

# Emerging nutrient management databases and networks of networks will have broad applicability in future machine learning and artificial intelligence applications in soil and water conservation

Jorge A. Delgado, Bruce Vandenberg, Donna Neer, and Robert D'Adamo

**N**utrient management, including management of nitrogen (N) inputs, was a key part of the Green Revolution, which increased global agricultural production and helped feed the world in the latter half of the twentieth century. While N is often applied to increase yields, and is indeed essential to meet the increased production demand that inevitably follows population growth, an extensive number of studies from regions throughout the globe have reported negative impacts related to N losses to the environment (Smith et al. 2018; Follett and Walker 1989; Hey 2002; Hey et al. 2005; Greenhalch and Sauer 2003; Delgado and Follett 2010; Juergens-Gschwind 1989; Dubrovsky et al. 2010; Glebe 2006), particularly when N was applied at excessive rates, allowing much of the unused N to quickly escape agroecosystems via atmospheric, surface runoff, and/or leaching pathways. Among the negative effects reported by these studies were contributions to the development of hypoxic zones and algae blooms; direct and indirect losses of nitrous oxide ( $N_2O$ ), a greenhouse gas (GHG) that exacerbates a changing climate; nitrate ( $NO_3^-$ ) leaching losses that can negatively impact groundwater and surface water quality; and other negative environmental impacts. There is widespread agreement in the scientific community that emissions of  $N_2O$  are an important source of changes in atmospheric composition that are contributing to a changing climate with higher temperatures and extreme weather events (IPCC 2007a, 2007b; Walthall et al. 2012). Additionally, the economic impacts of reactive N losses to the environment have been reported to be in the billions of dollars; for example, one report estimated that in the United States it costs US\$1.7 billion annually to remove from drinking water

supplies  $NO_3^-$  that originated from agricultural sources (Ribaudo et al. 2011). It has also been reported that these losses could potentially impact human health (Follett et al. 2010; Temkin et al. 2019).

## TWENTY-FIRST CENTURY NUTRIENT MANAGEMENT MUST AVOID THE ERRORS OF THE PAST

There is no question that the addition of N to agricultural systems has been very beneficial to humanity. The higher yields achieved with N application during the Green Revolution helped to combat food insecurity in many parts of the developing world, and arguably even contributed to environmental conservation by reducing the land area required for agricultural production and enabling more land to be set aside for conservation. Yet the fact remains that humans have been significantly impacting the global N cycle as seen in increased atmospheric concentrations of  $N_2O$ , increased levels of  $NO_3^-$  in groundwater and surface water resources, and increased transport of  $NH_3$  (ammonia) from agricultural systems to natural areas, where it can have ecological and other impacts. These negative impacts are sometimes intensified as the N moves through the environment in a phenomenon called the N cascade (Cowling et al. 2001; Galloway et al. 2003).

To protect human health, the USEPA (US Environmental Protection Agency) established the safe limit of  $NO_3^-$  in drinking water as 10 mg  $NO_3^-N$   $L^{-1}$  (USEPA 2019b). However, a recent paper by Temkin et al. (2019) has suggested that negative impacts on human health may be possible at lower concentrations. That paper reported that  $NO_3^-$  concentrations in drinking water as low as 0.14 mg  $NO_3^-N$   $L^{-1}$  were associated with a colorectal cancer risk of one in a million, with greater risk at higher concentrations. Furthermore, it 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 exposure to  $NO_3^-$ . They calculated that the economic costs

from medical expenses could range from US\$250 million to US\$1.5 billion, as well as potentially US\$1.3 to US\$6.5 billion in lost productivity.

