, and enhanced efficiency fertilizers, could potentially be used to manage/reduce $NO_3^-$ leaching. They reported that controlled drainage also could be used to reduce $NO_3^-$ leaching. For irrigated systems, use of water management tools such as irrigation scheduling, improved irrigation systems, and other water management tools is important. Monitoring on-site N management with in-situ tools and using real-time monitoring techniques and tools such as petiole analysis, pre-sidedress soil $NO_3^-$ tests, chlorophyll meters, and remote sensing could contribute to better N management and potentially to reduced leaching. Simulation models and N index tools could be used to assess the risk potential for each crop-landscape scenario. Precision agriculture approaches could also potentially improve N management.

It has been well-established that by using the right rate, right time, right method, and right source of N (Roberts 2007) and management zones (Delgado and Bausch 2005; Khosla et al. 2002), $NO_3^-$ leaching losses and losses of reactive N via other pathways could be reduced. Improving nutrient management with the 7Rs for nutrient management and conservation (often called 4R+) could contribute to lower nutrient losses across the environment than the use of the 4Rs alone (Delgado 2016). Precision conservation contributes to the use of the right conservation practice at the right place (e.g., placement of grass waterways), but also connects field management with off-site management practices such as buffers, riparian buffers, denitrification traps, and other soil and water conservation practices (Berry et al. 2003; Delgado et al. 2018). It has been shown that these practices can be used to minimize nutrient losses to the environment. Precision conservation increases the effectiveness of conservation practices.

***Development of Tools for Nutrient Management.*** With the development of standalone computer tools during the 1980s, the development of software tools for nutrient management exploded. A large number of computer tools were developed to assess nutrient management and assess the effects of management practices on the risk for potential nutrient losses. A tremendous success was the development of a P index, which was initially proposed by Lemunyon and Gilbert in 1993. Sharpley et al. (2003) described the use of different N indices across the United States in the early 2000s. The P Index was significantly expanded to be used across all states. An N index was developed by Delgado et al. (2006, 2008a) that could quickly quantify the potential for $NO_3^-$ leaching losses. Delgado et al. (2006, 2008b) discussed the advantages and disadvantages of previous indices used to assess $NO_3^-$ leaching. A large number of more complex models have been developed since then to assess the losses of N to the environment, such as the Nitrogen Loss and Environmental Assessment Package with GIS capabilities (NLEAP GIS) (Delgado et al. 2020; Shaffer et al. 2010), Environmental Policy Integrated Climate model (EPIC) (Williams 1983; Williams and Renard 1985), Leaching Estimation And CHemistry Model (LEACHM) (Wagenet and Hutson 1989); Root Zone Water Quality Model (RZWQM) (Ahuja et al. 2000), Adapt-N (Melkonian et al. 2008), DayCent (Parton et al. 2001), and Agricultural Policy/Environmental eXtender model (APEX) (Gassman et al. 2010), among others. Some models now can be used to assess the effects of management practices on losses of nutrients to the environment and trade the savings (reduction in nutrient losses) achieved with implementation of best management practices (e.g., Nitrogen Trading Tool [NTT] [Delgado et al. 2008b]; Nutrient Tracking Tool [Saleh et al. 2011; Saleh and Osei 2018]; CarbOn Management and Evaluation Tool—Voluntary Reporting [COMET VR] [Paustian et al. 2018]).

## The Future: Precision Farming, Precision Conservation, Precision Regulation, and Ecosystem Markets for Sustainable Agricultural and Natural Systems

Conservation of water quality is a wicked challenge that has yet to be resolved in the United States. The issue of erosion impacting water quality was significantly addressed with the creation of the SCS/NRCS and the FWPCA enacted in 1948, which contributed to reduction of erosion across the nation. The mitigation of erosion's impact on water quality is one of the great conservation success stories of the 20th century. However, even with the amazing advances in applied and basic research, and technology transfer for water quality (e.g., Universal Soil Loss Equation [USLE] and other the models that started the quantification of how land management affects erosion), including the development of precision agriculture, precision conservation, and new best management practices during the last 40 years, the problem of nutrient losses to water bodies impacting water quality endures (USEPA 2008; USGAO 2013).

Nonetheless, there are nutrient management success stories to be found, such as the new crop varieties that have been increasing N use efficiencies for cropping systems. Fixen and West (2002) and Snyder and Bruulsema (2007) analyzed the yields across the United States during the last three decades; they found that they have increased significantly during this period since corn yields have been increasing, even as the average fertilizer application rate remained unchanged. In contrast, Ribaudo et al. (2011) reported the need to increase N use efficiencies in a national report finding that only about one-third of the farmland in the United States was implementing all three best management practices of applying the best N rate, with the best method of N application, at the best time of N application. Legacy nutrients, especially legacy P, which can remain in the system for a long time and moves more slowly in the environment, can also be a source of nutrients. Losses of reactive N are more dynamic since N could be lost via many pathways such as $NO_3^-$ leaching, surface losses, $NH_3$ volatilization, denitrification, and emissions of nitrous oxide ($N_2O$), among others.

Recent in-depth reports by the EPA identify significant areas across the United States with impaired water quality. Additionally, hypoxic zones persist in some areas and are even expanding in some regions. The Gulf of Mexico continues to struggle with hypoxic zones exacerbated by N and P loads. A US Government Accountability Office publication reported that more than four decades after the enactment of the Clean Water Act, an EPA assessment had found that over 50% of the assessed waters in the United States did not meet the established water standards for fishing, swimming, or drinking, and that of the assessed lake acres and miles of rivers, 67% and 53% were impacted, respectively—a greater percentage than ever before. Recent data available from USGS about fluxes of N and P to the Gulf of Mexico reveal the stubborn persistence of water quality challenges related to nutrient loads. Delgado (2020) reported that the errors of the previous century cannot be repeated in the present one and that it is critical that we address the water quality issues related to nutrient contamination.

A modeling simulation of the effect of climate change across the Mississippi watershed should be conducted to test the hypothesis that there may be a correlation between weather and nutrient losses, with lower nutrient loads reaching the Gulf of Mexico in years with lower precipitation and higher precipitation increasing the loads, and to assess what management practices will be needed to minimize future impacts in tile and nontile systems. This evaluation should also consider the effects of extreme weather events since higher $NO_3^-$ leaching rates might be driven by large precipitation events. As the climate changes and extreme weather events occur more frequently, this will pose additional challenges to nutrient management. Fortunately, we can use conservation practices as a tool for climate change adaptation, and we have the technology and knowledge to continue our efforts to minimize nutrient losses from agricultural fields (Delgado et al. 2011). Using the right conservation practice for the right site (precision conservation) will help us adapt to a changing climate and these extreme weather events.

Precision agriculture and the 4Rs are a great start to reduce the losses of nutrients (Roberts 2007). However, as described by Delgado (2016), the 4Rs are not enough—there is a need for a joint precision agriculture and precision conservation approach; such an approach was first described as 7Rs by Delgado (2016) but has also come to be known as 4R+, where the "plus" signifies the implementation of the precision conservation component. We need to connect the flows from the field to the natural areas and implement precision conservation to increase the effectiveness of conservation practices across the landscape. This will contribute to improved water quality in the 21st century. As we face new challenges of more intensive agriculture in a changing climate, we cannot miss the opportunity to apply the available technologies, and voluntary precision regulation could be applied via implementation of ecosystem markets where farmers and ranchers are compensated for implementing best management practices that reduce the losses of nutrients to the environment by trading these "savings" in water quality and air quality markets (Sassenrath and Delgado 2018). Management practices could be applied in an agricultural field or in natural areas using precision technologies to maximize the effectiveness of conservation practices. There is potential to use these new technologies for environmental conservation, climate change adaptation, and improving water quality in the United States.

This review has not addressed air quality, but there are atmospheric pathways for N losses that contribute to movement of N in the environment and impact ecosystems, and these pathways should also be addressed even when we are trying to improve N management for water quality and thus warrant a brief mention. Emission of greenhouse gases from cropland agriculture is 46% of the emissions from agriculture (USEPA 2015b). About 95.8% of the carbon dioxide ($CO_2$-C) equivalents greenhouse gases emissions from cropland agriculture in 2013 were from net $N_2O$ (USDA 2016). The largest contributor in cropland agriculture to the emission of greenhouse gases is N fertilizer inputs. The first paper connecting emissions of $N_2O$ to fertilizer sources in agricultural systems was published by Mosier et al. in 1991, and since then key methods have been identified to minimize $N_2O$ emissions such as the use of nitrification inhibitors, controlled release fertilizers, and enhanced efficiency fertilizers in agricultural systems. Ammonia volatilization is also a problem and can contribute to significant amounts of N being deposited in natural areas, impacting the environment. The use of N fertilizer in the United States increased significantly from about 0.3 Tg N $y^{-1}$ in 1940 to 11.4 Tg N $y^{-1}$ by 2015 (Cao et al. 2018). Thus, when it comes to N inputs from fertilizer or manure sources, the atmospheric pathways for N losses also contribute to movement of N in the environment and impact ecosystems, and these pathways should also be addressed, even when trying to improve N management for water quality.

Precision farming, precision conservation, precision regulation, and ecosystem markets for sustainable agricultural and natural systems can potentially present some of the solutions that will be needed to address the formidable problem of water quality impacted by nutrients. The new agriculture that is being developed with machine learning and artificial intelligence, and increased use of cloud technologies, open-access databases, and robotics, presents great future opportunities to improve nutrient management and reduce nutrient losses. Additionally, the potential to develop new combinations of enhanced efficiency fertilizers and biostimulants also offers opportunities to increase nutrient use efficiencies in the decades to come. Research, education, and training of the upcoming generation that will use the technologies developed in the coming decades will also be an important part of technology transfer to address this wicked challenge.

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# 12

# Agricultural Drainage: Past, Present, and Future

*Vinayak S. Shedekar, Norman R. Fausey, Kevin W. King, and Larry C. Brown*

Agricultural drainage is removal of excess water from land surface and soil profile to sustain and enhance crop production. Surface and subsurface conduits (open channels or pipes), or artificial drainage, become essential for removing excess water in soils that do not exhibit adequate drainage naturally. Worldwide, about 1,500 million ha (3,700 million ac) of land is cultivated, of which about 625 million ha (1,544 million ac; 40%) are estimated to need improved drainage (Smedema et al. 2000). Although the true extent of agricultural drainage is unknown, some estimates suggest that about one-third (160 to 200 million ha [400 to 500 million ac]) of the land needing improved drainage has received some form of artificial drainage (Smedema et al. 2000). The drained areas span across three major global drainage zones: (1) the temperate humid zone (64%), where soil aeration and trafficability are major concerns; (2) the arid/semiarid zone (24%) for aeration and soil salinity management; and (3) the humid/subhumid tropics zone (12%), where removing excess surface water and prevention of waterlogging (aeration) are of concern (Smedema 2007). Although horizontal drainage in the form of surface and

**Vinayak S. Shedekar** is a postdoctoral researcher in the Department of Food, Agricultural, and Biological Engineering, The Ohio State University, Columbus, Ohio. **Norman R. Fausey** (retired) is a supervisory research soil scientist, USDA Agricultural Research Service (ARS) Soil Drainage Research Unit, and adjunct professor in the Department of Food, Agricultural, and Biological Engineering, The Ohio State University, Columbus, Ohio. **Kevin W. King** is a research leader and agricultural engineer, USDA ARS Soil Drainage Research Unit, Columbus, Ohio. **Larry C. Brown** is a professor and extension agricultural engineer in the Department of Food, Agricultural, and Biological Engineering, The Ohio State University, Columbus, Ohio.

subsurface drains is the most common, some areas of the world also rely on vertical drainage (using tube wells to pump out excess groundwater) and biodrainage (using trees with high consumptive water use to lower water table) (Schultz et al. 2007). In North America, about 37% (20.6 million ha [50.9 million ac]) of cropland in the eastern and midwestern United States, an unknown proportion of the irrigated areas of the western United States, and about 8 million ha (20 million ac) in Canada are estimated to be artificially drained (Pavelis 1987; Madramootoo et al. 2007; Zucker and Brown 1998).

The primary functions of drainage are to (1) remove excess surface water, (2) lower the soil water table, and (3) provide salinity control under irrigation. However, benefits of the practice extend well beyond the intended functions. Some benefits of the practice are (1) improved trafficability, (2) enhanced crop productivity, (3) timeliness of field operations, (4) improved aeration, (5) improved human health due to lesser risks of pests and diseases associated with waterlogged or marsh lands, (6) land conversion (i.e., bringing more land under intended uses such as cultivation), and (7) improved water quality by reducing surface runoff-induced erosion and nutrient loss. Conversely, drainage improvements may also lead to some negative impacts on cropping systems (e.g., limited water availability during the growing season due to loss of water from the soil profile), environment (e.g., accelerated nutrient and pesticide losses through drainage pathways), ecology (e.g., loss or alteration of habitat and associated species), socioeconomics (e.g., greater maintenance and operation costs of failing or outdated drainage infrastructure), and human health (e.g., impaired drinking water due to harmful algal blooms triggered by excessive nutrient contributions from drained landscapes in some watersheds). Nevertheless, in most systems, the benefits of drainage outweigh the negative impacts. In this chapter we discuss the past, present, and future of agricultural drainage. Although, the practice has a global presence and relevance, the primary focus of this chapter is on the surface and subsurface drainage in the context of the North American agriculture. We include additional resources that provide a more detailed assessment of the practice in the global context.

## Past

Drainage for the purpose of improved agricultural production has evidence in ancient citations (Pavelis 1987) (table 1). Most early drainage was accomplished by surface ditches, with occasional reference to placing branches, stones, boards, etc. in the bottom of the trench. While ditches do enable some drainage of the soil profile, ditches were widely spaced and primarily intended to facilitate removal of ponded water on the soil surface. Early documented examples in the United States include the drainage of the Great Dismal

**Table 1**

**A timeline of key milestones in the history of drainage by end of 20th century (Pavelis et al. 1987; Weaver 1964; LICA 2018).**

| Date | Event |
|---|---|
| 400 BC | Earliest reference to drainage: Egyptians and Greeks drained land using a system of surface ditches to drain individual areas |
| 250 BC | Oldest known engineering drawing of drainage system: A Greek plan of rectangular ditching illustrated on Egyptian papyrus |
| 13th to 17th centuries | Early drainage work in Europe:<br>• Dikes protect and reclaim lands in northern Europe, particularly Netherlands (13th to 14th century)<br>• French use modified form of clay roofing tile (14th to 15th century)<br>• Large drainage projects in England and Europe (15th to 17th century) |
| 1763 | Surveys of Dismal Swamp in the United States: George Washington leads surveys in Virginia and North Carolina with a view to land reclamation and inland water transport |
| 1838 | First tile drains in the United States: John Johnston installs first tile drains on his farm in Seneca County in New York State. Clay tile manufacturing begins in United States. |
| 1840s | Large drainage project in Holland drains 17,800 ha of Haarlem Lake<br>Some on-farm drainage in the United States using small open ditches |
| 1850 to 1880s | Expansion of tile manufacturing in the United States:<br>• Horseshoe tiles by John Dixon (1851)<br>• Concrete drain tile manufacturing (1862)<br>• Shinbone clay tiles (1870s)<br>• Pipe tiles by forming clay mortar around a pole (1875) |
| **1849 to 2019 (categorized by topic)** | |
| Key acts and regulations | 1849 Swampland Act, followed by Swamp Land Acts of 1850 and 1860<br>1862 An act to establish a Department of Agriculture (USDA)<br>1902 Reclamation Act, establishes US Bureau of Reclamation including a designated drainage specialist<br>1969 National Environmental Policy Act<br>1977 Clean Water Act (Section 404: Wetland Conservation Provisions – Swampbuster) |

| Recent important milestones in drainage science and engineering | | |
|---|---|---|
| | 1930s | Extension education programs begin at land grant institutions |
| | 1933 | Establishment of the USDA Soil Conservation Service (SCS) |
| | 1940s | Early research on drainage practices and benefits |
| | 1941 | Drainage and irrigation practices included by SCS for farm conservation plans |
| | 1954 | US Soil Salinity Handbook 60 |
| | 1957 | First Agronomy monograph on drainage |
| | 1965 | First ASABE Drainage Symposium (Chicago, Illinois) |
| | 1967 | Commercial versions of the laser-beam grade-control system on the US market |
| | 1967 | Manufacturing of corrugated plastic tubing (CPT) for drainage begins |
| | 1974 | First ASTM Standard F405 "Standardization Specification for Corrugated Polyethylene Tubing" |
| | 1974 | Second Agronomy monograph on drainage |
| | 1978 | DRAINMOD model release |
| | 1978 | USDA Drainage Manual published in 1978, updated in 1993 |
| | 1979 | First international drainage meeting held at Wageningen, the Netherlands |
| | 1983 | First Working Group on Drainage of the ICID established |
| | 1980s to 2000 | Awareness of water quality issues related to drainage (eutrophication due to nutrient losses from drained landscapes); development of drainage water management practices |
| | 1999 | Third Agronomy monograph on drainage |
| | 2000s | Significant focus on water quality issues and solutions with emergence of more innovative structural and management practices for water quality improvement and resiliency of agroecosystems (saturated buffers, denitrifying bioreactors, phosphorus removal structures, capture-storage-recycling of drainage water, etc.) |
| | 2002 | USDA Partnership Management Team authorized the formation of the Agricultural Drainage Management Systems Task Force; drainage industry partners organize Drainage Coalition |
| | 2019 | Conservation Drainage Network replaced the Agricultural Drainage Management Systems Task Force |

Swamp in the eastern coastal plain regions of Virginia and North Carolina and the 1860 Swamp Lands Acts passed by Congress to fund drainage of the glaciated lands in the north central United States to encourage economic development. Manufacture and use of fired clay drainpipes, or tiles, began sometime in the early 1800s, with the first recorded use in the United States in 1838 by John Johnston in upper New York State (Weaver 1964). The fired clay drainpipes were placed in hand-dug trenches, so the use was not extensive or common practice.

The first half of the 20th century brought significant innovations to agriculture, especially the introduction of tractors and electricity. Replacement of the horse as the primary source of power obviated the need for extensive production of oats and hay, the fuel source for the horse. Thus, a major change in crop rotation to more cash grain production began to emerge. Field size increased in both rainfed and irrigated areas. Drainage solutions for trafficability of wet soils and leaching of salt-affected soils became more prominent concerns. In the mid-1940s, commercial installation of clay and concrete drain tiles using gas powered trenching machines was commonplace. Land grant universities and US Department of Agriculture (USDA) personnel had developed research and extension programs to establish standards and procedures for farmers and the drainage industry. The state of the art and science of drainage up to that time is well documented in two major publications, namely American Society of Agronomy (ASA) Monograph 7, *Drainage of Agricultural Lands* (Luthin 1957), and USDA Agriculture Handbook 60: *Diagnosis and Improvement of Saline and Alkali Soils* (Allison and Richards 1954).

## Present

Major shifts occurred in US agriculture following World War II. Much progress occurred in drainage design, materials, installation practice, and operation during these ensuing 75 years. In response to world population growth and food demand, soybean for export became a major crop. Higher yielding varieties of corn, wheat, and rice along with the introduction of commercial fertilizer yielded abundant production for foreign markets and spawned the growth of concentrated animal production facilities. As crop production practices evolved resulting in fewer producers, larger fields, and larger equipment, demand for more intensive drainage to ensure economical agricultural production occurred (Madramootoo et al. 2007). Off-site environmental impacts of this accelerated agricultural production became apparent and put agricultural water management practices directly in the environmental protection spotlight. Due to competition for water resources in irrigated production areas, alternative irrigation management schemes were developed to minimize the use of drainage to meet the leaching requirement. Two additional ASA Drainage Monographs (Van Schilfgaarde 1974; Skaggs and Van Schilfgaarde

1999) were produced to capture and document these accomplishments. Several of the most impactful accomplishments are described here.

Drainage materials and their installation were revolutionized in the 1960s in a project conducted jointly by USDA Agricultural Research Service (ARS) and The Ohio State University. Major steps in this revolution were the development of corrugated plastic tubing (Fouss 1973), demonstration of its installation using a plowed-in method, and machine control of the drain grade using a laser light source (American Society of Agricultural and Biological Engineers [ASABE] Historical Landmark Recognition). The tubing was light in weight and coil-able reducing transportation and handling costs. Industry adopted the proof of concept provided by this research, and drainage installation expanded rapidly as a result. Over the years, major modifications to this system have been replacement of the laser grade control with satellite-based differential global positioning system (GPS) grade control and geographic information system (GIS)-based integrated software tools for drainage design and automated installation (Shedekar and Brown 2017).

During the 1970s, at North Carolina State University, the mathematically based hydrology and drainage simulation model DRAINMOD (Skaggs 1978) was developed. This tool has allowed researchers to study aspects of drainage design, management, and performance in ways that would not be possible through field studies and has been useful to researchers around the world. Additionally, several other field- to watershed-scale models (ADAPT, AnnAGNPS, APEX, DAISY, HSPF, HYDRUS, ICECREAMDB, PLEASE, RZWQM2, SOIL, and SWAT) have been developed that incorporate drainage processes with varying degrees of detail, accuracy, and parameterization options (Qi and Qi 2017). Some drainage-focused decision support frameworks such as the Drainage Integrated Analytical Framework (DRAINFRAME) have been developed to provide a conceptual framework and methodology for integrated planning of drainage interventions (Slootweg et al. 2007). With the growing use of models for decision-making in local to regional and global policy frameworks, recent efforts have focused on improving their accuracy with high-resolution input data and by linking models across disciplines and spatio-temporal scales.

Drainage of “wetlands” emerged as an environmental concern in the early 1980s resulting in a shift of government funding of drainage as a supported production practice. These regulations were referred to as “swampbuster” legislation and caused public perception of drainage to cast a negative connotation on the practice. However, because producers realized the economic return on the investment in drainage, the practice rebounded as a producer-funded practice. Without the restrictions imposed by the previous government subsidy regulations, drainage intensity began to increase in the form of closer drain spacings that provided producers with more uniform field conditions for planting and harvesting operations. This, in turn, encouraged even larger fields and equipment, and accelerated the trend to corporate cash grain farming practices.

Soil salinity management emerged as an important challenge in irrigated and naturally saline landscapes. Initial research focused on understanding the crop susceptibility to soil salinity and solutions to manage soil salinity using irrigation and drainage systems. Guidelines were developed for estimating leaching requirements (minimum amount of water required to maintain soil salinity at or below prescribed levels) as part of the seasonal irrigation requirement and design and management of surface and subsurface drainage systems for salinity management. Recent research advancements allow for more sustainable solutions through enhanced crop tolerance to salinity, use of more efficient irrigation systems, and innovative approaches such as allowing salinity to increase during growing season and preplant irrigation to provide leaching (Ayars and Evans 2015).

In the early 1990s the USDA Partnership Management Team authorized the formation of the Agricultural Drainage Water Management Task Force (ADMS-TF) to coordinate efforts among USDA Natural Resources Conservation Service (NRCS), ARS, and National Institute of Food and Agriculture (NIFA) research, education, and technical assistance programs to develop practices and programs that could address hypoxic and algal bloom issues in the Gulf of Mexico, Chesapeake Bay, Lake Erie, and other areas of concern. The drainage industry collaborated by forming the Drainage Water Management Coalition that worked in concert with ADMS-TF to address these environmental concerns. This joint effort brought a marked new exposure and public awareness of agricultural drainage resulting in public funding for producer adoption of practices to prevent and mitigate the delivery of pollutants from agricultural production fields to streams. Edge-of-field practices, including woodchip bioreactors, saturated buffers, and drainage water management, were identified and recommended as best management practices that are applied to reduce off-site nutrient delivery (Fausey 2005). Such coordinated joint efforts were also initiated at international levels in the early 1990s, with formation of the Working Group on Drainage of the International Commission on Irrigation and Drainage. The organization of drainage-focused symposia and meetings by these groups facilitated the global exchange for science and engineering of drainage (Smedema 2007). Some notable initiatives are the 11 international drainage workshops by the

International Commission on Irrigation and Drainage, and the 10 international drainage symposia organized by the ASABE.

The Soil and Water Conservation Society was instrumental in advancing drainage research from a conservation point of view. A search in Web of Science Core Collection and CAB Abstracts for "drainage" in title, abstract, descriptor, and keyword fields retrieves 239 journal articles published in the Society's *Journal of Soil and Water Conservation* (JSWC) out of a total of 3,408 indexed JSWC records (vast majority are journal articles). Since its inception in 1946, the JSWC has featured at least four special issues on subject areas related to drainage (e.g., Volume 67, Number 6, "Water Quality and Yield Benefits of Drainage Water Management in US Midwest;" and Volume 73, Number 1, "Edge-of-Field Monitoring for Nutrient Losses").

More recent drainage research has focused on better management of drainage systems and integration with other practices with purposes of reducing negative environmental impacts and building water resiliency for future production systems. The traditional plot-scale or within-field drainage research has thus transitioned into on-farm, real-time research that aims to study "real-life" systems (for example, edge-of-field research network described by Williams et al. [2016]). Furthermore, interdisciplinary teams are joining forces to conduct holistic drainage research that combines field studies with multiscale modeling and socioeconomic aspects. The five-year, eight-state Transforming Drainage project (2020) is one such example that involves a team of agricultural engineers, soil scientists, agronomists, economists, social scientists, and database and GIS specialists. The objective is to transform the way drainage is implemented across the agricultural landscape. The core of the project has roots in the early work on subirrigation and wetland reservoir subirrigation systems (Allred et al. 2003), proving the feasibility of capture, storage, recycling, and reuse of drainage water for irrigation.

## Future

As drainage research and technology evolve, significant changes may be expected in the design and operation of future drainage systems. The following excerpt from Ayars and Evans (2015) summarizes future challenges related to drainage:

- Drainage water quality will be a necessary criterion for system design.
- Active management of the groundwater table position and discharge to manage pollutant loads and to conserve water for crop use will be essential.
- Improved methods are needed for collection of soil physical and hydrologic properties to provide better spatial characterization to improve designs.

- The design will be an iterative process that includes agronomic production and environmental values.
- Methods of disposal of drainage water will have to be developed to minimize the environmental impact and maximize the use of the water resource.
- Impacted water supplies will be the future for irrigation and will have to be considered in the design and operation of drainage systems.
- Drainage in arid areas will become part of an integrated water management system that includes the design and operation of both the irrigation and drainage system to meet crop water requirements and provide maximum water productivity.

Subsurface drainage will be part of the solution to the world's future food and water security needs. The growing global population, climate change, and declining soil quality have put unprecedented pressure on shrinking agricultural lands to increase productivity and resource use efficiency. Integrated design and management of irrigation and drainage will be critical components of future agroecosystems. The shifting agroecological zones under changing future climatic conditions will likely increase the need for installation of new or intensification of existing drainage. This means the drainage materials and installation technology will continue to evolve. The application of autonomous robots and drones, or unmanned aerial vehicles (UAVs), mounted with multispectral sensors and GPS shows a great promise to the future of drainage-related assessments. Accurate assessment of the location and extent of drainage systems will become an important consideration for modeling and precision conservation planning at large scales (Jaynes and James 2007). To date, drainage research has primarily focused on water quantity, quality, and water level control. New frontiers of drainage research will emerge: linking drainage water quality and ecological health; assessing/modeling impacts of drainage on ecosystems; and integrating or stacking structural, behavioral, and ecological practices to mitigate negative impacts of drainage. As drainage water management will become important at field to community scales, networking and automation of water management infrastructure will become an important area of research. The complex interactions of drainage with the agricultural systems, connected ecosystems, and public infrastructure will require informed decision-making based on advanced decision support systems.

Advances in computer science, communication, and sensor technology have revolutionized the research capabilities of all fields of science, including those for drainage research. With availability of cheaper, faster technologies, high-frequency real-time monitoring and modeling of drainage systems has become possible. Furthermore, as regional-/global-/watershed-scale models are improving and becoming data intensive, the need for high-resolution data sets is growing. Future drainage research will likely adopt advanced monitoring and modeling tools. However, it will be critical to ensure the compatibility and transferability of the research data, methods, and models across various platforms and scales. Interdisciplinary collaborations and public-private partnerships will be crucial for the success of future drainage research, technology, and solutions. Furthermore, curricula (including extension education programs) at academic and research institutions that teach fundamentals of soil physics, soil water transport, and engineering and conservation aspects of drainage are and will remain essential to train the future generations of drainage professionals.

A new coalition of individuals, organizations, and government entities has been organized to carry on the collaboration that grew out of the ADMS-TF. Recently, the authorization for the Task Force expired, and the committed parties have formed the Conservation Drainage Network, which continues to provide coordination and leadership for addressing broad, national drainage-related issues. There are continuing needs at the producer level related to agricultural water management, especially emerging issues related to climate change effects on precipitation and the emphasis on recovery of soil health. Future attention needs to be directed to capture, storage, treatment, reuse, and recycling of drainage water as an irrigation water supply source. Drainage system design, installation, and operation will need to focus more on reducing water and pollutants export while still providing economically viable agricultural production. However, it has become increasingly clear that effective solutions to the environmental implications of intense drainage practice will need to be addressed on a broader, yet small, headwater watershed level. Collaborations will need to be developed between producers and elected local officials (township trustees, county government) to address problems holistically. Policy and programs are needed that reward producers for implementing win-win water management solutions for all watershed residents. With the need to translate complex drainage research for the general public and leaders, educational programs and outreach will be an inevitable part of the solution. With the diverse demographic of clientele, future educators will need to utilize traditional as well as modern delivery mechanisms for drainage education to ensure an inclusive outreach. Drainage, and its associated water management practices that address off-site effects and on-site water supply needs, will no longer be land manager issues; and will need to be addressed as public issues deserving of planning and development to achieve appropriate win-win solutions.

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## Resources to Learn More

- The Mike Weaver Drain Tile Museum and John Johnston's House. https://genevahistoricalsociety.com/visit/johnston-house/
- 1960-1974 USDA Agricultural Research Service Drainage Materials and Equipment Research "Stories." https://transformingdrainage.org/resources/usda-ars-history/
- History of Corrugated Plastic Tubing. https://fabe.osu.edu/about-us/history-department/corrugated-plastic-tubing
- Drainage Media Library. https://transformingdrainage.org/media/
- Drainage Hall of Fame. https://library.osu.edu/sites/default/files/collection_files/2019-03/drainage_hall_of_fame_osu.pdf
- ASABE Historical Landmarks Collection (includes clay tile and machine control of the drain grade using a laser light source). https://www.asabe.org/About-Us/About-ASABE/History/ASABE-Historic-Landmarks
- Journal Issues with Special Focus on Drainage:
    - International Commission on Irrigation and Drainage (ICID) special issue: Drainage: An Essential Element of Integrated Water Management. 25th Anniversary of the ICID Working Group on Drainage (Vol. 56, Issue S1). https://onlinelibrary.wiley.com/toc/15310361/2007/56/S1
    - Journal of Soil and Water Conservation special issue: Edge-of-Field Monitoring for Nutrient Losses (Vol. 73, No. 1). https://www.jswconline.org/content/73/1
    - Journal of Soil and Water Conservation special issue: Water Quality and Yield Benefits of Drainage Water Management in US Midwest (Vol. 67, No. 6). https://www.jswconline.org/content/67/6
    - American Society of Agricultural and Biological Engineers special collections: Advances in Drainage: Select Works from the 10th International Drainage Symposium, Transactions of the ASABE (Vol. 61, No. 1). https://www.asabe.org/sc18AID

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# 13

Practitioner's Perspective

# Seizing the Opportunity: Realizing the Full Benefits of Drainage Water Management

*Charles Schafer, Dave White, Alex Echols, and Thomas W. Christensen*

Drainage water management (DWM) offers great promise to improve environmental performance and farm economic viability on tile-drained cropland. The new availability of innovative automation features eliminates or mitigates many of the long-standing barriers to farmer adoption of DWM. On-farm research and field experience demonstrate that crop production and nutrient loading reductions can be compatible goals with DWM applied in a conservation systems approach. Millions of cropland acres in the Great Lakes and Upper Mississippi River Basins are suitable for the adoption of this approach. It will take a concerted private-public partnership effort that provides educational, technical, and financial assistance to farmers and furthers research and outcome assessment work to aid their adoption. The potential for crop yield increases could help offset DWM implementation, management, and maintenance costs not covered by conservation programs. Partners should focus their efforts in priority small watersheds with a preponderance of tile drainage and compelling nutrient loading concerns. These small watersheds are the best opportunity to efficiently and effectively grow farmer adoption. Success in initial watersheds will create momentum, facilitate sharing of lessons learned, and foster the partner commitment needed to "scale up" efforts across the cropland suitable for DWM.

**Charles Schafer** is president of Agri Drain Corporation, Adair, Iowa. **Dave White** is president of Ecosystem Services Exchange, Barboursville, Virginia. **Alex Echols** is executive vice president of Ecosystem Services Exchange, Alexandria, Virginia. **Thomas W. Christensen** is project manager at Ecosystem Services Exchange, Leesburg, Virginia.

## The Setting for Drainage Water Management

Agricultural land drainage has been a key to developing the viability and profitability of US agriculture since the early days of settlement. Surface and subsurface tile drainage enable farmers to remove excess water from poorly drained soils to improve workability and increase crop production and farm profitability. Tile drainage, first introduced to US agriculture in 1835 near Geneva, New York, now underlies 22.7 million ha (56 million ac) of the 129 million ha (320 million ac) of harvested cropland in the nation (USDA ERS 1987; USDA NASS 2017).

Federal legislation, through the 1962 Drainage Referral Act, first began to constrain the new application of agricultural drainage because of impacts to wildlife (USDA ERS 1987). In 1973, and strengthened in 1975, the US Department of Agriculture (USDA) Soil Conservation Service discontinued technical assistance for draining certain types of wetlands (Christensen 2020b). Presidential Executive Order 11990 (Protection of Wetlands) in 1977 further required avoidance of the destruction or modification of wetlands (USDA ERS 1987). The 1985 Farm Bill denied program benefits to farmers who grew annual crops on wetlands drained after December of 1985. Because of today's statutory and public policy setting, and better scientific understanding, subsurface tile drainage work is now largely focused on replacing and/or improving aged tile systems, installing new systems in soils where wetlands are not threatened, and retrofitting existing systems to enable farmer's adoption of manual or automated DWM.

Despite its agricultural production benefits, tile drainage provides a direct conduit for nutrient transport to water bodies and poses environmental concerns. Without voluntary action by farmers to actively manage these tile systems for both production and conservation, water quality improvement goals are impeded. DWM, in combination with other conservation practices, offers great promise to improve both environmental performance and farm economic viability in tile-drained landscapes.

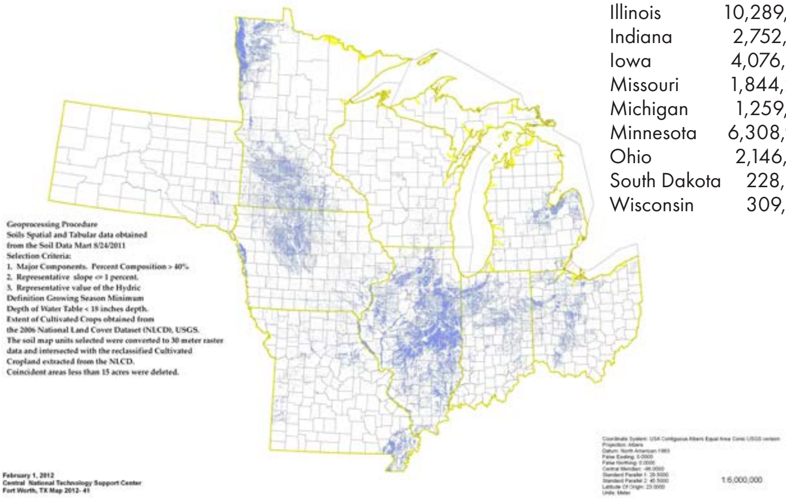
## The Opportunity and Challenge

DWM uses adjustable, flow-retarding water control structures placed in a tile system that allow the soil water table elevation to be adjusted. Automated management of drainage water is an innovative, cost-effective tool to better control the rate and timing of water discharge and may be operated remotely. Automation employs two-way telemetry to greatly reduce the labor burden for farmers and provide real-time data to automatically manage water levels and flow rates in tile drained fields.

## Figure 1

**Tile-drained cropland in the US Midwest suitable for drainage water management. Map courtesy of US Department of Agriculture Natural Resources Conservation Service, 2012.**

| Area (ac) | |
|---|---|
| Illinois | 10,289,165 |
| Indiana | 2,752,251 |
| Iowa | 4,076,072 |
| Missouri | 1,844,238 |
| Michigan | 1,259,731 |
| Minnesota | 6,308,982 |
| Ohio | 2,146,231 |
| South Dakota | 228,842 |
| Wisconsin | 309,427 |




In 2012, USDA Natural Resources Conservation Service (NRCS) estimated 11.8 million ha (29.2 million ac) of cropland in just nine Great Lakes and Upper Mississippi River Basin states were suitable for DWM (figure 1). The absence of DWM is a lost opportunity for farmers and the environment. The evidence from over three decades of experience and research is compelling—every suitable cropland acre where DWM is not applied results in environmental benefits, farm income potential, and agricultural resilience forgone.

On-farm experience and research confirm crop production and nutrient loading reduction can be compatible goals through proper DWM. Research results report reduced nutrient loading ranging from 10% to 80% for dissolved phosphorus and 8% to 94% for nitrates, depending on site-specific conditions and the water management regime (Christensen 2020a). Phosphorus-focused research has not been as robust compared to nitrogen, but the consensus conclusion is that DWM is directionally correct for reducing nutrient loading from tile drainage (King et al. 2015).

In-field research on the crop yield effects of DWM has been limited, site-specific, and variable. Tile spacing and depth, water control system design, management regime, and weather conditions impact yield effects on a site-specific basis. Further studies and synthesis of findings will be needed to better characterize the impact of DWM on long-term yields so that farmers have access to decision-making guidance and tools.

Yield increases from one field study showed sites with corn and soybean yield increases ranging from 1% to 19%, but also an equal number of sites showing no yield increases (Skaggs et al. 2012). Computer modeling has shown long-term yield benefits of up to 5% are possible in the Midwest, but not every year (Christianson et al. 2016). Multiple studies indicate DWM is likely to increase crop yields when plants are stressed and tile flow is managed to improve soil water availability. In contrast, DWM is less likely to influence yield when precipitation keeps soil water available to meet plant demands.

Ghane et al. 2012, evaluated crop yields under DWM over multiple settings in northwest Ohio and concluded a yield advantage for corn, popcorn, and soybeans over free tile drainage. These researchers concluded the yield advantages of DWM can provide financial incentives for farmers to adopt this practice (Allerhand et al. 2013).

