THE NITROGEN CASCADE AND IMPLICATIONS FOR AGRICULTURE

C.S. Snyder
International Plant Nutrition Institute, Conway, AR
csnyder@ipni.net (501) 336-8110

ABSTRACT

Fertilizer nitrogen (N) makes it possible to nourish 40 to 60% of the world's human family. As the global population has increased, there has been an increased demand for food, feed, fiber, and biofuels. Energy prices, commodity prices, and societal demands all influence the production of commercial crops and the amount of fertilizer N consumed. Yield per unit of N input has increased for several principal crops, which indicates that one measure of N use efficiency has improved. Yet, concerns have risen about alteration of the natural N cycle and the water quality and air quality affected by "reactive" N that has been lost from fields and farms. Some of the literature on the sequential effects of the N which has escaped our agricultural systems, known as the N cascade, will be reviewed. Challenges will be identified which underscore our need to enhance fertilizer N use efficiency and effectiveness through improved 4R nutrient stewardship in our major cropping systems.

INTRODUCTION

Approximately 40 to 60% of the world's people depend on fertilizer nitrogen (N) for their existence and food supply (Erisman et al., 2008, Ladha et al., 2005, Stewart et al., 2005), with possibly more dependence as the world's population reaches 9 billion by 2050. Fertilizer N consumption in the U.S. and world has increased during the last several decades (Figure1) in response to expanding global food, feed, fiber, and biofuel demands.

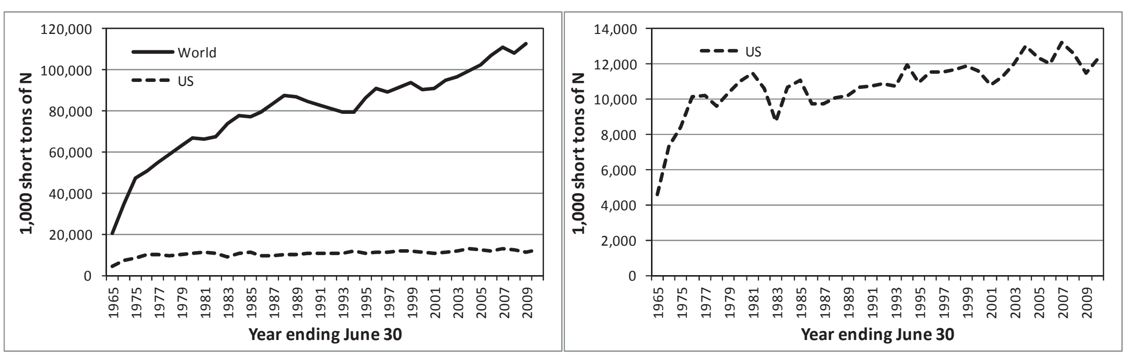

Figure 1. World and U.S. fertilizer N consumption, 1965 to current. (Sources: International Fertilizer Industry Association Statistics 2011 for world values. U.S. values from Commercial Fertilizers annual reports by Association of American Plant Food Control Officials and The Fertilizer Institute).

Scientific concerns are being increasingly expressed about the accumulation of "reactive N" (Nr) in the soil, surface and groundwater, coastal zones and the atmosphere. In contrast to non-reactive gaseous N_2, Nr includes all biologically active, chemically reactive, and radiatively active nitrogen compounds in the atmosphere and biosphere of the earth" (EPA, 2011). The Nr contributions to smog, haze, greenhouse gas (GHG) emissions and climate change, acid rain, coastal eutrophication and "dead zones", stratospheric ozone depletion, and the degradation of natural areas and associated losses in species and species diversity are receiving greater attention in public policy discussions and in regulatory circles. Galloway et al. (2008) called attention to the international flows of N and the Nr distribution patterns associated with the trade of fertilizer, grains, and meat, as well as the cascading sequence of reactions and events that can lead to harm of our soil-water-atmosphere systems and even to human health (Figure 2). "The cascade of Nr from one system to another is enhanced if there is limited potential for Nr accumulation or loss of N_2 through denitrification within a given system and thus increased potential for transfer to the next system" (Galloway et al., 2003). Selected examples of the environmental cascading Nr effects were offered in Galloway et al. (2003), including mention of N transfers in fossil fuel combustion. Attention was drawn to the fact that a large portion of applied N that is not incorporated into and removed in crop harvests may be transferred "downstream" or "downwind" as ammonia (NH_3) and nitrogen oxides (NOx) to the atmosphere, and to water resources as nitrate (NO_3^-) and other N forms.

