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Mass balance analyses of nutrients on California dairies to evaluate data quality for regulatory review

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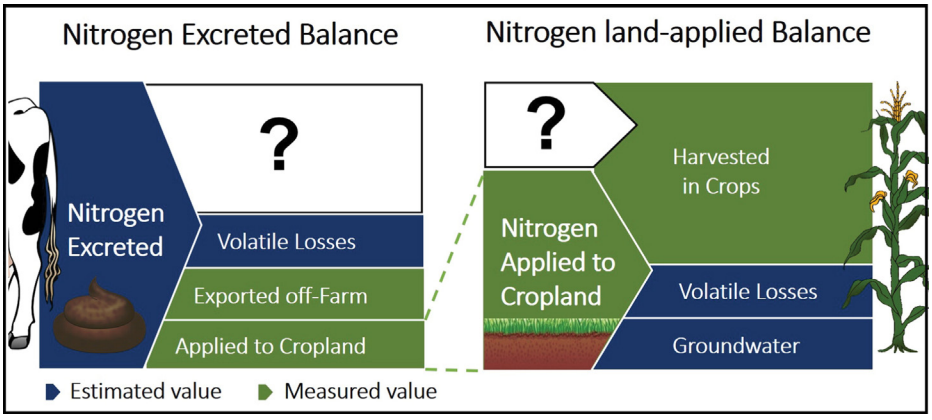
HIGHLIGHTS

- Groundwater regulations require precise nitrogen management on California dairies.
- Quality of reported nitrogen management data was evaluated through mass balance.
- Nitrogen excreted by cattle is unaccounted for in nitrogen management reports.
- Many reported nitrogen application rates are insufficient to maintain crop yields.
- Reducing error in manure nitrogen measurements should improve data quality.

GRAPHICAL ABSTRACT



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ABSTRACT

Effective regulations may help reduce nitrate contamination of groundwater from agriculture. Dairy farmers in California must maintain a ratio below 1.4 of total nitrogen (N) applied to total N-removed (N-Ratio) on cropland receiving manure application. In annual reports to the regulatory agency, farmers detail nutrients applied to cropland, removed in harvests, and exported off farm. Data were extracted from all available annual reports for 62 dairies from 2011, 2012, and 2013. Excretions of N, phosphorus (P), and potassium (K) were calculated using reported herd demographics and standard excretion equations from the American Society of Agricultural and Biological Engineers. Calculated nutrient excretion values were compared to the reported values of manure nutrients applied to cropland and exported off farm. Reported N-Ratios were compared to mass balance simulations exploring variable crop yields and alfalfa management. In the nutrient excretion balance, the distribution of the percent of N and P recovered in manures applied or exported peaked at 24% (median = 31%) and 26% (median = 53%) of excreted, respectively. The distribution of recovered K was fairly uniform from 0% to 300% (median = 146%) of excreted K. In N-ratio simulations, 62% and 66% of all reported N-ratios were lower than their respective simulated N-ratio, assuming alfalfa crops received no N fertilization and minimal fertilization (26% of N-removed in harvest) respectively. When simulated crop yields were normally (sd = 0.25) or Student's t distributed (df = 154) around expected crop yields, 28% and 57% of all reported ratios fell within the 95% confidence

Abbreviations: WDR, waste discharge requirements; RB5, California Regional Water Quality Control Board, Central Valley Region (5); N, Nitrogen; P, Phosphorus; K, Potassium; N-Ratio, ratio of N-applied to N-removed; PWW, process waste water; SM, solid manure; CVDRMP, Central Valley Dairy Representative Monitoring Program; ASABE, American Society of Agricultural and Biological Engineers; TDS, Total Dissolved Solids.

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interval of the simulations, respectively. Low and erratic recovery rates of excreted P and K existed. Additionally, reported N-Ratios were generally lower and more varied than necessary for farmers to maintain crop yields while complying with regulations. Greater understanding of low recovery rates is needed before data are used to assess the impact of regulations.

1. Introduction

Regulations to reduce nitrate contamination of drinking water from agriculture protect public health. Drinking water containing nitrate above the maximum contaminant limit (10 mg/L nitrates as nitrogen) can decrease the oxygen carrying capacity of blood (Cal. Code Regs. § 64432.1; Wolfe and Patz, 2002). Globally, nitrogen (N) application rates have increased to support higher crop yields to meet the demands of the growing population, leading to greater rates of N runoff and leaching. Accordingly, all active nitrate regulations aim to encourage farmers to apply N fertilizers precisely to meet plant growth needs. Dutch regulations monitor the absolute difference between N-applied and N-removed from cropland and levy fees for exceeding the acceptable limit, which depends on soil and crop type (Schröder and Neeteson, 2008). Nitrate vulnerable zones are defined in England where limits exist on the amount of plant-available N applied to vulnerable land (No. 2349, 2008). Existing regulations will serve as examples for future regulations as the concentration of nitrate in drinking water increases around the world (Spalding and Exner, 1993).