Previous yield studies were done without the benefit of real-time, "24/7" automatic management of water level control structures. We hypothesize that intensive soil moisture monitoring and automated real-time water level and flow rate management should result in increased yields, depending on precipitation amounts and timing.

The challenge is bringing site-specific planning and adoption of DWM and companion conservation practices to scale, first in priority small watersheds and then across the suitable cropland. The opportunity to realize and optimize both crop production and environmental benefits is present, and farmers should seize it now with assistance from agricultural and conservation partners.

## Producers' Adoption of Drainage Water Management

Producer adoption of DWM has lagged far behind its potential despite its benefits and the financial assistance provided by conservation agencies to cover much of the cost of adoption. A review of NRCS Environmental Quality Incentives Program (EQIP) data (USDA NRCS 2020) shows that financial assistance for DWM (NRCS practice code 554) in fiscal year (FY) 2019 resulted in 259 completions with 3,242 ha (8,010 ac) benefitted. EQIP code 554 data from FY2009 forward also show the peak adoption was in FY2013, with 301 completions and 6,946 ha (17,163 ac) benefitted. For FY2009 through FY2019 combined, the data show a total of 2,340 completions and 39,798 ha (98,344 ac) benefitted. Certainly not all DWM applied involves NRCS financial assistance, but these data clearly indicate that DWM has not been adopted at anywhere near the coverage needed to achieve its full production and environmental benefits.

Overcoming barriers to farmer adoption is essential if this conservation practice is to see widespread use consistent with the multimillion acre need. Promise exists to overcome these barriers with the new, data-assisted automated DWM. Both manual and innovative automated DWM afford many benefits for farmers and downstream communities, including

- increased crop production, resilience, and reduced risk of crop losses during weather extremes, such as drought;
- potential for reduced cost of federal crop insurance;
- potential reduced input costs;
- potential to apply subsurface irrigation management for greater conservation and production benefits;
- opportunities for improved farm income by trading on-farm conservation-system generated water quality credits with regulated point sources;
- seasonal flooding benefits for migratory waterfowl;
- potential flood reduction benefits by storing more water in the soil profile; and
- reduced nutrient loading, principally through flow volume reductions.

Automated DWM addresses many of the long-standing barriers to adoption. This technology operates by two-way telemetry to reduce the labor burden and provide real-time data to automatically manage soil water levels and tile flow rates. Automation also facilitates the implementation and management of subirrigation. On average, the all-inclusive cost to retrofit an existing tile system to implement automated DWM is about \$618 $ha^{-1}$ (\$250 $ac^{-1}$), much of which can be offset by financial assistance through conservation programs and typical crop yield increases.

## What Needs to Happen?

There is no single solution nor prescription to improve tile drainage water quality associated with almost 12.1 million ha (30 million ac) of suitable cropland in the Great Lakes and Upper Mississippi River Basins. However, a site-specific system of in-field and edge-of-field conservation practices including DWM has been demonstrated to be a cost-effective, efficient solution to reduce nutrient loss from tile drained fields and provide crop production and other benefits. Automated DWM greatly improves the ability of farmers to manage more efficiently, with less labor, and with more effective results.

Priority small watersheds, such as 12-digit HUCs (typically 4,047 to 16,187 ha [10,000 to 40,000 ac] in size), with a preponderance of tile drainage and compelling nutrient loading concerns present the best opportunity to grow farmer adoption of DWM. This "working" watershed level provides enough consistency in physiography and types of farming operations to more effectively evaluate results, gain lessons learned, and apply continuous improvements and adaptive management timely and effectively.

More specifically, emphasizing focused partnership action at the small watershed level will

- optimize efficient use of technical and financial assistance and target highly suitable cropland that can have an aggregated water quality improvement;
- facilitate coordinated monitoring and assessment at the field, farm, and small watershed scales;
- create opportunity for greater collaboration and synergy among partners;
- provide farmers and partners with a clear "line-of-sight" between water quality results and DWM actions; and
- supply more extensive, richer data for modeling and for use with continuous improvement and adaptive management.

The objective of this focused approach is to achieve concentrated DWM in a small watershed to further identify and pursue approaches to overcome barriers to adoption, create adequate water flow and quality monitoring data for modeling and assessment, and develop site-specific decision support tools to validate efficacy and transportability to other sites. Success in multiple small watersheds should create momentum, facilitate sharing of lessons learned, and the foster opportunity for scaling up. From this foundation, adoption of DWM can be achieved in larger watersheds and eventually across the preponderance of suitable cropland. Private-public partnerships will foster such small watershed projects. It will take dedicated partners each playing a role(s) and contributing resources, capabilities, and available resources. The effect of these partnerships will be greater than the additive sum of their parts.

## Scope of the Private/Public Investment Needed

The costs of implementing DWM vary based on site-specific characteristics, drainage system design, and the type of control system installed. Using the 2012 NRCS assessment of 11.8 million ha (29.2 million ac) in the nine Great Lakes and Upper Mississippi River Basin states where DWM can be easily applied provides a basis to examine the large-scale investment needed.

Cooke (2005) estimated \$49 to \$99 ha$^{-1}$ (\$20 to \$40 ac$^{-1}$) to retrofit a tile system to install control structures for manual DWM, and \$220 ha$^{-1}$ (\$89 ac$^{-1}$) for a new system in complex topography. Ecosystem Services Exchange has estimated the cost to retrofit tile drainage to implement the more efficient, effective, and innovative automated DWM at \$618 ha$^{-1}$ (\$250 ac$^{-1}$), including annual data transmission and management fees. Thus, using a conservative \$99 ha$^{-1}$ to retrofit tile drainage for manual DWM and \$618 $ha^{-1}$ for the all-inclusive automated system, and applying that to 11.8 million ha (29.2 million ac), the gross costs could range from a high of \$7.3 billion to a low of \$1.2 billion. While neither figure is realistic because (1) not every farmer will adopt DWM, (2) installations will be a combination of retrofit and new systems and manual and automated systems, and (3) the practice already has been adopted on some acres, it does provide a view of the private-public sector investment needed to achieve successful adoption of DWM across this landscape.

Financial assistance from conservation agencies offsets many of the costs of planning and implementing DWM and companion conservation practices, such as denitrifying bioreactors and saturated buffers. Costs should be further offset by yield increases beyond typical crop production responses from free-flowing drainage. With real-time monitoring and water flow/quality data from automated DWM, the income opportunity for farmers is even greater because they will be positioned to trade water quality credits for payments with regulated point sources. However, it will take continued innovation to reduce the costs of implementation/management further if systems are to be applied, managed, and maintained across the cropland acres of opportunity.

## Keys to Successfully Seizing the Opportunity

There are many keys to a successfully focused, lasting effort to foster adoption of DWM across the nine states identified in the NRCS 2012 assessment of suitable cropland. These keys to success include the following:

- Development of robust private-public partnerships with shared objectives/commitments consistent with each partner's mission, capabilities, and resources to lead efforts in each small watershed project.
- Small watersheds that have the key physical attributes for successful DWM, willing farmers, engaged local partners, and external drivers, such as downstream water quality concerns.
- Use of a conservation systems approach, with DWM supported by companion in-field and edge-of-field conservation practices.
- Quality technical assistance of sufficient quantity from both the private and public sectors, working in cooperation in each small watershed.
- An ambitious project timeline for each small watershed that strives to create momentum by sharing results from early adopters with other farmers.
- Concurrent research and development that take advantage of widespread adoption in a small watershed to grow the knowledge base for continuous improvement, adaptive management, and the science basis for decision-support tools.

- Partnership efforts that drive outcome assessment, not just in physical terms such as nutrient load reductions and crop productivity, but also regarding on-farm economics.
- Financial assistance for farmers that places value on off-site benefits, not just the costs incurred or income forgone in adopting DWM.
- Outreach and education across all farmers, partners, and stakeholders that is robust and maintains core consistency but is adapted to each small watershed and the uniqueness of its partnership.

## Conclusion

Farmers own or use the cropland where DWM can be applied, are the decision makers for their operations, bear the risks and consequences of their decisions, and are the ones that can adopt and improve this practice applied in a conservation systems approach. Their success individually and collectively in small watersheds can create the foundation, synergy, and momentum to achieve the adoption of DWM across the many million cropland acres of opportunity in the Great Lakes and Upper Mississippi River Basins. The introduction of innovative automated DWM removes many of the historic barriers to farmer adoption and will provide improved management and assessment of outcomes.

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# 14

# Wetland Conservation in the United States: A Swinging Pendulum

*David M. Mushet and Aram J.K. Calhoun*

## The Swinging Pendulum of Wetland Valuation

Over the course of time, people have both revered and demonized wetlands subject to historical context and the vicissitudes of politics. Prior to their displacement on the North American landscape, Native Americans relied on wetlands for food, animal fodder, water, and other less tangible resources, including aesthetic and spiritual sustenance (Vileisis 1997). Wetland plants, including wild rice, Indian potato, and water lily tubers, were valued food and medicinal sources. Other wetland plants such as cattails, brown ash, cordgrasses, and sweetgrass provided materials for weaving baskets and mats, thatching lodges, and spiritual ceremonies (Daigle et al. 2019). Native Americans had spiritual and religious beliefs associated with productive wetland areas. However, the European colonizers who displaced the Native Americans in the 1600s and 1700s brought with them a very different perspective toward wetlands.

To many European colonizers, wetlands were seen as a hindrance to crop production and animal husbandry. They worked to remove what were perceived as disease-ridden wastelands from the landscape and convert them into "useful" or "reclaimed" areas (Vileisis 1997). Technological advancements throughout the late 1800s and early 1900s expedited wetland conversions (figure 1). By the 1980s, approximately 53% of an estimated 89 million ha (220 million ac) of wetlands originally present in the conterminous United States

**David (Dave) M. Mushet** is a research wildlife biologist at the US Geological Survey, Northern Prairie Wildlife Research Center, Jamestown, North Dakota. **Aram J.K. Calhoun** is a professor in the Department of Wildlife, Fisheries, and Conservation Biology, University of Maine, Orono, Maine.

**Figure 1**

**The Bay City dragline at work "reclaiming" lands as part of the Everglades Drainage Project (photo courtesy of the State Archives of Florida, 1906 to 1926).**

had been destroyed (Dahl and Johnson 1991). In addition to the loss of over half of the nation's wetlands, the quality of many *remaining* wetlands had been degraded. In a recent assessment of the nation's remaining wetlands, 48% were found to be in good condition, while 20% were in fair and 32% were in poor condition (USEPA 2016).

When the Soil and Water Conservation Society (SWCS) was founded in 1945, wetland drainage was rapidly converting "wasteland" to cultivated cropland. The US government facilitated these land "improvements" through cost-sharing and the coordination of extensive wetland drainage projects within drainage districts. The US Department of Agriculture considered both surface and tile drainage of wetlands to be *conservation* practices up until the mid-1970s. This perspective was reflected in the SWCS; throughout the first 20 volumes (1946 to 1965) of the Society's *Journal of Soil and Water Conservation*, wetlands are indexed to only nine articles (Soil Conservation Society of America 1968), each with a focus on how to make these "wet lands" more productive.

Yet, at the same time that some parts of the federal government were promoting wetland drainage for agriculture, other federal initiatives were beginning to embrace the importance of wetland ecosystems to people and wildlife (Heimlich et al. 1998). In 1934, Congress passed the Migratory Bird Hunting Stamp Act, 16 USC 718-718j, 48 Stat. 452, to facilitate the acquisition and restoration of wetlands for waterfowl. Throughout the 1960s and 1970s the push favoring wetland conservation was prevailing. Herman and McConnell (1983) described the political perspective related to wetlands as a swinging pendulum, swinging from drainage and destruction prior to the 1960s, towards protection and conservation in the 1960s and 1970s, and back toward a destructive view in the 1980s. This pendulum swing continued as wetland conservation again became a focus throughout the 1990s and early 2000s. Currently, the pendulum has begun a swing back in the direction of policies expediting development and the conversion of wetlands to what are perceived as more economically beneficial uses. Thus, the pendulum's swing continues. It is key to note that with any pendulum the majority of the time is spent in the swing, not at the extremes, with the pull always being toward a centralized position. The question is, can we modulate that swing so that loss of wetland resources remains recoverable?

## Categorical Boundaries Cause Mental Roadblocks

Humans inherently categorize to understand the world around them, including its natural systems. We may categorize broadly or narrowly (i.e., be lumpers or splitters), but we all want control and try to impose predictability on our world. However, categories assigned for a good purpose can lead to unintended outcomes. For example, in religion and politics, divisions can become impermeable walls that divide communities, prevent the flow of ideas, and create misunderstanding. In the natural world, categories can lead to the misperception that different types of habitats or ecosystems, or geographically distant regions are discrete and independent of one another. This has led some to believe natural systems can be managed individually or as closed compartments with static boundaries. Just as the information age has opened global communication boundaries, human-induced climate change, rapidly expanding invasive species, rapidly declining native species, and other current conservation concerns have highlighted the interdependence of natural systems.

Numerous classification systems have been developed to facilitate the management and regulation of wetlands, and the science of wetland delineation that maps boundaries between wetlands and terrestrial or aquatic ecosystems has flourished in response. However, the establishment of boundaries, while necessary, can reinforce the idea that different types of wetlands and neighboring ecosystems (either drier or more aquatic) are not integrated, and indeed, that there is a physical demarcation tied to a line on a map. It is well established that ecosystems are highly dynamic and responsive to both internal and external environmental drivers (Euliss et al. 2004). Wetlands can grow and shrink in size, or shift location, in response to changing environmental influences as a result of climate change or changes in land use. For example, in the Prairie Pothole Region, increases in the amount and timing of precipitation have resulted in the expansion of many wetlands (McKenna et al. 2017). However, the most commonly used maps of wetlands in the region were created using decades-old imagery and do not reflect these natural or human-caused changes. Thus, acknowledging and allowing for the dynamism of wetlands is a key consideration in their conservation.

Perhaps the issue of wetland boundaries is so contentious because the physical compartments we have established influence the way we think about ecosystem management: there is a tendency to manage wetlands as discrete landscape components rather than as interconnected systems. However, wetland ecosystems serve as dynamic interfaces that integrate aquatic and terrestrial ecosystems, and provide unique attributes owing to that interface. Additionally, it is at that interface between ecosystem types where biogeochemical functions are often enhanced (Cohen et al. 2016).

To date, wetland regulation has driven the need to delineate wetland boundaries, mapping these discrete polygons as management units. Yet battles continue, in court and out of court, regarding delineation techniques and wetland definitions. This in turn creates public disaffection and frustration. However, to effectively regulate wetlands, boundaries must be identified. Given the key roles of soil and water in determining what makes an area a wetland, it is not surprising that the SWCS and many of its members have played leading roles in defining hydric soils and identifying hydric soil indicators. Wetland delineation manuals, such as those developed by the US Army Corps of Engineers, rely heavily on these hydric soil indicators of wetlands, as well as listings of wetland plants, another key indicator of wetlands (Lichvar et al. 2016).

While physical boundaries are needed to define regulatory units, these physical boundaries may foster mental roadblocks by promoting thinking in terms of discrete, isolated wetland units. We need wetland boundaries, but we also need the recognition that wetlands are a dynamic part of landscapes where boundaries change and ecosystems are integrated through flows of energy. While humans tend to prefer a world in which the locations of landscape features such as wetlands are constant, this is not the nature of the world in which we live. Wetlands may expand or contract in response to changing precipitation, temperature regimes, and land uses. In coastal areas wetlands might move upgradient in response to rising sea levels driven by the same increases in global temperatures. For effective wetland conservation in the 21st century, thinking in terms of landscapes that function as an integrated organism will likely have the most beneficial outcomes.

## In Other Words, Words Do Matter

As with the mapping of wetland boundaries, some of the terminology we use related to wetland conservation may have unintentional consequences. The commonly used term "temporary wetland" is a prime example. This term is a shortened version of the more accurate term "temporarily ponded wetland" that is used to denote wetlands that only contain ponded surface-water for a relatively brief period during any given year. By referring to these wetlands as "temporary wetlands" the perception can be that they are not valuable because they are only a "temporary" landscape feature, when in fact, it is only the ponded water in the wetland that is temporary in nature, not the wetland itself (van der Kamp et al. 2016).

As another example—one of our least favorite terms still commonly used in wetland conservation—is "isolated wetland" and its derivative, "geographically isolated wetland" (Mushet et al. 2015). If we view wetlands as transitional areas that integrate terrestrial and aquatic ecosystems, how can they be isolated, geographically or otherwise? All wetlands are intimately connected to their surrounding terrestrial and aquatic habitats in multiple ways. What happens in those surrounding lands greatly affects the wetlands. Additionally, even if a wetland has no direct surface water or groundwater connections, atmospheric water inputs and losses connect even the most widely separated wetlands. Acknowledging the role of wetlands in the water cycle clearly reveals their inclusion in an interconnected system; this and other important roles that wetlands play should not continue to be diminished by the terminology we use.

## Private Property versus the Commons

As their name implies, wetlands consist of both land and water. This combination has created a tension between cultural attitudes towards wetlands and wetland conservation efforts. This is because, in the United States, land is typically private property while water is typically viewed as a public or "common" resource. It is this commons component of wetlands that has stymied many conservation efforts since it can have both positive (e.g., providing flood protection) and negative (e.g., producing disease carrying mosquitos) influences. While the private property aspects of wetlands have long been accepted, a deeper recognition and appreciation of wetlands as part of the commons is needed to promote their conservation on the landscape (Vileisis 1997). This recognition and appreciation may come through the consideration of ecosystem services.

Ecosystem services are goods and services beneficial to society that are derived from ecosystems. As an example of an ecosystem service provided by wetlands, wetlands can reduce edge-of-field and drainage-water outputs of nutrients and thereby improve downstream water quality. Much research has been conducted to quantify these water quality improvement benefits (Woltemade 2000). Other examples of wetland ecosystem services include flood mitigation, recreation, habitat provisioning, timber production, food production, education, research, and aesthetics. While not all wetlands perform all of these services, their value as societal commons worthy of protection is clear.

## Protecting Our Natural Capital

The swinging pendulum of public perceptions toward wetland conservation is reflected in our laws and regulations. For example, George Washington's Dismal Swamp Company, formed in 1763 for the sole purpose of draining the Great Dismal Swamp, reflected the colonial era sentiment of reclamation of wasteland. The shift to conservation in the 1960s and 1970s was exemplified by the 1978 enactment of the Federal Water Pollution Control Act, 33 USC §1251 *et. seq.*, generally referred to as the Clean Water Act (CWA), arguably one of the most significant steps forward in protecting the nation's wetlands (Downing et al. 2003). For the first 30 years of the CWA, most wetlands were considered to be within its jurisdictional scope, i.e., were waters of the United States. However, Supreme Court of the United States rulings in 2001 and 2006 (Solid Waste Agency of Northern Cook County [SWANCC] v. US Army Corps of Engineers, 531 US 159 [2001]; and Rapanos v. United States, 547 US 715 [2006]) called into question the types and extent of wetlands that could be regulated under this statute.

In order to clarify the definition of waters of the United States, and thereby the wetlands protected by the CWA, the US Army Corps of Engineers and US Environmental Protection Agency worked together to draft the Clean Water Rule, 80 FR 37053. The Clean Water Rule, finalized in 2015, considered case law and current scientific understanding of watersheds as systems (Alexander 2015) in its definition of waters of the United States. However, in 2019 and 2020, the two agencies issued a new series of rules, culminating in a finalized rule, the Navigable Waters Protection Rule, 85 FR 22250. The Navigable Waters Protection Rule depends entirely on a narrow legal interpretation of the CWA statute and the 2001 SWANCC and 2006 Rapanos Supreme Court decisions. Thus, a significant number of wetlands (39% in one study basin) are destined to lose CWA protections under the Navigable Waters Protection Rule (Walsh and Ward 2019).

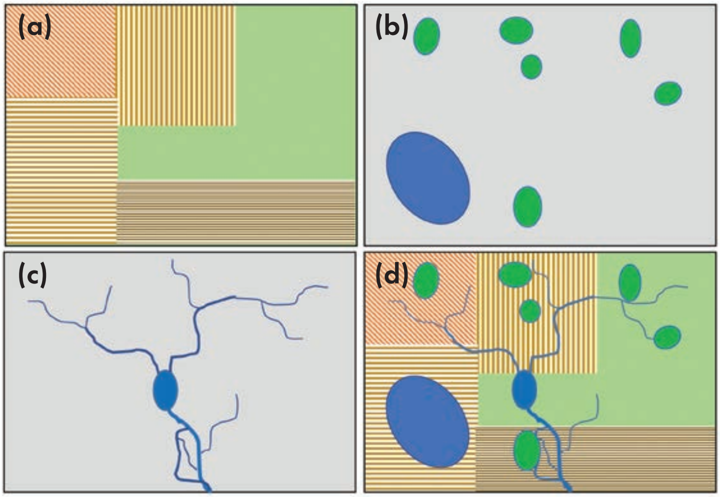
## A View for the Future

While great advances in wetland conservation have been made during the preceding 75 years, much remains to be accomplished. This job will be made even more difficult due to the uncertainties wrought by ever-changing national politics and uncertainties associated with a globally changing climate and constantly changing land uses and priorities. As wetland conservation moves into the future, one key will be recognizing the fact that wetlands are complex ecosystems that necessarily change through time in response to changing land uses and environmental conditions. Accepting that neither the wetland-terrestrial edge nor the wetland-aquatic edge is static will add an increased level of complexity to the lives of conservationists, who will need to adopt a practical approach that allows for wetlands to naturally change, adjust, and adapt to changes in environmental drivers. In addition to acknowledging that not all wetlands are stable in terms of their size, location, or permanency of ponded water, future perspectives should take into account that wetland functions may also evolve for any given wetland (McKenna et al. 2017; Mushet et al. 2018b). Wetlands must be seen as the dynamic landscape features that they are, dynamic features that also are integral to the integrity of other ecosystems.

Here the authors provide two examples of ways to envision wetland conservation that recognize the practicality of traditional delineations but together provide a more holistic approach of wetland conservation through an integrated vision. Mushet et al. (2018a) provide a view of wetlands and their surrounding lands that they describe as a freshwater ecosystem mosaic (FEM). In a FEM, wetlands are viewed as being intimately connected to the terrestrial matrix in which they are embedded. The full mosaic is not realized by examining the individual pieces (figure 2). It is only through examining all of the components, and how they are arranged, connected, and bonded to each other, that a complete picture is revealed. Within this perspective, the value of networks is fully realized and

**Figure 2**

**A (d) freshwater ecosystem mosaic is made up of (a) terrestrial ecosystems; (b) deep-water aquatic (blue) and shallow-water wetland (green) ecosystems; and (c) interconnected stream networks (Mushet et al. 2018a).**



can be strategically incorporated into conservation and management efforts. Additionally, the lands between the wetlands are seen to be part of the picture that must be considered. Thus, interfaces and the need to consider all components of the mosaic are recognized.

Calhoun et al. (2014) describe a long-term, collaborative approach to vernal pool conservation in Maine. This collaborative approach led to development of a Vernal Pool Special Area Management Plan that has been adopted by the New England Army Corps of Engineers. This is an example of a FEM for vernal pools. Their incentive-based approach provides an alternative wetland mitigation tool developed and implemented locally to address vernal pool losses in municipal growth areas by using development fees to conserve vernal pools and amphibian postbreeding terrestrial habitat in rural areas of municipalities (Levesque et al. 2019). Economic development is fostered in growth areas and, in the very same towns, conservation of pools is funded by this growth when rural landowners are provided compensation for conservation.

For wetland conservation, the question at hand now is not how to stop the swing of the pendulum, but how we can modulate the intensity of those swings. Neither extreme, either 100% conservation or 100% development, is possible or even desirable. Can we embrace a broader perspective that sees conservation and economic development as inextricably intertwined? We posit that we can if we pay attention to both language and outcomes that stress interconnectivity and the organic relationship between socioeconomic progress and wetland conservation, between wetlands and uplands. Rather than fomenting the cultural artifacts that set wetland conservation and economic growth at opposite ends of a polar construct, let us welcome a new holistic paradigm for wetland conservation. Then perhaps the central tendency of all pendulums will be realized as the swings become less intense.

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## Resources to Learn More

- USDA Natural Resources Conservation Service, Conservation Effects Assessment Project—Wetlands National Assessment. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/nra/ceap/na/?cid=nrcs143_014155
- US Geological Survey: History of Wetlands in the Conterminous United States. https://water.usgs.gov/nwsum/WSP2425/history.html

- Why Are Wetlands So Important to Preserve? https://www.scientificamerican.com/article/why-are-wetlands-so-important-to-preserve/
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# 15

Practitioner's Perspective

# Accelerating Implementation of Constructed Wetlands on Tile-Drained Agricultural Lands in Illinois, United States

*A. Maria Lemke, Krista G. Kirkham, Adrienne L. Marino, Michael P. Wallace, David A. Kovacic, Kent L. Bohnhoff, Jacqueline R. Kraft, Mike Linsenbigler, and Terry S. Noto*

Development and implementation of conservation practices that effectively reduce nutrient loss from tile-drained agricultural lands have never been

**A. Maria Lemke** is director of conservation science at The Nature Conservancy, Lewistown, Illinois. **Krista G. Kirkham** is an aquatic ecologist at The Nature Conservancy, Peoria, Illinois. **Adrienne L. Marino** is a water quality project manager at The Nature Conservancy, Peoria, Illinois. **Michael P. Wallace** is a research specialist in the Department of Crop Sciences, University of Illinois, Urbana, Illinois. **David A. Kovacic** is an emeritus professor, in the Department of Landscape Architecture and Department of Natural Resources and Environmental Science, University of Illinois, as well as director of the Wetlands Ecology Laboratory, Department of Landscape Architecture, Urbana, Illinois. **Kent L. Bohnhoff** is retired from USDA Natural Resources Conservation Service, where he served as district conservationist in Illinois. He currently serves as enrollment coordinator for the Precision Conservation Management program of the Illinois Corn Growers Association, Groveland, Illinois. **Jacqueline R. Kraft** is a watershed coordinator at the McLean County Soil and Water Conservation District, Normal, Illinois. **Mike Linsenbigler** is retired deputy director of USDA Farm Service Agency Conservation Environmental Programs Division and Conservation Reserve Enhancement Program (CREP) manager, and is cofounder of Conservation Strategies Consulting LLC, Rochester, New York. **Terry S. Noto** is an environmental attorney, consultant for Environmental Defense Fund (retired), and cofounder of Conservation Strategies Consulting LLC, Rochester, New York.

more critical in our efforts to provide healthy drinking water to growing populations and to protect increasingly threatened freshwater and marine ecosystems (Ward et al. 2005; Rabotyagov et al. 2014; Pennino et al. 2017). Small edge-of-field wetlands are highly effective at reducing nitrogen and phosphorus export from tile-drained agricultural fields (Kovacic et al. 2000, 2006; Kynkäänniemi et al. 2013; Groh et al. 2015), providing long-term, low-maintenance solutions to excess nutrient loss as well as wildlife habitat benefits. Despite their proven effectiveness, constructed wetlands are difficult to implement on private lands given that they provide downstream water quality improvements rather than direct on-farm economic and conservation benefits to agricultural landowners.

Increased adoption of effective nutrient reduction practices is especially critical in Illinois, which has the highest estimated total subsurface drainage area of any state in the Mississippi River Basin (Goolsby et al. 1999; Sugg 2007) and is among one of the highest contributors of total nitrogen (16.8%) and phosphorus (12.9%) flux to the Gulf of Mexico (Alexander et al. 2008). Illinois's goals of 15% reduction in nitrate-nitrogen loading to surface waters by 2025, and ultimately 45% reduction (IL NLRS 2015), will require a dramatic increase in the pace at which edge-of-field practices that effectively treat tile drainage are implemented (David et al. 2015).

Since 2006, The Nature Conservancy (i.e., the Conservancy) has worked with partners to construct more than 20 wetlands on private agricultural lands in central Illinois, 16 of which are designed specifically to intercept and treat tile drainage. Most recently, private and federal US Department of Agriculture Natural Resources Conservation Service (USDA NRCS) Conservation Innovation Grant funding (CIG) supported design, construction, and monitoring of 10 wetlands over five years (Lemke et al. 2017), 9 of which were the first in Illinois to be enrolled within the Conservation Reserve Program's (CRP) Farmable Wetlands Program (CP39; figure 1). We summarize our experiences navigating financial and programmatic challenges associated with constructing wetlands on agricultural lands and propose strategies to accelerate implementation of this practice.

## Implementation Challenges

***Financial and Resource Capacity.*** The CRP program is designed such that landowners pay all upfront practice construction costs and receive reimbursements upon completion and certification of the project. These engineered wetlands are expensive to construct, and upfront costs ranging in the tens of thousands of dollars can be a major deterrent for many landowners, especially as reimbursements can take three to six months. Excavation was the primary

**Figure 1**

**One of nine tile-treatment wetlands constructed in the upper Mackinaw River watershed, Illinois, that were enrolled in the Conservation Reserve Program's Farmable Wetlands Program (CP39). These edge-of-field wetlands were designed for maximum water retention and for water quality monitoring at the tile inlet (lower right corner) and outlet (upper left corner).**

expense and often exceeded estimated wetland construction costs by 60% to 200% due to factors such as requirements to move excavated soils off-site for wetlands constructed in the 100-year floodplain and unforeseen gravel lenses (Lemke et al. 2017).

Enrollment in new practices can be complicated and time-consuming, and participation in the process can be impractical for some landowners. Partnering with local soil and water conservation districts (SWCD) and NRCS offices was key to working through this process of outreach, site visits, enrollment, wetland design, construction, and final reimbursement. However, this iterative process assumed a tremendous commitment from agency staff that already had many demands on their time. Wetland engineering design and/or approval by NRCS can be an especially time-consuming requirement that in some cases impeded a timely enrollment process.

***Siting.*** Central Illinois sustains highly productive agricultural lands and is a leading producer of corn and soybeans in the country. Thus, wetlands are far more practical to site on cropland that has already been removed from production (e.g., CRP filter strips). Retrofitting existing filter strips with CP39 wetlands also increases water quality benefits by treating surface and subsurface runoff to create a fully functional edge-of-field conservation practice. Additionally, some landowners were more willing to site wetlands within flood-prone farmlands (e.g., historical floodplain habitat). Because no policy existed to retrofit CRP filter strips with wetlands and Illinois NRCS wetland guidance prohibited constructing wetlands in the 100-year floodplain, we addressed these two eligibility issues with USDA Farm Service Agency (FSA) and NRCS, respectively.

***Vegetation.*** Several concerns arose from state-level NRCS guidance that newly constructed wetlands be planted with rhizomes, stolons, and/or wetland plants at a minimum of 1 x 1 m (3 x 3 ft) spacing. Although this science-based guidance was designed to facilitate nitrogen microbial processes and provide wildlife benefits, estimates from local nurseries showed this would increase the cost of CP39 wetlands by an additional ~\$29,700 $ha^{-1}$ (~\$12,000 $ac^{-1}$). Furthermore, increased complexity and timing requirements for wetland planting overlapped with spring farming responsibilities and increased the likelihood of prolonging reimbursement processes.

## Addressing Implementation Challenges

***Supplementing Resources.*** To facilitate construction of CP39 wetlands during the five-year project period, the Conservancy and McLean County SWCD used private and state funding to cover all landowner expenses not reimbursed by FSA, including unforeseen costs such as additional tile installation and crop damage. Federal reimbursements were lower than expected for the first few wetlands due to a soil cap set by FSA County Committee that did not reflect actual current excavation costs. SWCD subsequently worked with FSA to increase the soil reimbursement cap by 83% based on real-time excavation data from multiple contractors. We used federal CIG funding to contract with a private engineering firm to design and supervise wetland construction. Engineering designs and construction were approved by NRCS engineers and met NRCS Field Office Technical Guide standards and USDA FSA 2 CRP Handbook guidelines.

***Siting Waivers.*** The Conservancy and partners initiated a waiver system with FSA to construct CP39 wetlands on existing CRP filter strips (CP21) by terminating part of the CRP CP21 contract and immediately reenrolling those acres into CRP CP39. FSA waived penalties ordinarily associated with early termination of a CRP contract. Development of a statewide or national policy that provides for retrofitting CRP filter strips with wetlands without requiring approval of individual waivers would accelerate the efficiency and scale of this practice.

NRCS floodplain siting restrictions were designed to protect public investment by ensuring wetland effectiveness and structural integrity during flood events. Given the prevalence of tiled farmland acres within the 100-year floodplain in central Illinois, we requested approval for wetland placement within several floodplain sites to evaluate benefits and potential setbacks during the project. NRCS agreed to waive the floodplain restriction for the project noting that CIG funding provided for private engineering assistance to design wetlands to structurally withstand flooding. Illinois NRCS guidance was subsequently revised to allow construction of CP39 wetlands in the floodplain provided design analyses ensured the wetlands can withstand flood events and that landowners agree to any additional maintenance requirements.

***Vegetation Modifications.*** We reached an agreement with NRCS to explore the potential for natural regeneration of wetland vegetation, a decision partially based on documented cases where diverse aquatic plants became established in constructed wetlands in Iowa and Illinois without seeding or planting. Subsequently, NRCS modified state guidance to provide cost-effective options to establish aquatic plants, including natural regeneration, seeding, and/or transplanted macrophytes to be determined by a NRCS biologist based on site location and characteristics. Should natural regeneration fail after year one, landowners must establish wetland vegetation through seeding and/or plantings.

## Moving the Needle

We gained valuable insights into the complexities of implementing constructed wetlands in agricultural landscapes during our work in Illinois. Foremost, it is imperative **to understand landowner/farmer perspectives** on the practicalities and economics of integrating conservation practices into their farm operations. Financial implications of converting highly productive farmland acres to wetlands was the primary constraint we encountered during this project. Farmers are stewards of the land and many are open to innovative ideas for agricultural and environmental improvements if they can fit practically into overall farming operations. Constructed wetlands are expensive and can entail substantial out-of-pocket costs for landowners, as well as potential loss of agricultural income. As such, **increased financial incentives** should be considered for landowners willing to remove highly productive farmland to install edge-of-field wetlands that benefit downstream users (Osmond et al. 2012), particularly enhanced cost-share that provides 90% to 100% of construction costs in addition to 120% annual rental rates.

Leveraging **public-private partnerships** is necessary to increase investment and support for watershed conservation. These partnerships can spur innovative funding mechanisms and incentive programs that increase cost-effectiveness, streamline program efficiencies, and provide the consistent financial and technical resources required for implementing conservation at the scale needed to meet national water quality goals. An important component of these programs should include **technical service providers and/or software** that can streamline enrollment and accelerate design of constructed wetlands.

Reliance on voluntary participation to effectively reduce pollution concerns such as hypoxia in the Gulf of Mexico, algae blooms in the Great Lakes, and nutrients threatening local drinking water supplies will require **increased investment in outreach** by local, knowledgeable, and trusted providers. Tile-treatment practices require especially intensive hands-on outreach by agency staff that are generally overcommitted and underfunded. Supporting the development and coordination of farmer-led outreach programs that partner with SWCDs, NRCS, and university extensions should be one avenue to build outreach capacity and influence within the agricultural community. Such coordination could lead to increased implementation of conservation practices that effectively attain nutrient loss reduction goals.

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# 16

# The Role of Soil Physics as a Discipline on Soil and Water Conservation during the Past 75 Years

*Francisco J. Arriaga, DeAnn R. Presley, and Birl Lowery*

## Changes in Agriculture Have Affected Soil Physical Properties

Soil physics is at the heart of soil and water conservation, with much of the work focusing on soil erosion and water quality. Land management affects physical properties such as bulk density, infiltration, aggregation, and hydraulic conductivity, which are crucial for soil and water conservation efforts. In the past 75 years, there have been significant changes in how agricultural and natural resources (soil and water) are viewed and used. These changes have occurred in soil and water conservation, from attempts to reduce soil erosion by implementing terraces, contour farming, and crop rotations, and in some areas installing structures to stop gully formation. During this period of time, an extensive development of numerous agricultural chemicals (herbicides, insecticides, fertilizers, and other amendments) allowed for soil conservation-friendly farming, such as reduced- and no-tillage (with significant surface crop residue cover). However, also during this time the pressure on our natural resources has increased. Somewhat ironically, along with the positive aspects of agricultural chemicals that made soil conservation farming possible, come concerns for soil health and water quality. The increased use of agricultural chemicals has resulted in decreased soil health, including

**Francisco J. Arriaga** is an associate professor in the Department of Soil Science, University of Wisconsin, Madison, Wisconsin. **DeAnn R. Presley** is an associate professor in the Department of Agronomy, Kansas State University, Manhattan, Kansas. **Birl Lowery** is a professor emeritus in the Department of Soil Science, University of Wisconsin, Madison, Wisconsin.

physical parameters (Hussain et al. 2001; Karaca et al. 2010; Reganold 1988). A decrease in physical soil health parameters, including structure (causing slaking, surface crusting, and decreased porosity), bulk density, water, and thermal regimes, can result in increased surface water and groundwater contamination. While there has been removal of some of the aforementioned conservation practices established 75 to 20 years ago, adoption of other conservation practices has increased (Hellerstein et al. 2019; Magleby et al. 1985). Cover crop use and reduced tillage techniques have helped soil conservation efforts and improved soil physical properties (Hellerstein et al. 2019). Another trend affecting soil physical properties and soil and water conservation during the past 75 years is the increasing size and mass of farm machinery (Kim et al. 2005). Larger farm equipment allows for improved productivity, but larger farm equipment can also result in increased soil bulk density because of soil compaction and therefore decreased yields (Bakken et al. 2009; Sohne 1958). This means a reduction in soil porosity, which reduces water infiltration and storage, resulting in increased soil erosion. Additionally, removal of conservation structures has occurred in order to allow for the larger equipment to operate more freely within fields.

## Methods for Assessing Soil Physical Properties

Many of the methods used to measure soil physical properties from 75 years ago are still being used. However, there have been many new methods developed and major changes to the measurement techniques of many older methods. The advent of electronics in other disciplines has transferred to soil physics as well. Some methods are more complex than in the past, with the use of sensors, computers, data-logging, and wireless communication capabilities, which allow for real-time data collection. The analyses of data have become more complex as well, with more advanced analysis techniques and application of complex computer model simulations (Huang et al. 2017; Zhang et al. 2020). An important development in soil physics was the application of time domain reflectometry (TDR) to nondestructively and rapidly determine soil water content (Topp and Davis 1985; Topp and Reynolds 1998). This application of TDR in soil physics has resulted in the development of other simpler, faster, and more cost-effective approaches for soil water content measurements using similar principles, making this once-difficult measurement now almost commonplace. These advances have allowed for soil water content and matric potential measurements in small time steps (Baker and Allmaras 1990; Lowery et al. 1986), which allows for improved irrigation scheduling for more efficient water use. This reduces the potential for runoff and groundwater contamination.

