



Determining socially optimal rates of nitrogen fertilizer application

Jesse D. Gourevitch^{a,b,*}, Bonnie L. Keeler^c, Taylor H. Ricketts^{a,b}

^a Gund Institute for Environment, University of Vermont, Burlington, VT 05405, USA

^b Rubenstein School of Environment and Natural Resources, University of Vermont, Burlington, VT 05405, USA

^c Institute on the Environment, University of Minnesota, Saint Paul, MN 55108, USA



ARTICLE INFO

Keywords:

Air quality
Cost-benefit analysis
Nitrogen
Non-market valuation
Uncertainty
Water quality

ABSTRACT

Effective management of nitrogen (N) fertilizer is central to enhancing agricultural productivity, while improving water and air quality and mitigating climate change. Quantifying “socially optimal” rates of N fertilizer (i.e. maximizing net benefits to society while minimizing social costs) is a key component of any regulatory or incentive program designed to better manage N application. Here, we estimate spatially-explicit socially optimal N fertilizer application rates for corn in Minnesota that account for uncertainty, both in valuation techniques and model parameters. We find that socially optimal rates of N fertilizer application are between 0 and 161 kg ha⁻¹, whereas the private optimum is 165 kg ha⁻¹. Choice of valuation methods shifts the spatial configuration and magnitude of the socially optimal N application rates illustrating the importance of valuation method and assumptions. Even after accounting for uncertainty in valuation methods, we find reducing rates of N fertilizer application offers significant opportunities to improve social welfare. By internalizing the social costs of nitrogen, net social benefits of N could increase by over \$1100 ha⁻¹, even while accounting for declines in agricultural yields.

1. Introduction

Modern agricultural practices have dramatically increased crop production, but have also caused widespread environmental degradation (Matson et al., 1997; Foley et al., 2005). Since 1970, reactive nitrogen (N) creation has increased by over 120% (Galloway et al., 2008), largely driven by increased inorganic N fertilizer application to meet growing global demand for agricultural commodities (Vitousek et al., 1997). However, excess levels of N in the environment have resulted in the degradation of air and water quality, exacerbation of climate change, and damages to human health (Erismann et al., 2013). These costs have historically been ignored or underestimated, particularly relative to the benefits of increased crop yields (Compton et al., 2011). Accounting for these costs in policies, payment schemes, or programs designed to influence land management offers the potential to mitigate these tradeoffs and substantially improve environmental and social outcomes, especially in agriculturally dominated landscapes (Polasky et al., 2011; Pennington et al., 2017).

Effectively managing the tradeoffs inherent in N use requires information on the true marginal benefits and costs of N to both private landowners and society. The benefits of N fertilizer application, measured in terms of improved crop yields, are easily quantified based on the market value of crop production. Regardless of how corn is used, its

value is reflected by its market prices. We define the privately optimal rate of N fertilizer application as the rate that maximizes yield benefits for private producers, accounting for the market price of N fertilizer (i.e. the agronomic optimum). In contrast, the social costs of N (SCN) are not captured in market prices for fertilizer or agricultural commodities and are incurred primarily by the public downwind or downstream of agricultural N application. In part due to these differences, the value of the SCN are less well understood and more uncertain relative to the value of corn production (Compton et al., 2011). We define the socially optimal rate of N fertilizer application as the rate that maximizes net benefits of N to society by accounting for the private benefits and costs of N.

Quantifying the externalized SCN is challenging because N is lost to aquatic, regional atmospheric, and global atmospheric pools in a variety of forms. These loss pathways are associated with damages to water quality, air quality, and climate change, respectively, that occur over heterogeneous spatial and temporal scales (Erismann et al., 2013). Valuing these damages requires tracking several forms of N across space to endpoints where people are impacted. Multiple groups of people suffer from N-related damages and often respond differently to these impacts depending on their preferences and social vulnerability (Lewandowski et al., 2008).

Monetary valuation and cost-benefit analysis are widely used

* Corresponding author at: Gund Institute for Environment, University of Vermont, Burlington, VT 05405, USA.
E-mail address: Jesse.Gourevitch@uvm.edu (J.D. Gourevitch).

decision-support tools for comparing and aggregating the costs and benefits of N. Several recent studies have shown that the SCN are potentially large (e.g. Keeler et al., 2016), possibly exceeding \$440 billion yr^{-1} in the United States (Sobota et al., 2015) and €320 billion yr^{-1} in Europe (Sutton et al., 2011). These published estimates of the SCN range by several orders of magnitude, highlighting considerable uncertainty in the true value of N-related impacts. Improving understanding of the sources of uncertainty in the SCN will enhance the credibility of this information in decision-making processes and increase the likelihood of its uptake in regulatory or policy tools. We address this need through a rigorous consideration of uncertainty in model estimates, including assessing the sensitivity of SCN to the choice of valuation approach and uncertainty in parameter estimates.

The diversity of N loss pathways and endpoints at which damages occur makes it challenging to integrate the multiple SCN into a single cost metric. Non-market valuation techniques allow for estimation of the multiple SCN in monetary terms, however these methods vary widely in their assumptions and model structure (Wegner and Pascual, 2011). For example, Keeler et al. (2016) valued the costs of atmospheric forms of N (i.e. NO_x and NH_3) using methods based on stated preferences for avoiding health impacts from reduced air quality, whereas costs associated with aquatic forms of N (i.e. NO_3^-) were valued using replacement costs for contaminated drinking water. These two sets of models are based on fundamentally different assumptions about human behaviors and preferences. Aggregating the results from these distinct methods into a single metric makes it difficult to interpret the SCN and understand the distributional impacts of different N-related costs on different groups.

