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The Growing Role of Dissolved Nutrients in Soil and Water Conservation

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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

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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.

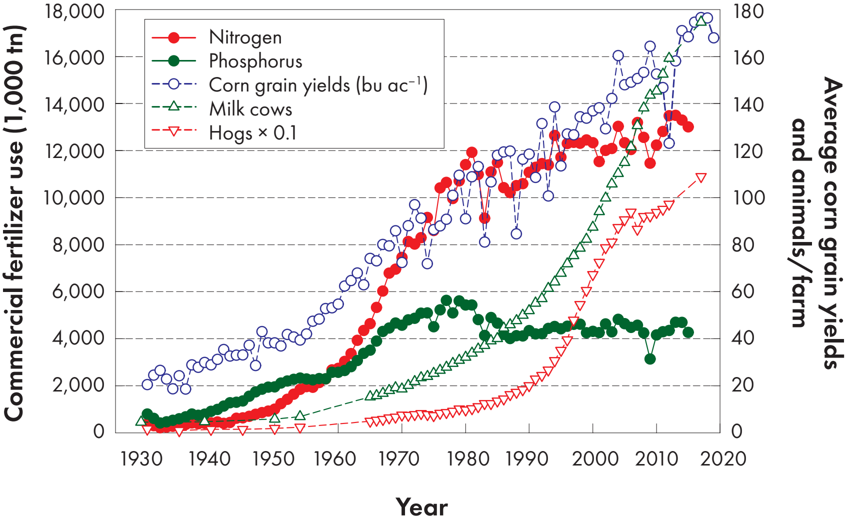
Agriculture Changing Rapidly and the Land Ethic

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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Resources to Learn More

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