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# Simulating soil nitrogen fate in irrigated crop production with manure applications

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## HIGHLIGHTS

- RZWQM2 adequately simulated N fate over a wide range of manure applications.
- RZWQM2 simulated crop production for a wheat-potato-barley-sugar beet rotation.
- Long-term repeated manure applications may adversely affect ground water quality.
- RZWQM2 effectively simulated irrigation practices.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Dairy manure is commonly applied to irrigated agricultural crops in the Magic Valley Region of southern Idaho, which has reported to impact the quality of surface and ground water. In this study, we used the Root Zone Water Quality Model (RZWQM2) to provide information about the long-term implications of manure applications. RZWQM2 was first calibrated and validated using 4 years of data from a long-term study with annual and biennial manure application rates of 18 Mg ha$^{-1}$, 36 Mg ha$^{-1}$, and 52 Mg ha$^{-1}$, along with a control and conventional fertilizer treatment for crop yield, soil water and soil N. The 4-yr crop rotation was spring wheat (2013), potato (2014), spring barley (2015), and sugar beets (2016). RZWQM2 simulated soil water content, crop yield, total soil nitrogen, and soil nitrogen mineralization effectively as PBIAS and RRMSE for soil water content and crop yields were within the acceptable range (±25% for PBIAS and <1.0 for RRMSE). Nitrate in the soil profile was overestimated, however in the acceptable range for the validation treatments. The calibrated model was then run for 16 years by repeating the management practices of the 4-year scenarios (4 crop rotations) for all treatments and 24 years for the 52 T Annual treatment (6 crop rotations). The 16-year simulation results showed that nitrogen seepage from annual manure treatments (for example, 18 T Annual vs 18 T Biennial) was 2.0 to 2.3 times higher than the nitrogen seepage from the biennial manure treatments. Increasing manure applications from 18 T Annual to 52 T Annual increased N seepage an average of 3.2 times for the 16-year rotation. Nitrogen seepage increased dramatically in rotations 3 and 4 compared to rotations 1 and 2 in the sixteen-year simulation. The 24-year simulation results showed after manure had been applied annually for 16 years and then

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applications terminated, the amount of N seepage returned initial levels in 8 years. In conclusion, to maintain clean ground water, manure applications would be best applied biennially, and high applications should be discouraged.



## 1. Introduction

Nitrogen (N) is one of the most essential elements for crop production and forms some of the most mobile compounds in the soil-plant-atmosphere system. Because N compounds are so mobile, there is an increased concern about N delivery into the environment (Follett, 2008). To prevent excess loss of N into the environment, it is important to reduce leaching, runoff, erosion and gaseous losses so N remains where it is needed for crop use (Follett, 2008). Organic wastes are an important source of N and animal manures account for most of the organic waste applied to agricultural land (Follett, 2008).

Idaho is the third largest producer of milk in the United States hence it produces large amounts of animal manures. Presently, there are about 640,000 milk cows in Idaho that produce 14 billion pounds of milk (www.agri.idaho.gov and www.idahomilk.com). Approximately 75% of these cows are in the Magic Valley region of south-central Idaho. Manure produced from the dairy industry can be a valuable source of nutrients and organic matter for crop production in the region; however, the challenge is finding the optimum level of application. Major crops grown in the dairy producing counties in Idaho are alfalfa hay, silage corn, potatoes, sugar beets, winter and spring wheat, barley, and dry beans. The climate is arid to semiarid with sagebrush and bunch grasses dominating the natural landscape. The annual precipitation for the region is about 28 cm, occurring primarily in the winter and early spring, therefore, all the agricultural land is irrigated (The Nature Conservancy, 2014).

The population of the Magic Valley region is approximately 186,000 people and groundwater supplies 95% of the drinking water. Nitrates are the most common groundwater contaminant in Idaho and the sources are inorganic fertilizer, human waste, and animal waste (www.deq.idaho.gov). The Idaho Department of Environmental Quality (IDEQ) has defined nitrate priority areas (NPAs) as areas where nitrate concentrations in the ground water are greater than or equal to 5 mg $L^{-1}$ for 25% of the wells sampled in an area (IDEQ, 2014). The NPAs are ranked in order of severity (one is the most impacted) based on factors such as population and number of public water systems in the area, water quality trends, and beneficial uses in addition to drinking water (IDEQ, 2014). In 2014, Marsh Creek, Twin Falls, and Minidoka NPAs in southern Idaho were ranked 1, 21, and 25, respectively, of the 34 NPAs. The average nitrate concentration in the well water was 7.16, 5.18, and 5.45 mg $L^{-1}$ for the three NPAs and the maximum was of 40, 41, and 83 mg $L^{-1}$ for Marsh Creek, Twin Falls, and Minidoka NPAs, respectively (IDEQ, 2014).