The development and application of geophysical techniques, such as electrical conductivity for soil mapping, has also helped advance soil and water conservation goals. Field maps of electrical conductivity can be used to develop management zones that can relate to soil organic carbon, different textural classes, soil depth, and other physical properties and features (Johnson et al. 2001; Kitchen et al. 2005; Luck et al. 2009). Depending on the application, these management zone maps developed with geophysical techniques can be used for precision agriculture or irrigation management to improve resource utilization.

Currently it is possible to log soil water and matric potential in real time using wireless telecommunications; together with rapid sophisticated computer analyses, this allows for assessing water drainage for a field or watershed. These detailed analyses were not possible 75 years ago, as such measurements were not possible and the necessary computer processing power was not available. Computed tomography (Gantzer and Anderson 2002) has been used to scan soil columns to assess soil density, porosity, and preferential flow caused by insect activity (Petrovic et al. 1982; Grevers et al. 1989; Bailey et al. 2015). These advanced techniques are in contrast to older devices for in situ water content, matric potential measurements, and drainage collection, including resistance gypsum and fiberglass blocks, gamma ray and neutron probes, tensiometers with manometers or gauges, and lysimeters (Dane and Topp 2002). An advantage of advanced techniques for measuring soil physical properties and processes is that information collected about different properties can be used to generate three-dimensional representations of soil properties at a field or landscape level that can be helpful for studying and determining management impacts for soil and water conservation efforts (Grunwald et al. 2001; Arriaga and Lowery 2005).

## Future Options for Application of Soil Physics to Soil and Water Conservation

Observations from drones, low-flying aircraft, and space are currently available for every corner of the globe and can help assess everything from crop growth and pest management to soil erosion (Wüpper et al. 2020). These detailed methods of data collection were not available 75 years ago, so in the future we anticipate that these sophisticated techniques will only be improved upon. An applied example is the use of remotely sensed data from satellites to estimate soil water content for agricultural fields without the use of sensors installed in the soil (Huang et al. 2019; Siegfried et al. 2019). Not too far in the future, one will be able to view, in real time, data that relates to man-made and natural disasters, such as mudslides, or for soil and water conservation management. Hourly, daily, and monthly changes to soil resources via space and drone crafts can be tracked. Improvements to these technologies focusing on the earth's surface will allow for rapid response to environmental problems including those associated with climate change. For example, scientists currently track changes to polar ice using remote sensed data from satellites (Strozzi et al. 2017). Space observations are also valuable for wildfire monitoring and evaluating natural recovery following these disasters. Algae growth and harmful algal blooms on surface freshwater bodies can also be monitored in real time using remote sensing platforms (Urquhart et al. 2017; Lekki eta al. 2019). Monitoring of cover crop use can be done via satellites (Hively et al. 2015). These real-time technologies are a contrast to simple hot-air balloon and low-flying aircraft monitoring of 75 years ago, and in the future there will be even more advances. The development of remotely sensed soil carbon with satellites provides a window of what the future will hold for soil physics in the context of soil and water conservation.

## Conclusion

Soil erosion was a significant concern of soil physics as a discipline 75 years ago. During the decades that followed, advancements in soil physics theory and measurement techniques were quickly recognized as useful for soil and water conservation efforts. Needs for soil and water conservation have changed somewhat, while soil physicists have continued to improve methods and modeling approaches. Over the next 75 years we can expect that the disciplines of soil and water conservation and soil physics will continue to depend upon and work with each other.

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# 17

# The Growing Role of Dissolved Nutrients in Soil and Water Conservation

*Kenneth W. Staver*

## The Starting Point: Soil Erosion and Nutrient Depletion

More than a century before the dust clouds reached Washington, DC, in the mid-1930s giving Hugh Hammond Bennett the prop he needed to push for passage of the Soil Conservation Act, soil erosion had already blocked ship access to ports built by early colonists to ferry tobacco back to Europe (Gottschalk 1945). Trimble (1974) chronicled the full extent of agriculture's impact on sediment transport from 1700 forward in the Southern Piedmont and identified the period of 1860 to 1920 as the most intense period of erosion since settlement. Bennett's efforts led to the formation of the US Department of Agriculture (USDA) Soil Conservation Service and a decade later, the Soil Conservation Society of America, setting the stage for a concentrated effort to reduce soil erosion, which rightfully was viewed as a threat to agricultural productivity and the economic wellbeing of rural communities.

While soil erosion was an obvious long-term threat to agricultural productivity, depletion of plant available nutrients was another challenge, especially in coarse-textured soils of the Atlantic Coastal Plain that came into production soon after European settlement. Early research related to soil chemistry focused on maintaining fertility and, specifically in the case of tobacco, on supplying nutrients needed to promote tobacco quality (Morgan et al. 1942). Although erosion was viewed as a national crisis by the pioneers in soil

**Kenneth W. Staver** is an associate research scientist at the University of Maryland College of Agriculture and Natural Resources, Wye Research and Education Center, in Queenstown, Maryland.

conservation early in the 20th century, leaching was identified as the primary route of nitrogen (N) loss nationally from cropland soils in the USDA 1938 *Yearbook of Agriculture* (Utz et al. 1938). The invention of the steel plow in the 1830s opened up the rich prairie soils to intense grain production, with tillage stimulating the breakdown of organic matter and release of plant available inorganic nutrients. Plow layer total soil carbon (C) losses have been estimated to have been approximately 50% in the first half century after conversion from native vegetation to agriculture (Parton et al. 1996), indicating large annual releases of inorganic N due to organic matter mineralization and net annual decreases of root zone total N of approximately 60 kg $ha^{-1}$ (54 lb $ac^{-1}$). Bray and Watkins (1964) reported that decreasing corn yields from 1920 to 1940 were due in part to depletion of soil nutrient reserves. While soil erosion was grabbing the headlines in the decades leading up to World War II, depletion of soil nutrients also was a growing threat to the national food supply, but public concern regarding agricultural impacts on water resources remained limited. The very names of the Soil Conservation Service and Soil Conservation Society of America underscored that the focus in the early years was almost solely on the loss and physical degradation of the nation's soil resource.

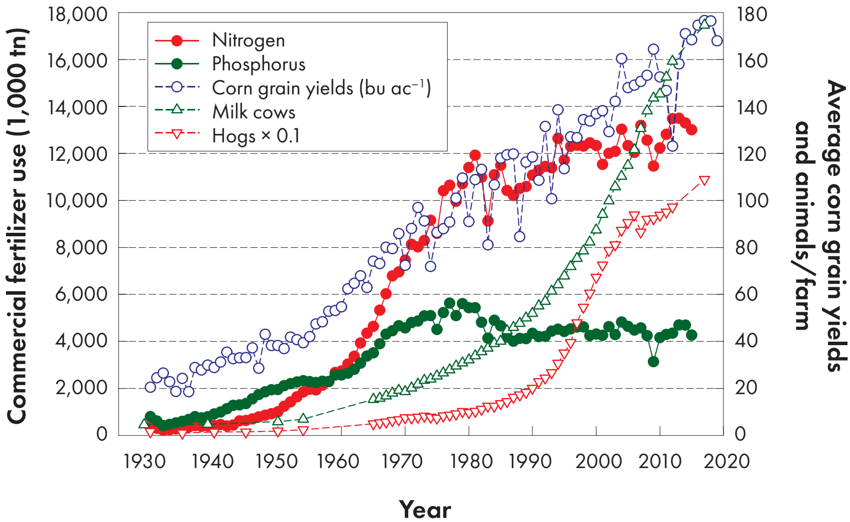
## Agriculture Changing Rapidly and the Land Ethic

Following the formation of the USDA Soil Conservation Service, a concentrated national effort began to stem the soil erosion that Hugh Hammond Bennett had labeled a "national menace." While this effort moved forward on scientific and implementation fronts following World War II, the nature of agricultural production also was changing as mechanization, transportation infrastructure, and, especially, the expansion of the commercial fertilizer industry altered the market forces that shaped the fundamental structure of crop and animal production systems (Lanyon 1995, 2000). Because of the tight constraint of nutrient availability on crop production, farms prior to the development of the commercial fertilizer industry were focused on conserving plant nutrients through integrated animal and crop production, and animal production was largely limited by on-farm feed production. With crop production no longer constrained by on-farm nutrient sources, nutrient applications, crop yields, and the size of animal operations increased steadily for the next several decades (figure 1).

Another change in the agricultural landscape occurring in the early days of the soil conservation effort was Aldo Leopold developing his land ethic, which went well beyond soil conservation in calling for careful stewardship of all natural resources as a part of agricultural production. His message was crystalized in *A Sand County Almanac*, published posthumously in 1949, in

**Figure 1**

**US total commercial nitrogen and phosphorus fertilizer use, average corn grain yields, and average number of milk cows and hogs on farms from 1930 to 2019 (USDA 1966; USDA Economic Research Service 2019; USDA National Agricultural Statistics Service 2019).**




which he fully developed the concept of conservation as harmony between man and the land. However, despite his broader vision, conservation in agriculture remained focused primarily on preventing the loss of the soil resource so critical to crop productivity.

The early strategy to reduce soil erosion employed a suite of practices to reduce exposed soil to the forces of wind and water. The basic approach was to protect the soil from direct raindrop impact using crop canopies and residue; to slow overland flow using modified tillage and crops residues; and to add mechanical practices, such as contouring, strip cropping, and terracing, to reduce slope lengths in settings where tillage and residue management were insufficient (Wishmeier 1976). The big breakthrough on controlling soil erosion in row crops came as chemical weed control approaches developed gradually from the 1940s onward, culminating with the creation of genetically modified crops in the 1990s that were tolerant of nonselective herbicides, such as glyphosate. Chemical weed control, along with advances in planting technology that allowed seed placement in high residue and even living mulch settings, allowed the widespread adoption of conservation tillage and no-till farming nationwide. Drastic reductions in tillage, along with the suite of other soil management practices, have drastically cut cropland soil erosion to levels not attainable in the early decades of the soil conservation movement and also advanced the overall health of soil resources (Reeder and Westermann 2006; LaRose and Myers 2019). These changes, however, altered soil water dynamics, the distribution of soil nutrients, and soil microbial activities, all of which play a role in conservation efforts.

## Soil Erosion Rates Falling, Soil Nutrients Rising

While the effort to control soil erosion was marching steadily forward, other changes in agricultural production, along with an increasing awareness nationally of water quality degradation, expanded the focus of agricultural conservation efforts in the 1960s to issues beyond soil erosion. Frink (1969) analyzed nutrient budgets of dairy farms in Connecticut in the context of eutrophication, reported large surpluses of N and phosphorus (P) in farm balance sheets, and suggested that the result was increased nitrate ($NO_3^-$) in groundwater and a buildup of soil P. Shortly thereafter, a special publication by the Soil Science Society of America (Nelson 1970) highlighted the need for research to answer the following question: Do fertilizers actually contribute to contamination of natural waters? Groundwater studies in Nebraska (Exner and Spalding 1979) gave some credence to Frink's supposition about agricultural $NO_3^-$ reaching groundwater by calculating that approximately 50% of N applied to irrigated cropland was eventually entering the groundwater system. Analysis of national cropland P balances (Bruulsema et al. 2019) found that the 1970s were the period of the largest net additions of P to cropland soil. Popular soil science textbooks were still referring to "the phosphorus problem" as the conversion of applied P into insoluble forms while efforts to reverse the effects of excess nutrient inputs to Lake Erie and Chesapeake Bay had begun. Clearly, conservation efforts needed to expand to include dissolved forms of N and P, which were not necessarily controlled by soil conservation practices.

After the first Earth Day in 1970 and passage of the first version of the federal Clean Water Act in 1972, the research community became fully engaged in the effort to clarify how nutrients moved in agricultural systems as a first step in developing strategies to reduce both sediment and nutrient losses. Early studies showed the potential for increases in dissolved nutrient losses in surface runoff when inorganic fertilizers were surface applied in no-till settings (Romkens et al. 1973). While it had long been known that algae growth in lakes is mostly controlled by P, a review by Sonzongni et al. (1982) concluded that it was the bioavailable forms of P that primarily stimulated algae growth and that eutrophication control strategies should prioritize controlling those forms. A year later in a special issue of the *Journal of Soil and Water Conservation* devoted to conservation tillage, Baker and Laflen (1983) summarized the water quality consequences of shifting from inversion to conservation tillage. A recurrent theme was the concentration of soluble nutrient forms, especially phosphate-P, in surface soil layers that were critical in controlling concentrations in surface runoff and losses to downstream surface waters. They concluded with a call for development of an approach to preserve the surface residue cover needed for erosion control while at the same time getting some degree of incorporation of nutrients to reduce runoff losses. Despite this early recognition of the critical role of bioavailable P in freshwater eutrophication and that shifting to less tillage could enhance bioavailable P losses, the agricultural component of the initial Lake Erie restoration effort focused on reducing soil erosion (Forster et al. 1985). This strategy, which also included increased controls on wastewater nutrient releases, initially resulted in restoration success, but re-eutrophication of Lake Erie in the last decade has been linked to increasing dissolved P loadings from cropland (Baker et al. 2014).

While the Lake Erie restoration effort was ramping up, water quality problems in coastal areas were gaining attention where N was thought to be the primary factor impacting algae growth. First in Chesapeake Bay and then later in the Gulf of Mexico (Rabalais et al. 1996), large volumes of oxygen-depleted water were documented and linked to excessive algae growth fueled by increasing N inputs. As with dissolved forms of P, early studies indicated that highly effective erosion control practices did little to reduce the loss of $NO_3^-$, which moved freely in dissolved form (Gilliam and Hoyt 1987). In the Mississippi River Basin, the big uptick in N loads came after 1970, driven mostly by increasing $NO_3^-$ concentrations (Goolsby and Battaglin 2001). In addition to ecological impacts in the Gulf of Mexico, elevated $NO_3^-$ also led to human health concerns and increasing water treatment costs (Vedachalam et al. 2018). This increase in riverine $NO_3^-$ was linked to an overall shift to less diverse crop rotations with less perennial forages, increased N applications, and expansion of artificial drainage (Dinnes et al. 2002). Large urban areas contribute to overall N loading of the Chesapeake Bay, but in concentrated agricultural watersheds, $NO_3^-$ transport through groundwater was found to be the major N delivery pathway (Staver et al. 1996).

## Changing Names and Expanding Focus

A half century later, although work remained, Hugh Hammond Bennett's menace of soil erosion had been greatly reduced, and agricultural productivity continued to increase steadily. But all was not well in the conservation community. The reduction in tillage that had been so critical to reducing soil erosion, combined with a steady buildup of soil P along with overall intensification of both crop and animal production, created a new set of conservation challenges for agriculture. Many of these challenges result from changes in soil chemistry that increase the availability of soluble forms of N and P for transport to downstream ecosystems. Reflecting these changing and expanding challenges, the Soil Conservation Society of America changed its name in 1987 to the Soil and Water Conservation Society (SWCS), and in 1993, USDA's Soil Conservation Service became the Natural Resource Conservation Service. At the policy level, the 1985 Federal Food Security Act (also known as the farm bill) included for the first time a conservation title, which linked producer eligibility for federal assistance programs to conservation performance. While most performance requirements were aimed at soil erosion, protection of wetlands was a new provision that expanded the conservation landscape to beyond field boundaries.

With the emergence of nutrient inputs as critical to water quality in both freshwater and coastal systems, the conservation effort in the last three decades gradually shifted from protecting the soil from erosive forces to modifying soil chemistry to reduce the availability of nutrient forms susceptible to transport. Most of the practices listed under the nutrient management heading (Sharpley et al. 2006) in one way or another are aimed at modifying availability of soluble forms of N and P in both space and time to reduce the risk of loss. Even practices like animal diet modification, farm gate nutrient balancing, and improved manure storage ultimately are most important as conservation practices because they make it possible to modify soil chemistry. These practices are prerequisites for long-promoted comprehensive nutrient input management strategies (Ribaudo et al. 2011), recently termed the 4R strategy (Bruulsema et al. 2019), that promote nutrient applications in time and space that maximize crop use and minimize availability for transport. A key challenge in managing nutrient inputs to minimize the potential for losses is that crops need the forms of N and P that are most susceptible to transport making yield reduction a real and perceived risk of restricting inputs. A second limit on the extent that input management can be used to reduce N losses is that $NO_3^-$ is released as a result of soil microbial breakdown of organic matter and the timing of release is not necessarily matched with crop needs (Staver and Brinsfield 1990). Although many factors come into play, $NO_3^-$ losses in row crops generally have been found to exceed acceptable levels even when N is applied at economically optimum levels (Jaynes et al. 2001).

Recognition of the limits of infield erosion control and nutrient input strategies to achieve desired water quality goals resulted in additional strategies to modify soil chemistry with the initial focus on using cover crops to scavenge $NO_3^-$ after crop uptake was complete. SWCS convened the Cover Crops for Clean Water Conference in 1993, with summary papers showing the potential of winter cover crops to reduce soil $NO_3^-$ concentrations and leaching losses (Meisinger et al. 1991). At the same time, interest was growing in using reestablished natural systems down gradient of crop fields to intercept both surface and subsurface loss of N and P. Riparian buffers were found to be sites where interaction of $NO_3^-$-rich groundwater with perennial vegetation and C-rich soils created favorable conditions for denitrification (Lowrance et al. 1997). Riparian buffers and restored wetlands were a major component of the USDA Conservation Reserve Enhancement Program established in Maryland in 1997, and remain a central component of the Chesapeake Bay restoration strategy. Large-scale use of natural nutrient attenuation practices also has been proposed for the Mississippi River Basin (Mitsch et al. 2001). More recently, engineered practices that promote denitrification, such as bioreactors and saturated buffers, have been added to strategies to reduce N losses from drained cropland (Christianson et al. 2016).

## Dissolved Nutrients: The 2020 Water Quality Menace

One emerging conservation challenge related directly to changing soil chemistry is control of dissolved P loss from cropland. It is especially relevant now as nationwide interest in soil health and using soils to sequester C has added to support for reduced tillage. While increasing dissolved P loss was detected early in the development of conservation tillage systems (Baker and Laflen 1983), until it was linked to the recent re-eutrophication of Lake Erie (Jarvie et al. 2017) concerns never reached the level of reconsidering the universal conservation benefit of reduced tillage. Adding to the challenge is that cover crops and riparian buffers are neutral on controlling dissolved P (Sharpley et al. 2006) and drainage management practices that promote low oxygen conditions to enhance denitrification may actually increase dissolve P losses. Evidence suggests that greater emphasis will be needed on nutrient placement, that is, the “right place” of the 4R strategy, if further reductions in tillage are going to be promoted for erosion control and soil health. The call by early researchers to look for ways to get soluble nutrient forms off the soil surface while maintaining erosion protection seems relevant today. While new technologies have been demonstrated to be effective (Liu et al. 2016), implementation remains limited, and comprehensive assessments of stream and river water quality data continue to indicate dissolved P increasing while sediment losses decrease in agriculturally dominated watersheds (Stets et al. 2020).

The dissolved nutrient issue becomes even more challenging in regions of concentrated animal production. For N, the low nutrient density and physical inconsistency of animal manures reduces the extent to which the 4R strategy can be used relative to inorganic fertilizers. Options for in-season applications are limited, and combined with storage limitations, often results in nutrient applications well in advance of periods of maximum crop uptake. This causes elevated soil $NO_3^-$ levels for long periods, thereby increasing the risk of loss. For both N and P, surface application of manure leads to the same elevated risk of runoff losses of dissolved nutrients as for inorganic fertilizers in the absence of any incorporation into the soil (Verbree et al. 2010). For P, there is the additional long-term flow of surplus P to animal production areas that accumulates in nearby cropland soils (Sims 2000), raising the potential for both dissolved and total P losses. Frink (1969) concluded that surplus nutrients on dairy farms that posed a threat to water quality "had arisen from economic pressures," that is, it was more profitable at the farm level to have nutrient budget surpluses. A more comprehensive analysis 40 years later of dairies in the northeastern United States (Ketterings et al. 2012) found similar patterns of surplus nutrients at the farm scale, suggesting little change in economic forces in intervening decades. Nutrient surpluses also have been documented in poultry-producing regions in the Chesapeake Bay watershed (Staver and Brinsfield 2001) and at the county level nationally where animal production is concentrated (Kellogg et al. 2000). While some progress has been made in reducing nutrient surpluses with diet modification, increasingly concentrated animal production remains a multilayered conservation challenge regarding dissolved nutrient losses, especially as tillage intensity continues to decrease.

## Summary and Moving Forward

During the last 75 years, the chemistry of cropland soils has changed dramatically as inputs and management have changed. Early conservation efforts focused on catastrophic soil erosion rates while at the same time soil nutrients were being mined and leached from soil organic matter pools. Development of the commercial fertilizer industry after World War II led to structural changes in farms and reversed the trend of soil nutrient depletion with net P additions to cropland soils increasing steadily through 1980. Availability of inorganic N fertilizers reduced the need for forage legumes and animal manures to grow cereals, and yields increased steadily. During the same period, animal agriculture became more concentrated at farm and regional scales, leading to nutrient surpluses relative to locally available crop needs. These two factors resulted in an overall buildup of soil P, with the increase accentuated in areas of concentrated animal production. A third trend during the first 50 years of SWCS was increasingly effective chemical weed control, which contributed to development and widespread adoption of reduced tillage and no-till production practices that have greatly reduced soil erosion but increased the stratification of soil nutrients. Near the end of this period, as soil erosion continued to decrease, water quality became a major public concern with $NO_3^-$ contamination of groundwater and accelerated eutrophication of freshwater and coastal areas bringing nutrients to the forefront in agricultural conservation.

As reducing nutrient losses became a central part of agricultural conservation efforts in the last three decades, focus shifted from modifying the soil physical environment to prevent erosion to modifying soil chemistry to reduce nutrient losses. Much of what falls under the heading of nutrient management is about managing root zone chemistry to minimize the potential for nutrient losses while providing for crop growth. Nitrate has long been known to move readily in dissolved form through overland, and both natural and artificial subsurface drainage. It is more recent that dissolved forms of P have been found to move in sufficient quantities and have been identified as the likely cause of recent setbacks in freshwater restoration efforts. The research community has developed a long list of infield and edge-of-field options for reducing $NO_3^-$ losses (Christianson et al. 2016) that generally are fully compatible with strategies to reduce erosion and build soil health. The main challenge for N, which is daunting, appears to be getting implementation of effective practices to sufficient levels to achieve reduction targets. Dissolved P presents a dilemma as the reduction in tillage that has been so valuable for reducing erosion and restoring soil health has led to increasing concentration of soil P in surface layers and development of soil structure more conducive to rapid movement of dissolved P into drainage systems. The key research challenge is to develop optimal animal/crop/soil management approaches that provide adequate levels of erosion control while limiting dissolved P losses. Managing soils to address climate change adds yet another term to the optimization equation. Overall success of conservation efforts will remain largely dependent on the public and policymakers supporting programs that counter market forces that deter implementation of conservation practices.

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# 18

Practitioner's Perspective

# From Nutrient Use to Nutrient Stewardship: An Evolution in Sustainable Plant Nutrition

*Lara Moody and Tom Bruulsema*

The pressures challenging farming systems of today both resemble and differ from those of 75 years ago. Relative to nutrient use, a main focus in 1945 was supplying nutrients to meet crop need and to build soil fertility. While these challenges remain today, they must be met with much more attention to environmental concerns. We review here the past and project from the present to describe how the practice of plant nutrition is evolving from nutrient use to nutrient stewardship.

In 1945, a speech by Mrs. Roy C.F. Weagly, President of the Associated Women of the American Farm Bureau Foundation, was entered into the Congressional Record by Senator George Radcliffe of Maryland. She stated, "The fertility of our soil has been greatly reduced by erosion, overcropping, leaching and man's failure to return sufficient nutrient to the soil." She called for a national plant-nutrient policy to make plant-nutrient fertilizer available to all areas of the country (Congressional Record 1945).

Content review from the 1945 volume of *Better Crops with Plant Food* (a publication from the International Plant Nutrition Institute) indicates fertilizer source, rate, timing, and placement were discussed extensively, even though the term "4R nutrient stewardship" was absent. Topics also indicate a focus on identifying soils suffering fertility depletion and crops needing nutrients to boost yields.

**Lara Moody** is vice president of stewardship and sustainability programs at the The Fertilizer Institute, Washington, DC. **Tom Bruulsema** is chief scientist with Plant Nutrition Canada, Guelph, Ontario, Canada.

Some articles did also address crop quality as affected by crop nutrition and the importance of controlling soil erosion to minimize nutrient loss.

Today, the term "4R nutrient stewardship" has become ubiquitous with many stakeholders. A 2017 survey indicated 96% of crop advisors were aware of 4R terminology (Moody 2018), and the 4Rs are the basis for nutrient management efforts at the US Department of Agriculture Natural Resources Conservation Service (USDA NRCS 2020). The 4Rs are guided by the following principles:

- Right Source—Ensure a balanced supply of essential nutrients, considering both naturally available sources and the characteristics of specific products, in plant available forms.
- Right Rate—Assess and make decisions based on soil nutrient supply and plant demand.
- Right Time—Assess and make decisions based on the dynamics of crop uptake, soil supply, nutrient loss risks, and field operation logistics.
- Right Place—Address root-soil dynamics and nutrient movement, and manage spatial variability within the field to meet site-specific crop needs and limit potential losses from the field.

The question arises: Was 4R nutrient stewardship practiced in 1945? A quote from one of the articles in the 1945 volume states, "Experience has shown that for maximum efficiency from use of fertilizers we not only must make sure we use the right amount of the right fertilizer ratio, but we must apply it at the right time and in the right place with respect to the feeding root." The context, however, was in a discussion of the merits of "plow-under" fertilizers for corn. Additionally, within the article, the word "stewardship" was used only in reference to stewardship of the soil, not of nutrients or fertilizers.

Some of what we consider new today was already in mind in 1945. A portent of precision farming, "selective service for each acre" was defined as "using the land according to its capabilities and treating it according to its needs, including application of needed soil and water conservation practices…treating these farms, fields, and acres in accordance with their needs and adaptabilities" (Sargent 1945).

While terms linked to nutrient source, rate, timing, and placement were a part of the nutrient use lexicon prior to the 1990s, it is late in the 20th century that we see a shift toward the nutrient management considerations of today. The *Journal of Soil and Water Conservation* (JSWC) database offers insight through the appearance of key terms relevant to nutrient stewardship. From 2000 to present, we see a five- to six-fold increase in the appearance of the terms "nutrient loss" and "nutrient pollution," respectively, in JSWC article text (figure 1). Noting that JSWC indexes are not as thorough nor searchable prior to 1981, it is notable that those two terms do not appear in the journal's printed index prior to 1981. Appearance of "sustainability" and "sustainable" also increase significantly between 2000 and 2020, and again neither appear in the pre-1981 journal index.

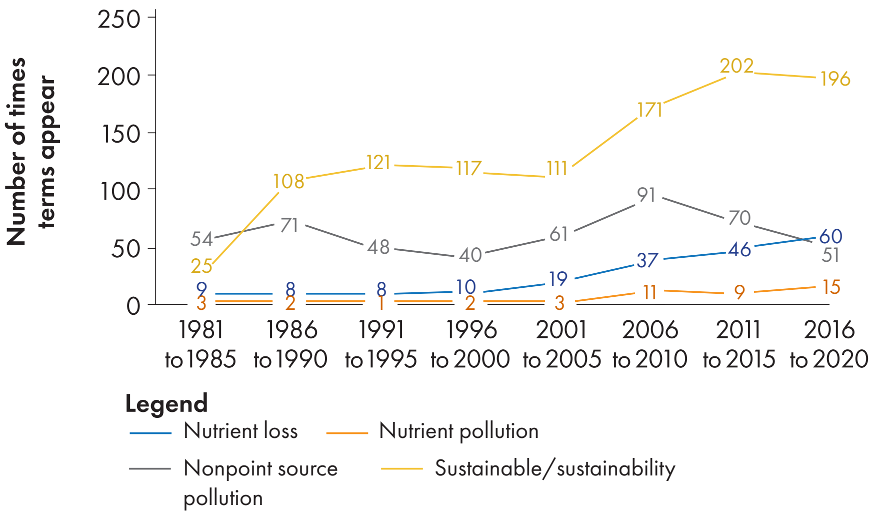
While the literature cited above shows that nutrient use around 1945 focused on building soil fertility and addressing crop deficiencies, a shift toward environmental considerations has occurred since that time. With this shift, the terms "management" and "stewardship" start to be applied to nutrients as well as to soils.

By 2010, the fertilizer industry had shifted its focus from solely considering soil fertility and crop needs to more broadly considering the impact of nutrient stewardship on economic, social, and environmental outcomes. These multiple outcomes include key sustainability performance areas including profitability, soil health, reduced losses to the environment, rural development, food security, land conservation, and habitat protection.

The number of tools to diagnose nutrient need and aid in nutrient application has expanded beyond soil testing and plant analysis to include sensors, crop and soil maps, global positioning system (GPS) guidance, and in-season crop models accounting for weather, as well as new fertilizer products and technologies. Dealership surveys, conducted by CropLife media and Purdue

**Figure 1**

**Number of times the terms "nutrient loss," "nutrient pollution," "nonpoint source," and "sustainable/sustainability" appear in *Journal of Soil and Water Conservation* text between 1981 and 2020.**



University, show that from 2004 to 2019, use of GPS guidance with autosteer/autocontrol has increased from 5% to 90% of respondents (Erickson and Lowenberg-DeBoer 2019). Between 1997 and 2019, variable rate fertilizer application among retailers increased from 9% to 64%. Data from The Fertilizer Institute (The Fertilizer Institute 2020b) indicate 24% of all nitrogen (N) is now applied with an enhanced efficiency fertilizer product. These products, tools, technologies, and practices are key components to implementing 4R nutrient stewardship on the ground.

The past 75 years saw great changes in nutrient balances. Nitrogen use efficiency (N removed in crop harvest as a fraction of that supplied by fertilizers, manures, and legumes) was as high as 175% in 1947 (Stanford et al. 1970), because the common use of moldboard plowing made a lot of N available from the organic matter of America's rich soils. It dipped as low as 51% in 1974 but has climbed to almost 70% today (Lassaletta et al. 2014).

Around 1945, crop harvests were removing less than one-quarter the amount of phosphorus (P) they do today. Annual P inputs, manure and fertilizer, amounted to 60% more than crop removal in 1945, remained in surplus through the 1970s and 1980s, but since 2008 have matched or fallen short of crop removals (Bruulsema et al. 2019).

Given the site specificity of 4R practice adoption and impact, a real-world example provides good insight into implementation outcomes. On a no-till corn operation in Illinois, the operator's management practices evolved from 2014 to 2018 to refine his nutrient management system (The Fertilizer Institute 2020a). As practices evolved (e.g., fine tuning the timing of N application to more closely match the crop's growth curve and refining spatial decisions for variable rate application), so did the cropping system outcomes. In addition to yields increasing across the four-year period, the cost for practice implementation decreased by \$40 to \$62 $ha^{-1}$ (\$16 to \$25 $ac^{-1}$), and the N application rate decreased with increasing yield, leading to an improved N use efficiency, going from 50 to 70 kg (0.9 to 1.25 bu) of corn per kilogram (pound) of N applied. Additionally, greenhouse gas nitrous oxide emissions were reduced by 34% (based on the carbon dioxide equivalent [$CO_2$eq]), based on the calculation utilized by Field to Market (2018) in the FieldPrint Calculator.

## Future

Optimizing nutrient use efficiency involves matching input rates as closely as possible to the needs of the system. It depends on choosing the right source, right time, and right place for each nutrient application, as well as on choosing the right crop, the right cultivar, the right pest control, and the right tillage and soil management. We project that as the products, tools, technologies, and practices described above are further fine-tuned and developed, nutrient use efficiencies will be further optimized while maintaining soil health. In addition, specific critical losses will be further reduced.

Today, the public and a broad group of agricultural stakeholders have heightened expectations of farmers and the fertilizer industry when it comes to nutrient use. The linkage of nutrient loss to algal blooms, eutrophication, ammonia loss, and nitrous oxide emissions (a potent greenhouse gas)—as well as the increased media attention on these topics—has placed an increasing focus on reducing nutrient loss to the environment. While crop production systems are considered nonpoint source, and therefore not regulated by the US Environmental Protection Agency Clean Water Act, in the last decade some states have implemented policies aimed specifically at reducing nutrient loss.

Consumer-facing retail chains and brands in the food supply chain are increasingly engaged in driving practice change on the farm. In its infancy in 2006, Field to Market (whose mission is to unite the food supply chain to deliver sustainable outcomes for agriculture) now has more than 120 regular members representing farmer, agribusiness, and conservation interest but also consumer brands such as Kellogg's, General Mills, PepsiCo, and Coca Cola. Fertilizer decisions are still driven by production and economic performance on the farm, but environmental perspectives are now a key consideration as our mindset has evolved from one focused on nutrient use to one focused on nutrient stewardship.

As in many other aspects of agriculture, a more informed consumer base has the power to continue to drive practice change on the farm. Consequences of a changing climate will impact decision making as stakeholders grapple with associated risk. Also, given the time requirements to address environmental concerns, we'll likely feel the pressure to address water quality and nutrient loss issues for years to come. However, we are on the forefront of new technologies, scientific discovery, and data evaluation that can lead to future nutrient management breakthroughs. Projecting forward 75 years, it will be fascinating to see what roles will be played by artificial intelligence, big data, fertilizer technologies, and knowledge of the soil microbiome in the development of tools to address the variable nutrition needs of crops within and among fields, and in response to each year's weather.

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# 19

# Soil Biology Is Enhanced under Soil Conservation Management

*Robert J. Kremer and Kristen S. Veum*

Soil biology embodies a stunning array of soil-inhabiting organisms ranging from viruses and microorganisms to macroinvertebrates and burrowing mammals, encompassing their activities and inter-organismal relationships, resulting in an environment with likely the most complex biological communities on earth. The "soil microbiome" is defined as the characteristic microbial community occupying specified microhabitats with distinct physio-chemical properties. The soil microbiome represents both taxonomic and functional diversity that is mediated by individual members as well as the overall community. This perspective provides a framework for describing and understanding how soil biological relationships interact with conservation management.

Historically, soil conservation goals focused on modification of land use and management practices to protect the soil resource against physical loss by erosion or chemical deterioration and loss of fertility. With recent scientific advancements, the emphasis of current efforts has shifted toward microbiome interactions with soil physical and chemical processes, and how this important soil biological component is also prone to degradation by poor management. The primary objectives of this chapter are to (1) consider detrimental land management effects on the soil microbiome and essential biological processes, and (2) consider how biological functioning of the soil microbiome can be improved through application of soil conservation practices to reverse soil

**Robert J. Kremer** is a professor of soil microbiology in the School of Natural Resources, University of Missouri, Columbia, Missouri. **Kristen S. Veum** is a research soil scientist at the USDA Agricultural Research Service, Cropping Systems and Water Quality Research Unit, Columbia, Missouri.

degradation and improve soil health. In addition, this chapter will illustrate current research efforts to identify soil properties most affected by land use and management, especially those associated with soil organic matter (SOM) and the diversity of the soil microbiome, and how this knowledge is shaping our understanding of the interactions that drive biological activity and fueling interest in soil health assessment.

## The Microbiome and Soil Health

Soil health is an evolving concept and may be defined as the capacity of a living soil to function within ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health (Doran 2002). Coleman et al. (1998) emphasized the role of the soil microbiome by asserting that the health and balanced activity of *all groups of organisms within an ecosystem* is implicit and should be specifically noted as a component of soil health. Lehman et al. (2015) affirmed the importance of microbial diversity and activity as the basis for soil function because critical environmental services are driven by diverse soil biological communities. Optimal soil health requires a balance between soil functions for productivity, environmental quality, and plant and animal health—all of which are greatly affected by management and land use decisions. Albrecht (1967) noted decades ago the relationship between healthy food quality and soil management practices that encourage healthy soil microbial communities and, hence, a healthy soil.

## Historical Perspective

Soil biology as a principal concept in soil science was advanced in the early 20$^{th}$ century by Jacob Lipman and refined by Selman Waksman (1931), who described soils as complex systems sustaining microbial communities that influenced soil fertility and crop production. During the mid-20$^{th}$ century, Hans Jenny recognized the community of microorganisms as a critical component of the organism soil factor (one of the five soil forming factors) in his seminal book, *Factors of Soil Formation* (1941). He illustrated a scenario beginning with chemolithotrophic bacteria breaking down parent materials and releasing minerals; phototrophic bacteria and algae establishing on the developing soil matrix and forming organic matter; nitrogen accumulation by nitrogen-fixing bacteria; mycorrhizal fungi promoting plant growth and stabilizing the soil; and various meso- and macrofauna aiding soil structural development (Jenny 1980).

In the aftermath of the Dust Bowl (1935 to 1938), W.A. Albrecht, writing in the *1938 USDA Yearbook of Agriculture—Soils and Men*, proposed that soil degradation caused by intensive tillage and subsequent erosion led to depletion of SOM that exhausted the substrates required for soil microbial contributions to plant nutrition and soil structural stability. He emphasized the restoration of SOM through additions of green manure crops and livestock manures to stimulate soil microbial communities to release plant-available nutrients and to stabilize soil structure. This represents an early recognition of the importance of microbial ecology in soil conservation. Albrecht (1967) also indicated that plants as sources of fixed carbon (C) and microorganisms as decomposers and synthesizers of numerous organic compounds together create a dynamic living environment within a naturally conserved soil.

Early studies of SOM established that the soil organic carbon (SOC) pool supported biological activity, serving as the primary source of energy and nutrients for the soil microbiome, and that in turn the soil microbial community drove the process of SOM formation primarily via decomposition of organic substances entering the soil environment. The rate of decomposition was generally assumed to be constant; however, several intensive studies beginning around the mid-20th century recognized that the SOM pool consisted of a complex of recent inputs of easily metabolizable plant materials (labile or "young SOM"), a component of partially decomposed compounds of plant and microbial origin decaying at an intermediate rate, all of which were intermixed with resistant SOM decaying at very slow rates. Thus, decomposition of the diverse organic substances in soil was determined to follow first-order reaction processes rather than a zero rate or constant process (Jenkinson and Rayner 1977; Janssen 1984). Application of the revised decomposition principles to field studies showed that decay rates of labile SOM pools were strongly influenced by ecosystem differences (i.e., native prairie versus cultivated), such as soil disturbance, aeration, and moisture, establishing that conventional soil management resulted in SOM losses whereas no-till, which mimicked natural conditions, increased SOM content (Buyanovsky et al. 1987).

These early efforts formed our current understanding of the dynamics of decomposition and identification of SOC fractions and were important in future development of sensitive biological indicators of soil health for assessments of soil management. Examples of these soil health indicators currently in use include soil respiration, microbial biomass C, and the active C fraction of SOM (discussed below).