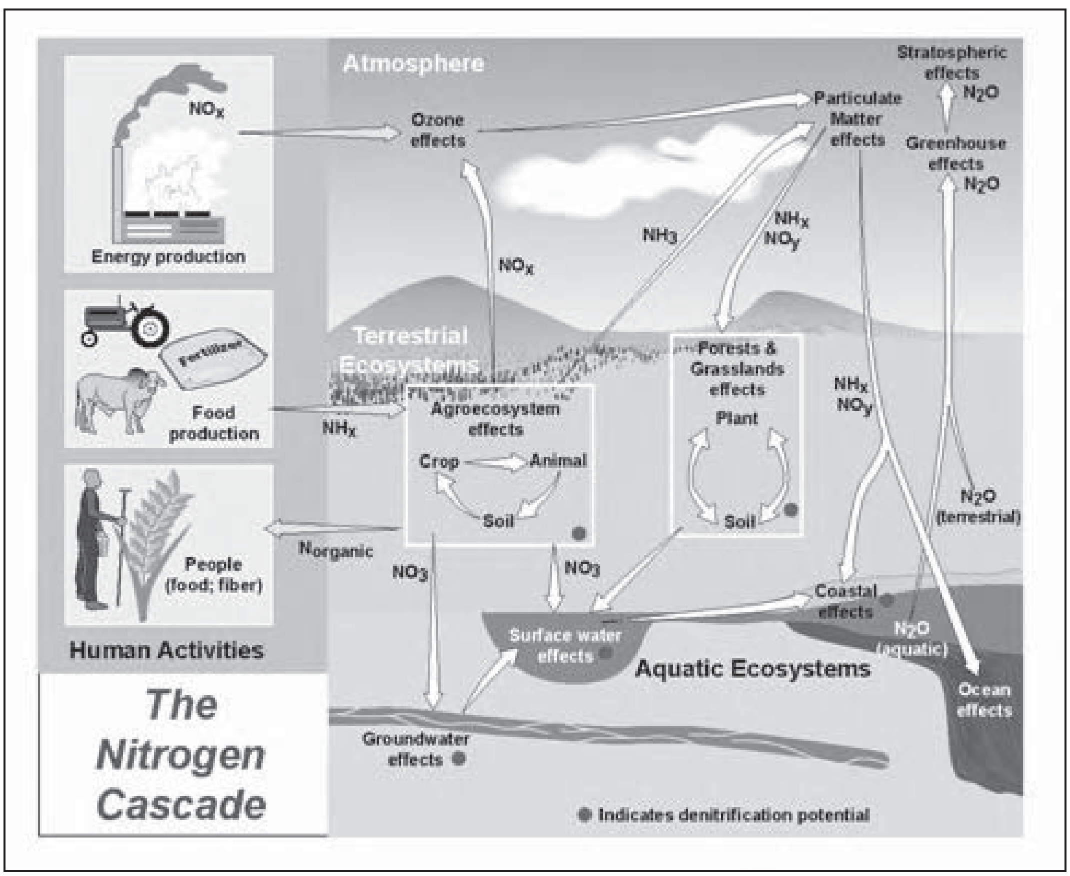

Figure 2. The N cascade (Source: Galloway et al., 2007).

DISCUSSION

Monitoring and modeling activities have rapidly expanded to identify and quantify ammonia emissions, NOx and nitrous oxide emissions, stream and river N discharge, nutrient-induced coastal eutrophication, and groundwater nitrate contamination. A panel of scientists recently completed a report for the EPA Science Advisory Board on the estimated amounts and sources of Nr pools in the U.S., and offered recommendations to reduce their size (EPA, 2011). They estimated the Nr introduced into the U.S. during 2002 as follows: *Agriculture* - Haber Bosch fertilizer N =12.0 million short tons (mst), cultivated biologically fixed N = 8.5 mst; *Natural* - biologically fixed N = 7.1 mst; *Fossil Fuel* - transportation = 3.4 mst, stationary = 2.1 mst; and *Industry* - Haber Bosch non-fertilizer N = 4.6 mst. Notably, that EPA report calls for a 25% increase in cereal crop N use efficiency (i.e. apparent N recovery) above the current range of 40 to 50% (Ladha et al., 2005). Most of us would agree that more intensive site-specific nutrient management is needed to raise the current apparent N recoveries to the 60 to > 70% range, which is possible and within the reach of many farmers for many cereal crops (Kitchen and Goulding, 2001; Dobermann and Cassman, 2002). Three other areas of needed intervention have been identified to lessen the impact of Nr on the environment: reduced fossil fuel combustion emissions, improved animal feeding and manure management strategies, and increased global sewage treatment (Galloway et al., 2008). Although we still face significant challenges in accurately quantifying the true spatial and temporal patterns of agricultural fertilizer N use (IPNI, 2010), the use and fate of Nr from many industrial activities and processes, are less understood and need better quantification. Public awareness of Nr concerns are being heightened through exposure to on-line educational tools like the "Personal N Footprint Calculator" (http://www.n-print.org/N-Calculator) - which is expected to be published in 2012, the European "Nitrogen Visualization" tool (referred to at www.nine-esf.org and shown at www.nine-esf.org/node/173), as well as multiple EPA Watershed Academy Webcasts (http://water.epa.gov/learn/training/wacademy/index.cfm).