Computer simulation and decision support models for soil-crop systems that emphasize the N cycle are viable alternatives for evaluating combinations of management scenarios that include applications of livestock manures (Follett and Hatfield, 2001). The Root Zone Water Quality Model 2 (RZWQM2 Version 4.2, 9.28.2020) is a comprehensive agricultural system model with the capacity to integrate and synthesize biological, physical, and chemical processes to simulate the impacts of water, agricultural chemicals, and crop management practices on crop production and water quality (Ahuja et al., 2000). RZWQM2 contains DSSAT (Decision Support System for Agrotechnology Transfer) crop growth models, SHAW (Simultaneous Heat and Water Transfer) energy balance module and the HERMES crop module (Ma et al., 2011). RZWQM2 has been used in several research studies involving manure applications various crops. Ma et al. (1998) found that the model provided good prediction of corn silage yield, plant N uptake, and $NO_3$-N in the soil profile in Colorado. They also developed criteria for calibration of soil organic pools and alternative manure management practices to reduce N leaching. Kumar et al. (1998) used the RZWQM2 to simulate swine manure applications (ranging from 82 to 502 kg total N $ha^{-1}$) on fields under continuous corn production in Iowa. Fang et al. (2015) applied poultry manure (rates as high as 202 kg total N $ha^{-1}$) on corn fields in Mississippi and their results indicate the model predicted $NO_3$-N in the soil satisfactorily.

Recently, Fang et al. (2015) compared several algorithms that simulate $N_2O$ emissions from several models and implemented the most appropriate into the RZWQM2. The modified model showed adequate responses of $N_2O$ emissions to fertilizer rate and conventional tillage management from an irrigated continuous corn system in Colorado (Gillette et al., 2017) and corn-soybean rotation in Iowa (Gillette et al., 2018). Although, the generation of nitrous oxide ($N_2O$) is one consequence of manure applications to cropland soils (Smith et al., 2008; IPCC, 2006 in Gillette et al., 2018), the effects of manure additions on emissions of $N_2O$ is unclear and few studies have measured $N_2O$ emissions for irrigated cropping systems (Leytem et al., 2019). $N_2O$ is produced by the soil processes of nitrification and denitrification which are influenced by manure properties and environmental conditions (Rotz, 2018). Empirical relationships have been used to estimate $N_2O$ emissions, however, simulation of soil processes provides a more robust prediction of emissions as they relate to soil and weather conditions (Rotz, 2018).

Another factor to consider when modeling manure applications and crop production is C:N ratio of the manure and soil. Qian and Schoenau (2002), tested different types of poultry, cattle and hog manure compositions (different amounts of straw, bedding and pelletized form) with varying carbon and nitrogen content and concluded that the C:N ratio is generally considered to be a significant factor influencing N mineralization of organic amendments. RZWQM2 has options to set the C:N ratio for the different residue and humus pools. Temperature and moisture also impact the decomposition of manure (Sierra et al., 2015) so the wetting and drying cycles from different irrigation regimes and the climate of southern Idaho would differ from other regions of the country, hence the importance of calibrating the RZWQM2 for the Magic Valley. All the manure generated by the dairy industry in the Magic Valley is applied to cropland/and or pasture. Because of potential leaching of $NO_3$-N into the ground water it is important to know how long-term application of manure impacts nitrate in the soil profile and ground water quality. Surface water quality is also important but much of the region is irrigated via sprinkler and there is little runoff therefore we did not address this issue in the current study. This study is unique in combining a crop rotation of spring wheat/potato/spring barley/sugar beet, irrigation, and high manure applications. The manure applied was from a typical open lot dairy and included a mixture of soil, straw, and manure with annual or biennial application rates varying from 18,610 to 70,170 kg $ha^{-1}$ dry weight.

The objectives of this study were to calibrate and validate RZWQM2 using data from the irrigated, semi-arid environment found in southern Idaho and to predict long-term impacts of high dairy manure applications on the crop and soil environment. RZWQM2 was calibrated for crop yield, $NO_3$-N in the soil profile, total N in the soil profile, annual N mineralization, and $N_2O$ emissions using 4 years of data with a crop rotation of spring wheat, potato, spring barley, and sugar beets from 2012 to 2016. After calibration, historical weather data from 2000 to 2016 were used to simulate 4 crop rotations (16 years) to investigate long-term effects of manure application. A 24-year simulation with 6 crop rotations, historical weather data from 1992 to 2016, and the 52 T Annual management practices was used to determine how long it would take for the soil to recover from the high manure application.

## 2. Materials and methods

### 2.1. Field experiment

A long-term study designed to evaluate the impacts of manure application rate and timing on nutrient cycling in a four-year crop rotation was used to calibrate the RZWQM2. The field is located at the USDA ARS Northwest Irrigation and Soils Research farm near Kimberly, ID (Lat 42°33′, Long 114°21′, 1187 m in elevation). The soil is a Portneuf silt loam (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplacalcid). The average annual precipitation for the Kimberly area is 284 mm, while the mean annual low, high and average temperatures are 1.8 °C, 15.6 °C, and 8.7 °C, respectively (https://www.usclimatedata.com).