The importance of soil as the essential foundation for life on Earth and awareness that past degradation and erosion needed to be addressed through conservation management to restore the dynamic nature of soil garnered public attention in the latter quarter of the 20th century through popular outlets including the September of 1984 issue of *National Geographic*. This issue featured USDA Agricultural Research Service microbiologist Dr. John Doran describing his soil respiration measurements as useful indicators of biological activity that increased in a robust, healthy soil. The restoration of soils, including inherent, critical biological functions, continues to be a major concern today as their role in food, climate, and human security become more fully understood, as was featured in the highly regarded scientific journal *Science* (Amundson et al. 2015).

## Soil Biology and Soil Conservation Practices

The impact of soil organisms in soil structure modification, long recognized by farmers and described by Jenny (1980), was first conceptualized for soil aggregation within the last 40 years (Barrios 2007). Soil aggregates, microbially induced through cementation and binding of soil particles by bacteria and fungi with microbial metabolites (i.e., extracellular polysaccharides or biofilms) and occluded SOM, and enmeshment with fungal hyphae, provide microhabitats for microbiomes, which mediate many functional activities. Stable aggregation ensures long-term subsistence of microbial habitats while disruption of unstable soil aggregates disperses SOM exposing it to mineralization and suppresses microbial activity. Conservation management practices promoting aggregate formation include no-till, residue retention, cover cropping, diversified and extended crop rotations, and organic amendments. These practices stimulate biofilm-producing bacteria and mycorrhizal fungi to improve aggregate stability and are based on studies that strongly correlate stability with active microbial biomass, microbial enzyme activity, SOM content, active C content, and mycorrhizal fungal abundance (Veum et al. 2015).

Further, soils under conservation management exhibit more abundant and active microbial biomass, lower specific respiration, and reduce environmental stress on the microbiome relative to conventional systems (Islam and Weil 2000). This was confirmed over a decade later by research showing that fungal-based soil food webs of grasslands were more resistant and more adaptive to drought relative to bacterial-based food webs in intensively managed wheat (de Vries et al. 2012). Using applied soil food web analyses, Coleman (2011) noted that complex, diverse soil food webs were highly functional under zero and conservation tillage and suggested conservation practices are an essential component of effective soil food web management. Recent developments in defining the quality of SOM through fractionation of pools of SOC allow realistic assessments of the effects soil degradation and soil conservation practices have on the ability of soil to retain C for supporting a diverse soil microbiome. The active C pool consists of easily decomposable organic substances that, along with very labile soluble C compounds mainly originating from plant root exudates, provide readily accessible substrates for the microbiome and mineralizable nutrients (Islam and Weil 2000). Active C from decomposing residues, including dead microbial biomass, also influences soil structural stability but is readily depleted if such organic additions are reduced or subjected to intensive tillage. The understanding of the active C pool as a SOC component may better predict effects of practices such as crop residue management illustrated by recent findings that "unharvestable C" sources, or labile C, of maize crowns, roots, and root exudates contribute nearly twice the amount of C to SOC than aboveground stover residue (Wilts et al. 2004). Thus, maize harvest practices (grain and stover) have implications for source C contributions into SOC and may guide in determining stover biomass amounts for bioenergy production (Wilts et al. 2004).

Many formative studies have demonstrated direct relationships between soil biological measurements and conservation management including microbial biomass, soil enzyme activities, active C, and phospholipid fatty acid (PLFA) microbial community profiles, which has led to the recommendation of these measurements as sensitive and informative indicators for soil health assessments (Islam and Weil 2000; Acosta-Martinez et al. 2003; Kennedy and Papendick 1995).

## Future Developments for Conservation in Improving Soil Biology and Soil Function

Functional diversity and microbial activity play key roles in soil ecosystem dynamics, including resilience and stability, productivity, nutrient cycling, and other ecosystem services. Thus, microbial community structure may be relatively less important in soil health assessment than a knowledge and understanding of the functional attributes of the soil microbiome (Barrios 2007; Coleman 2011). However, techniques are constantly evolving, and our knowledge of and ability to interpret genetic information on the abundance and diversity of microbial species is rapidly expanding (Manter et al. 2017). Molecular techniques were effectively demonstrated in a regional study of microbial diversity in midwestern US tallgrass prairie soils by Fierer et al. (2013) who applied metagenomics to describe soil bacterial community abundance patterns and the relationship of taxonomic composition to functional gene categories (e.g., carbohydrate metabolism). This original study revealed previously unknown soil bacterial diversity and associated biological functions under the naturally conserved environments of the native prairie and also provided important information for reviving the soil microbiome for successful restoration or reconstruction of prairie ecosystems as a conservation practice. A more recent study using a high-throughput gene sequencing approach found that within the soils under long-term crop production (more than 52 years), crop rotation combined with no-till soil management yielded the highest bacterial diversity and functional capacity based on predicted gene abundances (Sengupta et al. 2020). Interestingly, a legacy effect from conversion of the original forested sites to agricultural fields was apparent in lost soil microbial functional potential. Overall, application of modern molecular techniques to assess soil microbiome composition and function provides critical information on the impact of agricultural land management and may become a valuable tool in assessing soil health.

Characterization of the soil microbiome directly in the field for real-time assessment of soil health and conservation management impacts using field-based genomics diagnostic tools will become a reality in the near future. Genes coding for the various processes, or functions, mediated by the soil microbiome will also be assessed using diagnostic tools and thereby aid in measuring the dynamics of soil functions, or the changes induced by management, which will lead to development of practices to improve soil health (Vogel et al. 2018). Ultimately the use of diagnostic tests to directly evaluate soil functional dynamics in response to disruption or degradation due to inadequate management will effectively identify research needs for a better understanding of the overall behavior of soil systems, their stability, and resilience (Vogel et al. 2018). Recent work with portable, small-scale DNA sequence platforms and new DNA enrichment methods results in identification of hundreds of bacterial identifications in food in less than two hours and will be potentially expressed as real-time data collection (Krych et al. 2019). This diagnostic approach is expected to become a modern standard molecular-based method with applications in many life science disciplines, including agriculture (Krych et al. 2019).

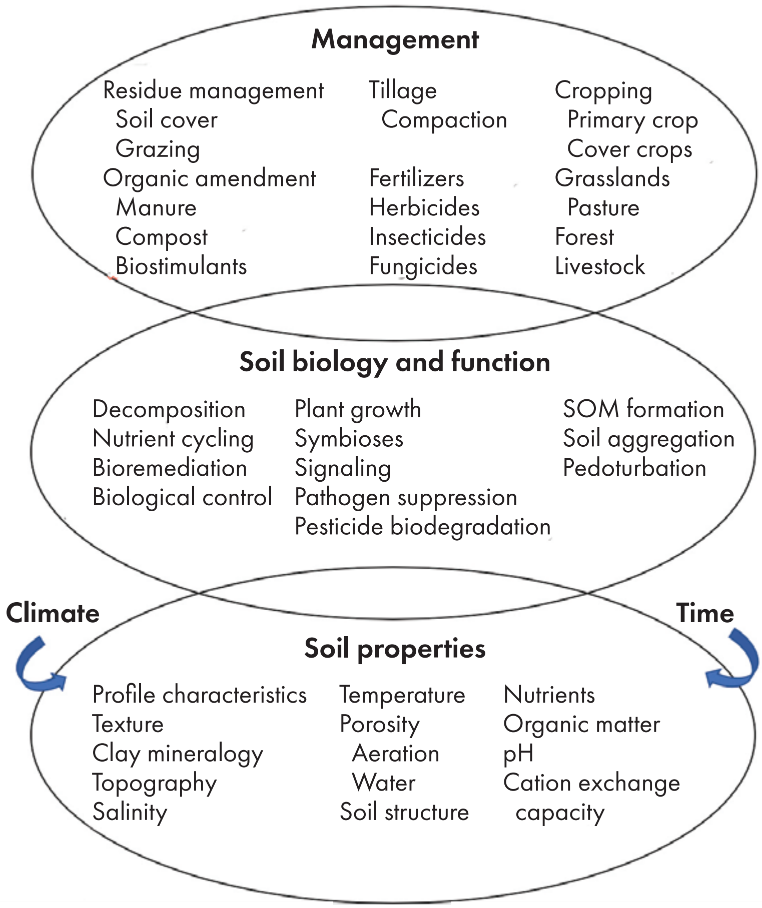
In addition, recent advances with in situ sensor technology outside the laboratory under farmers' field conditions are providing rapid, high-resolution data collection opportunities for soil health assessment (Veum et al. 2017, 2018). These tools, along with novel statistical approaches, offer the potential for real-time data collection with an environmentally relevant interpretation. Ultimately, taxonomic soil biodiversity paired with knowledge of microbial function and activity using laboratory or field techniques can provide a wealth of information on biological processes affected by conservation practices.

## Conclusions

Understanding soil biology in terms of structural and functional diversity suggests that management of the soil microbiome can lead to preservation of our soil resource and sustainably increase agricultural productivity. Taxonomic soil biodiversity paired with knowledge of microbial function and

**Figure 1**

**Conservation management practices and soil properties influence soil biology and function through simultaneous interactions within an ecosystem. Modified from Kennedy and Papendick (1995).**




activity provide a wealth of information on biological processes affected by conservation practices. Previous reviews established the link between management impacts on soil physical and chemical properties and subsequent changes in soil biology and function (figure 1 [Kennedy and Papendick 1995]). The current resurgence in the use of cover cropping, no-till, extended rotations, livestock integration, biostimulants, and organic amendments aid in management of the soil microbiome to promote soil biological activity and productivity. Advancements in development of tools and techniques for assessment of soil microbiome structure and function and other soil health indicators will guide future conservation management decisions that will ultimately lead to more resilient agriculture, a more stable food security, and improved environmental outcomes.

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# 20

# Soil Health: Evolution, Assessment, and Future Opportunities

*Douglas L. Karlen*

Seventy-five years have passed since the Soil and Water Conservation Society (SWCS), initially the Soil Conservation Society of America, was formed to advance the science and art of good land and water use. Many scientists and engineers have contributed to the SWCS mission and have planted seeds for current soil health endeavors. I define soil health holistically, reflecting soil biological, chemical, and physical property and process interactions, in response to inherent and/or anthropogenic forces. To some, soil health is a new concept, but I suggest it evolved slowly, reflecting SWCS endeavors like soil condition, soil management, soil protection, and soil quality. Recently soil health has been integrated not only into scientific and technical writings, but also in news articles, community discussions, and sustainability platforms of several large consumer-product companies. Focusing on soil health will improve soil management and decision making, and increase support for sustaining our fragile natural resources, including water quality and quantity, while simultaneously meeting increasing global food, feed, fiber, and fuel demand. Emerging developments in genomics and molecular-based characterization of the microbial community are beginning to unlock secrets of total soil organic matter (SOM). This knowledge, plus SWCS conservation advancements, provides an accomplishment truly worthy of celebration.

**Douglas L. Karlen** is retired from the USDA Agricultural Research Service and currently serves as a soil health and sustainable agriculture consultant with DLKarlen Consulting, LLC, St. Paul, Minnesota.

## Evolution of the Soil Health Concept

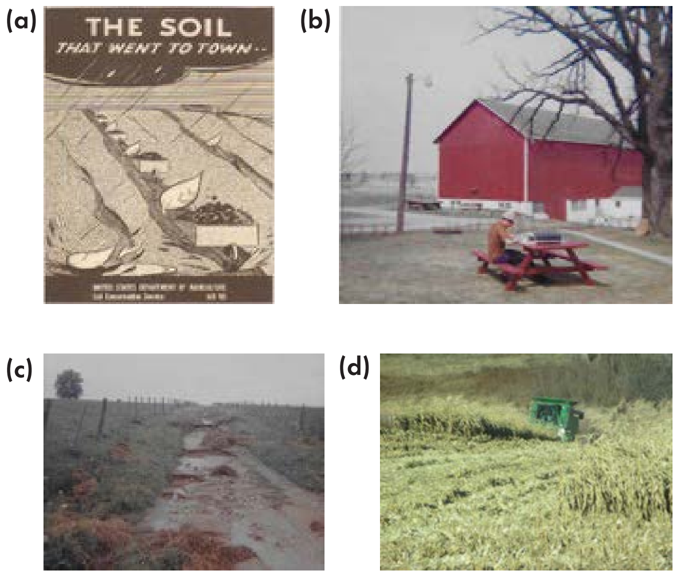
Soil health has become embedded in global technical and nontechnical writings during the first two decades of the 21st century. Some may regard the concept as new and unique, but I suggest the scientists, engineers, producers, conservationists, and policy makers who sustained the SWCS were the leaders who helped build better public awareness and concern for our fragile soil resources through what is now known and accepted as soil health. By defining soil health holistically, I envision that a combination of soil/water conservation and management efforts (i.e., water-, wind-, and tillage-induced soil erosion studies; concepts such as soil condition, tilth, productivity, quality, care, resilience, security, and degradation; and air or water assessments) have now made soil health a driver encouraging producers to recognize and adopt better soil and water conservation practices. Federal and state government, nongovernment organizations, foundations, institutes, college and university curricula, public-private partnerships, and numerous other entities have all embraced the soil health concept and thus embedded the term into the vernacular of many groups around the world. For those who have spent recent decades striving to encourage adoption of soil health principles, especially the US Department of Agriculture Natural Resources Conservation Service (USDA NRCS; see Chapter 21 by Fisher), global recognition and acceptance of soil health is gratifying, but I am confident that all who have contributed to soil health endeavors fully acknowledge our small and humble contributions were built on foundations provided by the SWCS and many others before us.

Having been significantly influenced by the SWCS throughout my career, I chose to personalize this chapter. My soil health journey was inspired by the SWCS and similar organizations who disseminated materials communicating soil and water conservation goals, not only to adults but also youth. As shown in figure 1, a USDA Soil Conservation Service (SCS) middle-school reading project (figure 1a), coupled with 4-H projects (figure 1b) examining on-farm soil erosion (figure 1c), ultimately led to a research career that provided many national and international opportunities to advocate for better conservation. This evolved into soil health and sustainable agriculture studies that included identifying inappropriate land use decisions that were unintentionally supported by crop insurance on land so steep a combine could barely climb the hill (figure 1d).

I credit the SWCS for the conservation inspiration that developed and sustained environmental awareness. My interest in science, coupled with a love for agriculture, led first to a bachelor's degree in soil science, followed by graduate research on soil fertility, plant nutrition, and water management interactions. Collectively, those events provided the foundation for my vision

**Figure 1**

**A personal collage reflecting my inspiration and perception of soil health.**




of soil health, which was further reinforced by SWCS leaders such as W.E. (Bill) Larson, who often described soil as "the thin layer covering the planet that stands between us and starvation" (Karlen et al. 2014a). Bill's quote parallels inspirational writings by two other soil conservation leaders whom I credit for indirectly helping formulate the soil health concept. The first is W.C. Lowdermilk (1953) who summarized his personal experiences in 1938 and 1939 in an often-reproduced publication entitled *Conquest of the Land through 7,000 Years*. This writing emphasized that human civilizations literally write their records on the land. Parallel to current soil health actions, Lowdermilk used his experiences to increase public awareness of soil erosion problems within the United States and around the world. I was also inspired by another influential soil scientist, Daniel Hillel (1991), who in his book, *Out of the Earth: Civilization and the Life of the Soil*, included a treatise that he states Plato had Critias proclaim:

> What now remains of the formerly rich land is like the skeleton of a sick man, with all the fat and soft earth having wasted away and only the bare framework remaining. Formerly, many of the mountains were arable. The plains that were full of rich soil are now marshes. Hills that were once covered with forests and produced abundant pasture now produce only

> food for bees. Once the land was enriched by yearly rains, which were not lost as they are now, by flowing from the bare land into the sea. The soil was deep, it absorbed and kept the water in the loamy soil, and the water that soaked into the hills fed springs and running streams everywhere. Now the abandoned shrines at spots where formerly there were springs attest that our description of the land is true.

Those inspirational writings, my small-farm roots, a love for diverse rural landscapes, and an admiration for conservationists like Hugh Hammond Bennett, as well as leaders such as Franklin Delano Roosevelt, who stated, "A nation that destroys its soils, destroys itself," were guiding principles that kept me focused on the SWCS goals of advancing the science and art of good land and water use for more than 40 years (figure 2). As a result, I connect soil health to "good land and water use" through a holistic definition of the concept that emphasizes interactions among soil biological, chemical, and physical properties and processes. Decisions regarding how we use or manage our fragile soil resources directly or indirectly influence water relations such as ponding, runoff, leaching, and availability to support plant growth and development. I also argue that neither soil health nor the SWCS mission should be considered new! Several years before the SWCS was formed, Keen (1931) wrote that the first recorded experiment on soil tilth (a precursor to soil quality and soil health endeavors) was published in a 1523 book entitled *Boke of Husbandry* by

**Figure 2**

**The author's (a) small-farm roots in Wisconsin and (b) the beauty of diverse rural landscapes led to (c) a soil and plant management career and (d) international opportunities to promote soil health.**

Fitzherbert. When describing how to sow peas and beans, Fitzherbert stated that the soil was not ready to be planted "if it synge or crye, or make any noise under thy fete" whereas "if it make no noyse and wyll beare thy horses, thane sowe in the name of God." Similarly, in a discussion about soils and their properties, Fream (1890) included the 17th-century quote, "Good tilth brings seeds, ill tilture weeds," which he attributed to Thomas Tusser.

As terminology for advancing the science and art of good land and water use evolved from soil tilth to soil quality to soil health, Karlen et al. (1990) reviewed several publications from the first seven decades of the 20th century. Those studies focused on soil tilth, structure, erosion, organic matter, tillage, crop rotation, and fertilizer management, and thus influenced evolution of my soil health perspectives. One of the most influential studies that laid groundwork for soil physical health was work by Yoder (1937). He concluded poor soil structure was a major problem because of its influence on granulation processes (aggregation); wetting, drying, freezing, and thawing cycles; organic matter accumulation and decomposition rates; biological activities; and plant root development, as well as tillage and crop rotation response. This was important for development of soil health assessments because it ultimately led to development of the "Yoder" water stable aggregate method that is currently being used for many assessment projects being led by the Soil Health Institute (SHI), Soil Health Partnership (SHP), and NRCS Soil Health Division (NRCS SHD). Wilson and Browning (1945) also emphasized soil aggregation and documented significant differences due to crop rotation. The importance of SOM and total nitrogen was documented by Whiteside and Smith (1941) as well as van Bavel and Schaller (1950). They and many others showed that soil erosion and crop rotation significantly affected SOM. They also concluded that gradual changes in soil productivity because of crop production and differences in the ability of crops to preserve, amend, or deplete soil resources have been documented since the beginning of agriculture.

It's not possible to fully acknowledge all of the research, laws, policies, or leaders in soil and water conservation that contributed to the scientific foundation upon which soil health has evolved. However, some key pioneers were Martin Alexander, Francis E. Allison, Hugh Hammond Bennett, Orville W. Bidwell, Francis D. Hole, Edward Hyams, Hans Jenny, Aldo Leopold, Thomas L. Lyon, Eldor A. Paul, Jerome I. Rodale, Robert S. Whitney, and Daniel H. Yaalon. Collectively, they improved our knowledge and understanding of how SOM, fertilizer, crop rotation, and tillage influenced numerous soil functions. Those studies provided the foundation for today's soil health movement, but the focus for most post-World War II studies was on soil physical and chemical properties and processes (i.e., soil chemical and physical health). This occurred, not because the importance of soil biology was being overlooked (Lyon et al. 1950), but due to very rapid advancements in machinery, fertilizer, weed, and insect control technologies. With regard to soil biology, Selma Waksman (known for discovering streptomycin) quantified SOM and nitrogen cycling by characterizing microbial decomposition of various plant components (Waksman and Hutchings 1935). He and colleagues also improved our understanding of how soil aggregates formed and were connected to microbial decomposition processes (Martin and Wakasman 1939, 1941). Those were important studies, but several decades passed before key biological advancements (e.g., understanding of DNA and development of modern instrumentation and methods of analysis) occurred. Thus, holistic soil health assessments were not feasible until soil biological, chemical, and physical health indicators could be combined and analyzed holistically.

## Soil Health Assessment

During the 1970s and 1980s, soil erosion and productivity (Pierce et al. 1983, 1984), as well as water quality and nonpoint pollution, were recognized as critical soil and water conservation issues. Protection of wetlands through USDA SCS participation in the Water Bank program and the need to provide incentives to landowners to protect wetland habitat, as well as increased authority to monitor and assess the nation's natural resource base through the National Resources Inventory began to create a need and focal point for future soil quality/soil health assessment studies. I argue that the same principles of soil and water management that influence erosion, productivity, runoff, leaching, or nutrient cycling are exactly the same as those that affect soil health. For example, during the mid-1970s, an increasing awareness that decreased use of crop rotations, increased size and weight of farm tractors and implements, as well as increased use of conservation tillage practices were having measurable soil tilth impacts began to spread throughout the northern Corn Belt (Voorhees 1979). I believe this research was also a precursor to what has become holistic soil health investigations.

Prior to the evolution of soil health assessment, the primary data evaluation techniques used to evaluate erosion control, soil fertility or tillage treatments, and other management practices were single factor (reductionist) analysis of variance (ANOVA) and/or multivariate regression analyses with a limited number of independent soil physical, chemical, and perhaps SOM measurements. Those studies provided information, but complexity associated with the emerging problems began to emphasize that soils were being called upon to simultaneously address multiple functions (i.e., food and fiber production, recreation, and recycling or assimilation of wastes or other by-products). This led Warkentin and Fletcher (1977) to introduce the concept of soil quality (soil health), which emphasized that (1) soil resources are constantly being evaluated for many different uses; (2) multiple stakeholder groups are concerned about soil resources; (3) society's priorities and demands on soil resources are changing; and (4) soil resource and land use decisions are made in a human or institutional context. Another soil and crop management challenge influencing SOM, erosion, and crop productivity during the 1980s was the suggested harvest of crop residues for off-site bioenergy generation (Karlen et al. 1984). Soil erosion and productivity questions associated with crop residue removal ultimately led to one of the first soil quality (soil health) studies, which focused on field experiments in southwestern Wisconsin where crop residues had been removed, doubled, or retained for 10 years (Karlen et al. 1994a) using no-tillage, chisel plow, or moldboard plow practices (Karlen et al. 1994b). Those two publications introduced an assessment framework that with major refinement became known as the Soil Management Assessment Framework (SMAF) (Andrews et al. 2004).

The exponential growth in soil health assessment during the past two decades is simply too broad to be thoroughly reviewed here. As expected, there are proponents and opponents of using either SMAF or the Comprehensive Assessment of Soil Health (CASH) to assess soil health. Nonetheless, as those tools continue to be improved and used to combine soil biological, chemical, and physical data into component or overall soil health indices, our integrated assessment of soil health will improve. With regard to SMAF, per se, the number of indicators it can accommodate has been expanded since its release in 2004 (Wienhold et al. 2009; Stott et al. 2010). SMAF has been used to effectively assess soil management scenarios in the United States (Stott et al. 2011; Karlen et al. 2014b; Veum et al. 2015b; Zobeck et al. 2015; Hammac et al. 2016; Ippolito et al. 2017), Spain (Fernandez-Ugale et al. 2009; Imaz et al. 2010; Apesteguía et al. 2017), and Brazil (Cherubin et al. 2016a, 2016b, 2016c). Furthermore, having contributed to the development of CASH, developers of the two tools continue to collaborate (Moebius-Clune et al. 2016; van Es and Karlen 2019) for the advancement of soil health assessment. For those interested in more detail regarding past, current, and future soil health uses, methods, and goals, please see the forthcoming two-volume Soil Science Society of America and Wiley International book series entitled *Approaches to Soil Health Analysis* and *Laboratory Methods for Soil Health Assessment* (Karlen et al. 2021).

## Scientific Advances Needed to Further Develop and Implement Soil Health Concepts

Research opportunities for science-based advancement of soil health assessment were recently reviewed by Karlen et al. (2019). Exponential growth in public interest and private support through the SHI, SHP, NRCS SHD, Foundation for Food and Agricultural Research (FFAR), and sustainability programs led by consumer-faced businesses, such as Walmart and Target, are providing new funding sources for many of those endeavors. This includes development of new tools and analytical techniques to improve soil and crop management. Those actions support my perception that holistic soil health activities are indeed helping to fulfill the SWCS mission of advancing the science and art of good land and water use. Therefore, I argue that improving soil health has emerged as one of the most effective conservation strategies for mitigating or even halting the global soil degradation that continues to occur through soil erosion, loss of SOM, and impaired water quality and quantities (Karlen and Rice 2015; Pandit et al. 2020).

Some infer that soil health is strictly an enhancement of soil biology. I disagree, although because of historical advances in soil chemical and physical properties and processes, new investments will likely have the greatest impact if focused on (1) improving our understanding of soil biology; (2) developing better in-field and remote-sensing data collection techniques; and (3) interpreting soil biological, chemical, and physical data more holistically. Techniques to help develop a better understanding of the soil microbial community include genomics and other molecular markers, such as phospholipid fatty acids, which are being actively pursued to ensure agricultural sustainability and optimization of all ecosystem services (Lehman et al. 2015). Research focused on the using soil enzyme activities to characterize soil microbial communities and provide soil biochemical health indices (Acosta-Martinez and Harmel 2006; Acosta-Martinez et al. 2017; Cano et al. 2018) should also be expanded. CASH and SMAF, too, should be expanded and improved using new and innovative data assessment techniques. Advancements in sampling and monitoring of soil health indicators are needed, perhaps by development and use of low-cost, in situ soil sensors (Karlen et al. 2019). This includes development of visible-near-infrared techniques to quantify soil organic carbon, total nitrogen, β-glucosidase activity, active carbon, microbial biomass carbon, particulate organic matter carbon, and soil respiration (Pietikäinen and Fritze 1995; Chang et al. 2001; Vasques et al. 2009; Kinoshita et al. 2012; Veum et al. 2015a; Cho et al. 2017). Sensors could also be used quantify apparent electroconductivity throughout the soil profile since those measurements can then be used to assess soil texture, mineralogy, cation exchange capacity, and water content simply by using different calibration techniques. Vertical penetrometers or mobile, horizontal sensors should continue to be improved so that penetration resistance (Sudduth et al. 2008; Hemmat and Adamchuk 2008) can be measured and used provide information on compaction and soil bulk density. Finally, these types of measured, in situ, and/or remote-sensed data should be combined and used to improve overall SMAF scores as well as individual chemical, biological, and physical soil health scores as already shown by Veum et al. (2017).

## Summary

This soil health overview commemorates the 75th anniversary of the SWCS. It also reflects my perception of the science that helped advance the concept exponentially during the past two decades. In contrast to more technical publications, I've included my personal experiences to reflect how the SWCS helped advance a career focused on the science and art of sustainable land, water, and crop management, integrated by the concept of soil health.

My perspective is that to provide meaningful and effective guidance for advancing soil and water conservation practices, science-based soil biological, chemical, and physical data must be collected, vetted, analyzed, and interpreted. Using a holistic soil health concept, assessment tools, such as the SMAF or CASH frameworks, will help meet those needs, but evolution of the concept is not finished. New and better techniques for measurement, data collection, and interpretation must continue to be developed. Understanding interactions among soil chemical and physical properties, biological communities, the environment, and human decision-making processes is essential to truly accomplish the SWCS mission.

## Acknowledgement

This article was written from a personal perspective that could only have evolved because of the inspiration and abundant support I received from my mentors, colleagues, and technical personnel throughout my career. There are too many to name individually, but to all, please accept my heartfelt thanks and gratitude for everything you have done to help protect "the thin layer covering the planet that stands between us and starvation."

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# 21

Practitioner's Perspective

# Building Resilient Cropping Systems with Soil Health Management

*Barry Fisher*

## Why Now?

Rebuilding soil health and function are the keys to achieving optimum productivity during extreme weather patterns, addressing environmental concerns, and narrowing profit margins. As agriculture technology, scale, and specialization have increased, production has also risen to levels unimaginable just a generation ago. However, costs of production have in many cases outpaced the gains in production, thereby reducing real income. Current production systems that are typical, across the United States and other countries, include limited crop diversity; extended fallow periods that leave soil bare and without living roots; and heavy reliance on physical, chemical, and biological disturbance. The unintended consequence of these activities has been reduced soil health and associated soil functions. Most farmers have grown accustomed to decreased soil function. For example, when we get an inch of rain overnight and see ponded fields or considerable runoff, we chalk it up to "crazy weather." Actually, most soils should be able to infiltrate an inch of rain water if soil aggregates were stable in water. Among farmers and research scientists there is typically consensus that soil function and soil health indicators such as water infiltration, water availability, nutrient and carbon (C) cycling, stability and support, aggregate stability, biodiversity, bulk density, and soil organic matter are important for yield as well as economic and environmental stability. We possess adequate knowledge and skill to improve soil function.

**Barry Fisher** is soil health specialist and central region team leader for the Soil Health Division of the USDA Natural Resources Conservation Service, Indianapolis, Indiana. He also operates a cash grain and livestock farm in west-central Indiana.

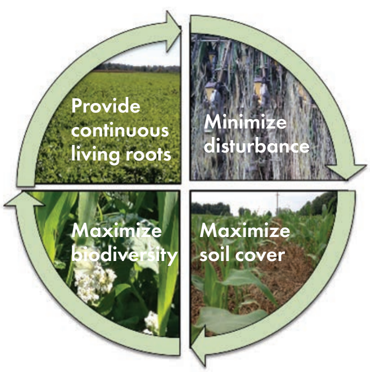
The question facing agriculture is whether the will exists to make the management changes necessary to achieve it.

## Soil Health—Are We All Talking about the Same Thing?

The US Department of Agriculture Natural Resources Conservation Service defines soil health as "the *continued capacity* of a soil to *function* as a vital, *living ecosystem* that sustains plants, animals, and humans." This definition contains some key words that carry important meaning. *Continued capacity* refers to the importance of resilience through time and extreme events. *Functions* inherent to soils are extremely important for production, environmental services, and habitat for soil life. Within the *living ecosystem*, billions of diverse organisms, when they have adequate habitat, are developing the foundation of a healthy, functioning soil.

**Figure 1**

**Soil health management principles. Image by Indiana Conservation Cropping Systems Initiative.**

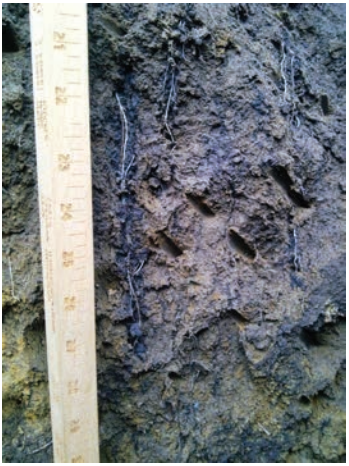



## Soil Health Management Principles

Production systems that are managed to improve habitat for soil organisms will be necessary to capitalize on the benefits obtained from the living ecosystem. Such production systems will require consideration of how each activity may affect the soil ecosystem. Remembering four principles will help with managing to improve soil health: minimize disturbance, maximize cover, maximize biodiversity, and maximize continuous living roots (figure 1). Minimizing disturbance and maximizing cover provide protection for soil aggregates and soil organisms from degradation by wind, rain, and extreme temperature. No-till farming can be effective for implementing these two principles and can significantly slow soil health degradation. However, to rebuild soil function, C capture needs to be maximized. Maximizing system biodiversity and the presence of living roots increase the quality and quantity of C entering and being stored in the soil to serve as energy for soil organisms. Biodiversity begins with the plants and animals that live on and in the soil. Plants capture the energy from the sun through photosynthesis. Some of that energy in the form

**Figure 2**

**Developing rhizosphere with continuous living roots. Photo by Barry Fisher.**



of carbohydrates is transferred to the animals that eat plant biomass and soil organisms that congregate along the living roots to feed on exudates that leak into the rhizosphere (figure 2).

## Adapting Systems for Soil Health Management

Building a soil health management system that is practical and successful for a specific region and enterprise requires understanding the adaptations necessary to achieve the soil health principles, while maintaining a profitable outcome. As tillage is reduced or eliminated, and soil cover, plant diversity, and the time live roots are present all increase, there will likely be a significant shift in the C, water, and nutrient cycles. Some of the management shifts needed to capitalize on these changes in cycling may not be intuitive to a producer moving from a full width tillage system. A step-in strategy will be needed to sustain production while building soil health. An example of a significant nutrient management adaptation involves the relationship between C and nitrogen (N). Studies have shown (Das et al. 1993) that plants obtain over half of their N from biological cycling in the soil rather than fertilizer-derived N. Under a full width tillage system, the tillage injects a dose of oxygen and exposes soil organic matter. The bacteria population explodes, respires carbon dioxide, and dies quickly, so the soil-supplied N releases in an early burst. Changing from spring full width tillage to no-till changes soil populations high in bacteria to more organisms with longer life cycles. These organisms, as well as cover crops, can tie up (immobilize) most of the available soil N early in the growing season. As soil disturbance decreases and organic matter pools stabilize, less N is available early in the season but more available later as organisms live and respire longer into the season resulting in gradual N release. This is a major change in the delivery of over half of the total N that a corn crop will use. It can have a significant effect on corn yield if timing, placement, and source of N aren't adapted to complement this transition. Some early work in the 1990s by Martens (2001) and adaptations common to successful early adopting farmers suggest that applying a higher portion of the planned N at planting time (usually as starter fertilizer injected 5 to 10 cm [2 to 4 in] beside the seed row) and using a source with nitrate, such as urea ammonium nitrate (UAN), is important to complement the changes in N and C cycles.

As cover crops are integrated into these systems, knowledge of biology and chemistry becomes necessary. Cover crop species have inherent differences in the amount of N that is stored in the tissues and thus differences in the ratio of C to N (C:N). Understanding these differences helps to optimize selection and management of cover crop species to complement the cash crop rotation. The higher the C:N, the more likely soil N will be immobilized. Therefore, a high C:N cover crop such as cereal rye is a better fit preceding a legume cash crop like soybeans. Managing for seeding windows that allow for earlier establishment of cover crop species with lower C:N ratios, such as legumes, annual ryegrass, or vegetative-stage terminated cover crop mixes, is a useful strategy ahead of grass crops like corn. By using insights like these, we can find more logical starting points and practices to initiate soil improvement.

## A Farmer Transition Scenario

The following is an abbreviated example of a "step-in" scenario for a simple corn–soybean (C–SB) rotation, summarized from successful operations across the Midwest and the scientific logic from above. Start by guarding against compaction and effectively spreading crop residues evenly during corn harvest. No-till (NT) plant a cereal rye cover crop (CC) into corn stalks. It's easy to establish and easy to kill. This is the first NT operation. Next spring, NT a relatively early maturity soybean into the cereal rye; try to plant these beans early in the planting season. Early group soybeans benefit from early planting and provide a wider window to seed a favorable CC mix next fall. This is the second NT operation, and soybeans do well in higher C:N cover crops like cereal rye. Next, plant a low C:N CC mix after SB. Cover crops prior to corn should trap or produce N in the fall and early spring but release N at the optimum time in the spring/summer. Corn does well into a mix such as oats/daikon radish that winter kills or annual ryegrass/crimson clover that release the N closer to the time of greatest need. This becomes the third NT operation. Finally, NT corn into the low C:N mix the following spring. This is the fourth NT operation. By now, diverse soil biological populations and processes are well on their way. Soil aggregates are stabilizing, and pores are opening. Water infiltration and holding capacity are on the rise. Nutrients are cycling and accessible from alternate pathways. By now, you've had a full season to update your planter and attend some good soil health workshops. The result is great production potential!

Certainly, this isn't the only scenario for steps to transition, and management will need to be adaptive to seasonal conditions; however, it shows

**Figure 3**

**Four principles of soil health supporting a living ecosystem. Photo by Barry Fisher.**

the importance of having a logical process. Transition is possible without a production penalty. Numerous farmer case studies offer evidence on many soil health management systems with sound principles that provide production efficiency and higher profitability (figure 3).

This is just one scenario, compiled from practical strategies that are employed by successful farmers who use soil health management systems to continually improve soil function. Across the country, these soil health strategists are forming and joining networks with like-minded farmers, specialists, and researchers. They meet or talk regularly in farmer shops or on social media to accelerate the understanding of soil ecosystems and share breakthroughs, new practices, and technologies for soil improvement. Most are utilizing new soil health tests to monitor progress. The technology available to today's farmer makes them a very viable partner for research projects. The opportunity for the research community is to continually reset the foundation for soil health research on the management plane where top soil health farmers have already landed. Researching these dynamically managed systems won't be easy, but necessary, to help solve problems, quantify benefits, and assist with broader adoption. The time is now to capture the potential of soil health!

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# 22

# Climate Change, Greenhouse Gas Emissions, and Carbon Sequestration: Challenges and Solutions for Natural Resources Conservation through Time

*Jean L. Steiner and Ann Marie Fortuna*

## Climate and Conservation Prior to 1945

Climate and land management are recognized as key drivers affecting soil and water conservation practices that maintain or enhance the capacity of land to withstand erosion or degradation (Delgado et al. 2011; Gantzer 2020; Lal 2020). Since recorded time, people have adapted to climate and climate change by developing innovative concepts and technologies that benefited past and present societies (Butzer and Endfield 2012). Stable climatic periods and the expansion of humanity's collective knowledge have led to stationary societies that are dependent on management of agriculture, forests, and other natural resources (Butzer and Endfield 2012). These factors in most instances have led to the expansion of our intellectual, cultural, and economic opportunities. However, humanity's ability to control the environment has also at times led to poor land management that has reduced or harmed the natural resource base and resulted in historic environmental and ecological disasters. Drought and erosion led to or contributed to societal instability and mass relocation of large numbers of individuals many times throughout history. For

**Jean L. Steiner** is an adjunct professor at Kansas State University, Manhattan, Kansas. **Ann Marie Fortuna** is a soil biologist at the Grazinglands Research Laboratory, USDA Agricultural Research Service, El Reno, Oklahoma.

example, Mesopotamia, one of the first empires of human history circa 4500 BC; the end of the classic Mayan period (800 to 1000 AD); and, more recently, the Dust Bowl of the 1930s in the United States all resulted in environmental and social devastation.

The effects of the atmosphere on climate, particularly concentration of carbon dioxide ($CO_2$), have been studied and related to Earth's temperature by physical and climatic scientists since the 1800s. The potential for atmospheric concentrations of gases to increase Earth's temperature was dubbed the "greenhouse" effect by Joseph Fourier. Fourier (1824) postulated that the earth's temperature was determined by the amount of heat absorbed from the sun and trapped by the atmosphere. He described the atmospheric effect as similar to sunlight passing through the glass of a greenhouse which retained the heat, and he theorized that the concentration of gases in the atmosphere was related to this effect. The greenhouse gas effect was quantified by Arrhenius (1896) who identified arithmetic increase in Earth's temperature with geometric increases in $CO_2$ in the atmosphere. Despite the existence of this knowledge base in the physical and atmospheric sciences, the concepts were not widely known outside of these scientific communities. As industrialization led to the development of mechanized equipment with associated greenhouse gas emissions, agriculturalists and conservationists did not understand the link between the use of fossil fuels and emissions that contributed to warming in the atmosphere.