Groundwater is a major source of drinking water in California and nitrate concentrations are increasing due primary to nitrate leaching from irrigated agriculture (California Department of Water Resources, 2013; Harter et al., 2012). In response, Waste Discharge Requirements (WDR) were adopted by California Regional Water Quality Control Board, Central Valley Region (RB5) to improve N-management on dairies (R5-2007-0035, 2007; R5-2013-0122, 2013). Current regulatory requirements went into effect in 2007 with a 5 year, phased implementation plan completed in mid-2012. The regulations require dairy farmers to monitor the ratio of N-applied to N-removed (N-Ratio) for each crop fertilized with manure. The WDR restricts N-application to 140% of the N harvested in each crop, an N-Ratio of 1.4 (R5-2013-0122, 2013). N-application beyond the regulatory limit may well result in groundwater nitrate loads that exceed the drinking water limit.

To assess compliance and impact, these regulations require both intensive record keeping on the part of dairy farmers and a groundwater monitoring program. All dairies must submit an annual report containing information on their animal population and N-Ratio measurements for each crop. Most dairies chose to participate in the Central Valley Dairy Representative Monitoring Program (CVDRMP) where numerous groundwater monitoring wells were installed on representative facilities to assess the effectiveness of the regulations (R5-2007-0035, 2007; R5-2013-0122, 2013). In addition to N, annual reports document phosphorus (P) and potassium (K) cycling on dairy farms. Annual report data must be consistent with mass balance theory before data can be used to assess impact of the regulations on groundwater nitrate concentrations.

The sum of nutrients applied to land and exported off-site combined with appropriate estimates for environmental losses should be within reasonable estimates of nutrients excreted by the dairy herd as mass must be conserved. Almost all Central Valley dairies manage two forms of manure in variable proportions: process wastewater (PWW) and solid manure (SM). Process wastewater is water that contacts animals, milk, manure or feed during dairy operations including cleaning and precipitation. Process wastewater is often recycled to flush manure from concrete lanes in cattle housing facilities. Process wastewater is stored in anaerobic lagoons until it is diluted with fresh water and applied to cropland via surface gravity irrigation systems. Solid manure is scraped from earthen corrals or filtered out of the PWW stream by various solid-separation techniques. Solid manure is often stored in large piles until it is used as bedding in freestall barns or incorporated into cropland between crops via various methods or exported off farm (Meyer et al., 2011). Accordingly, manure nutrients must be accounted for as they leave the dairy production area in exports off farm, applications to cropland, leaching from corrals, or volatilization to air. While some forms of N are volatile, manure forms of P and K are not, thus measurements of all nutrients provide parallel methods to evaluate mass conservation.

The mass of N applied to cropland must be accounted for within the N removed from the field in plant matter and the N lost to the environment. Reported N-Ratios summarize the balance of land applied N, by measuring the amount of N applied to and removed from cropland and also providing an estimate of N lost to the environment (assuming soil stores of N are constant). A portion of N applied to cropland is biologically unavailable or lost to the environment due to unavoidable inefficiencies in the infrastructure and biology of the system (Chang et al., 2005; Francis et al., 1993; Hanson et al., 2004; Harter et al., 2002; Meisinger and Randall, 1991). Consequently, farmers must apply more N than the crops require with the exception N-independent alfalfa crops. The N-application rates in annual reports must be sufficient to support crop yields given the biological and logistical limitations of the dairy cropping system.

The effectiveness of all active groundwater quality regulations depends on farmers' ability to accurately measure and report N application and removal. Accordingly, if N-management data collected by farmers is inaccurate or biased it could undermine the evaluation of regulatory effectiveness (Oenema et al., 2003). The extent to which data collected under various regulatory frameworks is affected by error or bias is unknown. Data contained in annual reports provide a unique opportunity to perform multi-year mass balances analyses of excreted and land-applied manure on an unprecedented number of dairy farms. Mass balance calculations and simulations investigate the quality of reported data and examine the extent to which different sources of uncertainty could affect future regulatory evaluations.

The objectives of this study were to evaluate annual report data quality by determining if reported values were consistent with mass balance analyses of 1) excreted nutrients and, 2) land-applied N. This study compared the sum of excreted nutrients to that of applied and exported nutrients submitted in annual reports and used simulations to determine if reported N-application rates were reflective of existing agronomic limitations.

2. Methods

2.1. Study farms

All dairies selected for this study were participating in the CVDRMP. Locations of study dairies are shown in Fig. 1. In 2011, the program enrolled 18 dairies. In 2012, the program began planning for an expansion and proposed 44 additional dairies for enrollment. All available annual reports from 2011, 2012, and 2013 were obtained from RB5 for the 62 dairies. Dairies were excluded from analyses when files were missing or partially incomplete. Because the expansion dairies were not proposed until 2012, 2011 records for those dairies were more likely to be missing.

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