This study was initiated in the fall of 2012 and consisted of a four-year rotation of spring wheat (2013)–potato (2014)–spring barley (2015)–sugar beet (2016) (study 1). The experimental design was a randomized complete block with four replications and individual plot sizes of 18.3 × 12.2 m. There were two identical studies installed side by side in the field with respect to treatment but a staggered crop rotation with study 2 having a crop rotation of spring barley, sugar beet, spring wheat, and potato. Soil gas emissions were measured in study 1 and the soil buried bag mineralization study was installed in study 2. The treatments are: no fertilizer or manure (Control), commercial fertilizer (Fertilizer), dairy manure applied annually or biennially at rates of 18 (18 T Annual & 18 T Biennial), 36 (36 T Annual & 36 T Biennial), and 52 (52 T Annual & 52 T Biennial) Mg ha$^{-1}$. These are target rates, the actual amount of manure applied (dry weight) to each treatment is listed in Table 1. Fertilizer applications (N, P, K, S) for wheat, barley and sugar beet were determined each spring based on pre-plant soil sampling nutrient concentrations following the University of Idaho Fertilizer Guidelines for each crop. For potato, fertilizer applications were determined based on pre-plant soil sampling nutrient concentrations following recommendations from the University of Idaho Fertilizer Guidelines as well as in season petiole sampling. The goal was to meet all necessary nutrient requirements to maximize yield as would be done by a commercial grower which resulted in application of fertilizer to some of the manure plots in some years (Table 2). Manure was applied each fall (Oct or Nov) by weighing the appropriate amount of manure per plot (based on manure moisture) and spreading with a manure spreader. Manure was immediately incorporated by disking to a 15 cm depth to minimize ammonia and P runoff losses over the winter; the fertilizer and control plots were also disked at this time as well for consistency purposes. After spring wheat and spring barley all treatments were moldboard plowed in the fall after disking in the manure. All treatments were sprinkler irrigated using the same irrigation regime: wheat in 2013 = 41 cm, potatoes in 2014 = 59 cm, barley in 2015 = 34 cm, and sugar beets in 2016 = 73 cm. The irrigation schedule was based on estimated ET from weather data collected at the AgriMet weather station located at the USDA-ARS Northwest Irrigation and Soils Research Laboratory (NWISL) at Kimberly, ID. Planting dates, plant density, and harvest dates are listed in Table A.1. The site has no history of prior manure applications.

Soil sample data used to initialize the model were taken from study 1 on September 25–26, 2012 prior to manure application. Soil on this field was subsequently sampled annually post-harvest and prior to manure application (September 30, 2013, October 9, 2014, September 24, 2015, and November 15, 2016). Soil samples were collected at 15, 30, 60, 90, and 120 cm, except in 2016 when the 120 cm depth was not sampled. The bulk soil samples were air dried and ground for $NO_3$-N, $NH_4$-N, and total soil N and C analysis. Inorganic soil N concentration was determined using the 2 mol L$^{-1}$ KCl extraction method (5 g soil:25 mL extractant, Mulvaney, 1996). The supernatant was analyzed via flow injection analyzer for $NO_3$-N concentration via cadmium reduction (Lachat Method 12–107–04-1-B) and $NH_4$-N concentration via the salicylate-hypochlorite method (Lachat Method 12–107–04-1-A; Lachat Instruments, Loveland, CO) Total C (TC) and total N were determined by dry combustion (Thermo-Finnigan Flash EA1112 CNS analyzer, CE Elantech, Lakewood, NJ) and inorganic C (IC) by the method of Sherrod et al. (2002). Soil organic C was determined by subtracting the IC from TC. Soil hydraulic properties were obtained from the literature (Robbins, 1977, Table A.2). Weekly soil water content measurements used in the model were taken at a depth of 15 cm using a TDR probe (Campbell Scientific, Logan, UT).

Composite manure samples were collected by combining subsamples from each plot and stored in a refrigerator until shipping to Soiltest Laboratory (Moses Lake, WA) for analysis. Total manure C and N content was determined via combustion with the CHN 628 analyzer (LECO, St. Joseph, MN). The inorganic $NH_4$-N concentration of the manure was measured (5 g soil: 25 mL extractant) with 2 mol L$^{-1}$ KCl extraction (Gavlek et al., 2005). The supernatant was analyzed via an automated flow injection analyzer for $NH_4$–N concentration via the salicylate-hypochlorite method (Lachat Method 12–107–06–2-A; Lachat Instruments, Loveland, CO).

Plant biomass samples were collected on July 30, 2013 for spring wheat, August 18, 2014 for potato, July 23, 2015 for spring barley, and September 26, 2016 for sugar beets (no below ground biomass was sampled for spring wheat or spring barley). Total N content was determined via combustion with the CHN 628 analyzer (LECO, St. Joseph, MN).

### 2.2. Organic nitrogen mineralization

Nitrogen mineralization was measured on field 2 (the field with the staggered rotation) utilizing the buried-bag method developed by Westermann and Crothers (1980) and adapted for this study by Graybill (2017). Nine to twelve 5.7 cm diameter cores were collected in the spring after planting from the 0–30 cm depth using a 5.7 cm diameter bucket auger within each study plot. The soil samples from each plot were composited and used to fill low density (0.10 mm thickness) polyethylene tube shaped bags. Soil was packed into the bags with vertical hand shaking and placed back in the original soil sample holes.