The Dust Bowl in the US Great Plains resulted from poor land management throughout the first two decades of the 20$^{th}$ century coupled with severe drought (Bennett et al. 1936). As the magnitude of the Dust Bowl became obvious, the Roosevelt administration established the US Great Plains Committee. Their report, entitled "The Future of the Great Plains," described how crop and livestock management, "modern equipment" costs, expansion of farm size, and absentee land ownership beginning in the early part of the 1900s played a greater role in the Dust Bowl disaster than the severe drought conditions themselves. Climatic variation, in contrast, was considered to be inevitable and beyond the scope of human intervention (Bennett et al. 1936). The committee's recommendations included, but were not limited to, soil erosion control, water conservation, and conservation education as well as economic investments, zoning, providing grants, and relocation of displaced persons. Additionally, by the 1930s, cropland in the humid southeastern United States had suffered decades of massive soil degradation by water erosion. These dramatic losses of soil to wind and water erosion led to recognition of the serious challenges erosion posed to the US agricultural and natural resource base.

The US Department of Agriculture (USDA) Soil Conservation Service (SCS) was established in 1935. During the early years of the conservation movement, erosion control on cropland received more abundant resources than erosion control on rangeland and grasslands. Similarly, erosion related to intense precipitation received greater scientific and policy attention than erosion related to intense winds. At the time of the establishment of US soil and water conservation programs, land managers, the public, and soil scientists viewed climate as a stationary process, where the climate of the past provided a basis for projecting future climate for a region.

## Progress to Present

***Milestones 1945 to Present.*** Gaps in knowledge and technology prevented most scientists and land managers in the early part of the 20th century from understanding the mechanisms behind the cycling of elements and energy between land, air, and water systems. This limited their ability to design experiments of sufficient complexity to understand what factors and interactions lead to climatic change. Infrastructure for data collection and minimal communication among disciplines was also limiting. Public interest and support of conservation policies, programming, and research were in their infancy. When the USDA Agricultural Research Service (ARS) was established in 1953, ongoing soil and water conservation research was transferred from SCS to ARS. Through the early years, when ARS quantified erosion processes and developed erosion prediction models (Flanagan 2020), climate was viewed as stationary, and climate factors in the models were calculated based on statistical properties of historic climate records.

Establishment of the long-term $CO_2$ monitoring station at Moana Loa, Hawaii, in 1956 by Charles Keeling (Keeling et al. 2001) was a seminal step toward widespread recognition of the increasing $CO_2$ concentrations in the earth's atmosphere and growing recognition of the risks of future climate change associated with increasing greenhouse gas concentrations. The findings from Keeling and colleagues were one key factor that led to establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1988 to access scientific, technical, and socioeconomic aspects of climate change, its potential effects, and options for adaptation and mitigation. Throughout the 20th century there was growing recognition of serious challenges of human-caused climate change, which require major efforts in adaptation and mitigation.

In the second half of the 20th century, major environmental laws were enacted, which resulted in paradigm shifts in conservation management and support for the creation of networks for the collection of environmental variables descriptive of soil, vegetation, water, climate, and species. The Clean

Water Act (CWA), initially enacted in 1948, focused primarily on discharge of industrial and sewage waste into open waters. It was revised in 1972 to include surface water quality standards. The Clean Air Act of 1963 regulates air quality at the federal level via the US Environmental Protection Agency (EPA). Similar to the CWA, the EPA works through state and local agencies to monitor and enforce the regulatory standards. Conservation priorities broadened with enforcement of these environmental laws that extended the natural resources of concern to include soil, water, air, wetlands, biodiversity, and endangered species (Gantzer et al. 2020). This shift in focus was reflected in the name change of the USDA SCS to the USDA Natural Resources Conservation Service as well as the name change of the Soil Conservation Society of America to the Soil and Water Conservation Society (SWCS).

Throughout the mid-20$^{th}$ century to present, diverse conservation practices were developed and implemented, including structural practices, such as terraces, grassed waterways, and flood retarding structures; and agronomic practices, such as improved crop varieties and crop rotations, conservation tillage, nutrient management, more efficient irrigation, and soil health management, which involves the assessment of inherent and dynamic soil properties serving as indicators of soil function (Fox 2020; Delgado 2020). In recent decades, there has been increased recognition of the role of soil biology in maintaining the functions of hydrologic regulation, nutrient retention, filtration, buffering, degradation of organic and inorganic materials, and carbon (C) sequestration, leading to a "soil health" movement in agriculture. As the scope of conservation programs broadened and understanding of climate change increased, research programs in USDA evolved to a more systems research approach to understanding interconnected processes that impact mitigation of and adaptation to climate change to sustain agriculture, forestry, and the natural resource base (Kremer and Veum 2020; Karlen 2020; Fisher 2020).

The US Global Change Research Program was established in 1989 by a presidential initiative, followed by passage of the Global Change Research Act of 1990, which mandated that National Climate Assessments be delivered to Congress at intervals no longer than four years. Four National Assessments have evaluated climate projections, potential impacts for key sectors and regions of the United States, as well as adaptation and mitigation options (USGCRP 2018). Since then, the scientific community has applied a variety of models to evaluate soil and water processes, crop growth and management, rangelands, and watershed-scale hydrologic processes (Flanagan 2020) in order to evaluate management impacts and options. In the meteorological community, national databases of climate were developed that were applied using stochastic approaches to evaluate climate impacts on a wide range of land management and conservation practices. However, as the climate community produced ever-improving models of the global climate system, the magnitude of climate change and impacts became clearer. Specifically, simulations of land use and management and conservation practices under future climate scenarios have highlighted the serious risks to the sustainability of our food production systems and natural resource base. Increasing computational capacity with the advent of computer applications and digital imaging have enabled researchers to improve understanding of environmental services from the land on scales ranging from a soil pedon to landscapes, from genomics to ecosystems, and from in situ gas measurements to global climate processes. The new knowledge base and technology have enabled researchers to capture the transient nature of climate and to link climatic effects to land management and plant growth and on a regional and global scale.

The SWCS has undertaken a number of special projects and communication efforts that relate to climate change at the local chapter to international levels. The outcome of these efforts culminated in reports that highlighted increased risk to soil and water conservation for cropland (SWCS 2003) and a need for better understanding of and tools to deliver conservation in an age of intensification of precipitation and increased concentrated flow across the landscape (SWCS 2007).

***Lessons Learned.*** As we moved from the 20th century into the 21st century, it became increasingly clear that we are in the midst of a changing climate. The onset of climate change has been more rapid than projected and the societal impacts more severe. This poses a challenge to accelerate efforts to develop robust new technologies and to take a systems approach to avoid unintended consequences of solutions to one problem giving rise to the next, often greater, problem. It also places a burden on practitioners to stay abreast of new understanding and technologies as they respond to immediate needs for conservation on the land. Because of the large contrasts in climate and vulnerabilities of agricultural and forestry systems across the United States, the USDA established Regional Climate Hubs in 2013 to identify critical regional vulnerabilities and impacts and to foster effective communications and partnerships to promote adaptation and mitigation strategies, practices, and technologies. The Climate Hubs have demonstrated enhanced communication within USDA; with other federal, state, and local agencies; and most importantly, across stakeholder, practitioner, and researcher networks.

## Plans for the Future

Climate change is ongoing and complex within an inherently dynamic system. Agricultural and forest systems dominated by human intervention are equally complex and dynamic, spanning from the natural resource base to production enterprises to the human dimensions of food security and rural community sustainability. There are large economic, ecological, and social risks of vulnerable agricultural, forestry, and natural ecosystems exposed to climate stressors. Therefore, it is essential to develop new knowledge and technologies for adaptation at multiple scales of agricultural and forest systems and strategies to improve resilience of the systems themselves and the people dependent on them.

Adaptation is defined by the IPCC as the process of adjustment to actual or expected climate and its effects. In human systems, including agriculture, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, such as forestry or rangelands, human intervention may also reduce emissions of greenhouse gases, thereby mitigating against future intensification of climate change. Adaptation requires an understanding of climate effects, but also the capacity to resist or become more resilient to change or to transition. At some level of stress, the existing agricultural or forestry or rangeland system may become so maladapted to the prevailing conditions that transition to a different system is required. For annual crops, this may be reasonably straightforward. However, for forestry and rangelands, the long-lived, perennial species cannot easily migrate to other regions nor can new species be easily introduced. Many practices, technologies, and strategies for an agricultural or forestry system to respond to climate stresses will have both adaptation and mitigation elements, and should be approached in an integrated manner following climate smart agriculture principles (Mann et al. 2009).

The agricultural sector contributes to greenhouse gas emissions, particularly nitrous oxides associated with fertilization of crops and methane associated with ruminant livestock production and manure management. Additionally, the long history of cultivation and erosion have resulted in large amounts of soil C being emitted to the atmosphere over the centuries. However, because agriculture is based on primary production whereby plants fix $CO_2$ from the atmosphere into carbohydrates, the building blocks of plant and animal life, there is a large potential for agriculture to mitigate greenhouse gas emissions by sequestering C in soils and plants, particularly perennial plants or plants that are harvested as a renewable energy source.

***Future Research Questions and Technology Needs.*** The SWCS Board of Directors adopted a position paper in 2011 stating that climate change poses a formidable challenge to food security and the environment, and that soil and water conservation could play a large role in mitigating and adapting to climate change (SWCS 2011). The position paper focused on increasing soil C, maintaining soil cover, cultivating perennial bioenergy crops, adopting agroforestry practices as buffers, targeting conservation to sensitive areas of the landscape, and increasing the efficiency of crop production inputs. Moorberg (2020) recently published an annotated bibliography about these and other conservation practices that may provide adaptation or mitigation benefits for a wide range of land uses. Because of the complex, interactive processes involved in soil, water, and biodiversity conservation, all of which are impacted by a changing climate, support for diverse, robust science and technology development is critical in several areas, including basic research in genetic and biogeochemical processes, applied science and technology development and delivery, integrated landscape-scale and systems-level research, the human dimension of soil and water conservation in an age of climate change, and knowledge science (table 1).

***Goals.*** In the face of climate change, action is needed now. It is important to develop clear and focused goals so that actions and investments can have the greatest impacts on mitigating climate change risks and helping individuals and communities adapt to the changing conditions. The goals delineated in table 2 will require considerable public, private, and government support to move in the right direction.

***Opportunities.*** While the challenges are daunting, there are many opportunities to accelerate our response to the changing climate to reduce future risks. With the imperative to stabilize and then reverse greenhouse gas concentrations in the atmosphere, there are opportunities for mitigation on agricultural and forestry landscapes by applying an integrative systems approach to land management and conservation that recognizes the multiple objectives and benefits needed from working landscapes (Shukla et al. 2019). In science and technology development, there are exciting new frontiers in genetics and knowledge science that can accelerate development of robust crop materials, more efficient agronomic inputs, better risk assessment, and improved models and forecasts to guide decision making. For practitioners, there is great potential in tapping entrepreneurial opportunities in consulting and marketing that will come with evolving environmental markets and climate-smart conservation technologies. For policymakers, there is opportunity to embrace the power of environmental markets and climate-smart incentives and the need to address environmental justice issues whereby the most vulnerable are most impacted by the changing climate, both in the United States and globally. As these challenges are addressed, there is a pressing need for SWCS

**Table 1**

**Research and technology needs to advance the art and science of soil and water conservation.**

| Areas of research | Research and technology needs |
| --- | --- |
| Basic research to improve understanding of genetic and biogeochemical processes | • Support research on genomics through applied breeding to develop plant and animal germplasm, varieties, and breeds with heat, cold, drought, flooding, and pest tolerance, to enhance primary productivity.<br>• Develop better understanding of soil health and rhizosphere processes. |
| Applied science and technology development and delivery | • Develop and deliver improved technologies to promote efficient use of water of varying quality and assessments of policy option impacts.<br>• Support engineering research to improve systems, processes, and measurement capacity, including realizing the potential of unmanned aerial vehicles, remote sensing, and other high spatial-temporal data from multiple sources.<br>• Develop and implement technological infrastructure and institutions to use big data from drones and remote sensing for adaptation research.<br>• Develop systems that promote soil health and soil carbon sequestration on working lands. |
| Integrated, landscape-scale or systems-level science | • Improve understanding of how ecosystems respond to and recover from extreme events and provide education and outreach to enhance adaptive capacity.<br>• Support landscape-scale and systems-level research to discern tradeoffs and better optimize agroecosystems to changing climates, including knowledge to guide transformational change when existing systems cannot be sustained under new climate conditions.<br>• Develop methods for valuation of noncommodity ecosystem services.<br>• Evaluate interactive effects of nonclimate and climate stressors on ecosystem responses. |

| | |
|---|---|
| The human dimension | • Develop improved understanding of and methods to increase adaptive capacity in the social, ecological, and economic realms and deliver programs to enhance adaptive capacity.<br>• Conduct cost-benefit analyses of adaptation and mitigation practices and develop improved tools for life cycle analyses of agricultural systems under contrasting management, economic, policy, and climate scenarios.<br>• Describe the effects of risk tolerance and barriers to adoption of practices and develop education and outreach programs to overcome barriers.<br>• Use behavioral science approaches to understand and support adoption of new practices.<br>• Apply behavioral sciences to support stakeholder/community engagement and participatory science. |
| Data to information to knowledge science | • Across all sectors, there is a need for improved decision support models and planning tools. Different users will have different specific requirements, but with the level of uncertainty about climate and the multiple objectives of various users, such tools can support dialog and consensus building about possible options. |

**Table 2**

**Actions needed now to secure the soil, water, and biodiversity resource base into the future.**

| **Goals** | |
|---|---|
| For protection of the environment | • Stabilize and then reverse greenhouse gas concentrations in the atmosphere.<br>• Mitigation practices to build soil health and sequester carbon in soils and working landscapes.<br>• Mitigation practices to help species and ecosystems adapt to changing climate.<br>• Structural and operational mitigation of sensitive infrastructure. |

| | |
|---|---|
| For science, research, and technology | • Public support for science.<br>• Better understanding of soil biological, chemical, and physical interactions.<br>• Continued improvement in global climate models, adaptation models, and decision support systems.<br>• Better understanding of ecosystem response to changing climate. |
| For practitioners | • Translation of science to real-world land management applications.<br>• Interdisciplinary teams equipped with state-of-the-art communication tools.<br>• Training and life-long learning opportunities. |
| For policymakers | • Translation of science to real-world policy applications.<br>• Incentives that promote climate smart technologies and systems, and disincentives for technologies and systems that accelerate climate change.<br>• Risk management instruments and safety net programs to support individuals and communities impacted by climate change. |
| For the public | • Literacy about climate, soils, water, and other natural resources.<br>• Affordable, climate-smart products and services.<br>• Structural and operational mitigation of sensitive infrastructure.<br>• Support for adaptation and access to safety net programs. |

to continue to lead in the art and science of conservation, to provide venues to bring together diverse groups to tackle tough issues, and to educate and advocate for conservation of the natural resource base, which we will leave to our future generations.

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## Resources to Learn More

- History of Research at the US Department of Agriculture and Agricultural Research Service. https://www.ars.usda.gov/oc/timeline/about/
- More Than 80 Years Helping People Help the Land: A Brief History of NRCS. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/about/history/?cid=nrcs143_021392
- USDA Climate Hubs. https://www.climatehubs.usda.gov/
- US Department of Commerce, National Oceanic and Atmospheric Administration NOAA Research, Earth System Research Laboratory Global Monitoring Division. https://www.esrl.noaa.gov/gmd/obop/mlo/webmuseum/timeline/1956dedicationofmlo.html

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# 23

# Conserving Soil and Water to Sequester Carbon and Mitigate Global Warming

*Rattan Lal*

Soil degradation by erosion strongly perturbs the global carbon (C) cycle (Lal 2003) and reduces crop yield and productivity (Gomiero 2016). Thus, a better understanding of the processes governing the distribution and fate of soil organic C (SOC) transported by erosional processes is needed to credibly and objectively assess the impact of accelerated erosion on the C budget at local, regional, and global scales. Water erosion is a selective process involving a preferential removal of clay and SOC contents (Shi and Schulin 2018; Billings et al. 2019). Therefore, the impact of erosion on redistribution, mineralization, and burial of SOC at the global scale must be evaluated to credibly assess its impacts as a source or sink of atmospheric carbon dioxide ($CO_2$).

Soil erosion by water is a four-stage process: detachment, transport, redistribution, and deposition (Lal et al. 2004). Particle detachment is caused by the shearing force of the impacting raindrops, shallow overland flow, and interaction between them. Detached particles, along with SOC and particulate organic C (POC), are transported and redistributed over the landscape. Depending on the micro and macro-relief and the slope gradient, deposition of the sediment occurs following the Stokes' Law. The magnitude of soil erosion depends on climate erosivity, soil erodibility, slope (gradient, length, and shape), management (tillage, crop, and cropping system), and conservation practice (terraces, etc.) (Wischmeier and Smith 1978). Decline in SOC content

**Rattan Lal** is a distinguished university professor of soil science and is the director of the Carbon Management and Sequestration Center, The Ohio State University, Columbus, Ohio.

can increase water runoff and erosion (Fullen 1991), partly due to an increase in soil dispersion (Watts and Dexter 1998) and an attendant increase in erodibility (Wischmeier and Smith 1978).

Accelerated soil erosion destabilizes SOC (Bailey et al. 2019) through disruption of soil aggregates by climatic erosivity, and exposure of the hitherto encapsulated SOC to microbial processes (Lal et al. 2004). Among several mechanisms of destabilization of SOC, release from biophysical occlusion (Bailey et al. 2019) by erosion-induced disruption of aggregates can impact the global carbon cycle (GCC) . Because soil erosion displaces a large amount of SOC, as POC and/or mineral associated C (MOC), it is an important pathway affecting the GCC, leading to on-site and off-site impacts. On-site, it depletes SOC content and plant nutrients (i.e., nitrogen [N], phosphorus [P], sulfur [S], and potassium [K]), truncates the surface horizon, reduces water storage in the root zone, degrades soil structure by slaking and breakdown of aggregates, and aggravates crusting and surface sealing. Off-site, at depositional locations, erosion leads to run-on of water and agrochemicals, inundation, and burial of seedlings, increase in SOC content, and emission of greenhouse gases (GHGs). Similar trends are observed in wind erosion processes (Lal 2020).

The fate of SOC transported by erosional processes must be understood to assess its net effect as a source or sink of GHGs. Whereas the eroding site is progressively depleted of its SOC content, the depressional site where sediments are deposited is enriched. In northeastern China, for example, depositional sites store 5.9 times more SOC than eroding sites and 3.3 times more than the noneroding sites (Li et al. 2019).

The objectives of this article are to (1) deliberate the fate of SOC transported by erosional processes, and the attendant emission of GHGs; (2) discuss if erosion is a source or sink of atmospheric $CO_2$; and (3) explain the importance of soil conservation to sequestration of atmospheric $CO_2$ and adaptation/mitigation of climate change. The discussion is based on the following three hypotheses: (1) the SOC redistributed over the landscape, including that stored in transient depressional sites, is prone to decomposition, methanogenesis, and nitrification/denitrification leading to enhanced emission of GHGs; (2) even a fraction of SOC transported into streams, reservoirs, lakes, and ocean and buried under anoxic conditions is prone to decomposition, and may be sequestered over a long period of time; and (3) adoption of conservation-effective measures sequesters atmospheric $CO_2$ and mitigates global warming.

## Carbon Enrichment Ratio

Being the light fraction of low density and concentrated in vicinity of the surface layer, SOC/POC fractions are preferentially removed by erosional processes. Thus, the SOC enrichment ratio ($ER_{SOC}$) of the transported sediment increases vis-à-vis the SOC concentration of the uneroded soil (Lal 1976). The $ER_{SOC}$ can be as much as 40 for wind-blown sediments (Webb et al. 2013), and 4 or 5 for water-deposited sediments (table 1) (Wang et al. 2014; Nachimuthu and Hulugalle 2016).

The magnitude of $ER_{SOC}$ is affected by several factors (i.e., erosivity of rain or wind, time of sampling during the event, slope gradient and length, and sediment load). On the basis of data from a long-term repeated field rainfall simulation experiment, Hu et al. (2013) observed that $ER_{SOC}$ in sediment increased at first, peaked at a time when steady-state runoff was achieved, and declined

**Table 1**

**Enrichment ratio of sediment for soil carbon.**

| Type | Enrichment ratio | Location | Country | Land use | Reference |
|---|---|---|---|---|---|
| Wind | 0.6 to 1.9 | Washington State | United States | Summer fallow | Sharratt et al. (2018) |
| | 0.85 to 1.21 | Loess Plateau | China | Laboratory simulation | Li et al. (2016) |
| | 1.28, 14.35, 3.07, 17.63, 9.27 | Queensland | Australia | Field measurement | Webb et al. (2013) |
| Water | 0.61 to 2.13 | Cropland | China | Field rainfall simulation | Nie et al. (2015) |
| | 1.3 to 4.0 | South Limburg | Netherlands | Rainfall simulation | Wang et al. (2014) |
| | 3.1 | Rangelands | Argentina | Rainfall simulation | Chartier et al. (2013) |
| | 1.2 to 3.0 | Loess | Belgium | Rainfall simulation | Wang et al. (2010) |
| | 0.9 to 2.6 | Maarkedel | Belgium | Laboratory | Schiettecatte et al. (2008a, 2008b) |
| | >2 | Hyderabad | India | Watershed | Cogle et al. (2002) |
| | >1 for slope of >3% | Queensland | Australia | Rainfall simulation | Palis et al. (1997) |
| | 0.39 to 5.0 | New South Wales | Australia | Agriculture | Nachimuthu and Hulugalle (2016) |

afterwards. Temporal changes in $ER_{SOC}$ depend on the formation of crust, which must be duly considered in both water and wind erosion. The $ER_{SOC}$ also decreases with increase in sediment concentration (Wang et al. 2013), climate erosivity (Martínez-Mena et al. 2012), the degree of aggregation of sediment (Schiettecatte et al. 2008a, 2008b), and slope gradient (Palis et al. 1997). Wang et al. (2014) observed that erosion, transport, and deposition enhanced $ER_{SOC}$ from 1.3 to 4.0 because of increase in POC and the MOC.

In western Queensland, Australia, Webb et al. (2013) reported that wind-blown sediment from aggregated clay soil has lower $ER_{SOC}$ than that of a sandy soil. Some wind-blown sediments contain 15% to 20% SOC compared to 0.3% to 4.2% in soil. The highest values of $ER_{SOC}$ of wind-blown sediment were 48.4, 31.2, 30.7, 18.2, 13.9, and 14.4. Based on these data for Australia, Webb et al. (2013) estimated total SOC loss at 5.4 Mt C $y^{-1}$ (6.0 million tn C $yr^{-1}$) in 100 Mt (110.2 million tn) of sediment, and 147 Mt C $y^{-1}$ (162.0 million tn C $yr^{-1}$) globally in 3 Gt (3.3 billion tn) of sediment.

Any structural/physical change of SOC during its transport over the landscape and passage to the ocean (Aufdenkampe et al. 2011; Raymond et al. 2013; Regnier et al. 2013) can strongly affect its fate emissions of GHGs. Further, the fate of C transported over the landscape may differ widely in natural versus managed ecosystems. The latter have high sediment yield, and the transport of POC is primarily affected by the sediment yield (Galy et al. 2015). Tan et al. (2017) reported a regression equation of C yield (CY) and sediment yield (SY) as $CY = 0.081\ SY^{0.766}$, $r = 0.89$, and hypothesized that POC and sediment are physically bound in soils and are affected (e.g., detached and transported) similarly by the hydrological processes. Similar observations were made by Nie et al. (2015) with regards to $ER_{SOC}$. The exponent of 0.766 (less than 1) indicates that transport of POC decreases with increase in the sediment yield (Lal 1976).

Concentration of SOC in river sediment varies widely. In general, the concentration of POC in sediment decreases with increase in suspended sediment concentration (Meybeck 1993), while the effect may be offset because of the increase in total sediment discharge. In the Mississippi River, SOC content of the suspended sediment was 1.8% ± 0.3% (Trefry et al. 1994), with 66% of total C comprising of POC.

## The Fate of Soil Organic Carbon Transported by Sediments and the Impact on the Global Carbon Cycle

Because of a high concentration of POC and the labile fraction, the SOC removed by erosion is especially susceptible to decomposition, which has important implications to the GCC. Thus, the nature of SOC removed (POC versus MOC, or labile versus recalcitrant) must be considered in evaluating its impact on GCC. Particulate form, after rupture or dispersion of aggregates, may be easily mineralized (Martínez-Mena et al. 2012). Based on a study across a Mediterranean catchment, Martínez-Mena et al. (2019) observed that mineralization of the most labile SOC (or POC) was predominant during transport.

From a study of nine river basins in China, Wang et al. (2019) observed that 47% to 57% of eroded SOC was deposited over land, 25% to 44% was deposited in the channel, and 8% to 18% was delivered into the sea. Wang and colleagues observed that, over a short period of simulated erosion, only 1.5% of the transported C was mineralized. Yue et al. (2016) documented that severe water erosion in China displaced 180 ± 80 Mt C $y^{-1}$ (198.4 ± 88.1 million tn C $yr^{-1}$) over two decades, of which 45 ± 25 Mt C $y^{-1}$ (49.6 ± 27.6 million tn C $yr^{-1}$) is buried in aquatic ecosystems. Fiener et al. (2015) applied the SOC turnover model (SPEROS-C) to a 4.2 ha (10.4 ac) arable catchment in Germany for a 57-year period, and a total of 901 model runs were performed. The overall C balance of the catchment indicated a maximum C source of 44 g C $m^{-2}$ (0.081 lb C $yd^{-2}$).

## Gaseous Fluxes from Depositional Sites

There is an erroneous and mythical belief that erosion-induced transport of C leads to mitigation of climate change because of the long-term burial of SOC under anaerobic environments (Berhe et al. 2007; Van Oost et al. 2007; Quinton et al. 2010; Fiener et al. 2015). Indeed, the role of fluvial sedimentary areas as SOC sinks remains largely unquantified for the drier Mediterranean (Martínez-Mena et al. 2019) and several other regions prone to accelerated erosion. Yet, such misinterpretation has numerous adverse consequences to attempts in aligning policies for soil conservation and sustainable management with those of adaptation and mitigation of climate change. Adverse effects of accelerated soil erosion, already the second largest source of GHG emissions, are likely to be exacerbated with the current and projected climate change. Furthermore, SOC and related nutrients, such as N, P, K, and S, transported and buried in depositional sites are also major sources of GHGs, especially those of nitrous oxide ($N_2O$) and methane ($CH_4$). However, the input of labile materials in the depositional sites plays an important role in soil respiration and emission of GHGs from the surface layer. Emission of $CO_2$ tends to increase in deposition positions of eroded landscape because of the profound influences of added N supply on functioning of microorganisms, which drive the soil C efflux (Meng et al. 2016). Based on a study conducted in temperate forests of the Sierra Nevada, California, Stacy et al. (2019) observed that sediment transported in drier years was more enriched in unprotected POC derived from surficial soils. Incubation of these sediments produced

72% to 97% more $CO_2$ during decomposition than soil C did. Thus, Stacy and colleagues concluded that without stabilization (through burial or reaggregation), sediment-transported SOC is prone to decomposition.

Wang et al. (2014) concluded that $CO_2$ emission was the predominant form of overall C loss, accounted for 90.5% of the total erosion-induced C loss, and was equal to 18 g C $m^{-2}$ (0.033 lb $yd^{-2}$) in a four-month study. In comparison, only 1.5% of the total redistributed C was mineralized into $CO_2$ indicating the stabilization of deposited/buried SOC. In the subsoil, however, stabilization of SOC within microaggregates may reduce respiration (Li et al. 2018). Furthermore, dispersed clay at the depositional sites may be reaggregated and stabilize some of the SOC/POC/MOC encapsulated within reformed stable aggregates (Cheng et al. 2010). Reaggregation of clay and formation of stable microaggregates within aggregates can occur in the upper layers of depositional areas, as well as in the deeper layers where SOC gets stabilized (Martínez-Mena et al. 2019).

Deemer et al. (2016) estimated that reservoirs created by dams account for 0.8 (0.5 to 1.2) Gt $CO_2$ eq $y^{-1}$ (0.88 [0.55 to 1.32] billion tn $CO_2$ eq $yr^{-1}$), with a majority of the forcing due to $CH_4$. Transport of a large stock of SOC into the reservoirs is a major source of $CH_4$ and $N_2O$, which are 34 and 298 times more potent than $CO_2$ on a 100-year time scale (Etminan et al. 2016). Deemer et al. (2016) estimated that global reservoirs emit 13.4 Mt $CH_4$-C $y^{-1}$ (14.8 million tn $CH_4$-C $yr^{-1}$), 36.8 Mt $CO_2$-C $y^{-1}$ (40.6 million tn $CO_2$-C $yr^{-1}$), and 0.03 Mt $N_2O$-N $y^{-1}$ (0.033 million tn $N_2O$-N $yr^{-1}$). Hamdan and Wickland (2016) reported that total global $CH_4$ emissions range from 500 to 600 Mt $CH_4$ $y^{-1}$ (551.2 to 661.4 million tn $CH_4$ $yr^{-1}$), of which 30% to 35% of the total are from natural sources including reservoirs. In Poland, Gruca-Rokosz and Tomaszek (2015) calculated fluxes of $CH_4$ and $CO_2$ at the sediment-water interface in the Rzeszow Reservoir. The fluxes ranged from 0.01 to 2.19 mmol $m^{-2}$ $d^{-1}$ (0.008 to 1.83 mmol $yd^{-2}$ $day^{-1}$) for $CH_4$ and 0.36 to 45.33 mmol $m^{-2}$ $d^{-1}$ (0.30 to 37.90 mmol $yd^{-2}$ $day^{-1}$) for $N_2O$. Further, the 24% to 72% of $CO_2$ in the top layer of sediment that came from degradation of organic matter by methanogenesis was greater than that in the deeper layers.

Erosion-induced emissions are also increased at the depositional sites of eroding landscapes (Meng et al. 2016). Dominant sources of $N_2O$ also include sediments and water bodies (Butterbach-Bahl et al. 2013; Oertel et al. 2016). Meng et al. (2016) observed that an average of 72% C incorporated by all microbial groups in depositional sites (foot slopes) was derived from SOC, indicating that a large amount of SOC was mineralized at the depositional sites. Prevalence of anaerobic conditions at these sites may also lead to methanogenesis and emission of $CH_4$.

## Erosion Control and Carbon Sequestration

Effective erosion control and restoration of eroded soils can create a net sink of atmospheric $CO_2$ (figures 1a and 1b). Indeed, it takes much less energy to keep soil in place than it does to rebuild SOC. An example of a C sink through erosion control is that of exchange in the terrestrial C budget between 1970 and 2017 through the revegetation program of the severely eroded Yellow River basin in China. In comparison with the baseline data from 1950 to 1970, through effective erosion control through afforestation and installation of other control measures 20.6 Mt C $y^{-1}$ (22.7 million tn C $yr^{-1}$) was sequestered (Ran et al. 2018). Furthermore, the erosion-induced decomposition of transported SOM declined by 34% from 8 to 5.3 Mt C $y^{-1}$ (8.82 to 5.84 million tn C $yr^{-1}$) (table 2). Ran and colleagues observed that effective soil erosion control measures also collectively conserved 20.6 Mt C $y^{-1}$ (22.7 million tn C $yr^{-1}$) from 2000 to 2015, and the rate of C accumulation in the terrestrial biosphere (soil and vegetation) may continue because the C sink capacity has not yet been saturated. Further, reduction in C emissions by 2.7 Mt C $y^{-1}$ (3.0 million tn C $yr^{-1}$) from 8 to 5.3 Mt C $y^{-1}$ (from 8.8 to 5.8 million tn C $yr^{-1}$) accounted for 63% of the net primary production of 4.3 Mt C $y^{-1}$ (4.7 million tn C $yr^{-1}$) (Ran et al. 2018). Therefore, effective soil conservation measures can have a drastic impact on C capture from the atmosphere and transfer it into the terrestrial sink. An example of the terrestrial sink created by effective erosion control and restoration of eroded lands is given in table 3. The hypothetical example shows that if all the mineralizable SOC in eroded sediment were decomposed,

**Table 2**

**Effect of conservation measures and afforestation of the Yellow River basin on fate of the erosion-induced transport of carbon (C; recalculated from Ran et al. [2018]).**

| Parameter | Baseline (1950 to 1970) (Tg C $y^{-1}$) | After conservation (2000 to 2015) (Tg C $y^{-1}$) |
|---|---|---|
| Soil erosion | 21.4 ± 5.2 | 11.1 ± 4.1 |
| Decomposition | 8.0 ± 8.8 | 5.3 ± 4.6 |
| Redistribution | | |
| • Dam trapping | — | 3.3 ± 1.5 |
| • Hillslope deposition | — | 1.0 ± 1.3 |
| • Channel sedimentation | — | 0.3 ± 0.5 |
| • Sediment diversion | — | 0.5 ± 0.3 |
| Ocean transport | 6.1 ± 4.3 | 0.7 ± 0.6 |

**Figure 1**

**(a) Soil erosion as a source, or (b) soil conservation as a sink of atmospheric carbon dioxide and other greenhouse gases.**

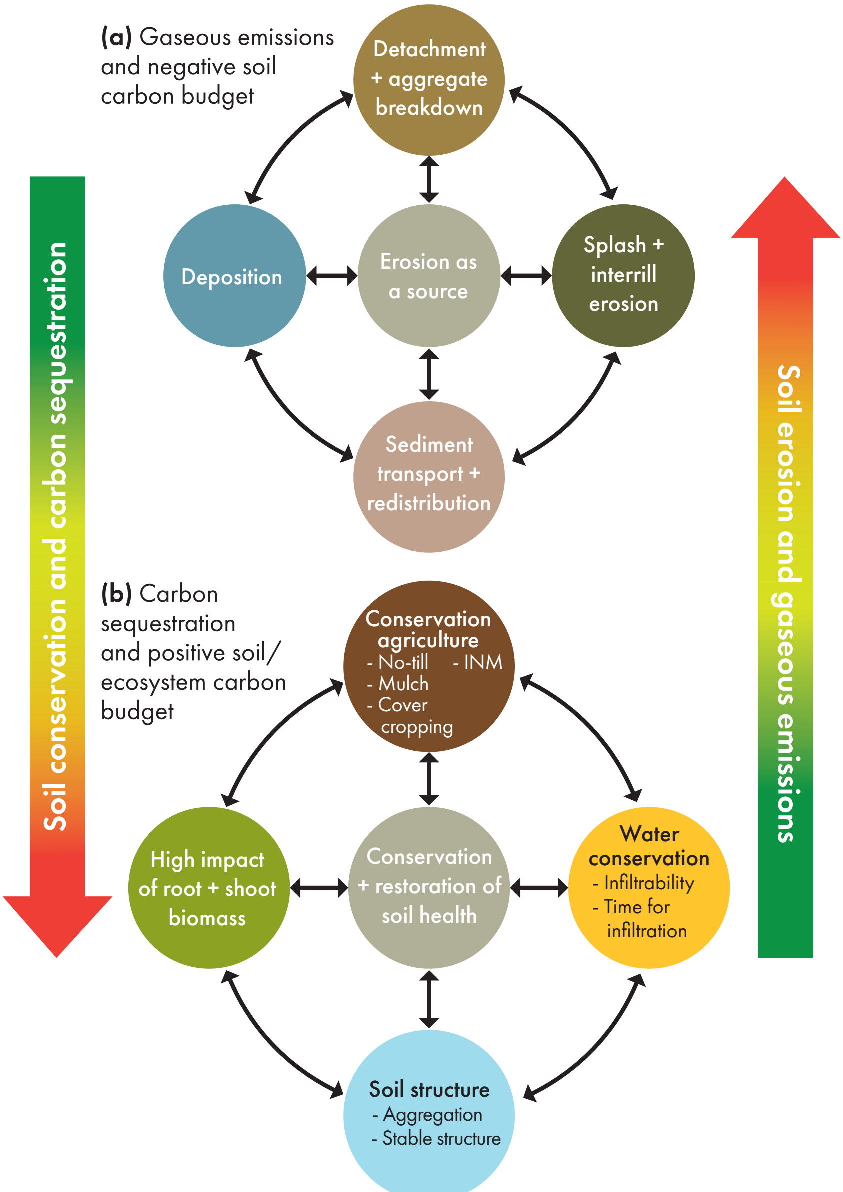

**Table 3**

**Global carbon sink (C) through effective erosion control and afforestation of eroded landscape.**

| Parameter | Units | Magnitude | Reference |
|---|---|---|---|
| Land area affected | $10^6$ ha | 1,100 | Oldeman (1994) |
| Global sediment transport | Gt $y^{-1}$ | 36.6 | Walling (2008, 2009) |
| Sediment delivery ratio | | 0.1 to 0.3 (0.2) | Doetterl et al. (2016) |
| SOC concentration in sediment | % | 1.8 ± 0.3 | Trefay et al. (1994) |
| Total C transported | Gt C $y^{-1}$ | 3.29 | |
| Emission factor from soil erosion | t $t^{-1}$ of erosion | 0.3 t $CO_2$ eq $t^{-1}$ of erosion | Worrall et al. (2016) |
| Total global emissions ($CO_2$, $CH_4$, $N_2O$) | Gt $y^{-1}$ | 54.9 Gt $CO_2$ eq $y^{-1}$ (14.5 Gt C $y^{-1}$) | |

it would be equivalent to 14.5 Gt $C_{eq}$ $y^{-1}$ (16.0 billion tn $C_{eq}$ $yr^{-1}$). Thus, global soil conservation is an absolute necessity.

## Aligning Agriculture with Global Climate Policy

The impact of agriculture on gaseous emissions ($CO_2$, $CH_4$, and $N_2O$) is a global issue (Muñoz et al. 2010; Oertel et al. 2016). Soil processes, and their perturbation by human activities are significantly impacting the emission of GHGs into the atmosphere. Sequestration of SOC can be enhanced by identifying appropriate soils and ecoregions where conservation agriculture can be adopted (Ogle et al. 2019), where cover cropping can improve soil quality by controlling erosion and improving input of biomass C (Poeplau and Don 2015; Ruis and Blanco-Canqui 2017), and where use of compost (White et al. 2020) can ensure that the Soil Conditioning Index is positive (Zobeck et al. 2007; Franzluebbers et al. 2011). Conservation agriculture, based on no-till farming and the related components, is useful to reducing soil erosion, creating climate-resilient agriculture, and advancing food security with additional co-benefits of C storage (Lal 2015). Therefore, it is important to develop a soil guide for adoption of conservation agriculture (Lal 1985). The recommended soil conservation practices must ensure that soil erosion does not exceed the tolerable soil loss (T) value, because erosion rates equivalent to two T may be excessive with adverse effects on SOC stock.