There are also recent reports of N contributing to increased microcystin concentrations via impacts to the cyanobacterial community. Microcystin contamination could contribute to gastroenteritis and liver and kidney damage in humans. Both the World Health Organization and the USEPA have established guidelines for microcystin concentration limits that are safe for humans. The World Health Organization (WHO 2011) guidelines recommend microcystin levels in drinking water not exceed 1.0  $\mu g$   $L^{-1}$ , and the USEPA has reported that the safe limit for children under six years old is 0.3  $\mu g$   $L^{-1}$  (USEPA 2015). Hypoxic zones and algae blooms resulting from or exacerbated by nutrient losses could contribute to increased microcystin levels (Monchamp et al. 2014; Smith et al. 2018). Losses of phosphorus (P) have also been reported to contribute to hypoxic zones, which can impact water bodies of economic importance (e.g., Lake Erie) (International Joint Commission 2013). Algae blooms contribute to dead zones that reduce fish populations, as well as to temporarily closed beaches, lakes, and other water bodies, having a significant economic impact on local tourism and fishery industries across the United States.

The environmental, economic, and health questions that emerge as more research is done on the potential impacts of losses of nutrients such as reactive N underscore the importance of learning from the errors of the past: although N fertilizer has provided an unprecedented increase in the global food supply, it has also contributed to increased N losses to the environment. We know that nutrient management will continue to have positive impacts during the twenty-first century but it will also continue to have environmental costs unless we avoid the errors made in the twentieth century. Twenty-first century N management must

Jorge A. Delgado is a research soil scientist, Bruce Vandenberg is an information technology specialist, Donna Neer is a biological science technician, and Robert D'Adamo is a physical science technician at the USDA Agricultural Research Service, Fort Collins, Colorado.

improve and avoid the errors of the past to feed 9.5 billion people by 2050 while simultaneously adapting to a changing climate, increasingly limited water resources, and more frequent extreme weather events, all of which make the task of N management more challenging.

**ADVANCEMENTS IN AGRICULTURAL MANAGEMENT TECHNOLOGY COULD BRING A POSITIVE REVOLUTION FOR HUMANITY DURING THE TWENTY-FIRST CENTURY**

In the 1980s and 1990s, we started integrating technologies such as computers, the Internet, remote sensing, geographic information systems (GIS), and global positioning systems (GPS) in areas such as N management and soil and water conservation to develop tools to help nutrient managers make more informed management decisions. These technologies paved the way for the development of precision farming systems (Pierce and Nowak 1999) and the concept of the 4Rs (Roberts 2007) for improved N management. The first two decades of the twenty-first century have built upon these successes and witnessed innovations such as drones, the widespread use of cellular phones, cloud computing, and growing information systems that are helping us to merge and use big data for soil and water conservation. Modern technologies are allowing us to develop precision conservation systems that can make applying conservation practices in the field that account for spatial and temporal variability a reality (Berry et al. 2003; Delgado et al. 2018a; Tomer et al. 2010, 2013, 2018). Delgado et al. (2019) has proposed that the next revolution will be in precision agriculture, and agriculture in general will be driven by Sustainable Precision Agriculture and Environment (SPAEE, similar to the expanded concept of the 7Rs [Delgado 2016]), which could capitalize on established technologies combined with big data analysis, merging precision agriculture and precision conservation into one management system.

Delgado et al. (2019) reported on the use of big data analysis for sustainable agriculture in a geospatial cloud framework that will allow us to implement machine learning and artificial intelligence for development

of SPAEE. The research impact of these technologies is enhanced by the application of the Findable, Accessible, Interoperable, and Reusable (FAIR) Data Principles described by Wilkinson et al. (2016). Data in harmony with these principles are findable, available for download, interoperable (e.g., between machines), and understood by humans for reuse in in new analyses.

This new revolution in SPAEE will depend heavily on data that will help construct new practices in the virtual world to reduce the

time to deploy new practices that lead to better environmental outcomes (Delgado et al. 2019). The USDA Agricultural Research Service (ARS) Agricultural Collaborative Research Outcomes System (AgCROS) is a growing network of networks (figure 1), and if this data repository expands, it would be able to help researchers conduct local, regional, and national-scale agricultural analyses, and would be able to be used in the future with new technologies such as robotics, artificial intelligence,