**Table 1**
The manure parameters used for the scenarios in the RZWQM2. Each manure application was incorporated immediately after application. A after the year represents the annual treatment and BA is the biennial treatment. All weights are dry weights.

| Treatment | Date applied | Manure | NH4 | Total N | C:N | Fraction C |
|---|---|---|---|---|---|---|
| Year | | kg Ha$^{-1}$ | kg Ha$^{-1}$ | kg Ha$^{-1}$ | | (%C/100) |
| 18 T | | | | | | |
| 2012, A | Oct. 17, 2012 | 19,044 | 53.68 | 295.18 | 19.78 | 0.307 |
| 2012, BA | Oct. 17, 2012 | 19,925 | 43.59 | 308.84 | 18.59 | 0.300 |
| 2013, A | Nov. 6, 2013 | 22,587 | 64.08 | 420.12 | 17.45 | 0.325 |
| 2014, A | Oct. 23, 2014 | 20,013 | 43.78 | 196.86 | 15.61 | 0.181 |
| 2014, BA | Oct. 23, 2014 | 16,971 | 37.12 | 232.15 | 15.13 | 0.159 |
| 2015, A | Oct. 22, 2015 | 18,610 | 52.64 | 267.99 | 14.54 | 0.210 |
| 36 T | | | | | | |
| 2012, A | Oct. 17, 2012 | 38,017 | 107.16 | 558.85 | 19.12 | 0.281 |
| 2012, BA | Oct. 17, 2012 | 38,166 | 107.59 | 561.05 | 19.81 | 0.289 |
| 2013, A | Nov. 6, 2013 | 43,986 | 124.78 | 809.84 | 16.97 | 0.312 |
| 2014. A | Oct. 23, 2014 | 40,529 | 88.66 | 478.25 | 15.79 | 0.187 |
| 2014, BA | Oct. 23, 2014 | 36,640 | 88.66 | 432.35 | 15.69 | 0.187 |
| 2015, A | Oct. 22, 2015 | 39,117 | 106.40 | 563.28 | 14.16 | 0.204 |
| 52 T | | | | | | |
| 2012, A | Oct. 17, 2012 | 55,414 | 156.20 | 864.45 | 19.24 | 0.300 |
| 2012, BA | Oct. 17, 2012 | 55,648 | 156.02 | 863.43 | 19.84 | 0.287 |
| 2013, A | Nov. 6, 2013 | 70,170 | 199.07 | 1298.15 | 16.63 | 0.308 |
| 2014, A | Oct. 23, 2014 | 55,494 | 121.39 | 699.22 | 15.79 | 0.199 |
| 2014, BA | Oct. 23, 2014 | 57,793 | 126.42 | 728.19 | 16.14 | 0.214 |
| 2015, A | Oct. 22, 2015 | 57,622 | 160.16 | 829.76 | 15.07 | 0.217 |

**Table 2**
The fertilizer applications for each year and scenario in the RZWQM2 project, an empty cell indicates no fertilizer was applied. The units are nitrogen in kg $ha^{-1}$.

| Crop | Date applied | Fertilizer | 18 T Annual | 18 T Biennial | 36 T Annual | 36 T Biennial | 52 T Annual | 52 T Biennial |
|---|---|---|---|---|---|---|---|---|
| Wheat | Apr. 4, 2013 | 43.46 | 43.46 | 43.46 | 43.46 | 43.46 | 43.46 | 43.46 |
| Potato | Apr. 16, 2014 | 84.0 | 112.0 | 84.0 | 84.0 | 112.0 | 84.0 | 112.0 |
| Potato | May 20, 2014 | 134.4 | 112.0 | 134.40 | 89.6 | 134.40 | 89.6 | 112.0 |
| Potato | July 24, 2014 | 44.8 | 44.8 | 44.80 | 44.8 | 44.8 | 44.8 | 44.80 |
| Barley | Mar. 31, 2015 | 53.76 | – | – | – | – | – | – |
| Sugar beet | Apr. 20, 2016 | 123.20 | 31.36 | 123.20 | – | 40.32 | – | – |

Soil-filled bags were removed monthly (April and May) and bi-weekly (June, July, August, September, and October) intervals throughout the growing season. Once removed the soil was analyzed for $NO_3$-N and $NH_4$-N using the flow injection method described above. The mineralized N used for the RZWQM2 scenarios was calculated as the final N – initial N for the growing seasons from April 12, 2013 to August 16, 2013; May 3, 2014 to October 9, 2014; April 13, 2015 to October 12, 2015; and May 5, 2016 to October 11, 2016.

Nitrous oxide ($N_2O$) measurements were conducted using a vented, non-steady state, closed chamber technique built according to USDA-ARS GRACEnet sampling protocols (Parkin and Venterea, 2010). The methods used for the data presented in this study are described in detail by Leytem et al. (2019). Field measurements from April through October for years 2013 to 2016 were used to compare with model output from the corresponding time periods. Excel forecast was used to interpolate data for the daily time periods between actual field measurements. Therefore, the experimental values used to compare with the daily RZWQM2 output is the total estimated emission for April thru October in each year.