Since 2015, policy makers have focused on soil C sequestration for food and climate by adopting the "4 per Thousand" initiative globally and Adapting Agriculture in Africa (Lal 2019). A similar program, called Platform on Climate Action in Agriculture, focused on soil management and making agriculture a solution to climate change, was launched at COP 25 in Chile/Madrid in December of 2019. There is also a growing interest in industry to enhance SOC sequestration (e.g., Danone, Indigo Agriculture, and Patagonia) through adoption of regenerative agriculture. Thus, soil scientists must seize the moment and support such initiatives.

## Conclusions

A synthesis of the literature indicates all three hypotheses are proven and also supports the following conclusions:

1. The SOC transported and redistributed by erosional processes (water, wind) is prone to decomposition; methanogenesis and nitrification/denitrification; and emissions of $CH_4$ and $N_2O$, along with that of $CO_2$.
2. Some of the SOC carried into the aquatic ecosystems and depressional sites is buried and is subject to reaggregation and stabilization of SOC. Nonetheless, a sizeable part of the SOC in these sites is also prone to mineralization, methanogenesis, and nitrification/denitrification by increase in microbial activity at the depositional position.
3. Adoption of conservation agriculture and cover cropping lead to a positive soil conditioning index, protect the existing SOC stock, and sequester additional C within soil and the biomass. Erosion control and soil conservation enhance SOC sequestration.
4. Conservation effective measures should be adopted to limit the soil erosion within the tolerable limit (one T-value).

Overall, based on the net effect of all four phases, erosion is a major source of GHGs. SOC/POC enriched sediments are transported, redistributed, and exposed to a wide range of environmental (moisture, temperature, etc.) conditions. Thus, soils of agroecosystems must be protected through adoption of conservation-effective measures so that risks of soil erosion are minimized. Aligning science with policy is an important step forward. International initiatives can make an important difference. Soil conservation and restoration of eroded soils is a win-win option to improve productivity and mitigate global warming.

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# 24

# Modeling Soil and Water Conservation

*Dennis C. Flanagan, Larry E. Wagner, Richard M. Cruse, and Jeffrey G. Arnold*

Great strides have been made over the past 75 years toward conserving the United States' precious soil and water resources. The earliest national soil conservation efforts began in the 1930s when the US Department of Agriculture Soil Conservation Service (USDA SCS) was created in response to severe wind erosion during the Great Plains' Dust Bowl. In addition to working with farmers and landowners to implement soil conservation practices on the land, SCS also conducted research at 35 soil conservation experiment stations located across the United States. These locations provided long-term natural rainfall/runoff plot data that were used in the development of the Universal Soil Loss Equation (USLE), the first widely used erosion prediction model. Modeling efforts after development of the USLE expanded into effects of erosion on soil productivity; runoff and water quality from agricultural lands; watershed-scale runoff, sediment, and pollutant losses; and systems for process-based predictions of water or wind erosion. Wind erosion research and modeling was a direct response to the Dust Bowl, with the empirical Wind Erosion Equation (WEQ) first published in 1965. This chapter looks back through history at soil and water conservation modeling efforts, describes current state-of-the-art models, and discusses future modeling needs.

**Dennis C. Flanagan** is a research agricultural engineer, USDA Agricultural Research Service (ARS), National Soil Erosion Research Laboratory, West Lafayette, Indiana. **Larry E. Wagner** is a research agricultural engineer, USDA ARS, Rangeland Resources and Systems Research Unit, Fort Collins, Colorado. **Richard M. Cruse** is a professor and director of the Iowa Water Center, Iowa State University, Ames, Iowa. **Jeffrey G. Arnold** is a research agricultural engineer, USDA ARS, Grassland Soil and Water Research Laboratory, Temple, Texas.

## Early Water Erosion Research and Modeling Efforts

The first field research in the United States to focus on soil erosion by water was conducted by F.L. Duley in 1917 on seven erosion plots in Columbia, Missouri (Duley and Miller 1923). Soil Conservation Experiment Stations (SCES) were installed by the USDA beginning in 1930, initially at 10 locations (9 east of the Rocky Mountains and 1 in Pullman, Washington), and ultimately expanded to 35 sites (Gilley and Flanagan 2007). Plots were commonly 2 m wide by 22 m long (6 ft wide by 72.6 ft long; 1% of an acre). Slope gradients used were those available at each site, and some locations had plot lengths shorter or greater than 22 m. Experimental treatments usually included continuous tilled fallow for a baseline worst erosion case, as well as various cropping and management practices, with typical crops and crop rotations for each station's region of the country. Different soil conservation practices were also tested at these stations (e.g., contouring, strip-cropping, etc.) to gauge their effect on reducing erosion caused by water.

The first mathematical description of soil erosion, developed by Austin W. Zingg in 1940 using experimental data from natural and simulated erosion studies on a loam soil in Missouri, was

$$X = C \times S^{m} \times L^{n}, \qquad (1)$$

where $X$ was total soil loss (kg [lb]) from a land slope of unit width, $C$ was a constant, $S$ was land slope (%), $L$ was horizontal length of land slope (m [ft]), and $m$ and $n$ were exponents. Zingg calculated average soil loss per unit area from a unit width slope as

$$A = C \times S^{m} \times L^{n-1}, \qquad (2)$$

and the values of $C$, $m$, and $n$ were 0.026, 1.4, and 1.6, respectively (Zingg 1940).

D.D. Smith (1941) expanded on Zingg's work, and expressed average soil loss as

$$A = C \times S^{1.4} \times L^{0.6} \times P, \qquad (3)$$

where $P$ was the ratio of soil loss with a mechanical conservation practice to soil loss without the practice. He retained the $m$ and $n$ values derived by Zingg and used equation 3 with measured annual values of $A$, and values of $S$ and $L$ from individual plots on the loam soil in Missouri to compute $C$ values for various soil treatments and crop rotations. Smith also established the concept of an allowable soil loss—now referred to as the tolerable soil loss "T" value—that he based on soil fertility maintenance, which was about 9 Mg $ha^{-1}$ $y^{-1}$ (4 tn $ac^{-1}$ $yr^{-1}$) for the Shelby loam soil in Missouri. (T values across the United States range from 1.1 to 13.4 Mg $ha^{-1}$ $y^{-1}$ [0.5 to 6.0 tn $ac^{-1}$ $yr^{-1}$] [Smith and Stamey 1965].)

A full soil erosion prediction model, based on Smith's work, which included a soil erodibility ($K$) factor, was presented by Browning et al. (1947). They developed $K$ factors and allowable soil loss values for several soils in Iowa, and used Smith's equation for managing these soils with slope length limits, though the equation was still site specific. Musgrave (1947) presented an alternative equation to predict soil erosion, which included a rainfall term (maximum precipitation falling in 30 minutes within a storm) and was the first complete equation to predict erosion by water from individual rain storms.

A national effort began in the 1950s to incorporate the effect of rainfall on soil erosion by water, and assemble and analyze all of the existing runoff and soil loss data collected from the SCES. There was widespread interest in having a single technology for erosion by water calculation, to replace the multiple regional equations. The newly created (in 1953) USDA Agricultural Research Service (ARS) established the National Runoff and Soil Loss Data Center (NRSLDC) at Purdue University in West Lafayette, Indiana, in 1954. The NRSLDC became the central location for over 10,000 plot years of natural runoff plot data. The research leader, Walter H. Wischmeier, conducted extensive statistical analyses to isolate the major factors affecting soil erosion by water, which culminated in the development and publication of the USLE in Agriculture Handbook 262 (Wischmeier and Smith 1965). USLE is

$$A = R \times K \times L \times S \times C \times P \,, \tag{4}$$

where $A$ is average annual soil loss in tonnes per hectare (tons per acre), $R$ is the rainfall/runoff erosivity factor (MJ mm ha$^{-1}$ h$^{-1}$ y$^{-1}$ [100 ft-tn in ac$^{-1}$ hr$^{-1}$ yr$^{-1}$]), $K$ is the soil erodibility factor (t ha h ha$^{-1}$ MJ$^{-1}$ mm$^{-1}$ [0.01 tn ac hr ac$^{-1}$ ft-tn$^{-1}$ in$^{-1}$]), $L$ is the slope length factor, $S$ is the slope steepness factor, $C$ is the cover and management factor, and $P$ is the support practice factor. USLE has been extensively applied by SCS and others and was updated in Agriculture Handbook 537 (Wischmeier and Smith 1978).

## Early Wind Erosion Research and Modeling Efforts

Wind erosion observations in the United States were first noted in the Midwest and West, beginning in the late 1800s (Tatarko et al. 2013). Severe wind erosion occurred in the Great Plains as a direct result of the combined effects of tilling of prairie soils to grow wheat, bare soil practices that left the land exposed, long stretches of landscape with little resistance to wind velocities, and consecutive years of drought and failed crops. This was especially the case during the 1930s in the Dust Bowl regions of Kansas, Oklahoma, Colorado, Texas, and New Mexico, where frequent huge dust storms detached and transported soil particles hundreds to thousands of miles away.

The extreme environmental and economic effects of the Dust Bowl resulted in the US government funding erosion control and research activities, and the establishment of the SCS in 1935, as part of the Soil Conservation Act. SCS continued research efforts at the SCES mentioned earlier, which focused mainly on water erosion research and control, while Congressional action to more fully address wind erosion research and control efforts was part of the Agricultural Marketing Act of 1946. This act established an SCS Wind Erosion Project and laboratory on the campus of the Kansas State Agricultural College in 1947, which later became part of ARS in 1953. Groundbreaking research was conducted there, first by mechanical engineer Austin W. Zingg and later by soil scientist William S. Chepil, on wind erosion measurement techniques (Zingg 1951a; Zingg and Woodruff 1951) and process mechanics (Zingg 1949, 1951b, 1953; Zingg and Chepil 1950; Zingg et al. 1952). This research group identified five main factors affecting wind erosion: climate, soil cloddiness, ridge roughness, field length, and vegetative material (Chepil and Woodruff 1954, 1959, 1963; Chepil 1960; Chepil et al. 1962). The group's initial wind erosion model was

$$E = I \times R \times K \times F \times B \times W \times D\,, \tag{5}$$

where $E$ was the quantity of soil eroded (t ha$^{-1}$ y$^{-1}$ [tn ac$^{-1}$ yr$^{-1}$]), $I$ was a factor for soil cloddiness, $R$ was a factor for residue, $K$ was a factor for roughness, $F$ was a factor for soil abradability, $B$ was a factor for wind barrier, $W$ was the width of the field (m [ft]), and $D$ was the wind direction (Chepil 1959). $I$, $R$, $K$, $F$, and $B$ were all dimensionless and were determined from soil and field properties and use of nomographs and charts. However, wind velocities at different locations were not addressed by this equation. In 1965, the WEQ, based on Chepil's and his coworkers' previous work, was published by Woodruff and Siddoway (1965). WEQ has the form of

$$E = f\,(I \times K \times C \times L \times V)\,, \tag{6}$$

where $E$ is average annual soil loss in tonnes per hectare (tons per acre), $f$ indicates functional relationships that are not direct mathematical calculations, $I$ is a soil erodibility index (t ha$^{-1}$ y$^{-1}$ [tn ac$^{-1}$ yr$^{-1}$]), $K$ is the soil surface roughness factor, $C$ is the climatic factor, $L$ is the unsheltered distance (field length in m [ft]), and $V$ is a vegetative factor. $K$, $C$, and $V$ were dimensionless. WEQ was initially applied on an average annual basis, but was later also applied by the SCS (and USDA Natural Resources Conservation Service [NRCS]) for conservation planning using the Critical Period Method (WEQ Management Period Procedure) that estimated wind erosion during times of the year when fields were most susceptible to soil loss, and when erosion control practices and land management changes would be most effective. This method was later computerized (Skidmore et al. 1970) and eventually implemented as a Microsoft Excel Spreadsheet application by NRCS.

## Model Developments to 2000

The 1970s were a time of growing awareness and concern over environmental issues and pollution, with landmark legislation including the Clean Air Act, Clean Water Act, and Endangered Species Act. Modeling efforts during that time expanded from solely soil erosion by water or wind into additional considerations, especially water pollution as well as air and water quality. Where USLE and WEQ were empirical statistical models, new efforts on spatially distributed, process-based and/or hybrid natural resource models began to be developed. Many new models were developed to assess land management practice and chemical application effects on watershed-scale responses (runoff, sediment loss, pollutant losses), in order to meet new water quality goals or target pollutant limits that came about from new environmental regulations. Some of the models developed after USLE and WEQ are listed here.

***MUSLE—Modified Universal Soil Loss Equation.*** This modification of the USLE substituted a runoff factor in place of the *R* factor, allowing prediction of sediment yield from small watersheds for individual storm events (Williams 1975). MUSLE was used for watershed sediment yield predictions and was incorporated as an option into larger catchment models (e.g., SWAT).

***ANSWERS—Areal Nonpoint Source Watershed Environment Response Simulation.*** This was one of the first gridded distributed parameter watershed models and was developed at Purdue University by Beasley et al. (1980) as part of the Black Creek Watershed Project in northeastern Indiana in the 1970s.

***CREAMS—Chemicals, Runoff, and Erosion from Agricultural Management Systems.*** This was a major USDA effort to comprehensively simulate hydrology, sediment detachment and transport, and chemical loss and transport from agricultural fields (Knisel 1980) that included both empirical and process-based components for hydrology, erosion by water, and chemical transport. It evolved into the GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) model (Leonard et al. 1987). Improvements were made in GLEAMS to better represent soil layering, crop rotations, irrigation, soil water routing, and chemical movement (Knisel and Douglas-Mankin 2012). Many of the components, especially the water quality logic and equations, were adapted and used in other subsequent models.

***EPIC—Erosion Productivity Impact Calculator.*** This tool was developed by USDA ARS to estimate the effect of soil erosion on soil productivity (Williams et al. 1984) and effects of management decisions. It simulated hydrology, weather, erosion, nutrients, soil temperature, plant growth, tillage effects, plant environmental controls, and economics. EPIC has evolved into the Environmental Policy Integrated Climate model, as its functionality was expanded to include irrigation, pesticide losses, carbon dynamics, and climate change effects (Izaurralde et al. 2006).

***RUSLE/RUSLE2—Revised Universal Soil Loss Equation (Versions 1 and 2).*** RUSLE (Renard et al. 1997) and RUSLE2 (USDA ARS 2013) were developed by USDA ARS and built upon the empirical USLE technology with updated factors and the addition of some process-based science to allow for simulation of erosion and deposition on complex slopes and management systems where sediment deposition may occur (slope concavities, filter strips). NRCS databases allow application to over 20,000 land management scenarios. While RUSLE functioned on a 15-day time interval, RUSLE2 operates on a 1-day time step, with time-varying erodibilities and crop residue decay.

***AGNPS—AGricultural NonPoint Source Pollution Model.*** This was an event-based model developed by USDA ARS to simulate runoff, sediment, and nutrient losses from agricultural watersheds (Young et al. 1989). In a cooperative project with NRCS, the tool was converted into a continuous simulation model, which allows for detailed evaluations of cropping/management and conservation practice effects on runoff, sediment, and pollutant losses from hillslopes, channels, and streams. AnnAGNPS (Annualized AGNPS) includes updated routines for stream network processes, ephemeral gully erosion prediction, a stream corridor model, an instream temperature model, and several salmonid models (Cronshey and Theurer 1998; Yuan et al. 2001).

***APEX—Agricultural Policy/Environmental eXtender Model.*** This extends the capability of the EPIC model to application to fields and small watersheds and farms with spatially varying soils, cropping, and land management practices (Williams et al. 1995; Wang et al. 2012). The impacts of soil conservation practices on control of water and wind erosion, as well as losses of nutrients and pesticides from agricultural systems, can be evaluated. APEX has been used in nationwide Conservation Effects Assessment Project (CEAP) evaluations, to examine the effects that use of conservation practices on private lands have had on soil erosion and water quality.

***SWAT—Soil and Water Assessment Tool.*** SWAT (Arnold et al. 1998, 2012) is a continuous simulation, basin-scale, distributed parameter model that allows for analysis of the effects of land and water management practices on flow discharge, sediment losses, and various pollutant losses (nutrients, pesticides, bacteria, pathogens, etc.). SWAT was developed by USDA ARS in Temple, Texas, in cooperation with Texas A&M University, and incorporates many of the components from other modeling efforts (MUSLE, EPIC, APEX, etc.). SWAT and APEX have been used extensively in recent national Conservation Effects Assessments by NRCS and ARS, and SWAT has an immense group of users worldwide (Gassman et al. 2014).

***WEPP—Water Erosion Prediction Project.*** This is a process-based, continuous simulation, distributed parameter soil erosion prediction tool for application to hillslope profiles and small field-sized watersheds. It was developed in a national project by USDA (ARS, NRCS, and Forest Service [FS]) and US Department of the Interior (Bureau of Land Management) from 1985 to 1995, and ongoing maintenance, updates, and applications continue (Flanagan and Nearing 1995; Flanagan et al. 2007). WEPP simulates the important processes controlling upland soil erosion by water, including hydrology (infiltration, runoff, lateral subsurface flow, percolation, etc.), flow hydraulics, detachment by raindrops and flow, sediment transport, sediment deposition, tillage disturbance and soil consolidation, plant growth, residue decomposition, etc. A variety of interface programs have been developed for standalone use within Windows, within a geographic information system (GIS) framework (GeoWEPP), or via web browsers. The hillslope erosion model (HEM) from WEPP has been extracted and utilized in other models for erosion by water predictions. WEPP has been extensively used by the USDA FS for erosion predictions on forested lands and effects of wildfires and forest management practices (Elliot 2013).

***WEPS—Wind Erosion Prediction System.*** This is a process-based, continuous simulation wind erosion modeling system developed by USDA (ARS, NRCS) to replace WEQ (Hagen 1991; Wagner 2013). In addition to greatly improved science describing the detachment, transport (by saltation, suspension, creep modes), and deposition of wind-blown sediments, WEPS also allows for extensive soil conservation practice simulations, including use of windbreaks of varying size and density, conservation tillage practices, and emergency tillage to roughen the soil surface to impede detachment. NRCS has been using WEPS in their field offices since 2010 as a replacement for WEQ.

***SWEEP—Single-event Wind Erosion Evaluation Program.*** This is the wind erosion submodel in WEPS, which is a standalone subdaily timestep program containing its own graphical user interface. If the surface friction velocity threshold is exceeded by the actual surface friction velocity generated by the wind on the specified surface, SWEEP will predict soil loss by wind for a single day given the surface (soil and plant/residue) and wind conditions provided.

## Conservation Modeling and Recent Developments

Modeling of soil and water conservation practices today is considerably advanced from the early applications of USLE and WEQ. Continuous simulation models allow updating of soil, plant, and residue conditions for every simulation day, potentially within a long period (100+ years). Thus, climate effects (rainfall, temperatures, wind) combined with land management (tillage, conservation practices), plant growth responses (canopy development, biomass production, yield), and their interactions affect the ultimate response in terms of soil loss, runoff, sediment transport, and pollutant losses. Also, modern models allow for evaluation of conservation effects from hillslopes to channels and streams. For example, a no-till cropping system may adequately control sheet and rill erosion, but could increase surface and/or subsurface water flows that can end up initiating or increasing ephemeral gully or channel erosion. With today's models, the potential for ephemeral gully erosion can be assessed, as well as the effects of conservation practices, such as installation of a grassed waterway. It is also easy to simulate many conservation practices, including no-till, buffer strips, residue/mulch additions, cover crops, contour planting, and strip-cropping.

During the past 10 years, efforts in soil and water conservation modeling have shifted to more process-based modeling efforts, and web-based interfaces and databases served to users via "the cloud." Specifically related to NRCS field-based conservation planning activities, extensive development on these types of erosion prediction tools have been underway as part of cooperative projects between NRCS, ARS, FS, and several universities. These tools provide substantially more output information than just average annual soil loss; simulate numerous environmental and crop/management interactions; and are extremely easy to use, maintain, and update. Some of the most current developments are described below.

***RHEM—Rangeland Hydrology and Erosion Model.*** This is a process-based tool to predict runoff and erosion specifically from rangelands and is based on fundamentals of infiltration, plant science, hydrology, and erosion science (Nearing et al. 2011). It has been recently updated (Hernandez et al. 2017) with improved detachment and sediment transport functions, parameterization equations, and an improved user-friendly web-based interface.

***DEP—Daily Erosion Project.*** This web-based tool was initially the Iowa Daily Erosion Project (IDEP). IDEP utilized NexRad radar precipitation data in Iowa, WEPP, and National Resource Inventory (NRI) data for soils, slope, and cropping to provide near real-time estimates of runoff and soil erosion on a township basis for all of Iowa (Cruse et al. 2006). DEP is an updated version that estimates on a daily basis and publicly reports WEPP-predicted runoff and hillslope sheet/rill erosion at the hydrologic unit code 12 (HUC-12) watershed scale. It uses remotely sensed data and electronic database inputs for precipitation; slope profile identification; and slope, soil, and land management input parameterization (Gelder et al. 2018). DEP is being extended to neighboring states and has a state-of-the-art web interface (figure 1).

***IET—Integrated Erosion Tool.*** Developed by the NRCS Information Technology Center in cooperation with Colorado State University and ARS, IET2 is a common interface program designed for conservation field office users allowing wind and water erosion simulations using WEPS and WEPP, with a single set of common input screens and utilizing web-based climate, soils, and cropping/management databases. An initial version of IET utilized WEPS and RUSLE2.

***WEPP—Water Erosion Prediction Project.*** This is an updated version of WEPP, with changes made specifically targeted for NRCS field office users and better capabilities to simulate conservation practices including contouring, strip-cropping, buffers, etc. (Flanagan et al. 2017, 2018). A new web-based interface for hillslope profile simulations is available (figure 2), and a companion one for field and small watershed simulations is under development. Updated climate (Srivastava et al. 2019), cropping, and operation databases have been extensively tested by NRCS and ARS. The same new web-based services developed as part of this implementation project are also being used in IET2.

**Figure 1**

**Screen capture showing estimated 24-hour precipitation and hillslope soil loss for May 24, 2019, from the Daily Erosion Project (Gelder et al. 2018).**

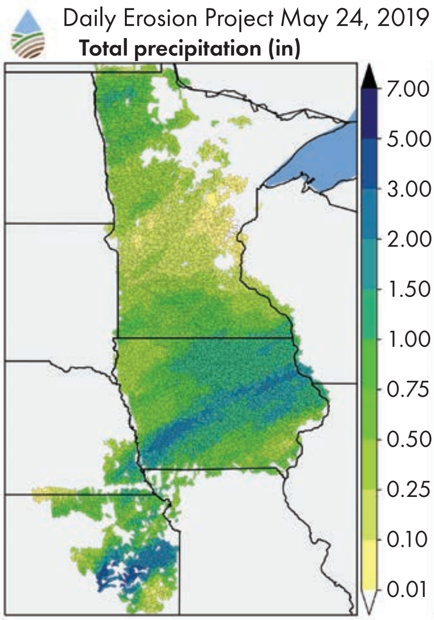
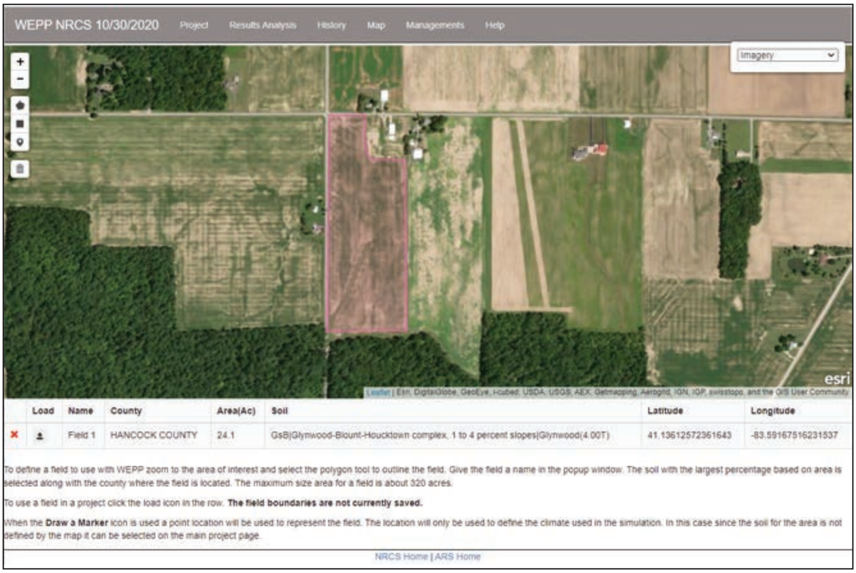


**Figure 2**

**Screen capture of a part of the new Water Erosion Prediction Project (WEPP) web-based interface developed for USDA Natural Resources Conservation Service field office use. A field polygon drawn here provides the geographic coordinates to automatically identify soils, climate, and cropping/management zone inputs available for use in the erosion prediction simulations.**

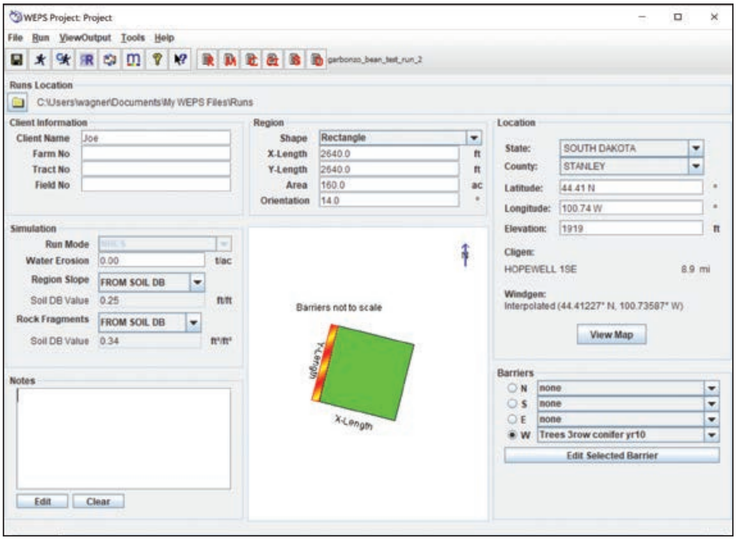



*WEPS—Wind Erosion Prediction System.* WebStart WEPS is an updated version of WEPS using Java WebStart (figure 3) to install and automatically update WEPS on a client's computer via a web link. It incorporates the use of CSIP (Cloud Service Integration Platform) services (David et al. 2014) for remote access to databases and execution of climate generators, as well as the WEPS science model. This updated version can work with multiple sub-regions, so it can handle fields with multiple soil types and multiple spatial cropping/management practices applied, e.g., strip cropping, cropped/pasture areas, cropped/forested windbreaks. A new interface is being created to allow users to specify the spatially explicit inputs for multi-subregion WEPS and SWEEP simulations. The WEPS science model is also currently incorporating UPGM (Unified Plant Growth Model) to enhance plant growth simulations.

*SWAT+—Soil and Water Assessment Tool.* SWAT+ is a completely restructured modular version of SWAT (Bieger et al. 2016). This update improves code development and maintenance; supports data availability, analysis, and

**Figure 3**

**Screen capture of the main WebStart Wind Erosion Prediction System (WEPS) user interface window with the five required inputs populated: (1) field location (auto selects climate and wind inputs); (2) field geometry; (3) management/crop rotation; (4) soil component; and (5) field boundary wind barriers (if any).**




visualization; and enhances the model's capabilities in terms of the spatial representation of elements and processes within watersheds. The most important changes are (1) spatial object modules allowing more flexible channel and landscape routing, and (2) a relational data input file structure. Also, SWAT+ offers more flexibility than SWAT in defining management schedules, routing sediment and constituents, and connecting managed flow systems to the natural stream network. In addition to use in the USDA CEAP project for national conservation planning (White et al. 2014), a web-based interface was developed for the US Environmental Protection Agency for national environmental assessment (Yen et al. 2016).

## Looking to the Future

Natural resources modeling and applications for soil and water conservation will continue to evolve while attempting to adapt to very rapidly changing information technologies and smaller and faster personal electronic devices. Conventional personal computers are being replaced with multifunctional cell phones or tablets, using "apps" (applications) downloaded from the cloud!

The challenge for scientists and modelers is how to adequately simulate the important physical processes controlling hydrology, soil erosion, sediment transport, and pollutant transport for users desiring very minimal data input requirements and summarizing and displaying the most important model output information. With increasingly complex and data-driven models there is also a need for improved input data (e.g., finer spatial and temporal resolution soil data). Runoff, erosion, and pollutant loss forecasting under changing climate and economic analyses of conservation practice costs/benefits are also becoming increasingly important. Evolutionary changes and improvements are underway and expected in many of the current models, but potentially revolutionary changes in interfaces and information delivery may be here soon. Better optimized models are also required for interdisciplinary applications in a constantly changing world.

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# 25

# From the Dust Bowl to Precision Conservation

*Jorge A. Delgado and Gretchen F. Sassenrath*

## 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

**Jorge A. Delgado** is a research soil scientist with the USDA Agricultural Research Service Soil Management and Sugar Beet Research Unit, Fort Collins, Colorado. **Gretchen F. Sassenrath** is a professor of agronomy at Kansas State University, Parsons, Kansas.

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).**

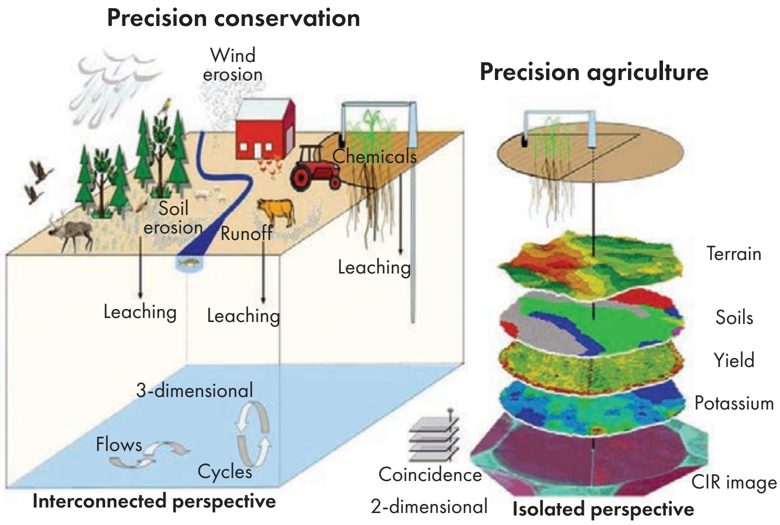
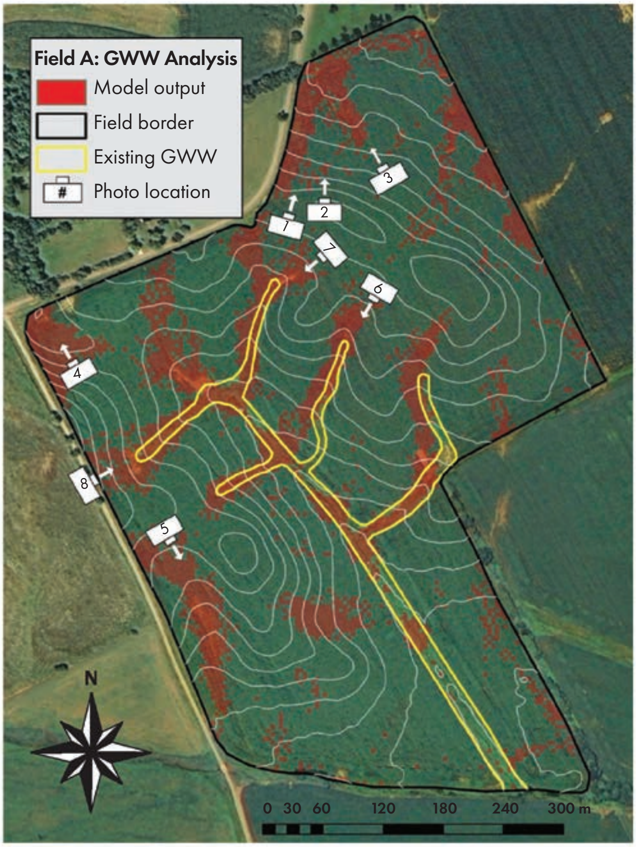


**Figure 2**

**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

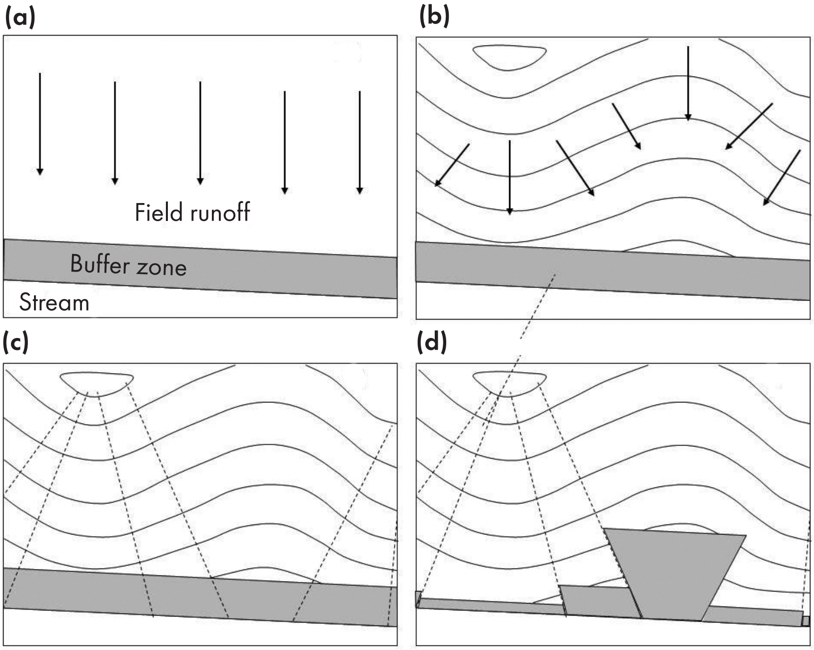
One of the greatest challenges of the 21st century will be adapting to a changing climate while increasing agricultural productivity to feed the growing global human population. A changing climate is contributing to droughts, floods, and intensive precipitation events that are impacting agricultural 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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# 26

Practitioner's Perspective

# Developments in Midwestern Precision Conservation

*Clay Bess*

Farmers in Illinois and other states in the Mississippi River valley are facing potential regulation due to excess nutrients and sediments that are lost from agricultural fields and, eventually, flow into the Gulf of Mexico. In 2015, the Illinois Department of Agriculture and the Illinois Environmental Protection Agency, together with a multistakeholder working group, developed the Illinois Nutrient Loss Reduction Strategy (NLRS) to address urban and rural nutrient losses from both point and nonpoint sources within the state (IDA 2015); only five more growing seasons remain to meet the interim goals set by the state's NLRS plan. The final goals of 45% reduction of total nitrogen (N) and total phosphorus are set for 2035. Planting cover crops, reducing tillage, and reassessing fertilizer applications are scenarios backed by NLRS research to reach these goals. Farmers stand at the crossroads, weighing their options—their decisions affecting not just their own destinies, but the lives and livelihoods of farmers who have not even been born yet. Their decisions will literally shape what it means to be a farmer, to work in agriculture, or even to live in a rural community for future generations. *Sustainability*, *regenerative agriculture*, and *soil health* are the current buzzwords used to describe the practices that many in the nonfarming community hope growers will incorporate into their production management practices. From a farmer perspective, however, the most important factors are the most difficult to capture: "What's it going to cost me?" and "When will I see a return?" This farmer focus is the essence of the Illinois Corn Growers program, Precision

**Clay Bess** is lead conservation specialist at Precision Conservation Management, Bloomington, Illinois.

Conservation Management (PCM), which was established to address the NLRS requirements (ICGA 2018).

PCM gathers actual on-farm agronomic data, pairs it with economic analysis from the long-standing farm financial program, Farm Business Farm Management (http://www.fbfm.org/who.asp), and delivers the personalized, individualized results to growers for them to understand how various conservation practices are likely to impact their financial bottom line as well as how they are likely to address the farmer's conservation concerns. The goal of PCM is to increase conservation practices while providing a financial risk understanding for the Midwestern farmer, who has been assigned the unenviable task of protecting local and national water quality, improving soil health, addressing climate change, and maintaining national food security. Now in their fifth year, the PCM team has exceeded their own expectations, along with the expectations of cooperating farmers.

Conventional wisdom has held that producing more crop yield would produce a higher profit. This mindset emphasized smooth fields for the tractor to get across in less time and to maximize the likelihood of plant emergence. It emphasized clean fields to minimize competition of "weeds" (certain cover crop species being lumped in here). Additionally, it emphasized the perceived importance of not letting nutrients (especially N) be the limiting factor for crops—creating the "more is better" paradigm that results in over-application of nutrients and decreasing nutrient use efficiency. When commodity markets were great (only falling behind for small grains, which quickly left the typical farmscape), these ideologies ruled for corn and soybeans. Dad did it that way, just like grandpa, and great-grandpa. Now things have changed, and the son or daughter is stuck between family convention and family legacy. This adherence to convention has created an environment resistant to the kinds of changes required to meet the goals of the NLRS.

The word *sustainability* may refer to the environmental aspect for most, but for farmers, it means staying in business. It means sustaining the financial success of the farm to keep it there for generations to come. That is the driving factor to pinch every penny and assess each trip through the field. Still, just getting by in the comfort zone is more attractive than adding risk when adopting a new conservation practice. But what if conservation could improve the farm's bottom line? And what if, over time, conservation could minimize risk? That is where PCM plays a role.

PCM separates each practice into standards:

- Tillage: no-till, strip-till, 1-pass light/heavy, 2-pass light/medium/heavy, and 2+ passes.

- Nitrogen application: greater than 40% fall, mostly preplant, mostly sidedress, 50% preplant/50% sidedress, and three-way split.
- Cover crops: over-wintering, winter terminal, and no cover crops.
- Expenses to calculate bottom lines: fertilizer, pesticides, seed, drying, storage, field work, harvesting, and machine hire/application cost.