**Figure 1**

**Conceptual diagram showing the potential for the Agricultural Collaborative Research Outcomes System (AgCROS), a network of networks, to expand to include additional database networks. Presently, AgCROS comprises the Nutrient Uptake and Outcome Network (NUOnet), Greenhouse gas Reduction through Agricultural Carbon Enhancement Network (GRACEnet), Long-Term Agroecosystem Research (LTAR) Network, Agricultural Antibiotic Resistance (AgAR) Network, the Soil Health Assessment Network (SHAnet), Dairy Agriculture for People and the Planet (DAPP; Dairy Grand Challenge), and Resilient Economic Agricultural Practices (REAP) Network. Additionally, by integrating data from networks such as the Climate Hubs, FoodData Central (FDC), Plant Hardiness Zone Map (PHZM), Animal Germplasm Resource Information Network (A-GRIN), Germplasm Resource Information Network - Global (GRIN-Global), Sustaining the Earth's Watersheds, Agricultural Research Data System (STEWARDS), and Conservation Effects Assessment Project (CEAP) networks, AgCROS will facilitate data flow from current and future AgCROS networks and will promote cooperation among participants in AgCROS, such as NUOnet.**



machine learning, and other technologies (Delgado et al. 2018b). The use of FAIR Data Principles in AgCROS will facilitate this exchange and use of information across many networks (figure 1).

AgCROS was developed in a form that allows for future expansion and connection to additional research networks. One of its networks is the Nutrient Uptake and Outcome Network (NUOnet), which has a vision of “efficient use of nutrients to optimize production and product quality of food for animals and humans, fuel, and fiber in a sustainable manner that contributes to ecosystem services” and also includes the effort to connect nutrient management databases with food quality information for humans and animals (Delgado et al. 2016). Released to the public in November of 2018, NUOnet includes certain types of nutrient management data that were not previously available in AgCROS, such as losses of N via different pathways that contribute to indirect emissions of N<sub>2</sub>O. For additional information about NUOnet and AgCROS, visit the AgCROS and/or NUOnet webpages at the National Agricultural Library website (figure 2; <https://data.nal.usda.gov/dataset/agricultural-collaborative-research-outcomes-system-agcros> and <https://data.nal.usda.gov/dataset/nuonet-nutrient-use-and-outcome-network-database>).

AgCROS (NUOnet) has data about the effects of conservation practices in increasing nutrient use efficiencies and yields and reducing NO<sub>3</sub><sup>-</sup> leaching, GHG emissions, and other nutrient losses. AgCROS (NUOnet) also has data about the effects of new conservation practices and improved N management, such as use of enhanced efficiency fertilizers (EEF) in reducing emissions of N<sub>2</sub>O (<https://data.nal.usda.gov/dataset/nuonet-nutrient-use-and-outcome-network-database>; see data from Dr. Venterea in the USDA ARS open access NUOnet database). It is important that losses of reactive N via surface, leaching, and atmospheric pathways are reduced, including losses via emissions of N<sub>2</sub>O, which contribute to a changing climate; NH<sub>3</sub> volatilization; and NO<sub>3</sub><sup>-</sup> leaching. Additional information about the use of EEF can be found in



AgCROS, which integrates NUOnet with other databases such as the Greenhouse Gas Reduction through Agricultural Carbon Enhancement Network/Resilient Economic Agricultural Practices, previously known as the Renewable Energy Assessment Project (GRACEnet/REAP) (Del Grosso et al. 2014; Jawson et al. 2005; Leytem and Dungan 2014). GRACEnet and REAP have a large collection of data about the effects of conservation practices on reductions in GHG emissions, including use of conservation practices as a mitigation strategy for direct N<sub>2</sub>O emissions.

Recent advances in technologies and best management practices can contribute to reductions in losses of reactive N (Berry

et al. 2003; Delgado and Follett 2010; Snyder and Fixen 2012; Delgado et al. 2018a.). For example, Snyder and Fixen (2012) reported that using best management practices we could reduce N<sub>2</sub>O emissions by 20% to 80% or more. We could use controlled release fertilizers, nitrification inhibitors, and other EEFs to cut back on N<sub>2</sub>O emissions (Delgado and Mosier 1996; Snyder and Fixen 2012). Cavigelli et al. (2012) reported that N<sub>2</sub>O emissions can be reduced by 50% with nitrification and urease inhibitors in dry climates, but there are mixed results in humid climates, and that N<sub>2</sub>O emissions can be reduced by 50% with polycoated ureas in some locations but not in other sites.