Wheat and barley were harvested with an Almaco plot harvester (1.5 m by 9 m) followed by bulk harvesting of the field. All straw was baled and removed from the field as is typical in the area. Potato tuber yield was determined for each plot by harvesting a single row, 33.5 m long with a potato plot harvester (Grimme, Lincolnshire, UK). Sugar beet roots were mechanically harvested with a two-row beet harvester (21 m row).

### 2.3. RZWQM2 calibration

The RZWQM2 consists of seven main components: water balance, heat and chemical transport, nutrient processes (carbon and nitrogen), plant growth processes, soil chemical processes, evapotranspiration processes, pesticide processes and management. The RZWQM2 includes the DSSAT V4.0 crop growth models (Decision Support System for Agrotechnology Transfer) for modeling plant growth and development. We used the DSSAT crop parameters for wheat, potatoes, and barley in this study. The HERMES growth model in RZWQM2 was used to model sugar beet growth (Kersebaum, 2011). The DSSAT sugar beet crop parameters were tested but the simulated crop yield and N uptake did not respond to the manure treatments in this study. Weather data were from the Kimberly, Idaho AgriMet weather station located at the NWISRL, Kimberly, ID. Background water chemistry in the rain and irrigation water was set at 0.85 and 0.88 mg $L^{-1}$, for $NO_3$-N and $NH_4$, respectively (http://nadp.slh.wisc.edu/NADP/, Logan, Utah site).

The soil profile was divided into six layers at depths of 15, 30, 60, 90, 122, and 154 cm from the soil surface to correspond the depths that soil was sampled in the field experiment. Soil residue pools were initiated using a 20 yr scenario of standard management practices until the humus pools were stabilized (Ma et al., 1998) and are reported in Table A.3.

Ma et al. (2012) recommend the RZWQM2 be calibrated using multiple years and multiple treatments so the calibrated model parameters are more robust. Calibration for this study was conducted using 4 years of data from the control, fertilizer and 52 T Annual manure treatments because of differences in nitrogen mineralization rates between fertilizer and manure-treated soils (Cassity-Duffey et al., 2018; Lentz and Lehrsch, 2011). The measurements used for calibration were total $NO_3$-N in the soil profile, mineralization during the growing season, total soil N, crop yield and below ground biomass (sugar beets). Zeckoski et al. (2015) suggests optimizing parameters with some subjective level and two standard deviations (stds) was chosen for this

**Table 3**
The RZWQ2 performance rating measures for each treatment scenario using the 4-year data. Calibration treatments are the Control, Fertilizer and 52 T Annual. Validation treatments are the 18 T Annual, 18 T Biennial, 36 T Annual, 36 T Biennial, and 52 T Biennial. Default denitrification parameters were used in RZWQM2 so there was no calibration for $N_2O$ emissions.

| Treatment | Yield | Soil $NO_3$-N | Mineralization | Total N | Plant uptake | $N_2O$ emissions | Soil H2O |
|---|---|---|---|---|---|---|---|
| PBIAS (%) | | | | | | | |
| Control | −0.03 | −42.49 | 13.58 | 3.64 | −57.08 | 37.63 | −8.26 |
| Fertilizer | 1.21 | −20.16 | −1.57 | 6.42 | −12.65 | 33.89 | −8.66 |
| 18 T Annual | 1.02 | −29.46 | 18.44 | 12.09 | −13.24 | −1.10 | −5.86 |
| 18 T Biennial | −0.11 | −11.61 | −18.48 | 16.21 | −16.94 | – | −7.21 |
| 36 T Annual | 1.80 | −8.83 | 18.10 | 9.38 | 0.56 | – | −6.35 |
| 36 T Biennial | −0.62 | −26.94 | 12.87 | 9.30 | −11.39 | 1.45 | −7.51 |
| 52 T Annual | −0.70 | −28.87 | 16.10 | 13.36 | 11.17 | 18.71 | −3.73 |
| 52 T Biennial | −3.41 | −19.77 | −3.22 | 9.16 | 6.35 | – | −5.45 |
| Calibration Treatments | 0.16 | −29.48 | 12.09 | 8.47 | −8.93 | N/A | −6.83 |
| Validation Treatments | −0.23 | −18.73 | 13.62 | 11.23 | −5.99 | 15.51 | −6.47 |
| RRMSE | | | | | | | |
| Control | 0.16 | 0.59 | 0.37 | 0.15 | 0.97 | 0.55 | 0.10 |
| Fertilizer | 0.03 | 0.80 | 0.31 | 0.11 | 0.43 | 0.49 | 0.10 |
| 18 T Annual | 0.04 | 0.61 | 0.33 | 0.16 | 0.20 | 0.31 | 0.08 |
| 18 T Biennial | 0.02 | 0.42 | 0.60 | 0.17 | 0.31 | – | 0.08 |
| 36 T Annual | 0.06 | 0.51 | 0.45 | 0.12 | 0.14 | – | 0.08 |
| 36 T Biennial | 0.01 | 0.82 | 0.49 | 0.10 | 0.17 | 0.33 | 0.09 |
| 52 T Annual | 0.08 | 0.65 | 0.56 | 0.14 | 0.23 | 0.44 | 0.07 |
| 52 T Biennial | 0.05 | 0.61 | 0.51 | 0.13 | 0.09 | – | 0.07 |
| Calibration Treatments | 0.09 | 0.74 | 0.59 | 0.14 | 0.44 | N/A | 0.09 |
| Validation Treatments | 0.04 | 0.61 | 0.47 | 0.14 | 0.18 | 0.49 | 0.08 |
| Overall $R^2$ | 0.99 | 0.43 | 0.29 | 0.65 | 0.40 | 0.62 | 0.70 |