PCM farmers are starting to implement conservation based on the financial data that the program provides and the technical assistance that PCM specialists offer to farmers for planning and program enrollment. Of the farmers on highly productive soils in PCM-Illinois (Soil Productivity Rating [SPR] of "high" is a score of 136 or higher [University of Illinois 2000a, 2000b]), the most profitable farmers applied 0.5 kg (1 lb) of N for every 25 kg (1 bu) of corn produced or less (table 1; ICGA 2018). This has been seen consistently every year in the PCM dataset. Another finding regarding N is the timing of application. Those who applied more than 40% of their N in the fall, regardless of type and including N contained in monoammonium phosphate (MAP) and/or diammonium phosphate (DAP), have a nonland net return that is \$32 $ha^{-1}$ (\$13 $ac^{-1}$) lower than the next closest PCM class (50%/50% sidedress) and \$109 $ha^{-1}$ (\$44 $ac^{-1}$) below the most profitable class, which is a mostly preplant system (table 1; ICGA 2018). These increased returns with in-season N applications are convincing PCM farmers to move more N application to the spring or summer, even though it sometimes creates challenges logistically. Farmers are accepting the risk of not having fertilizer applied at an exact time or the conventional time because data prove a spring/in-season system is ultimately more profitable. During the individual visit between a conservation specialist and farmer, PCM may frame the conversation as follows: "Field A has consistently been your worst producing corn field for the past four years. Since you have told me that there are no issues like drainage problems, it is time to consider changing the rate of nitrogen to be closer to the one-to-one ratio of nitrogen to yield, since that is the strategy that we are seeing as most profitable throughout the program on ground similar to yours."

These conversations have led to decreased rates of N applications on lower-producing fields and have even led to higher rates of applied N on better-producing fields, but always with the objective of improving N use efficiency. This strategy also forces farmers to become precise in their thinking about management goals and plan each field on its own. PCM understands that cover crops and no-till are not going to work on every acre. However, if we and the farmer can understand which field has the best chance for success, then that becomes the field to use for greater exploration of a new

**Table 1**

**Economic returns resulting from various nitrogen (N) fertilizer management strategies for corn production in central Illinois from 2015 to 2019 (ICGA 2020).**

| Illinois corn, 2015 to 2019 high SPR | Mostly fall | Mostly preplant | Mostly sidedress | 50% preplant/ 50% sidedress | 3-way split |
|---|---|---|---|---|---|
| Average NUE (lb N $bu^{-1}$ grain) | 1.01 | 0.93 | 0.92 | 0.91 | 0.94 |
| Yield (bu $ac^{-1}$) | 219 | 218 | 220 | 221 | 230 |
| Fields (*n*) | 732 | 492 | 612 | 228 | 52 |
| **Gross revenue ($)** | **789** | **785** | **791** | **793** | **827** |
| N fertilizer($) | 84 | 78 | 76 | 84 | 95 |
| Other direct costs ($)* | 320 | 286 | 307 | 311 | 338 |
| **Total direct costs ($)** | **404** | **364** | **383** | **395** | **433** |
| Field work ($) | 16 | 16 | 16 | 18 | 19 |
| Other power costs ($)** | 97 | 89 | 94 | 95 | 93 |
| **Total power costs ($)** | **113** | **105** | **110** | **113** | **112** |
| **Overhead costs ($)** | **37** | **37** | **37** | **37** | **37** |
| **Total nonland costs ($)** | **554** | **506** | **529** | **545** | **582** |
| **Operator and land return ($)** | **235** | **279** | **261** | **248** | **246** |

Notes: SPR = Soil Productivity Rating. NUE = nitrogen use efficiency. Mostly fall = >40% of total N application rate applied in fall. Mostly preplant = more than 50% of total N applied at or before planting in spring. Mostly sidedress = more than 50% of total N applied after planting. 50% preplant/50% sidedress = total N application is split roughly evenly between preplant and sidedress. 3-way split = <40% total N is fall-applied and balance is roughly evenly applied between preplant/sidedress.

*Direct costs include fertilizers, pesticides, cover crop seed, drying, storage, and crop insurance.

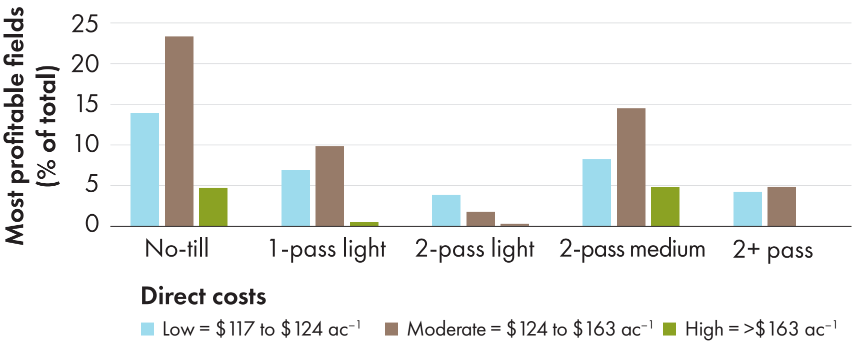
**Other power costs include fall fertilizer application, spraying, planting, cover crop planting, spring/in-season fertilizer application, harvesting, and grain hauling.

technology while accepting the least risk possible. That is how PCM is delivering precision conservation.

Another PCM practice standard, tillage, demonstrates the most profitable classes of tillage prior to planting corn and soybeans on high SPR soil (figure

**Figure 1**

**Most profitable soybean, high Soil Productivity Rating (SPR), tillage and direct cost classes, 2015 to 2019 (ICGA 2020).**




1). Of the most profitable corn fields grown between 2015 and 2019, 1-pass light was the tillage system used on 35% of those fields (ICGA 2018). For the most profitable soybean fields in the same timeframe, no-till was the most common tillage practice on nearly 41% of fields. The other interesting metric regarding this breakdown of soybean fields was that farmers who were able to keep their direct costs between \$306 and \$403 ha$^{-1}$ (\$124 and \$163 ac$^{-1}$) were the most profitable for all tillage systems. Using this data, PCM specialists helped influence and build the confidence of farmers to back down from a conventional tillage system. Given the supporting data, farmers are revising tillage systems toward less-intensive, more conservation focused practices.

A dataset on using cover crops is still being built. In the east-central region of Illinois (Champaign, Coles, Douglas, Edgar, Ford, and Vermilion counties), cover crops ahead of soybeans on low SPR soils produced a better soybean yield in 2019 and only fell a few dollars short on the bottom line relative to soybean crops produced without a cover crop. In all other instances, however, the nonland net financial return for a cover crop system fell far short of a system without cover crops (high SPR, low SPR for soybeans, over-wintering, and winter-kill), even though corn following a winter-kill species (i.e. oats, radishes) resulted in a better yield.

*Partnership* has become a catch phrase thrown around almost as frequently as *sustainable* and *regenerative* in today's socially tuned vernacular. Whether it be farmer-to-farmer networks; farmers participating in ecosystem service markets; or corporations, conservation groups, and agriculture programs teaming together, the prospect of diverse groups sitting at the same table engaging support from around the web offers exciting new possibilities to increase conservation practices and avoid agricultural regulation. When effective conservation practices, such as cover crops, do not result in a bottom line that breaks even, it may be partnerships that can provide the incentive to put the practice on-farm without burying the farmer in risk.

In this way, when PepsiCo offered a \$24 $ha^{-1}$ (\$10 $ac^{-1}$) cover crop cost-share and PCM consulted their supply chain growers, 63 farmers planted 5,232 ha (12,929 ac) of cover crops (9% of total area farmed), which is triple what the cost-share could cover. When strip-till ahead of corn has consistently been financially reliable in most PCM regions, but the cost of the equipment and additional labor has increased risk, PCM was able to provide a custom strip-till operator who would provide the service for farmers to simply test the practice on their land. PCM partners with Field-to-Market to provide sustainability metrics for farmers to gauge where they rank compared to their neighbors and make improvements on topics such as soil conservation and energy use. A similar metric, carbon sequestration, has provided the incentive for a new pilot partnership between PCM and the Ecosystem Services Marketing Consortium to be unveiled this year. State and local programs are offered through the US Department of Agriculture Natural Resources Conservation Service and county soil and water conservation districts, both of which partner with PCM to identify farmers interested in taking advantage of opportunities to address natural resource concerns or try out new conservation practices at reduced costs. These programs and partnerships are how the agriculture community will move forward. The data from multiple on-farm sites and one-on-one consultation are how PCM is successfully delivering precision conservation.

## Acknowledgements

Precision Conservation Management's (PCM's) pillar partners, the Illinois Corn Growers Association, USDA Natural Resources Conservation Service, and University of Illinoi's Farm Business Farm Management, established and developed the program. Through collaboration, PCM has been fortunate to offer additional conservation support with PepsiCo, Illinois Soybean Association, The Nature Conservancy, Association of Illinois Soil and Water Conservation District, Growmark, Ecosystem Services Market Consortium, Soil Health Partnership, and Archer-Daniels-Midland, to name a few of a multitude of partners. PCM's Portal and data analysis platform are developed and maintained by Heartland Science and Technology Group. For a full list of partners and acknowledgements, please visit PCM's website: https://www.precisionconservation.org/.

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# 27

# Cover Crops: Progress and Outlook

*Eileen J. Kladivko*

## Past Use and Understanding of Cover Crops

Cover crops are literally "crops that cover the soil" in agricultural fields during times of the year when the soil is typically fallow. The classic purposes of cover crops have been to protect the soil against water and wind erosion and to increase soil productivity by providing nitrogen (N) as green manures. Many ancient cultures, including those in China, the Middle East, and Rome, used cover crops as green manures to improve soil fertility (Lal 2015). American colonists and early settlers used cover crops to restore land that was "worn out" from continuous cropping. Thomas Jefferson planted "green dressings" as a normal part of his crop rotations, to ameliorate the soil, provide fertility for the succeeding cash crop, and not leave his fields fallow to grow weeds (Betts 1953). His farm book (Betts 1953) includes interesting correspondence with contemporaries, including George Washington, about new plants and how well they worked for different purposes—an 18th century example of farmers learning from other farmers to find cover crops that fit different niches!

Research during the early part of the 20th century included many topics familiar today. The motivation for much of the work was the reduction of fertility in agricultural lands and the recognition that there was little remaining virgin land to bring into crop production. Prior to the widespread availability of inorganic N fertilizers, green manures were a common method to fertilize the main crop. The microbiologist Selman Waksman, however, disagreed with the chemists of the time who suggested that N, phosphorus (P), potassium (K), and pH were the only aspects of importance for crop production, and he articulated many of the benefits of soil organic matter that went beyond

**Eileen J. Kladivko** is a professor in the Department of Agronomy at Purdue University, West Lafayette, Indiana.

fertility. He studied decomposition of green manures and elucidated many principles and concepts we know today about carbon (C):N ratios, the rapidity of decomposition, and the balance between mineralization and immobilization of N (Waksman 1929). Löhnis (1926) stated that N availability from green manures depended on quality and quantity of the green manure as well as the time of application and quality of the soil. He cautioned against incorporating N-rich green manures in fall if there was not going to be a crop planted until the following spring, as the N would be released and "washed away by a few heavy rains."

Pieters and McKee (1938) suggested that if legume green manures were turned under in the fall, then a cereal should be planted to capture the N released for later use. Their chapter in the *Yearbook of Agriculture* (1938) also provided many other recommendations for how to use cover and green manure crops as well as a listing of many of the common cover crops of the time. In this chapter and other writings (Pieters and McKee 1929), they discussed the importance of identifying the main purposes of the cover crop/green manure crop, for both selection of the appropriate species and its subsequent management for each region, soil type, and cash crop. It's interesting to note their comments on the lack of reliable seed supply, the need for practical economics analyses, and the need to consider green manures as an investment in the same way as lime or fertilizers.

## Progress to Present: Key Milestones

During the 75 years in which the Soil and Water Conservation Society has been in existence, cover crops have waxed and waned in their importance in our agricultural systems (figure 1). The Dust Bowl galvanized attention on the state of US soils and our ability to sustain agricultural productivity over the long term. Soil conservation practices were researched and implemented to reduce erosion by water and wind. Hugh Hammond Bennett, in his text on soil conservation (1939), stated, "Soil completely covered with vegetation is in an ideal condition to absorb moisture and resist

**Figure 1**

**Cereal rye cover crop in southeastern Indiana. Photo by Eileen Kladivko.**

the inroads of erosion, provided the cover is continuous and the soil is well permeated with roots." Later he discussed seasonal cover crops as a way to keep the soil protected during times of the year when the regular crop is off the ground. In addition to erosion control, he identified cover crops as useful for "conserving those soluble plant nutrients subject to loss by leaching," and adding organic matter to the soil.

Cover crop use took a giant step backward during much of the 1960s and 1970s, as the "miracles of chemistry, genetics, and machinery" increased crop yields tremendously and masked the deterioration of the soil. Maintaining or building soil organic matter was not seen as important, because crop yields continued to increase with improved genetics and more fertilizer, and soil degradation and loss were overcome with tillage by larger, faster, and more powerful machinery. In addition, as farmers changed from small, mixed grain, forage, and livestock farms to larger, more specialized grain production farms, they no longer had a specific reason to grow forage crops or cover crops for livestock feed. Cover crops were not seen as necessary or important. Nitrogen fertilizer was inexpensive and readily available, so the use of cover crops as green manures was not needed. Erosion was still a problem, but the more powerful tillage machinery could till more acres, remove compaction, fill in rills and ephemeral gullies, and mix shallower topsoils with underlying soil to allow for continued high crop production. Much of the knowledge and experience of cover crops was likely lost during this "dark ages" of cover crops.

As no-till planting and other conservation tillage systems evolved from experimental to practical through the 1970s and 1980s, cover crops were seen as an addition to no-till to improve fertility, to enhance weed control, to increase surface cover, and to ameliorate compaction. In South America, cover crops were often considered as a natural complement to no-till. In the United States, studies on using legume cover crops for N production for no-till corn were implemented. Conferences and special publications documented the knowledge and research needs for better integration of legumes into these systems (Power 1987).

Work on cover crops started increasing significantly in the 1990s and has really exploded over the past decade or so. Topics being studied have expanded much beyond the earlier interests in erosion and green manuring. Key drivers for both researchers and farmers have been the concerns about water quality and soil health, but many other topics have also become of interest.

***Water Quality.*** Concerns about water quality, both locally and in places like the Gulf of Mexico and the Chesapeake Bay, drove interest in the potential role of cover crops in reducing nitrate leaching and in controlling erosion and loss of sediment-bound phosphorus in surface runoff. Many researchers have documented reductions in nitrate loads from agricultural fields by growing cover crops during the fallow periods of grain crop rotations (Kaspar et al. 2012; Kladivko et al. 2014), and cover crops are now part of the nutrient loss reduction strategies of many states (figure 2). Phosphorus losses with sediment are generally reduced by cover crops due to their reduction of erosion, but effects on soluble phosphorus are less clear (Blanco-Canqui 2018).

**Figure 2**

**Cycle of the year illustrating times of corn growth (or other summer annual crop), fallow periods, and times with drainage and nitrate leaching. Cover crops can help fill the fallow periods in fall and possibly spring. Illustration by Lou Jones.**

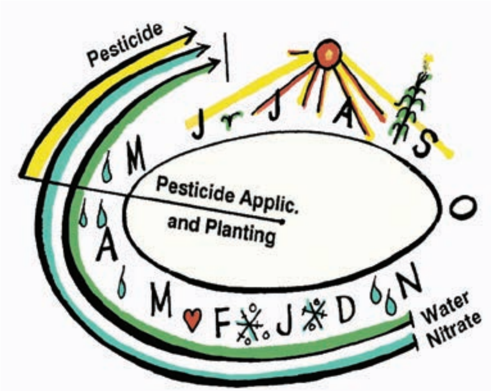


**Figure 3**

**Corn silage field with and without cereal rye cover crop in Iowa. Photo by Tom Kaspar.**


*Soil Health.* Interest in soil health among farmers and researchers has skyrocketed in the past decade, in part due to a strong educational effort by the US Department of Agriculture's Natural Resources Conservation Service. The basic rationale behind the use of cover crops to improve soil health is to have a living, growing plant for more months of the year than our typical annual cropping systems do, thus shortening fallow periods (figure 3). This concept applies whether the purpose is soil erosion and nitrate leaching management, as articulated by Bennett (1939), or whether the goals are broader and include feeding soil organisms, building soil organic matter, improving soil physical properties, and improving overall productivity (Kaspar and Singer 2011; Fisher 2020).

***Nutrient Cycling.*** Nutrient cycling is one aspect of the larger soil health umbrella affected by cover crops. Studies include both the use of legumes to produce N and the use of nonlegumes to scavenge and recycle N. Many questions are being asked, including the amount of N produced or scavenged and the timing and amount of N released, for both shoots and roots for different cover crops, soil types, and locations. Some recent work discusses managing the tradeoffs between N supply and N retention when growing cover crop mixtures (White et al. 2017), as an example of the complex interactions occurring.

***Crop Yield.*** Cover crop effects on cash crop yield is of major interest to farmers as well as researchers. Because cover crops improve soil health, cover crops might be expected to have uniformly positive yield effects. Unfortunately, yield effects vary with the type of cover crop and cash crop, and the specific management practices used in the study. A meta-analysis by Marcillo and Miguez (2017) showed a neutral to positive yield response of corn to cover crops, with more positive responses occurring with legume cover crops, as expected due to N contributions from the legume. Soybeans have in general shown more positive yield responses to cover crops than has corn, although yield response is also sometimes neutral. Although yield improvements are usually a goal, the bottom line profitability may still be improved even when yields are not, due to a variety of other factors (Myers et al. 2019). Even so, understanding why cover crops have not consistently improved crop yields over the long term will allow us to reach the full potential of cover crops.

***Water Conservation.*** Cover crops protect the soil surface and often lead to increased infiltration and less evaporation, thus conserving water for use later in the growing season. The effectiveness of cover crops in improving crop water supply depends very much on the management of the cover crop system, and whether water supply is a primary purpose of the manager or not (Ogilvie et al. 2019).

***Climate Resiliency, Greenhouse Gas Emissions, and Carbon Sequestration.*** Improving resilience to climate stresses has become of great interest over the past decade, along with contributing to mitigation of climate change by sequestering carbon and reducing greenhouse gas emissions. Recent meta-analyses have reviewed the literature about cover crops for both mitigation and adaptation (Kaye and Quemada 2017). Overall the authors noted very few tradeoffs between the adaptation and mitigation purposes for cover crops, suggesting that researching and promoting cover crops for ecosystem services related to climate resiliency would be synergistic with services related to mitigation. Increased climate resiliency may arise from cover crop impacts on water infiltration and retention, erosion control, nutrient cycling, and overall soil health.

***Grazing and Forage.*** One of the places where cover crops may provide economic benefit over the short term is when they can be grazed by livestock or cut for forage (Myers et al. 2019). Farmers have implemented numerous variations on the theme, including single species covers or simple or complex mixtures of covers. They gain the forage value of the cover along with soil health improvements from the cover crop roots and the shoot growth remaining after grazing/cutting, along with manure from the grazing animals.

***Pest Control (Weeds, Insects, and Natural Predators).*** Cover crops may have effects on weeds, insects, natural predators, and diseases. Work is being conducted on the balance between pests and beneficials, for example, and management strategies to increase populations of natural predators. Similarly, research on the impact of cover crops on soil fungi and bacteria in terms of diversity and presence of both beneficial and pathogenic species is ongoing. The ability of cover crops to suppress weeds is also highly dependent on the specific cover crops and management practices used, including planting and termination dates of the covers, seeding rates, tillage system, and other weed management practices used (Osipitan et al. 2019). The challenge of herbicide-resistant weeds in some locations has provided extra motivation for research on cover crop alternatives for control of these weeds.

***Economics.*** As mentioned earlier, the economics of integrating cover crops into a cropping system is of paramount importance to farmers. Although the many benefits to soil health and water quality are well known, they often don't provide an immediate economic benefit to the farmer in terms of yield increase or input cost decrease. Myers et al. (2019) provided an assessment that includes some less obvious ways that cover crops can pay over the shorter term, before yield increases are evident. Some of the potentially short-term benefits have already been discussed (grazing, herbicide resistant weeds, soil moisture management), but others include ameliorating soil compaction, speeding up the transition to no-till, and sequestering manure nutrients. The report also reminds readers to consider cover crops as an investment, akin to some other actions like lime addition or new machinery purchases, that may not pay off in the first year.

***Tools Developed to Facilitate Progress.*** Modern no-till planters and drills have been crucial to the adoption of cover crops as well as for no-till cash cropping itself. Being able to no-till the cover crop in fall into the cash crop residues saves time, allowing farmers to seed covers immediately after harvest without waiting to do fall tillage. Likewise, terminating the cover crop in spring and no-till planting the cash crop into the cover crop, without needing multiple tillage passes to incorporate the cover crop, saves time and increases options for the farmers. In fields that are not in a no-till system, the ability of cover crop seeding implements to establish a stand quickly in the fall are still key. Other innovations for seeding cover crops, like high-clearance seeders, aerial seeders, interseeders, and planters that work well for "planting green" (planting cash crop into still living cover crops), are increasing the options for getting covers established. Improved herbicide technology and development of roller-crimpers have allowed for termination of cover crops without the necessity of tillage, for those covers that are winter-hardy.

## Progress to Present: Lessons Learned

Research and farmer experience over the past 75 years have provided many advances in knowledge and practice along with some lessons learned. First, there is a learning curve for farmers, researchers, crop advisors, and others as they start to integrate cover crops into their farming operation or their research studies. Management practices must be tailored to the site, cropping system, machinery, logistics, and available time and labor. Additionally, the intended purpose of the cover crop is important. Management practices and timing that might be best for one cover crop purpose may cause problems or failure for another purpose. For example, growing large amounts of a grass cover crop may be best for N scavenging and weed suppression, but can cause cash crop yield declines due to N immobilization. Conversely, if a cover crop is planted too late or does not overwinter and there is very little growth, then it is unlikely to provide any benefits regardless of the purpose. Not only does the cover crop management need to be tailored to the purpose, but the overall cropping system management will likely need to be modified to integrate cover crops successfully. There are numerous examples of farmers or researchers saying that a new practice "doesn't work," when in fact the management was inappropriate for the site and the desired purpose. Some of this learning must occur through trial and error as the practice is adapted to the cropping system, machinery, and logistics of a particular operation. Some of the learning, however, should occur by reading previous work and talking with farmers and others with experience. Thus, today there are many efforts to facilitate learning of farmers, advisors, and researchers in field days, workshops, and outreach materials of many types.

## Plans for the Future

A recurring theme is that both the selection and the management of a cover crop depends on the specific purpose for the cover crop and on the specific soil, climate, and cropping system. Thus, future research should include studies of basic principles related to cover crop suitability for different purposes, and locally based studies to evaluate cover crop effectiveness in specific soils, climates, and cropping management systems. Delgado and Gantzer (2015) expressed this idea as the 4Rs for cover crops: choosing the *right* cover crop, seeding and terminating it at the *right* time, and using the *right* management practices at the *right* location.

Future research should continue to build on the knowledge gained over the past 100+ years, related to cover crop effects on crop yields, economics, water quality, soil health, water conservation, pest management, grazing, and resiliency to climate stresses. In particular, more attention is needed on (1) site specific selection and management for specific purposes; (2) multifunctional cover crop systems to meet several purposes in an optimized way, including the use of multispecies mixes; (3) cover crop breeding and selection for different purposes and environments; (4) how long it takes for measurable benefits to occur and ways to speed up this process; (5) practical economics at the farm scale for better accounting of cover crop benefits; and (6) improved technologies for cover crop seeding and termination, especially given a changing and variable climate.

An important goal for policymakers would be to remove various disincentives and barriers that hinder cover crop adoption and innovation by farmers. This includes integrating cover crops into regular farm policy, programs, and crop insurance. It may also include new types of incentives that reward farmers for using cover crops for the many ecosystem services they provide.

New opportunities for agribusiness have been opened by the increased interest in cover crops. Advice and service can include helping customers evaluate their desired goals for cover crops, developing site-specific recommendations for their fields, and offering seeding and termination services. As labor and cover crop expertise are often limited on many farms, co-ops and other agricultural infrastructure have an opportunity to provide timely service to increase cover crop adoption.

Cover crops have many benefits and offer new opportunities to improve crop production, the environment, and the agricultural economy. There is momentum surrounding cover crops, and the time is ripe to integrate cover crops more fully into our modern agricultural systems to reap their full potential!

## Resources to Learn More

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- Northeast Cover Crops Council (NECCC). http://northeastcovercrops.com/
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- Sustainable Agriculture Research and Education (SARE). https://www.sare.org/
- USDA Natural Resources Conservation Service (NRCS), Soil Health. https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/
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# 28

Practitioner's Perspective

# Marketing Conservation Agronomy: Cover Crops from Two Practitioners' Points of View

*Sarah Carlson and Alisha Bower*

The creation of the Soil and Water Conservation Society 75 years ago came during a period of immense loss of the natural resource base upon which US agriculture had developed. The Society's overarching goal was to bring together professionals to better foster the science and art of conservation practices. Early practitioners focused predominantly on edge-of-field practices or built natural infrastructure to reduce soil losses from a field. Practices like terraces and erosion control structures were key to reducing soil erosion. In a sense, the Society's role was to perform the function of an advocacy organization for conservation and better environmental stewardship. Today many conservation professionals are realizing that to reach every acre our focus must double down at the intersection of conservation and agronomic production. We feel the same urgency to be promoters of practices that benefit the natural resources that agriculture depends on, but from an agroecological lens. Why can't we create an agriculture that does not just benefit from a strong natural resource base but that improves it?

Our work as professionals at Practical Farmers of Iowa (PFI) is focused on the intersection of conservation and agronomy. We tackle the forbidden, tricky space of pushing the dominant cropping system to do better, for example focusing on practices in the field like cover crops, managed grazing, and diverse crop rotation. PFI exists to advocate on the behalf of agriculture as a solution to many of our natural resource and conservation challenges. The

**Sarah Carlson** is strategic initiatives director and **Alisha Bower** is operations director at Practical Farmers of Iowa, Ames, Iowa.

recent history of cover crop adoption in Iowa shows a similar change in message from conservation professionals over time toward a more agroecological focus that can impact natural resource stewardship at scale.

"Cover crops for water quality" was the main mantra of farmers, the US Department of Agriculture Natural Resources Conservation Service, and conservation professionals as the soil health and regenerative agriculture movement reached Iowa around 2010. Presentations focused on the nitrate-reducing benefits of cover crops, the soil erosion reductions from cover crops, and the overall idea of better soil health. Studies at the Iowa State University agronomy farm showed increases in organic matter from long-term cover cropping in a corn and soybean system. These messages reinforced the idea that natural resource stewardship could occur in the dominant agricultural system, but little attention was made as to how these practices also improved agronomic production.

Many early adopter farmers began experimenting with these practices of greater continuous living cover. They tried the famous cover crop radish and sometimes grew radish tubers as big as a small child. They seeded legumes from planes and tried to co-seed cover crops into standing corn. They may have even grown big summer cover crops after harvesting small grains for cover crop seed in July and then brought cows to graze those summer covers. These early adopters learned that in a corn–soybean system in Iowa there are only a couple of cover crop options that will consistently work—cereal rye is king. Our message and farmers' message focused on how cover crops benefited natural resources and not much else. After initial rapid growth from 4,047 to 101,171 ha (10,000 to 250,000 ac) from 2010 to 2013, cover crop adoption slowed to around 40,469 additional ha (100,000 additional ac) annually, falling short of Iowa's 9 million ha (23 million ac) of corn and soybean production. PFI staff started seeing farmers conducting research around ways cover crops could benefit more than natural resources. In the late 2000s, farmers who had used cover crops for four to five years began to notice improved weed control from a cover crop. Some farmers growing a diverse crop rotation with a legume cover crop saw that they could cut their nitrogen (N) use by 100 kg ha$^{-1}$ (90 lb ac$^{-1}$) and yield the same amount of corn. Others with cattle in feedlots noticed that if those animals left the feedlot and winter grazed cornstalks with an oat and cereal rye cover crop mix they could save on expensive stored-feed costs. All of these projects resulted in PFI and farmers shifting the message to ways the stewardship of natural resources benefitted agricultural production.

Today at meetings around the state of Iowa and beyond, PFI staff and farmers are using slightly different rally cries, including "cover crops for better weed control," "cover crops for less nitrogen," and "cover crops for grazing cattle." The message is now about ways that cover crops, diverse crop rotations, and managed grazing can benefit farmers' pocketbooks in the short term while benefits to natural resources accrue. These messages are more enticing for farmers in the middle adopter group who are less interested in joining the soil health movement. One central Iowa farmer who has used cover crops and no-till for six years commented that two of his neighbors who use full width tillage and don't use cover crops asked him how he was able to harvest his 2019 crop on time. The neighbors' combines were constantly stuck in the mud forcing them to delay harvest. The continuous living-cover farmer remarked that his soil structure must have changed. He shared with his neighbors that cover crops and no-till over the past few years were allowing his combine tires to stay up out of the mud and able to run. His story was not the only one shared at meetings and on social media during the falls of 2018 and 2019 across the Midwest.

What are the short-term economics of continuous living-cover practices in Iowa? From data that PFI collects for our cover crop programs, farmers are spending about \$77 $ha^{-1}$ (\$31 $ac^{-1}$) on seed and application of a cover crop. The cover crop seed of choice is usually cereal rye, and the favored application method shifts between airplane, drill, or spread with fall fertilizer depending on the fall weather conditions. When there is more rain at harvest or harvest is predicted to be delayed, farmers use a plane, but when harvest is on time, they prefer the cheaper fall fertilizer or drill method. Fall fertilizer application is the fastest way to get cover crops established. Where can a farmer offset the \$77 $ha^{-1}$ (2019) cover crop expense to afford cover crops in the short term? On a crop-only farm, PFI farmer-researchers eliminated an entire second pass of herbicides—the postemergence application—when they achieved a good cover crop stand. That can be valued close to \$99 $ha^{-1}$ (\$40 $ac^{-1}$). Others have seen that they are yielding about 336 kg $ha^{-1}$ (5 bu $ac^{-1}$) more soybeans when following an overwintering cover crop compared to a fallow field ahead of soybeans. Other farmer-researchers are cutting some herbicides and piecing that together with reductions in tillage, which together more than cover the \$77 $ha^{-1}$ in cover crop expense. These changes can occur within the first three years of adding the practice as farmers become more comfortable with the changes. When livestock are present on the farm or can be contracted from a neighbor, additional profitability can be made by feeding cover crops to livestock. Cow-calf and feedlot owners have worked on improving their fall establishment by using an airplane or Hagie overseeder to get an early start on growth prior to fall harvest by overseeding the cover crop into standing corn or soybeans. Once crops are harvested, farmers are able to chase the combine with cows ready to glean grain, cornstalks, and sugary cover crops in the field. This has allowed cattle producers to cut their stored-feed costs by \$222 $ha^{-1}$ (\$90 $ac^{-1}$) when hay costs \$136 $t^{-1}$ (\$150 $tn^{-1}$).

However, farmers are not stopping the cover crop innovation with cutting costs through less herbicides and stored feed. Farmers are paying attention to N application rates for corn and wondering if after six or more years of a cover crop holding at least 30% more N in the field and out of the tile line, that there should be some returned to the crops. Maybe purchased N could be reduced. Farmers are conducting N rate trials to see if in randomized, replicated strips 22.7 kg (50 lb) less N after repeated use of a cover crop yields the same as a control with higher rates of N. So far, on-farm data suggest that farmers can apply less than the recommended Maximum Return to Nitrogen (MRTN) values and still maintain corn yield.

Practices like cover crops, diverse rotation, and managed grazing can have clear benefits for a farmer's pocketbook when they are used strategically for production purposes. PFI's main goal is to help farmers conduct the necessary research and share those results and observations with other farmers and the wider community to help everyone in agriculture save time and money. Getting the numbers right on cover crops and its potential return is a game changer. The short-term costs of a cover crop can be almost fully offset through reduced inputs in the crop year. The long-term benefits, like reduced reliance on N fertilizer, take more commitment, but can double the economic impact of the practice and be realized after continuous cover cropping for more than five years. These new messages all work to entice middle-adopter farmers to try these practices, but the information needs to be shared more.

If we are to improve natural resources at scale, covering every acre and inspiring greater adoption of continuous living cover practices among all farmers, professionals must start working at the nexus of agriculture and conservation and shift our lens to an agroecological focus. We must use new messages like "cover crops for better weed control" to reach every acre. Fortunately, the time is right. Decreased effectiveness of inputs such as herbicides due to greater weed resistance across wide swaths of the country make practices like cover crops and diverse crop rotations affordable solutions that also happen to conserve and protect resources through reduced soil erosion and improved water quality. Tackling our natural resource concerns will take a massive change on the landscape, one that we can only afford by tying conservation to production agriculture.

# 29

# The Future of Soil, Water, and Air Conservation

*Jorge A. Delgado, Clark J. Gantzer, and Gretchen F. Sassenrath*

The Soil and Water Conservation Society (SWCS) held its 75th conference in 2020, a journey that started with its first meeting held in Chicago in December of 1946. At the time, there was not a professional society to support the new profession of soil conservation. However, Hugh Hammond Bennett, the "father of soil conservation," and a few other conservationists began discussions about the need to develop a professional society in this emerging new field. In addition to meetings, these founding members provided an outlet for research and discourse through the *Journal of Soil and Water Conservation*. Today, the SWCS (first known as the Soil Conservation Society of America) is a multidisciplinary professional society that serves as a catalyst to bring together conservation practitioners, scientists working in conservation, and other professionals working in related fields.

The chapters of this anniversary publication have primarily focused on the history of conservation during the last 75 years, with some including even earlier history. This unique collection covered the history of soil and water conservation practices, irrigation, adaptation to a changing climate, soil health, nutrient management, carbon (C) sequestration, soil and water conservation modeling, conservation policy, conservation economics, social aspects of implementation of conservation, precision conservation, water quality and quantity, and other

**Jorge A. Delgado** is a research soil scientist with the USDA Agricultural Research Service Soil Management and Sugar Beet Research Unit, Fort Collins, Colorado. **Clark J. Gantzer** is an emeritus professor of soil and water conservation in the School of Natural Resources at the University of Missouri, Columbia, Missouri. **Gretchen F. Sassenrath** is a professor of agronomy at Kansas State University, Parsons, Kansas.

related topics. Both scientific and practitioner manuscripts explored the topics to present a more complete view. The authors presented their topics from the perspective of how the history of conservation in the United States during the last 75 years has advanced the goals of soil and water conservation.

## Evolution of Soil and Water Conservation

In "The Soil and Water Conservation Society: The Society's Beginning," Gantzer and Anderson (2020) described some of the early history of SWCS and reported that in the early 1900s there was a misconception that soil productivity was inexhaustible and soil fertility was permanent. The authors reported that efforts of conservationists, led by Hugh Hammond Bennett, shifted the perception that natural resources were absolute and raised public awareness that the United States needed a soil and water conservation movement and policy. The 1929 US congressional budget approved the first 10 US Department of Agriculture (USDA) research stations, which conducted soil erosion research and generated key data in the early 1900s. Gantzer and Anderson (2020) reported that Bennett used this early data, together with the detrimental effects of soil erosion leading to the disastrous Dust Bowl during the 1930s, to call attention to the need for a national policy for soil and water conservation. Bennett's work contributed to the enactment of Public Law 46, which established the USDA Soil Conservation Service (SCS) in 1935. Bennett, who was appointed the first chief of SCS, and a few other conservationists began discussions about the need to develop a professional society in this emerging new field. The field of soil and water conservation has evolved since the 1930s and has been embraced around the world, including by the United Nations, which promotes conservation agriculture for food security and sustainability.

Providing a global perspective, Lal (2020a) presented recommendations for "Advancing Climate Change Mitigation in Agriculture while Meeting Global Sustainable Development Goals." He discussed some of the sustainable development goals of the United Nations, such as ending poverty, achieving zero hunger, clean water, and sanitation, pointing out that we are behind in reaching these goals. Lal reported that if they are not achieved, it will be difficult to improve sustainability; for example, if the goal to achieve zero hunger is not met, that will continue to complicate other sustainability efforts. Lal explained how soil C sequestration, which can benefit climate change adaptation and mitigation, can also improve soil properties and advance sustainability. The information presented supports the author's conclusion that we will need to use soils to sequester C and promote soil health in order to decrease greenhouse gas emissions and achieve the goal of zero emissions by 2050. Lal argued that agriculture can be a key solution for climate change mitigation and adaptation during the 21st century, rather than a source of greenhouse gas emissions, while also addressing related environmental problems. Lal also delved into the ways worldwide restorative/regenerative agriculture can contribute to sustainable development goals. Lal reported that adoption of conservation agriculture and other practices that sequester C are critical for advancing sustainability and food security.

## Importance of Social and Economic Factors

The relationship between socio-technical and economic changes during the last 75 years, agricultural land use, and soil and water conservation adoption in the United States was covered by Arbuckle (2020) in "Ecological Embeddedness, Agricultural 'Modernization,' and Land Use Change in the US Midwest: Past, Present and Future" and Morton (2020) in "Social Understandings and Expectations: Agricultural Management and Conservation of Soil and Water Resources in the United States." Morton discussed the importance of the Morrill Acts of 1862 and 1890, which formed the basis for the land grant university system, the key to transferring scientific knowledge related to agriculture. She stressed that in the last 75 years, and even since the creation of the Morrill Acts over 100 years ago, there was a social benefit in training of farmers for agricultural production. She reported that basic research in agricultural disciplines was translated for training and use by farmers to better manage agricultural systems to increase production. Morton (2020) reported that promoting the adoption of conservation practices by agricultural landowners has been a challenge since the 1935 establishment of the SCS. She noted that although farmers' decisions have always been complicated by production, price, and technology risk, public policies, insurance products, and expert advice have helped farmers manage the risk of sustainable farming practices and decisions that enhance conservation.

Economic incentives have been crucial for on-the-ground conservation practice application during the last 75 years. In "A History of Economic Research on Soil Conservation Incentives," Wallander et al. (2020) discussed the ways economic incentives have helped policymakers and conservation planners encourage practice adoption. The authors presented the early framework for applying economic tools to analysis of soil conservation as well as recent, more complex, and targeted approaches. These conservation economics efforts laid the groundwork to make environmental markets a reality today. Reed (2020) suggested in "Ecosystems Services Markets Conceived and Designed for US Agriculture" that potential market values are large and can provide economic opportunities for farmers who apply soil and water conservation practices. The potential market value is currently estimated at \$5.2 billion for C credits and \$8.7 billion for water quality credits (Reed 2020). These new pollution mitigation markets will require involvement of farmers and their advisors, corporate entities, market administrators, and verifiers. The credits that the farmers acquire by implementing best management conservation practices and soil and water conservation practices need to be quantified, monitored, and verified using satellite imagery, soil testing, and other methods. In chapter 8, Fox and Brandt (2020) presented a case study for protecting ecosystems with a water quality trading program for the Ohio River basin. They reported that there are currently 20 water quality trading programs in the United States and that a breakthrough in water quality trading was achieved by the Ohio River Basin Water Quality Trading Project (the first multistate trading program) through use of soil and water conservation best management practices to trade the benefits of ecosystems services in a watershed.