The USEPA (2019a) reported that in 2011 about  $1.16 \times 10^7$  t ( $1.28 \times 10^7$  tn) of N fertilizer was purchased in the United States; this information, together with Ribaudo et al. (2011) data from 2006 showing that the use of commercial and manure N was about  $1.61 \times 10^7$  t ( $1.77 \times 10^7$  tn), can be used to estimate that about  $4.4 \times 10^6$  t ( $4.9 \times 10^6$  tn) of manure N was used in 2006 in the United States. The level of N fertilizer used in 2011 is similar to the average of the N fertilizer purchased in the United States in 2005 and 2007, which was  $1.16 \times 10^7$  t (USEPA 2019a). Additionally, the USEPA (2011) reported that in 2002 there was about  $7.7 \times 10^6$  t ( $8.5 \times 10^6$  tn) of N added to agricultural systems with biological N fixation. In other words, agricultural systems in the United States were receiving about  $2.37 \times 10^7$  t ( $2.61 \times 10^7$  tn) of N from these sources in the first decade of the twenty-first century. Nitrogen fertilizer use has trended upwards in recent years, and this trend is projected to continue (Mordor Intelligence 2019).

With this in mind, if we then apply some of the Cavigelli et al. (2012) coefficients for potential reductions in  $N_2O$  emissions from different best management practices and we assume an SPAE approach (precision farming plus precision conservation), we could obtain a rough estimate of the potential reduction in direct and indirect  $N_2O$  emissions from applying best management practices. We propose that by using the right conservation practice(s) with the right N management practice(s) such as nitrification and urease inhibitors, polycoated ureas, the 4Rs of cover crops (Delgado and Gantzer 2015), EEF, no-till, and the use of the 4Rs for improved fertilizer management (right rate, right time, right source and right place [Roberts 2007]), we could potentially reduce direct  $N_2O$  emissions, as well as indirect emissions of  $N_2O$  due to  $NH_3$  volatilization,  $NO_3^-$  leaching, and other pathways of reactive N losses. There is potential to use these practices across the United States to reduce the total emissions of  $N_2O$  (whether from direct or indirect pathways) from commercial and/or manure N fertilizer in the agricultural sector in the United States by 30% to 40% or perhaps even more.

### SPECIAL JOURNAL ISSUE WITH EXAMPLES OF NUTRIENT RESEARCH DATA THAT CAN BE ADDED TO AGCROS FOR POTENTIAL APPLICATION IN SOIL AND WATER CONSERVATION EFFORTS

This special issue about the USDA ARS AgCROS/NUOnet features a series of papers that present data related to soil and water conservation efforts. These papers cover areas related to N balances (Sainju 2019); runoff and leaching (figure 3) (Vadas and Powell 2019); N management in different tillage systems (Balkcom 2019); nutrient distributions in grazed pastures (Franzluebbers et al. 2019); runoff and nutrient losses from conventional and conservation tillage systems (Endale et al. 2019); infiltration into saturated buffers (Jaynes and Isenhardt 2019); a conservation planning and evaluation tool (White et al. 2019); N sources and rates (Mikha et al. 2019); the Conservation Practice Effectiveness (CoPE) Database (Smith et al. 2019); and integration of data for a sustainable food system (Finley and Fukagawa 2019). Data from some of these papers have already been uploaded to NUOnet or to the USDA ARS National Agricultural Library.

The goal of this special issue is to present data about soil and water conservation and showcase the kinds of

diverse data that could eventually appear in NUOnet and AgCROS, which could range from research plot data to regional and national assessments. The next agricultural revolution will be driven by SPAE using databases, networks of networks, and systems of systems (Delgado et al. 2019) that will have data similar to the kinds presented in this special issue. USDA ARS databases such as NUOnet and the USDA ARS networks of networks, AgCROS, are examples of emerging systems that could contribute to the application of machine learning and artificial intelligence in soil and water conservation, which could contribute to reduced erosion and offsite transport of N and P, increased cycling of macro- and micronutrients, and greater adaptation to the twenty-first century's greatest challenge to agricultural sustainability: a changing climate (figure 1). The new revolution driven by SPAE could potentially contribute to food security while reducing environmental impact and helping humanity avoid repeating the errors of the past by helping nutrient managers make informed management decisions that increase nutrient use efficiencies and reduce losses of nutrients to the environment.