European scientists have estimated the "total annual Nr-related damage" in Europe (EU27) as ranging between 150 and 750 euro per capita (about 200-1,000 dollars per capita), of which 75% was attributed to health damage and air pollution (Brink and van Grinsven, 2011). The primary Nr-related health costs in the EU27 were believed to be associated with emissions of nitrogen oxides (NO_x). Secondary ammonia particles, GHG effects of nitrous oxide, ecosystem impacts via runoff and drainage, and atmospheric N deposition were considered intermediate Nr costs. Health costs of drinking water nitrate-N contamination and stratospheric Nr GHG-induced ozone depletion were estimated to be lowest. Not surprisingly, there is a body of scientists in the U.S. who are currently organizing to develop a comparable U.S. N assessment. In contrast to misperception, the U.S. partial N balance of 21-25 lbs N/A on a total cropland basis from 1987 to 2007 (IPNI, 2011) is comparable to balances in Canada (31 lbs N/A), but considerably lower than the total agricultural land N balance reported for 2002-2004 in several countries in Europe: 204 in the Netherlands, 101 in Germany, 48 in France, and 38 lb N/A in the U.K. (OECD, 2008).

Nitrogen application rates below crop uptake demand can impair farmer profitability (Archer and Halvorson, 2010; Sawyer and Randall, 2008). Nitrogen rates below the economic optimum can also reduce biomass production and carbon capture, which are necessary for soil organic matter maintenance, replenishment, and sustainability (Ladha et al., 2011; Lemke et al., 2010). In certain areas of the U.S., we are learning more about the effects of N rates that may considerably exceed crop uptake demand and result in greater risks for negative environmental consequences, including: increased emissions of nitrous oxide (N_2O) (Delgado and Follett, 2010; Mosier et al., 2004; Snyder et al., 2009), increased soil profile nitrate-N accumulation and/or groundwater contamination (Andraski et al., 2000; Exner et al., 2010 Hong et al., 2007), and increased nitrate loss via subsurface drainage (Randall et al., 2010). As agronomist and soil scientists, we know that optimum crop response, soil retention, and limited environmental loss of applied N do not depend strictly on the "right" N rate, but also on the other 3Rs: right source, right time and right place of N application (Bruulsema et al, 2008 and 2009) – that incorporate appropriate nutrient balance (Johnson et al., 1997; Malhi et al., 2010; Schlegel et al., 1996) and site-specific nutrient management. Scientists and non-scientists alike are learning that many productive crop and soil systems are inherently "leaky" (David et al., 2010; Hatfield et al., 2009) and that some N loss to the environment will occur, regardless of dedicated conservation actions. Greater inclusion of slow and controlled-release N sources, nitrification inhibitors, urease inhibitors, and improved timing and placement of N sources in farmer's "N management toolboxes" is being observed in many parts of North America. Sensor-based, site-specific, variable N rate management has also attracted considerable interest and has potential in providing improved crop N recovery and economic yield responses (Hong et al., 2007; Li et al., 2009). Yet, it has proven somewhat difficult to quantify benefits such as reduced soil profile nitrate-N levels, or consistently reduced soil water/shallow groundwater nitrate-N concentrations, because of the spatial and temporal variability often experienced in large sub-field or large plot scales (Ping et al., 2009; Roberts et al., 2010).

CONCLUSIONS

Much has been learned since the 1960s about the agronomic benefits of fertilizer N, yet much work remains to better understand the environmental fate of N in diverse and more intensively managed soil-cropping systems; especially work to simultaneous measure runoff, leaching, volatilization, nitrification/denitrification N loss pathways, along with dynamic crop N uptake and soil retention . Great challenges and opportunities exist to help crop advisers, other agricultural professionals and farmers improve crop N use efficiency and effectiveness. In addition, we will need to increasingly interface with other members of society in economic, social and environmental nutrient management discussions that will affect policies and regulations in the future. A" business-as-usual" approach to N management is no longer being considered acceptable within and outside the agricultural community. Our best management practices (BMPs) for N need to ramped up, constantly evaluated, and updated under current soil, cropping system, and climate scenarios. Resulting nutrient management information will need to more rapidly become an integral part of comprehensive 4R Nutrient Stewardship than in the past, with more extensive adoption and on-farm implementation and documentation. Are we prepared as agricultural N managers to meet the future food security needs of the human family without further risking the cascade of Nr damage to the environment?

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