study because of the variation in manure treatments. Measurement of $N_2O$ emissions were included in the results, however, no model parameters were adjusted for $N_2O$ emissions in the calibration process. Since the release of nitrogen was slow in the 52 T Annual manure treatment, the model was revised to include transformation of slow residue pool to slow humus pool and from fast residue pool to slow humus pool. The C:N ratio of the slow residue pool was set at 20 which approximated the C:N ratio of the manure. The C:N ratios for the fast, intermediate, and slow humus pools were set at 8 (default), 9, and 9, respectively, representing the ratio of soil organic carbon:nitrogen in the soil at the beginning of the study in Fall 2012. The same soil hydraulic properties, soil bulk density, interpool transfer coefficients, and organic matter decay rates were used for all eight scenarios where each scenario represents an experimental treatment. The calibrated parameters for DSSAT crops, HERMES sugar beet parameters, organic matter pools, and organic matter decay rates are listed in Tables A.4, A.5, A.6, and A.7, respectively. The DSSAT spring wheat cultivar was DS3585, the DSSAT potato cultivar was Russet Burbank, DSSAT spring barley cultivar was DSBA02 and the HERMES sugar beet model was used to model sugar beet yield (output as below ground biomass in RZWQM2).

### 2.4. Long-term simulations scenarios

After calibrated with the 4-year rotation, the RZWQM2 was used to simulate a long-term 16-year rotation of wheat-potato-barley-sugar beets. Tillage, irrigation, fertilizer, and manure applications and schedules