#### Figure 3

Location of the study from the Vadas et al. paper published in this special issue. The dataset of this study is part of the USDA Agricultural Research Service Agricultural Collaborative Research Outcomes System (AgCROS) Nutrient Uptake and Outcome Network (NUOnet). This barnyard study was conducted in dairy cattle lots at the US Dairy Forage Research Center farm in south-central Wisconsin, United States. The barnyards of this study are indicated by blue squares. For additional information, see the Vadas et al. paper in this issue, and go to the NUOnet webpage.



## REFERENCES

- Balkcom, K.S. 2019. No tillage and noninversion tillage comparisons across wheat nitrogen rates in Alabama. *Journal of Soil and Water Conservation* 74(6):560-570, doi:10.2489/jswc.74.6.560.
- Berry, J.R., J.A. Delgado, R. Khosla, and F.J. Pierce. 2003. Precision conservation for environmental sustainability. *Journal of Soil and Water Conservation* 58(6):332-339.
- Cavigelli, M.A., S.J. Del Grosso, M.A. Liebig, C.S. Snyder, P.E. Fixen, R.T. Venterea, A.B. Leytem, J.E. McLain, and D.B. Watts. 2012. US agricultural nitrous oxide emissions: Context, status, and trends. *Frontiers in Ecology and the Environment* 10(10):537-46.
- Cowling, E., J. Galloway, C. Furiness, M. Barber, T. Bresser, K. Cassman, J. Willem Erisman, R. Haueberg, R. Howarth, J. Melillo, W. Moomaw, A. Mosier, K. Sanders, S. Seitzinger, S. Smeulders, R. Socolow, D. Walters, F. West, and Z. Zhu. 2001. Optimizing nitrogen management in food and energy production and environmental protection: Summary statement from the Second International Nitrogen Conference. *The Scientific World* 1(S2):1-9.
- Delgado, J.A. 2016. 4 Rs are not enough. We need 7 Rs for nutrient management and conservation to increase nutrient use efficiency and reduce off-site transport of nutrients. In *Soil Specific Farming: Precision Agriculture, Advances in Soil Science Series*, eds. R. Lal and B.A. Stewart, 89-126. Boca Raton, FL: CRC Press.
- Delgado, J.A., and R.F. Follett, eds. 2010. *Advances in N Management for Water Quality*. Ankeny, IA: Soil and Water Conservation Society.
- Delgado, J.A., and C.J. Gantzer. 2015. The 4Rs for cover crops and other advances in cover crop management for environmental quality. *Journal of Soil and Water Conservation*. 70(6):142A-145A, doi:10.2489/jswc.70.6.142A.
- Delgado, J.A., and A.R. Mosier. 1996. Mitigation alternatives to decrease nitrous oxides emissions and urea-nitrogen loss and their effect on methane flux. *Journal of Environmental Quality* 25:1105-1111.
- Delgado, J.A., G. Sassenrath, and T. Mueller, Eds. 2018a. *Precision Conservation: Geospatial Techniques for Agricultural and Natural Resources Conservation*. Agronomy Monograph 59. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.
- Delgado, J.A., N.M. Short Jr., D.P. Roberts, and B. Vandenberg. 2019. Big Data analysis for sustainable agriculture on a geospatial cloud framework. *Frontiers in Sustainable Food Systems*. doi:10.3389/fsufs.2019.00054.
- Delgado, J.A., B. Vandenberg, N. Kaplan, D. Neer, G. Wilson, R. D'Adamo, J. Carter, L. O'Gan, N. Grow, R. Marquez, D. Arthur, M. Eve, S.J. Del Grosso, J.M.F. Johnson, D.L. Karlen, L. Durso, J. Finley, V. Acosta-Martinez, D.B. Knaebel, D. Harmel, and J.D. Derner. 2018b. Agricultural Collaborative Research Outcomes System (AgCROS): An emerging network of networks for national food and environmental security and human health. *Journal of Soil and Water Conservation* 73(6):158A-164A, doi:10.2489/jswc.73.6.158A.
- Delgado, J.A., S. Weyers, C. Dell, D. Harmel, P. Kleinman, K. Sistani, A. Leytem, D. Huggins, T. Strickland, N. Kitchen, J. Meisinger, S. Del Grosso, J. Johnson, K. Balkcom, J. Finley, N. Fukagawa, M. Powell, and S. Van Pelt. 2016. USDA agricultural research service creates Nutrient Uptake and Outcome Network (NUOnet). *Journal of Soil and Water Conservation* 71(6):147A-148A, doi:10.2489/jswc.71.6.147A.