Another key source of uncertainty in the SCN arises from the parametric relationships that drive the model (Refsgaard et al., 2007). We represent model parameters with probability distributions in order to provide a more complete understanding of the range, likelihood, and magnitude of the SCN. We demonstrate the value of this information by showing how parametric uncertainty may alter effective N management strategies under various levels of risk tolerance. For example, the epidemiological research linking the relative risk of nitrate exposure in drinking water and various forms of cancer has found both positive, negative, and neutral effects (Ward et al., 2010). As such, the SCN will vary depending on risk tolerance and how these findings are interpreted. The SCN will be higher when N is assumed to increase cancer risks; inversely, the SCN will be lower when N is assumed to have neutral or positive impacts on health.

The overall aim of this study is to improve N management strategies that balance tradeoffs among crop production, the protection of water and air quality, and climate change mitigation. To achieve this goal, we ask two sets of questions:

- 1) What are the marginal social costs and benefits of N? How uncertain are these estimates and what are the primary sources of uncertainty underlying the valuation of these costs and benefits?
- 2) What are the privately and socially optimal rates of N fertilizer application? How do these vary spatially and by valuation approach, and what is their impact on society?

We answer these questions using a spatially explicit modeling framework that integrates biogeochemical and economic processes and accounts for variation in non-market valuation techniques and parametric uncertainty.

2. Methods

2.1. Overview

We determined socially optimal rates of N fertilizer application by evaluating the private and social costs and benefits of N and identifying the rate at which net benefits of N to society are maximized. We

conducted this analysis in the state of Minnesota (MN), which produces over 10% of corn grown in the United States (U.S.) (U.S. Department of Agriculture – National Agricultural Statistics Service, 2013). While crop yields in MN are N-limited and substantially increase with nitrogen fertilization, groundwater aquifers in several regions of the state are highly vulnerable to nitrate contamination (Porcher, 1989; Keeler and Polasky, 2014). Therefore, N loss from fertilizer application creates tradeoffs between benefits to agricultural production and costs in terms of clean air and water and climate change mitigation. Private benefits of N were calculated based on the market value of increases in corn yields minus the cost of fertilizer to farmers. We focused on the SCN caused by groundwater nitrate (NO_3^-) contamination, air pollution by small particulate matter ($\text{PM}_{2.5}$) formed from ammonia (NH_3) and N oxides (NO_x), and global climate change from nitrous oxide (N_2O) emissions. Benefits and costs were both calculated at the county-level to account for the spatial heterogeneity in the SCN and to match the resolution of publically available datasets. We then assessed how variation in the assumptions underlying the non-market valuation functions used to value these costs and benefits on management decisions. We also computed the probability distribution of model outputs and parameters' contribution to variance with a Monte Carlo simulation. Using a cost-benefit analysis framework, we then estimated socially optimal rates of N fertilizer application and the associated impacts of internalizing the SCN on private and social returns to N.

2.2. Conceptual framework for estimating the SCN

We adopted the conceptual framework proposed by Keeler et al. (2016) for estimating the SCN. The framework explicitly accounts for the costs (C) of exposure to elevated concentrations of N for differentiated forms of N (j) applied at specific locations (i). This framework accounts for the complex biogeochemistry of the N cycle, where a single unit of reactive N is transported, transformed, and accrues damages over time and space. We made several simplifying assumptions regarding the transportation and transformation of N over time to make this framework empirically tractable. Limited by data availability and current understanding of the N cycle, we only estimated costs associated with the first transformation of the N cascade (see Galloway et al., 2003) from fertilizer to atmospheric or aquatic pools (Eq. (1)), and ignore any subsequent transformations of N.

$$SCN_i = \sum_{j=1}^J \sum_{i=1}^I N_{ij} C_{ij} \quad (1)$$

N_{ij} and C_{ij} both depend on where N is applied ($i = 1$), the location of the endpoints ($i = 1, 2, \dots, n$), and its form at those endpoints ($j = \text{N}_2\text{O}, \text{NO}_x, \text{NH}_3, \text{or } \text{NO}_3^-$). N_{ij} is a function of the allocation of N loss into the appropriate concentration (i.e. ppm, $\mu\text{g m}^{-3}$) and form, transport of N across the landscape to endpoints of residence, and transformation and attenuation of N between the source location and the endpoints. C_{ij} is a function of human populations' exposure to N at the endpoints, the social vulnerability and preferences for various alternatives of the exposed populations, and the marginal damages incurred by the populations' exposure to N in form j.

Using this framework, we estimated the marginal SCN applied as fertilizer in each county in MN as a function of damages to water and air quality and climate change. Water quality damages reflect costs incurred to drinking water consumers who rely on groundwater in MN, air quality damages are assessed regionally based on health impacts incurred in MN and downwind in adjacent states, and climate change damages reflect global costs. Most of the drinking water in this region is from groundwater sources, and therefore, most of the exposure and associated health impacts are linked to N in groundwater rather than surface water. Air pollution and greenhouse gas emissions from fertilizer application also represent significant damages and have well-established approaches for evaluating costs. In addition to these damages,

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