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RESEARCH INTRODUCTION

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

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Nutrient 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).

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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 μg L^{-1}, and the USEPA has reported that the safe limit for children under six years old is 0.3 μg 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

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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

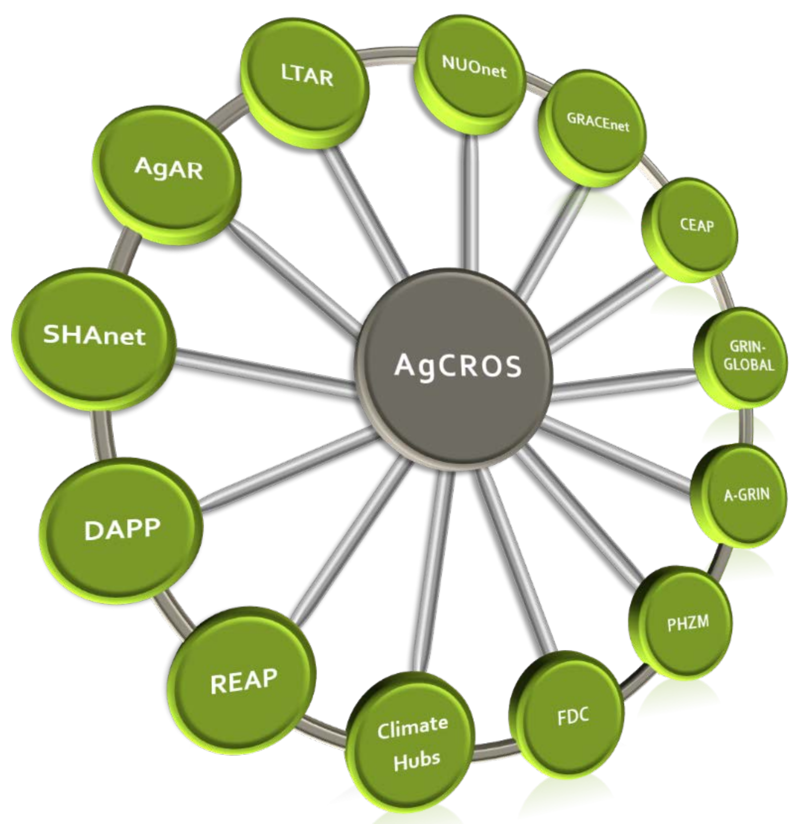
In the 1980s and 1990s, we started integrating technologies such as computers, the Internet, remote sensing, geographic information systems (GIS), and global positioning systems (GPS) in areas such as N management and soil and water conservation to develop tools to help nutrient managers make more informed 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 (SPAE, 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 SPAE. 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 SPAE 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.



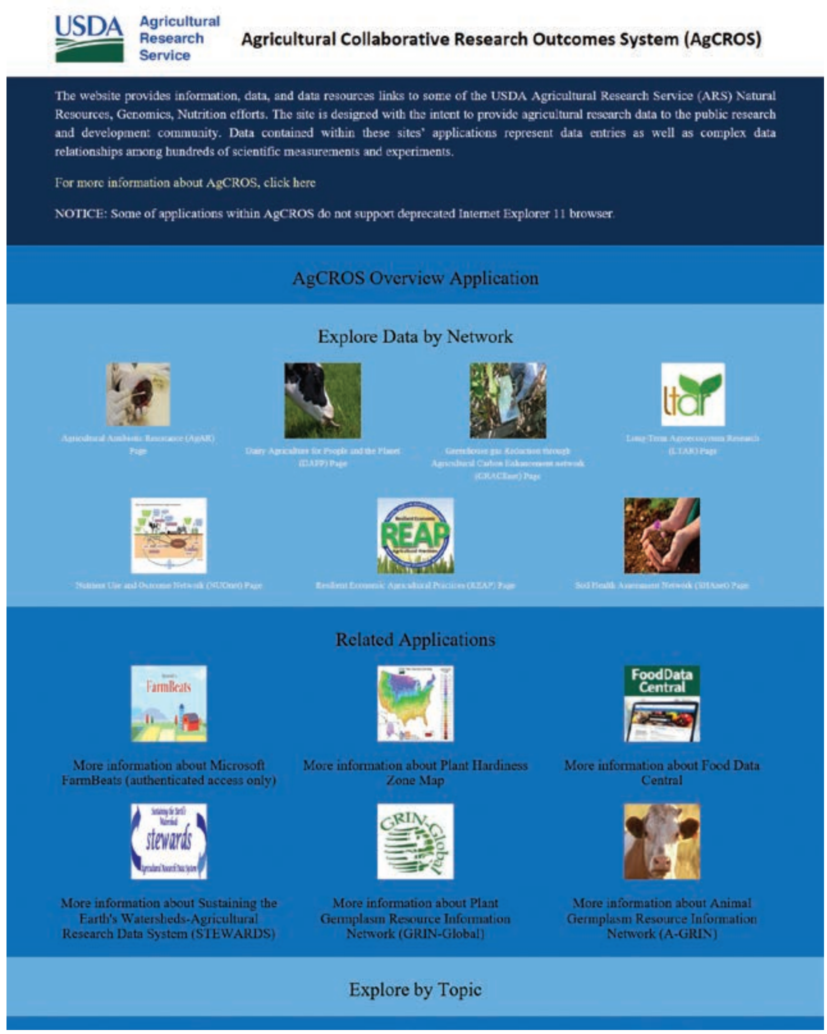
machine learning, and other technologies (Delgado et al. 2018b). The use of FAIR Data Principles in AgCROS will facilitate this exchange and use of information across many networks (figure 1).

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_2O. 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_3^- 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_2O (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_2O, which contribute to a changing climate; NH_3 volatilization; and NO_3^- leaching. Additional information about the use of EEF can be found in

Figure 2

Webpage of the Agricultural Collaborative Research Outcomes System (AgCROS), a network of networks.



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_2O 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_2O emissions by 20% to 80% or more. We could use controlled release fertilizers, nitrification inhibitors, and other EEFs to cut back on N_2O emissions (Delgado and Mosier 1996; Snyder and Fixen 2012). Cavigelli et al. (2012) reported that N_2O 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_2O 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 1.16×10^7 t (1.28×10^7 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 1.61×10^7 t (1.77×10^7 tn), can be used to estimate that about 4.4×10^6 t (4.9×10^6 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 1.16×10^7 t (USEPA 2019a). Additionally, the USEPA (2011) reported that in 2002 there was about 7.7×10^6 t (8.5×10^6 tn) of N added to agricultural systems with biological N fixation. In other words, agricultural systems in the United States were receiving about 2.37×10^7 t (2.61×10^7 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 Isenhart 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.

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