- Del Grosso, S.J., J.W. White, G. Wilson, B. Vandenberg, D.L. Karlen, R.F. Follett, J.M.F. Johnson, A.J. Franzluebbers, D.W. Archer, H.T. Gollany, M.A. Liebig, J. Ascough, M. Reyes-Fox, L. Pellack, J. Starr, N. Barbour, R.W. Polunsky, M. Gutwein, and D. James. 2014. Introducing the GRACEnet/ REAP data contribution, discovery, and retrieval system. *Journal of Environmental Quality* 42:1274-1280.
- Dubrovsky, N.M., K.R. Burrow, G.M. Clark, J.A.M. Gronberg, P.A. Hamilton, K.J. Hitt, D.K. Mueller, M.D. Munn, L.J. Puckett, B.T. Nolan, M.G. Rupert, T.M. Short, N.E. Spahr, L.A. Sprague, and W.G. Wilbur. 2010. *Nutrients in the Nation's Streams and Groundwater, 1992-2004*, Circular 1350. Reston, VA: US Geological Survey.
- Endale, D.M., H.H. Schomberg, C.C. Truman, D.H. Franklin, I.A. Tazisong, M.B. Jenkins, and D.S. Fisher. 2019. Runoff and nutrient losses from conventional and conservation tillage systems during fixed and variable rate rainfall simulation. *Journal of Soil and Water Conservation* 74(6):594-612, doi:10.2489/jswc.74.6.594.
- Finley, J.W., and N.K. Fukagawa. 2019. Integrated data across multiple and diverse disciplines are essential for developing a sustainable food system. *Journal of Soil and Water Conservation* 74(6):632-638, doi:10.2489/jswc.74.6.632.
- Follett, J.R., R.F. Follett, and W.C. Herz. 2010. Environmental and human impacts of reactive N. In *Advances in N Management for Water Quality*, eds. J.A. Delgado and R.F. Follett, 1-37. Ankeny, IA: Soil and Water Conservation Society.
- Follett, R.F., and D.J. Walker. 1989. Groundwater quality concerns about N. In *N Management and Groundwater Protection*, ed. R.F. Follett, 1-22. Amsterdam, Netherlands: Elsevier Science Publishers.
- Franzluebbers, A.J., M.H. Poore, S.R. Freeman, and J.R. Rogers. 2019. Soil-surface nutrient distributions in grazed pastures of North Carolina. *Journal of Soil and Water Conservation* 74(6):571-583, doi:10.2489/jswc.74.6.571.
- Galloway, J.N., J.D. Aber, J.W. Erisman, S.P. Seitzinger, R.W. Howarth, E.B. Cowling, and B.J. Cosby. 2003. The N cascade. *BioScience* 53(4):341-356.
- Glebe, T.W. 2006. The environmental impact of European farming: How legitimate are agri-environmental payments? *Review of Agricultural Economics* 29:87-102.
- Greenhalch, S., and A. Sauer. 2003. *Awakening the Dead Zone: An Investment for Agriculture, Water Quality, and Climate Change*. World Resources Institute: Washington, DC.
- Hey, D.L. 2002. N farming: Harvesting a different crop. *Restoration Ecology* 10:1-10.
- Hey, D.L., L.S. Urban, and J.A. Kostel. 2005. *Nutrient farming: The business of environmental management*. *Ecological Engineering* 24:279-287.
- International Joint Commission. 2013. *Lake Erie Ecosystem Priority: Scientific Findings and Policy. Recommendations to Reduce Nutrient Loadings and Harmful Algal Blooms*. Draft Summary Report. Washington, DC, Ottawa, Canada, and Windsor, Canada: United States Section Office, Canadian Section Office, and Great Lakes Regional Office. [https://legacyfiles.ijc.org/tiny\\_mce/uploaded/FinalDraft%20LEEP-Aug29.pdf](https://legacyfiles.ijc.org/tiny_mce/uploaded/FinalDraft%20LEEP-Aug29.pdf).
- IPCC (Intergovernmental Panel on Climate Change). 2007a. Summary for policymakers. In *Climate Change 2007: The physical science basis*, ed. S. Solomon, et al. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press.
- IPCC. 2007b. *Climate Change 2007: Impacts, adaptation and vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Press.
- Jawson, M.D., S.R. Shafer, A.J. Franzluebbers, T.B. Parkin, and R.F. Follett. 2005. GRACEnet: Greenhouse gas Reduction through Agricultural Carbon Enhancement network. *Soil and Tillage Research* 83:167-172.
- Jaynes, D.B., and T.M. Isenhardt. 2019. Increasing infiltration into saturated riparian buffers by adding additional distribution pipes. *Journal of Soil and Water Conservation* 74(6):545-553, doi:10.2489/jswc.74.6.545.
- Juergens-Gschwind, S. 1989. Ground water nitrates in other developed countries (Europe)—Relations