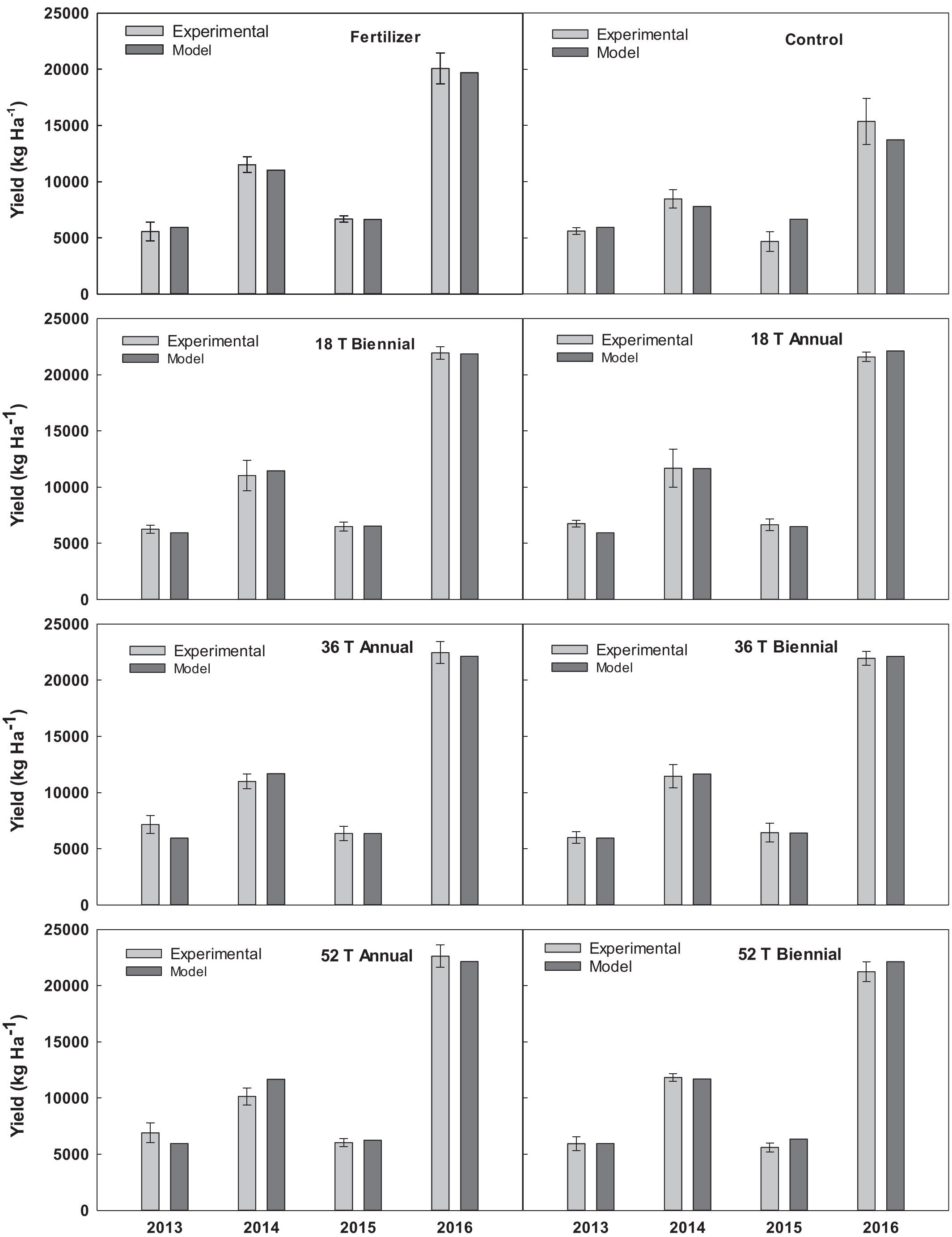


**Fig. 1.** Experimental and model results for crop yield for each treatment over the 4 years. The crop rotation is wheat, potato, barley, and sugar beet for 2013, 2014, 2015, and 2016, respectively. The error bars represent one standard deviation.

from the 4-year scenarios were repeated four times for the 16-year scenarios. Historical weather data for Oct. 15, 2000 to Dec. 13, 2016 was used for the scenarios. The goal of the 16-year scenarios was to observe the consequences of repeated high dairy manure treatments over several crop rotations.

Another question is how many years it would take for the soil to recover after repeated high manure applications. Two 24-yr scenario using the 52 T Annual management practices were simulated; one where the management practices from the 4-yr 52 T Annual were repeated for 6 rotations and a second scenario where after 4 crop rotations no manure or chemical fertilizer was applied. Historical weather data from 1992 to 2016 was used for these scenarios.

### 2.5. Model evaluation criteria

The RZWQM2 was evaluated using PBIAS (percent bias) and RRMSE (relative root mean squared error). The equations for PBIAS and RRMSE are as follows:

$$PBIAS = \frac{\sum_{i=1}^{N}(O_i - P_i) * 100}{\sum_{i=1}^{N} O_i}$$

$$RRMSE = \frac{\sqrt{\left(\sum_{i=1}^{N}(P_i - O_i)^2\right)/N}}{O_{avg}}$$

where $O_i$ = observed (experimental) value, $P_i$ = the simulated or model value, and $N$ which represented the observed values from multiple treatments in this study (Ma et al., 2011). The optimal value of PBIAS is 0.0, with the low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias (Moriasi et al., 2007). RRMSE = 0 indicates a perfect match between experimental and modeling results. RRMSE <1 may be interpreted as simulation error of less than one standard deviation around the experimental mean (Ma et al., 2011). Ma et al. (2012) suggest PBIAS ±15%, however, Moriasi et al. (2007) rated model performance as acceptable when PBIAS was ±25% which was used for this study because there is such a wide range of manure treatments.

The question as to whether or not the simulated treatment results follow the same trend as experimental results was answered by calculating a percent difference as follows: {(4-yr average fertilizer variable − 4-yr average treatment variable) / 4-yr average fertilizer variable} ∗ 100 where the fertilizer treatment represents conventional management practices. Pearson correlation coefficient (SAS 9.4, SAS Institute Inc., Cary, NC, USA) was used to analyze the calculated percent difference.

The nitrate-N budget balance is calculated from the 'seasonal' budget option in RZWQM2 as the Initial Inorganic N − Final Inorganic N + Mineralization + Fertilizer (includes N in irrigation and rainwater) − N Uptake − Denitrification − N2O emission − N Loss (seepage + lateral flow) − Volatilization − Other Losses. Each season begins with the late summer/fall irrigation after harvest and ends with crop harvest.

## 3. Results and discussion

### 3.1. Crop yield, plant N uptake, and soil water content

Treatments were managed to maximize yield, in other words, fertilizer was added when necessary to manure treatments to meet the nutrient requirements of the crop determined from a spring soil sample taken before the crop planting date (Table 2). When comparing the percent difference from the experimental fertilizer treatment ranged from −0.42% to 7.7% for all the experimental manure treatments, and the control percent change was −20%. The percent change for the simulated average crop yield ranged from 3.0 to 3.9% for the manure treatments and was −15% for the simulated control crop yield. There is less variation in the simulated average crop yield when compared to the fertilizer treatment, however, there is little difference in the trend between experimental vs simulated crop yield as the Pearson correlation coefficient for experimental vs simulated percent change was 0.96, Prob >|r| = 0.0005. Calibration of RZWQM2 for simulated crop yield was acceptable for PBIAS and RRMSE (0.16% and 0.09, respectively, Table 3, Moriasi et al., 2007). The simulated crop yield for the validation treatments was −0.23% and 0.04 for PBIAS and RRMSE, respectively (Table 3). Simulated crop yield for all treatments was within the acceptable range (Fig. 1, Table 3). It is important to note that crop quality, especially for potato and sugar beets, are important and not considered in RZWQM2.