Social and economic factors influencing conservation practice knowledge and adoption are greatly affected by policy, and in the United States, farm bills have been important for development of conservation policy. Delgado (2020a) reported that agricultural legislation contributed to the development of a national policy creating the SCS and soil and water conservation policies that were catalysts in achieving one of the larger successes in natural resources during the last century: the significant reduction of soil erosion rates to improve the sustainability of agricultural systems, which are critical for food security nationally and worldwide. Agricultural legislation helped to shift the false notion that soil productivity is unaffected by poor management to the understanding that soil resources need protection as a national asset for food security. In "Soil and Water Conservation Society and the Farm Bill: A Historical Review," Otto (2020) tracked the 18 farm bills passed by Congress and explained how civic engagement and efforts such as those of Hugh Hammond Bennett, farmers, and conservationists were funneled to confront the disastrous national issues of the Dust Bowl and lost productivity from eroded soils. Civic engagement has been converted into action through a series of bills passed to address specific, timely issues over the last 75 years, benefitting the nation and the world.

## Managing Water Quantity and Quality Challenges

The history of soil and water conservation in the United States and the world has shown that great challenges are dynamic, and once a given challenge is addressed, others emerge. New challenges for water resources are described by Tsegaye et al. (2020), who discussed water availability for agriculture, current impacts of management, and the potential effects of a changing climate.

They reported that agriculture in the Northeast is driven by abundant precipitation. While southeastern agriculture is also driven by rainfall, the authors noted that irrigation has increased in the region, with negative impacts to groundwater resources via groundwater depletion occurring in the Atlantic Coastal Plain, along the Gulf Coastal Lowlands, and in the Mississippi Embayment. Agriculture in the southeastern United States will potentially be negatively impacted due to a changing climate that could cause droughts and extreme precipitation events (Tsegaye et al. 2020). Additionally, although the Midwest is one of the most productive areas of the world, and it enjoys an abundant water supply driven by precipitation, it is also one of the regions of the United States that is projected to be impacted by climate change due to warmer and wetter winters and springs, more severe and prolonged summer droughts, and greater intensities of storms throughout the year (Tsegaye et al. 2020). Tsegaye et al. (2020) reported that the increased intensity and duration of summer droughts will put pressure on development of irrigation systems for this region, which will increase the use of surface water resources.

The Great Plains region is among the parts of the country that are negatively impacted by a lack of precipitation, as it is a dry region with low water availability, but it is a region where irrigation plays an important role driven by climate, with rainfall and snowfall increasing from west to east. Another important factor is that evapotranspiration increases from north to south in the Great Plains. This region, where agricultural productivity can be doubled or tripled with increased availability of water, is dependent on irrigation from surface water and groundwater resources. Tsegaye et al. (2020) reported that water availability in the Pacific Northwest is highly dependent on winter snowpack, and agriculture and intensive livestock production are driven by irrigation. A changing climate will potentially reduce western mountain snowpack and increase variation in snowpack storage of water, which will continue to drive competing demands.

Since agriculture is one of the largest water users, an important goal is increasing water use efficiency. In "Water Optimization through Applied Irrigation Research," Yost et al. (2020) reviewed irrigation systems and how they have been used to improve water use efficiency. Policymakers, scientists, engineers, practitioners, educators, and farmers have contributed to the improvement of irrigation systems and agricultural water use, and technologies have been the main reason for these achievements. Yost et al. wrote that technological advances have contributed to continued increases in irrigation optimization.

Improving water use efficiency is one way to conserve water, but another component is water quality. In "Water Quality," Delgado (2020) reported that advances during the last 75 years in soil and water conservation contributed greatly to protecting water quality. This was realized by conservationists who raised awareness of the national erosion problem, policymakers who enacted laws that protect water quality, and personnel who collected data, developed best management practices, and implemented conservation practices on the ground. Delgado asserted that one of the biggest environmental successes of the 21st century was the enactment of laws that contributed to the study of soil erosion and amazing advances in applied and basic research and technology transfer (e.g., research programs that provided data used to create the Universal Soil Loss Equation [USLE] and other models that started the quantification of how land management affects erosion). Delgado observed that the SCS transferred technology to farmers to apply conservation practices to prevent future catastrophic erosion events like those that occurred in the 1930s, and to increase conservation on the ground for food security and the sustainability of agricultural systems. The Federal Water Pollution Control Act of 1948 brought the concept of water quality to national attention and also contributed to reducing erosion and sediment nutrient transport to water systems. However, with the advent of the Green Revolution and increase in nutrient and agrochemical application beginning in the 1950s, nutrients were lost from agricultural systems. Congress responded with the Federal Water Pollution Control Act Amendments of 1972, the Clean Water Act of 1977, and the Water Quality Act of 1987 to address these developing concerns. Delgado (2020a) noted that although reduction in erosion was an incredible 20th century conservation success story that contributed to the protection of water quality, the losses of nutrients remain an unresolved environmental problem to this day. Humanity cannot repeat the errors of the past century if it is to improve future water quality (Delgado 2020a, 2020b).

Drainage of land also affects water quality and water budgets. In "Agricultural Drainage: Past, Present, and Future," Shedekar et al. (2020) discussed drainage systems in the United States related to soil and water conservation. Benefits of drainage include removal of excess surface water, improvement of trafficability, and enhanced crop productivity. Disadvantages include greater nutrient and pesticide losses through drainage pathways and loss or alteration of habitat and associated plants and animals. The authors concluded that the benefits of drainage in most systems outweighed the disadvantages. Schafer et al. (2020) presented the potential benefits of implementation of drainage water management systems in the field to improve environmental performance and farm economic viability.

Staver (2020) further described the growing role of dissolved nutrients related to water quality and soil conservation in chapter 17. He discussed the history of dissolved nutrients from the 1830s, when the moldboard plow was introduced, to current times. Excessive tillage, which causes losses of organic C and nitrogen (N), occurred through the 1940s, when yields declined due to lost organic matter and N, and continues in some areas today. The Green Revolution altered the soil nutrient balances, and soil nutrient accumulation and losses increased because of the added nutrients. To address this water quality menace, Moody and Bruulsema (2020) suggested a new nutrient management approach including use of the "4R nutrient stewardship" approach. They reported that the industry's view has changed from an approach of building depleted soil fertility to a new, 21st century approach, where the fertilizer industry considers the impact of nutrient stewardship on economic, social, *and* environmental outcomes. Moody and Bruulsema related that consumers are more aware of environmental issues related to nutrient losses, and this will put more pressure for changes at the farm level to increase stewardship.

Also related to water management and quality, Mushet and Calhoun (2020) discussed how, with regard to wetlands, management has altered during the last 75 years, changing the landscapes across different regions. The authors reported that by the 1600s to 1700s, some farmers were already working to eliminate wetlands by draining and converting them to agricultural land. This process was accelerated in the 1800s to early 1900s when advanced technology for drainage was introduced. These massive efforts to drain wetlands to increase agricultural production prior to the 1960s changed to wetland conservation beginning in the 1960s to 1970s, following recognition that wetlands provide ecological benefits (services) as an essential part of the landscape. Mushet and Calhoun made a strong case for the consideration of wetlands as an integral part of ecosystems. Lemke et al. (2020) presented the case for advancing constructed wetlands to improve ecosystem benefits but acknowledged that the primary constraint for establishment of wetlands was the cost of converting highly productive farmland acres to wetlands.

In summary, there have been tremendous achievements in preserving soil and water quality, including one of the greatest in the 20th century, reduction of erosion rates in the United States. These advances in technology increased water use efficiencies and the capability to grow more food per unit of water applied. Additionally, these advances in conservation of water quantity and quality have helped feed a large percentage of the human population. With that said, we have not resolved the challenge of nutrient losses from agricultural systems, and we continue to significantly impact water (e.g., nitrate [$NO_3$-N]) and air (e.g., nitrous oxide [$N_2O$-N], ammonia [$NH_3$-N]) resources. The emerging challenge of a changing climate will exacerbate the challenges in water quantity and quality, and we will need to continue finding solutions during the 21st century for water management and food security.

## Advancing Assessments of Erosion and Implementation of Soil and Water Conservation on the Ground

In "Modeling Soil and Water Conservation," Flanagan et al. (2020) reviewed conservation modeling efforts during the last 75 years. They reported that the first research on water erosion was in 1917 on seven erosion plots in Columbia, Missouri, and that the creation of the USDA SCS in the 1930s provided the inception for modeling soil erosion. The SCS expanded research on the effects of water on erosion with the creation of 35 soil conservation experiment stations located across the nation. Erosion data were used for calibration and validation of mathematical equations and modeling efforts in soil erosion. Flanagan et al. reported that with the creation of the USDA Agricultural Research Service (ARS) in 1953 and the establishment of the ARS National Runoff and Soil Loss Data Center (NRSLDC) in 1954 at Purdue University, research on soil erosion increased. Both ARS and the NRSLDC, in cooperation with university cooperators, significantly advanced soil erosion modeling efforts. Flanagan et al. reported advances with mathematical descriptions of soil erosion before 1965. They also reported that the NRSLDC stored 10,000 plot years of natural runoff plot data that were statistically analyzed to develop the first erosion prediction model in 1965, the USLE, as well as the first wind erosion equation (WEQ). They observed that modeling erosion has significantly advanced with the models that followed USLE and WEQ and described the more recent models' functions and impact.

The last 75 years has seen a change in how we understand the effects of intensive agriculture on soil health. In the 1930s we used the impact of management on erosion to assess how soil productivity is diminished and how conservation practices can reduce rates of erosion and transport of sediment, soil organic matter, and nutrients off site. Kremer and Veum (2020) discussed in "Soil Biology Is Enhanced under Soil Conservation Management" how those historical goals, which initially focused on protection against soil erosion and losses of nutrients, evolved into new goals that included the care of soil biology and soil health. Karlen (2020) reviewed the evolution, assessment of, and future opportunities of soil health. He proposed that although soil health is a new concept, it has evolved slowly, reflecting SWCS efforts in areas of soil condition, management, protection, and quality. Karlen also noted that many scientists and engineers have contributed to the SWCS mission of advancing the science and art of good land and water use and have contributed to current soil health endeavors. Karlen suggested that a focus on soil health will improve soil management and can help achieve increased global food, feed, fiber, and fuel. Fisher (2020) provided in-field examples of practices that can improve soil health and build resilient cropping systems, including cover crops. The potential negative impacts of intensive agriculture to soil health and soil organic C content could be reduced by applying soil and water conservation practices or switching to less intensive management. Use of cover crops, conservation agriculture, and conservation tillage are examples of management options that can minimize losses of soil C and negative impacts to soil health.

In "Cover Crops: Progress and Outlook," Kladivko (2020) reviewed the history of cover crop use. She reported that cover crops have been used as green manures for thousands of years in China, the Middle East, and Rome to improve soil fertility. In the 1930s, Bennett recommended the use of cover crops to reduce erosion. However, after the 1930s cover crops use declined, due to the Green Revolution and intensive agriculture with increased use of fertilizer inputs, an era Kladivko called the "dark ages" for the use of cover crops. As the use of many practices, such as wetlands and minimum tillage, began to increase in the 1970s and 1980s, the use of cover crops increased, especially in areas where no-till was emerging. As we increase use of cover crops, we should use the 4Rs of cover crops as described by Delgado and Gantzer (2015), selecting the "right cover crop, using the right time of seeding and termination, using the right management practices, and planting the cover crop at the right location" (Kladivko 2020). Kladivko promoted the need to build on the research that has been conducted during the last 100 years to expand the use of cover crops. Carlson and Bower (2020) reported that from a conservation practitioner's point of view, when we use cover crops, we obtain different benefits in agricultural systems and conservation, and they can be part of the solution to many natural resource and conservation problems.

The many conservation practices that have been discussed in the chapters of this book affect soil chemical, physical, and biological properties. Several chapters have reviewed how management practices affect availability of nutrients and nutrient losses. Delgado and Sassenrath (2020) reported that 4R+ management (also called precision conservation or the 7Rs) is an approach that can help reduce nutrient transport across watersheds by connecting nutrient flows from fields to buffer areas, riparian areas, wetlands, and watersheds. Other practices affect soil health and soil biology. Arriaga et al. (2020) wrote about how physical properties of soils have changed with land management, conservation practices, and machinery during the last 75 years. Soil physics measurements are key to assessments of impacts of management and conservation efforts. Knowledge of chemical, physical, and biological soil properties has been used to develop tools that can conduct assessments of management practices. These technological advances of the last 75 years have facilitated assessments of how management can affect erosion processes or other pathways of nutrient losses, such as atmospheric and leaching pathways. Advances in basic and applied research have helped provide solutions that have been implemented on the ground for soil and water conservation.

## Climate Change Creates New Challenges in Soil and Water Conservation for Food Security

Current and future conservation challenges include a changing climate. In chapter 22, Steiner and Fortuna (2020) discussed use of natural resource conservation for managing aspects of climate change. They wrote that in 1953 the soil and water conservation research conducted at the SCS was transferred to the ARS to quantify erosion processes and develop erosion prediction models. In 1956, the long-term carbon dioxide ($CO_2$) monitoring station at Moana Loa, Hawaii, was established, and it has been important in monitoring the effect of anthropogenic activities on atmospheric concentrations of greenhouse gases. The authors asserted that agriculture can be part of the solution to mitigate and adapt to climate change since it has great potential to mitigate greenhouse gas emissions by sequestering C in soils and plants. Steiner and Fortuna reported that it may be easier to adapt cropping systems to a changing climate than rangelands and forests systems that cannot easily migrate to other climatic regions where different species cannot easily be introduced. Lal (2020b) reported in "Conserving Soil and Water to Sequester Carbon and Mitigate Global Warming" that erosion reduces C sequestration by removing organic matter. Although some transported soil C is subject to reaggregation and stabilization, erosion significantly contributes to emissions of methane ($CH_4$), $N_2O$, and $CO_2$, which then contribute to increased greenhouse effects. Because of this, soil and water conservation is important for maintaining the C sequestration process in agricultural systems. Lal (2020b) argued that we need to implement soil and water conservation practices to reduce losses of $CH_4$, $N_2O$, and $CO_2$, which generate greenhouse emissions, and noted that cover cropping can be a significant method to reduce erosion and contribute to C sequestration. Climate change has been identified as one of the greatest challenges that we will be confronting during the 21$^{st}$ century by a large number of scientists and organizations, such as the Intergovernmental Panel on Climate Change (United Nations 2018).

## The Future of Conservation

The chapters of this book describe the last 75 years of successes and failures in soil and water conservation; the impact that they have had on sustainability, agricultural productivity, and food security; and the potential to use agriculture for climate change mitigation and adaptation. Together, this presents a compelling case for the importance of soil and water conservation for all of humanity. The authors reviewed the past and present of soil and water conservation as well as discussed future conservation opportunities. They showed that key advances in soil and water conservation were driven by research that was used to transfer information to policymakers and inform the public of the need for soil and water conservation efforts. An example of this is the creation of the SCS and the national soil and water conservation policies that were implemented to address tremendous challenges of the Dust Bowl and loss of productivity caused by nutrient depletion in the early 1900s. This **golden era of soil and water conservation** (1930s to 1980s) saw many policy developments and the positive impacts that conservation research and practice implementation had on the land.

The greatest successes of soil and water conservation in the 20$^{th}$ century were driven by joint efforts of policymakers (e.g., US Congress), conservation practitioners, universities, and extension personnel—agencies that were formed during this era. These include the SCS (today known as the Natural Resources Conservation Service [NRCS]) and the ARS, federal and university scientists, farmers, the private industry, professional societies such as the SWCS, nongovernmental organizations, and others. Advances in soil and water conservation have contributed to reduced erosion, protection of water quality, and the development of more sustainable agricultural systems. There is much to learn from this era in soil and water conservation and how society responded to major conservation challenges.

In the 1950s and 1960s, society responded to another great challenge that arose as global human population exploded and food demand surged. During the Green Revolution (1950s to 1970s), one of the greatest figures was Norman Borlaug, the "father of the Green Revolution," who received the Nobel Peace Prize in 1970 for his work to intensify agriculture and increase production across the United States and the world. Research during this time had also contributed to conservation practices that were implemented to maintain the sustainability of agricultural systems. Although soil and water conservation are not often mentioned as an important factor in the Green Revolution, by conserving soils and helping maintaining the sustainability and productivity of agricultural systems during the latter half of the 20$^{th}$ century, soil and water conservation was indeed an essential component of the success.

***New Challenges.*** The history of agriculture in the 20$^{th}$ century shows that independent of achievements and advances in soil and water conservation in one decade, they may be followed by new challenges, some that may emerge from the successful solutions to a given problem. For example, new water quality problems surfaced due to the excessive application of nutrients following the success stories of past soil conservation efforts and the Green

Revolution. It became clear by the new millennium that there are both persistent and new challenges, which include the following:

- Water quality challenges because of losses of nutrients, mainly N and phosphorus (P). As detailed in this book, N and P have been identified as major and persistent nutrients degrading water quality across the United States, contributing to hypoxic water bodies.
- A continuing need to increase agricultural production for the growing global population.
- The new effects of intensive agriculture. Although sustainability has been improved from soil and water conservation practices, intensive agriculture still contributes to loss of soil organic C and soil quality and health. (This challenge bears some resemblance to the early 1900s when the plow increased the cycling of nutrients and soil nutrient content was reduced. Today, intensive agriculture continues to reduce soil organic matter levels, and although nutrients are being applied, intensive agriculture nonetheless has some detrimental impacts on soil health and quality.)
- The new challenge of climate change. A changing climate and the occurrence of extreme weather events in some regions because of more extensive storms will increase the potential for erosion and flooding. Conversely, limited precipitation causing extensive droughts in drier climates of the country will increase the potential for wind erosion. Declining snowpack, lower water balances, and higher evapotranspiration resulting from climatic changes will likely increase demand on available surface and groundwater water resources for irrigation and reduce water for aquatic species. Climate change presents major challenges to soil and water conservation and sustainability efforts as well as to agricultural production, highlighting the need for research on use of conservation practices for climate change mitigation and adaptation (Delgado et al. 2011).

These challenges will influence environmental quality and productivity. History has taught us that to confront the soil and water conservation challenges of the 21st century, such as a changing climate, we need to use a focused joint approach that includes actions and cooperation from all stakeholders (e.g., US Congress, conservation practitioners, universities, extension personnel, federal agencies, scientists, farmers, private industry, etc.). Lal et al. (2012), in a *Journal of Soil and Water Conservation* feature paper about adapting agriculture to drought and extreme weather events, wrote, “Together, we must move away from a piecemeal and crisis-driven approach, and adopt holistic and integrated national policies aimed at sustainable management of limited and fragile natural resources."

## Mitigating Soil Losses to Adapt to Climate Change Will Provide Billions of Dollars in Returns

Using the Argabright et al. (1995) assessment of the changes in erosion rates from 1930 to 1992, as well as data from a USDA NRCS (2010) report on the changes in erosion rates from 1982 to 2007, together with the history of the development of policies, agencies, laws, best technologies, and practices for soil and water conservation in the United States, Delgado (2020a) concluded that the period from 1930s to the 1980s was a **golden era of soil and water conservation**. Argabright et al. (1995) reported that the 1930s water (sheet and rill) erosion rates for crop agriculture in the northern Mississippi Valley Loess Hills decreased from 33.4 Mg $ha^{-1}$ (14.9 tn $ac^{-1}$) from 1930 to 14.1 Mg $ha^{-1}$ (6.3 tn $ac^{-1}$) in 1992, with 80% of the reduction occurring by 1982. The reduction in erosion rate via water (sheet and rill) and wind pathways from 1982 to 1992 was about 30% for US cropland (USDA NRCS 2010), and Argabright et al. (1995) reported a reduction of 20% for the Mississippi Valley Loess Hills region. The USDA NRCS (2010) reported a reduction in water (sheet and rill) erosion in US cropland from 9.0 Mg $ha^{-1}$ (4 tn $ac^{-1}$) in 1982 to 6.1 Mg $ha^{-1}$ (2.7 tn $ac^{-1}$) in 2007. For this same period, the wind erosion rate decreased from 7.4 to 4.7 Mg $ha^{-1}$ (3.3 to 2.1 tn $ac^{-1}$). Delgado (2020a) extrapolated that the Argabright et al. (1995) erosion reduction estimates from the 1930s to the 1990s was a good ballpark estimate for the United States. He also used the percentage of reduction in erosion rate from 1992 to 2007 reported by USDA NRCS (2010) to estimate the erosion rate nationally. We acknowledge that erosion rates vary across the landscape and depend on many factors, including site-specific ones. For example, there are sites that are being eroded (e.g., top of a catena), sites that are receiving soil deposition (e.g., bottom of a catena), and sites that being eroded and receiving soil deposition (e.g., middle of a catena).

Delgado (2020a) estimated that by 2007 the United States was losing soil at an average rate of 0.51 mm $y^{-1}$ (0.02 in $yr^{-1}$) compared to the 1930s when the United States was losing soil at a rate of 2.9 mm $y^{-1}$ (0.11 in $yr^{-1}$; readers will recall that the 1930s was when the Dust Bowl occurred, before the establishment of polices and a federal agency [SCS/NRCS] to reduce erosion rates). The Delgado (2020a) rate of 0.51 mm $y^{-1}$ strongly overlaps with the average rate of soil loss for US cropland presented by Montgomery (2007), who reported a range from 0.2 to 1.5 mm $y^{-1}$ (0.01 to 0.06 in $yr^{-1}$) for US and global croplands, with an average soil loss of 0.95 mm $y^{-1}$ (0.04 in $yr^{-1}$) for US croplands. The Delgado (2020a) estimate of the erosion rate for US cropland of

0.51 mm $y^{-1}$ for 2007 agrees with the average soil loss of 0.95 mm $y^{-1}$ reported by Montgomery (2007).

Bakker et al. (2004) reported that for every 10 cm (3.9 in) of soils lost from the surface, 4.3% of soil productivity is lost (yields are reduced). They also reported that the reduction in yields due to the erosion of the next 10 cm will be much larger since the relationship is not linear, but convex. Using the soil erosion rate estimated by Delgado (2020a), we estimate that US cropland has lost an average of 117 mm (4.6 in) of soil since the 1930s. If it were not for the critical actions that took place during the golden era of soil and water conservation, such as the enactment of key pieces of legislation and policies that contributed to the creation of the SCS/NRCS, and collaborative efforts among agencies, farmers, conservationists, universities, the private industry, and others, this loss would have been as high as 261 mm (10.3 in). These joint efforts prevented an average loss of 144 mm (5.7 in).

Using the Bakker et al. (2004) estimate of the impacts of erosion on yields, we estimate that although erosion rates have decreased since 1930, intensive agriculture has reduced potential yields by 5.2%. However, if no conservation practices were implemented, we estimate that reduction in potential yields would be close to 16.5%. This suggests that the implementation of national soil and water conservation policies and the development of best practices during the last 75 years have resulted in 11.3% higher yields than if no soil and water conservation policies or practices were developed and implemented since the 1930s. In 2019 the value of the corn crop was approximately $52.9 billion (Statista 2020a), and the wheat crop value was around $8.8 billion (Statista 2020b). From these numbers, we can estimate that the 11.3% higher productivity is equivalent to a crop production value of about $7.0 billion. If we consider the entire crop area in the United States and the economic value of all the soil conserved since the 1930s, the impact of all of the soil and water conservation policies and practices since then is likely in the hundreds of billions of dollars. This conservation analysis shows that soil and water conservation practices help agricultural systems maintain higher yields and increase crop production value by billions of dollars.

Climate change threatens to increase negative impacts to soil productivity, and there is a need to use conservation practices to adapt to this threat (Delgado et al. 2011). Pruski and Nearing (2002) reported that erosion rates will increase by 1.7% for every 1% increase in total rainfall due to climate change. If, as projections suggest, climatic changes will alter precipitation patterns (e.g., droughts that lead to increased wind erosion), we will again be facing a soil erosion menace in the next 75 years. Even with the increase of soil and water conservation efforts in intensive agriculture, it has been estimated we have lost about 11.7 cm (4.6 in) of soils during the last 75 years, which translates to a significant productivity loss. There are opportunities to use conservation agriculture, minimum tillage, no-till, cover crops, crop residue management, and other practices while considering site-specific factors to minimize the loss of soils during the next 75 years. The challenge of climate change to soil in the next 75 years is real, and its impact will be measured in how many millimeters of soil we lose each year. We can continue reducing the rate of soil loss with conservation agriculture, precision conservation, the 4Rs of cover crops, and other conservation strategies to reduce erosion and help us adapt to a changing climate. Using this assessment to project and compare the effects of climate change on future soil losses under scenarios with and without the use of conservation practices for climate change adaptation, we project that the use of these conservation practices will provide returns in the billions of dollars.

## Forecasting Future Conservation Developments

It is difficult to forecast where soil and conservation may go in the future. To better understand this difficulty, consider technology 75 years ago. In 1945 there were no personal computers, no geographic information systems (GIS), no modeling, no global positioning systems (GPS), no artificial intelligence, no machine learning, no remote sensing, no drones, no big data, no Internet, no cell phones, no capability for spatial assessments of nutrient management or geostatistics, no agricultural machinery for precision management of fertilizer and agrochemical applications spatially across a field. None of these technologies were available in 1945. We simply don't know what solutions will be available in 2095 and how they will benefit soil and water conservation, nutrient management, and ecosystem services.

However, if we project where soil and conservation may be headed, a question to ask is, Where will humans be living in 2095? Will humans be living on the moon or Mars? Among the goals of space programs, such as the National Aeronautics and Space Administration (NASA) Artemis program, is to develop a sustained, long-term presence on the moon. It is unclear where we will be in 75 years as far as the potential for a permanent presence on the moon and sources of food for future exploration of space, but if we develop a permanent presence on the moon or even other planets, conservation will be at the center of future space agriculture for nutrient management and water management. Liu et al. (2016) reported on the potential to use artificial photosynthetic systems to chemically reduce $CO_2$ in combination with microorganisms to synthesize biomass, fuels, or chemical products. We need to ask ourselves if in the future we could capture solar energy using bioengineering with a computer chip that could perform artificial photosynthesis to feed humans and/or animals while in space or on Earth.

A second question for the future is, How will food be grown? Data suggest that most food will still be produced in agricultural fields. However, it is possible that more vertical farming will be done in urban environments or close to urban centers. Vertical farming is controlled-environment agriculture where plants are grown using hydroponics and similar techniques and are sometimes accompanied by aquaculture where fish are farmed in the same system (Wikipedia 2020). These techniques are being used today to grow food but are costly and energy dependent. While these techniques are viable in some small markets today, current projections do not suggest that these production systems will be used to feed large population centers in the next 75 years. Costs of producing food this way will have to be significantly reduced. However, it appears likely that the future of food security for humanity will depend on care of finite soil and water resources to improve water quality and soil health, and to increase agricultural productivity for a growing global population in a changing climate. One question to ask is, Could solar energy provide cheaper energy, together with more efficient management using robotics to make vertical agriculture more viable when located close to large urban centers?

There is potential for microbiome research to improve soil health understanding and connect improvements in soil health to crop quality and animal and human nutrition in the future. It is conceivable that new advances in soil biology will enable the development and application of new biostimulants (materials for environmental modification to stimulate bacteria) to soil and cropping systems as amendments to help increase nutrient use efficiencies, water use efficiencies, and yields, and possibly increase food quality and agricultural sustainability. Advances in soil biology will continue, and there is potential to maximize the interactions of soil microbes and crops to increase productivity. We may also benefit from developing a national soil repository (Manter et al. 2018). Research in these areas is needed to improve knowledge of how cropping systems, varieties, soil, and weather interact with management, and how this knowledge can be used for improving long-term sustainability. It may also be possible to learn how to use new biostimulants to address issues related to climate change mitigation and adaptation. More questions emerge: Could genetic engineering, nanotechnology, and nanorobotics in crops, animals, or microbes provide solutions in the next 75 years that could contribute to increased soil and water conservation, including regeneration and improvement of soil systems that have been degraded? What about solutions that improve monitoring of agricultural systems for better management with these technologies?

Advances in modeling are cascading, and big data, artificial intelligence, and machine learning will likely help provide solutions to challenges in soil and water resource management (Delgado et al. 2019a, 2019b). Future decades should advance robotics use in agriculture, and management methods will contribute to increased agrochemical use efficiencies and reduced environmental impacts (Delgado et al. 2019a, 2019b). Open-access databases, including Agricultural Collaborative Research Outcomes System (AgCROS), are facilitating expanded exchange of agricultural data (Delgado et al. 2018). As databases grow in the future, artificial intelligence and machine learning should enable access to large volumes of information and contribute to the development of new models and analyses across regions, nations, and the globe. Recent advances in machine learning and artificial intelligence should facilitate the development of new agronomic management practices to increase nutrient use efficiencies while reducing nutrient losses to the environment in the next decade. Additionally, new monitoring tools, sensors, and biosensors may allow better monitoring of field conditions for improvement of water management to reduce nutrient leaching and off-site transport of agrochemicals. Another question to ask is, Could robotics, artificial intelligence, machine learning, drones, and other related technologies help improve management for soil and water conservation, and improve weather forecasts to help make improved management decisions?

While the 4R approach is a helpful tactic to improve nutrient use efficiencies, to reduce transport of nutrients across a watershed it will be necessary to use precision farming and precision conservation together. This concept has been developed into the 7Rs for nutrient management and conservation, also called 4R+ (Delgado 2016; Delgado et al. 2019a). Precision conservation has the potential to improve placement and design of buffers, riparian buffers, sedimentation traps, denitrification traps, wetlands, and other conservation practices that could contribute to reducing the transport of nutrients across watersheds and subsequent environmental impacts (Berry et al. 2003; Delgado and Berry 2008). Precision conservation will also help improve the placement of waterways, contour stripping, and other conservation practices within a field. Such measures will increase the effectiveness of conservation practices in the future. When thinking about the future, there are many variables to consider, but one point is certain: no matter where we grow food or how we grow food, or what new technologies we use for agricultural production, soil and water conservation, including management of water and nutrient cycles (e.g., C, N), will need to be at the center of agricultural systems and their surrounding environments.

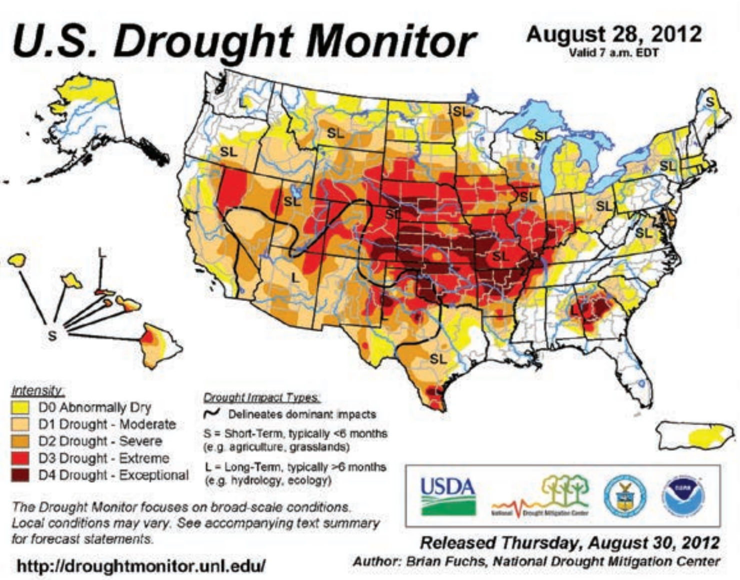
***Climate Change Mitigation and Adaptation.*** The 21st century will be very different from the 20th, which had a more consistent, temperate climate. With climatic changes enhancing projected extreme weather events in coming years (heavy rainfall, droughts, and severe weather), we will need to factor this variability into plans to manage agricultural systems and use risk factors when we design conservation systems and make management decisions for agricultural systems. Hundred-year storm events may be bigger and may occur more frequently (perhaps to the extent that they may even become a norm), so conservation practices will need to be adjusted for the variability and intensity of these weather events, and managers will need to consider how such weather will influence nutrient losses, erosion losses, surface transport of nutrients and agrochemicals, denitrification, and atmospheric losses of N.

There still could be points in the future for a given region where the effects of a changing climate may affect water balances, temperatures, or weather to such a great extent that drastic changes may be required to successfully adapt to them. Lal et al. (2012) reported that during some years extreme weather events may be so severe that it may not be possible to adapt, as was the case in 2012 when the nationwide drought was so great that crop failure was observed at some locations (figure 1). Farmers, policymakers, and personnel working in conservation will need to consider such future changes and evaluate what will be the best crop rotation or agricultural systems, consider introduction of different crops better suited to adapt to the changed climatic conditions, or even develop and use new plant varieties. Another factor limiting productivity may be precipitation changes that alter water resources requiring adaptation of irrigation systems. For example, in regions where there has historically been sufficient precipitation but more frequent growing-period droughts are projected, farmers may need to develop water storage systems to supplement water for irrigation or develop infrastructure for pumping water from groundwater resources that are not currently used. However, if floods increase, altered drainage systems or different planting systems, such as raised beds, may need to be considered. Delgado et al. (2011) described the principles for using soil and water conservation management practices for climate change mitigation and adaptation and noted that only countries that implement policies and practices for climate change mitigation and adaptation will have the opportunity to achieve food security (figure 2).

If responses to a changing climate start influencing the choice of irrigation methods used (such as switching from surface to drip irrigation to increase water use efficiencies), farmers may need to begin to monitor the potential

## Figure 1

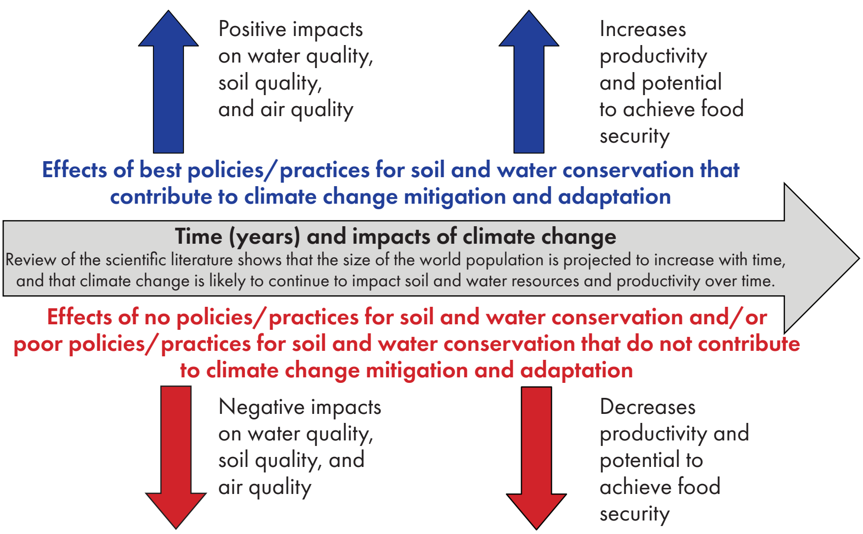
**Drought severity levels across the United States. Notice the severity and extensiveness of drought across the middle region of the United States that extends from the Colorado Rockies, across the Great Plains, and to the Mississippi and Ohio River valleys (Simeral 2012; Lal et al. 2012).**




effects on salinity levels and may need to consider use of varieties or crops more resistant to higher salinity. While it is difficult to predict weather changes, authors in this book present projections of future weather events that suggest shifts in the water balance for regions in the United States. Research will be needed to better integrate the use of models projecting a changing climate with erosion models to make better erosion assessments for regions and evaluate how management practices will address the projected weather changes at the regional level (e.g., Northeast, Pacific Northwest, etc.). There is also a need to connect weather and erosion analyses to models that can assess the impacts on soil health and greenhouse gas emissions. While it will surely be a daunting effort to join these models for regional evaluations, this work may be achieved within the next 75 years. Such an undertaking will require the use of open-access databases, big data, machine learning, and artificial intelligence to help in conducting regional evaluations and plans for soil and water conservation.

**Figure 2**

**There is a close relationship between climate change, limited global water and soil resources, population growth, and food security. As climate change impacts the world's soil and water resources, it threatens to negatively impact food production (i.e., decrease food production and/or food production potential). As the climate changes, conservation practices have the potential to help us achieve maximum sustainable levels of food production, which will be essential to efforts to feed the world's growing population. Good policies/practices for soil and water conservation will contribute to positive impacts on soil and water quality, soil productivity, and efforts toward achieving and/or maintaining food security. These good policies/practices will contribute to climate change mitigation and adaptation. Poor policies/practices for soil and water conservation (or a lack of policies/practices) will contribute to negative impacts on soil and water quality, soil productivity, and efforts toward achieving and/or maintaining food security (Delgado et al. 2011).**




## A Bright Future in Soil and Water Conservation

Independent of future climate changes, we project that new technological advances (e.g., new varieties resistant to drought, new biostimulants, new models, and use of robotics in agriculture with machine learning and artificial intelligence) will aid in the development of new conservation and best management practices to create a changed agriculture in the 21$^{st}$ century. In the 1930s, a new agriculture was created with an emphasis on conservation efforts (**golden era of soil and water conservation**), followed by a period of more intensive agriculture with higher nutrient inputs and greater cultivation (**Green Revolution**). In recent decades, agriculture has increasingly been shifting to a new, smart agriculture using GIS, GPS, remote sensing, and modeling (**era of smart agriculture**). The era of smart agriculture started in the 1990s with precision farming and also encompasses the introduction of precision conservation in the early 2000s and the more recent technological advances (1990s to present). Scientific breakthroughs in biostimulants, genetic engineering, machine learning, artificial intelligence, robotics, and bioengineering will contribute to a new era in soil and water conservation during the next 75 years.

Society has learned that we need to keep conservation management at the center of land use to develop sustainable agricultural systems for food security. History shows that when we develop or implement new agricultural advances, we must conserve the soil, water, and biologic resources to provide solutions for wise land use. Cooperation among policymakers, research centers, conservation practitioners, federal agencies, the private industry, farmers, consultants, nongovernmental organizations, and all others working in conservation will be necessary to conduct research, identify and implement best practices, and confront the challenges of the future. Even if we successfully tackle current great challenges, we must remain vigilant to emerging challenges. With new tools and technologies, we must not forget to use and improve existing tools such as cover crops. We must learn from history. For example, while wetlands were once perceived as only obstacles to farming, we now understand that these ecosystems are a key component of the landscape, with essential functions for a sustainable environment and society. All working in conservation of soil and water need to be mindful to develop systems to maximize productivity and reduce environmental impacts in the future. With all the tools available in the conservation toolbox today, the future looks bright. However, as described by authors in this book, teams who have worked together in the past must continue soil and water conservation efforts, which are an integral part of both food security and national security, in the United States and globally.

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