- to land use patterns. *In* N Management and Groundwater Protection, ed. R.F. Follett, 75-138. Amsterdam, Netherlands: Elsevier Science Publishers.
- Leytem, A.B., and R.S. Dungan. 2014. Livestock GRACEnet: A workgroup dedicated to evaluating and mitigating emissions from livestock production. *Journal of Environmental Quality* 43:1101-1110.
- Mikha, M.M., A.K. Obour, V. Kumar, and P.W. Stahlman. 2019. Soil physicochemical properties influenced by nitrogen sources and rates in the central Great Plains. *Journal of Soil and Water Conservation* 74(6):584-593, doi:10.2489/jswc.74.6.584.
- Monchamp, M., E.R. Pick, B.E. Beisner, and R. Maranger. 2014. N forms influence microcystin concentration and composition via changes in cyanobacterial community structure. *PLOS ONE* 9:e85573.
- Mordor Intelligence. 2019. United States Fertilizer Market – Growth, Trends, and Forecast (2019-2024). Gachibowli, Hyderabad, India: Mordor Intelligence. <https://www.mordorintelligence.com/industry-reports/united-states-fertilizers-market>.
- Pierce, F.J., and P. Nowak. 1999. Aspects of precision agriculture. *Advances in Agronomy* 67:1-85, doi:10.1016/S0065-2113(08)60513-1.
- Ribaudo, M., J. Delgado, L. Hansen, M. Livingston, R. Mosheim, and J. Williamson. 2011. N in Agricultural Systems: Implications for Conservation Policy. Economy Research Report. Washington, DC: Economic Research Service.
- Roberts, T.L. 2007. Right product, right rate, right time, and right place...the foundation of best management practices for fertilizer. *In* Fertilizer Best Management Practices: General Principles, Strategies for Their Adoption, and Voluntary Initiatives vs Regulations. Paper presented at the IFA International Workshop on Fertilizer Best Management Practices, Brussels, Belgium, March 7-9, 2007. Paris: International Fertilizer Industry Association.
- Sainju, U.M. 2019. Improving nitrogen balance with irrigation practice and cropping system. *Journal of Soil and Water Conservation* 74(6):622-631, doi:10.2489/jswc.74.6.622.
- Smith, D.R., M. White, E.L. McLellan, R. Pampell, and R.D. Harmel. 2019. Using the Conservation Practice Effectiveness (CoPE) Database to assess adoption tradeoffs. *Journal of Soil and Water Conservation* 74(6):554-559, doi:10.2489/jswc.74.6.554.
- Smith, D.R., R.S. Wilson, K.W. King, M. Zwonitzer, J.M. McGrath, R.D. Harmel, R.L. Haney, and L.T. Johnson. 2018. Lake Erie, phosphorus, and microcystin: Is it really the farmer's fault? *Journal of Soil and Water Conservation* 73(1):48-57, doi:10.2489/jswc.73.1.48.
- Snyder, C.S., and P.E. Fixen. 2012. Plant nutrient management and risks of nitrous oxide emission. *Journal of Soil and Water Conservation* 67(5):137A-144A, doi:10.2489/jswc.67.5.137A.
- Temkin, A., S. Evans, T. Manidis, C. Campbell, and O.V. Naidenko. 2019. Exposure-based assessment and economic valuation of adverse birth outcomes and cancer risk due to nitrate in United States drinking water. *Environmental Research* 176(2019):108442. <https://doi.org/10.1016/j.envres.2019.04.009>.
- Tomer, M.D. 2010. How do we identify opportunities to apply new knowledge and improve conservation effectiveness? *Journal of Soil and Water Conservation* 65(4):261-265, doi:10.2489/jswc.65.4.261.
- Tomer, M.D., D.B. Jaynes, S.A. Porter, D.E. James, and T.M. Isenhardt. 2018. Identifying riparian zones best suited to installation of saturated buffers: A preliminary multiwatershed assessment. *In* Precision Conservation: Geospatial Techniques for Agricultural and Natural Resources Conservation, eds. J.A. Delgado, G. Sassenrath, and T. Mueller. Agronomy Monograph 59. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.
- Tomer, M.D., S.A. Porter, D.E. James, K.M.B. Boomer, J.A. Kostel, and E. McLellan. 2013. Combining precision conservation technologies into a flexible framework to facilitate agricultural watershed planning. *Journal of Soil and Water Conservation* 68(5):113A-120A. doi:10.2489/jswc.68.5.113A
- USEPA (US Environmental Protection Agency). 2015. Drinking Water Health Advisories for Two Cyanobacterial Toxins. Office of Water 820F15003. Washington, DC: US Environmental Protection Agency. [https://www.epa.gov/sites/production/files/2017-06/documents/cyanotoxins-fact\\_sheet-2015.pdf](https://www.epa.gov/sites/production/files/2017-06/documents/cyanotoxins-fact_sheet-2015.pdf).
- USEPA. 2019a. Commercial Fertilizer Purchased. Washington, DC: US Environmental Protection Agency. <https://www.epa.gov/nutrient-policy-data/commercial-fertilizer-purchased>.
- USEPA. 2019b. National Primary Drinking Water Regulations. Washington, DC: US Environmental Protection Agency. <https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations>.
- USEPA. 2011. Reactive Nitrogen in the United States: An Analysis of Inputs, Flows, Consequences, and Management Options. EPA-SAB-11-013. Washington, DC: US Environmental Protection Agency.
- Vadas, P.A., and J.M. Powell. 2019. Nutrient concentrations in leachate and runoff from dairy cattle lots with different surface materials. *Journal of Soil and Water Conservation* 74(6):613-621, doi:10.2489/jswc.74.6.613.
- Walthall, C.L., J. Hatfield, P. Backlund, L. Lengnick, E. Marshall, M. Walsh, S. Adkins, et al. 2012. Climate Change and Agriculture in the United States: Effects and Adaptation. USDA Technical Bulletin 1935. Washington, DC: USDA.
- White, M.J., M. DiLuzio, M. Gambone, D. Smith, E. McLellan, K. Bieger, J. Arnold, R. Haney, and J. Gao. 2019. Development of Agricultural Conservation Reduction Estimator (ACRE), a simple field-scale conservation planning and evaluation tool. *Journal of Soil and Water Conservation* 74(6):537-544, doi:10.2489/jswc.74.6.537.
- Wilkinson, M.D., M. Dumontier, I.J. Aalbersberg, G. Appleton, M. Axton, A. Baak, and J. Bouwman. 2016. The FAIR Guiding Principles for scientific data management and stewardship. *Scientific Data* 3(1):160018.
- WHO (World Health Organization). 2011. Guidelines for Drinking-Water Quality. Fourth edition. Geneva, Switzerland: WHO Press.