Nitrogen uptake by crops is important and it accounts for most of the nitrogen removed from the soil in this study (Table 4). The experimental annual manure treatments had an increased N uptake compared to the fertilizer treatment of 22, 42, 62% for the 18, 36, and 52 T annual treatments, respectively (Fig. 2) and the simulated increases for the same treatments were 27, 29, and 31%, respectively. The increased N uptake for the experimental biennial manure treatments was 11, 23, and 53% for 18, 36, and 52 T biennial treatments, respectively, and 17, 25, and 30% for the simulated biennial treatments, respectively (Fig. 2). The percent difference in N uptake for the experimental and simulated control treatment was −41 and −22%, respectively. Once again, the trend for N uptake was similar for experimental and simulated results (Pearson correlation coefficient = 0.93, Prob > |r| = 0.0022), although the simulated N uptake was less than the experimental for the highest manure treatment. The overall simulated results for the calibrated and validated treatments are in the acceptable range as indicated by a PBIAS of −8.93% and −5.99%, respectively, and a RRMSE = 0.44 and 0.18, respectively (Table 3). Simulated plant N uptake for the control

**Table 4**
Simulated average seasonal budget for all treatments from fall 2012 thru fall 2016. The nitrate-N budget balance equation is: Initial Inorganic N − Final Inorganic N + Mineralization + Fertilizer (includes N in irrigation and rainwater) − N Uptake − Denitrification − N2O emission − N Loss (seepage + lateral flow) − Volatilization − Other Losses. Each season begins with the late summer/fall irrigation after harvest and ends with crop harvest. The manure is applied in the fall after the late summer/fall irrigation.

| Treatment | Initial inorganic N | Final inorganic N | Mineral. | Fert + Irrig + Rain[a] | N uptake | Denit. | $N_2O$ Emission | N Loss | Volatil. | Other losses[b] | Additions-losses |
|---|---|---|---|---|---|---|---|---|---|---|---|
| kg N $Ha^{-1}$ | | | | | | | | | | | |
| Fertilizer | 134.2 | 105.8 | 106.0 | 134.4 | 220.8 | 0.2 | 0.5 | 25.1 | 20.4 | 1.8 | 0.0 |
| Control | 180.5 | 118.8 | 105.3 | 13.5 | 147.5 | 0.1 | 0.3 | 31.6 | 0.0 | 1.0 | 0.0 |
| 18 T A | 207.8 | 166.6 | 160.7 | 153.0 | 293.9 | 2.8 | 1.2 | 41.7 | 13.2 | 2.8 | −0.7 |
| 18 T BA | 175.1 | 139.4 | 146.2 | 141.2 | 266.9 | 1.4 | 0.9 | 30.6 | 21.1 | 2.3 | −0.4 |
| 36 T A | 209.5 | 209.9 | 191.3 | 185.7 | 299.9 | 6.2 | 1.8 | 47.7 | 18.8 | 3.6 | −1.4 |
| 36 T BA | 211.3 | 174.6 | 164.4 | 156.3 | 290.3 | 2.8 | 1.2 | 43.6 | 17.5 | 2.8 | −0.8 |
| 52 T A | 271.5 | 304.5 | 234.6 | 238.2 | 306.4 | 10.5 | 2.5 | 84.5 | 33.6 | 4.5 | −2.1 |
| 52 T BA | 251.3 | 230.2 | 184.2 | 162.2 | 302.2 | 4.7 | 1.5 | 47.7 | 9.2 | 3.3 | −1.1 |

[a] Fertilizer applied + N in irrigation water + N in rain water + NH4 in manure.
[b] Other losses = N in runoff, $N_xO$ release, $N_2O/N_xO$ adsorption during diffusion from greenhouse gases.

treatment was overestimated by RZWQM2 and the only individual treatment that was in the unacceptable range (Table 3). Spring barley was the crop most difficult to calibrate where N uptake was overestimated when 36 T of manure or less was applied and underestimated with the highest manure rate of 52 T (Fig. 2).

Soil water in the profile from 0 to 15 cm was evaluated because it is important in the movement of $NO_3$-N in the soil profile. The PBIAS and RRMSE were −5.81% and 0.09, respectively, for the calibrated treatments (Table 3). RZWQM2 performance was acceptable for the validated treatments as PBIAS and RRMSE were −5.30% and 0.08, respectively (Table 3). Therefore, the values in Table A.2 are adequate for simulating soil water content for the Portneuf silt loam soil type. All treatments had the same irrigation schedule, therefore, no difference in the soil water content between treatments would be expected.

### 3.2. Soil nitrogen

Soil carbon and nitrogen parameters were the most difficult to calibrate for RZWQM2 to simulate conditions with and without manure application. Presently there are few studies that have calibrated the RZWQM2 using, $NO_3$-N in the soil profile, soil mineralization, and total soil N simultaneously. The fit of the model predictions to experimental

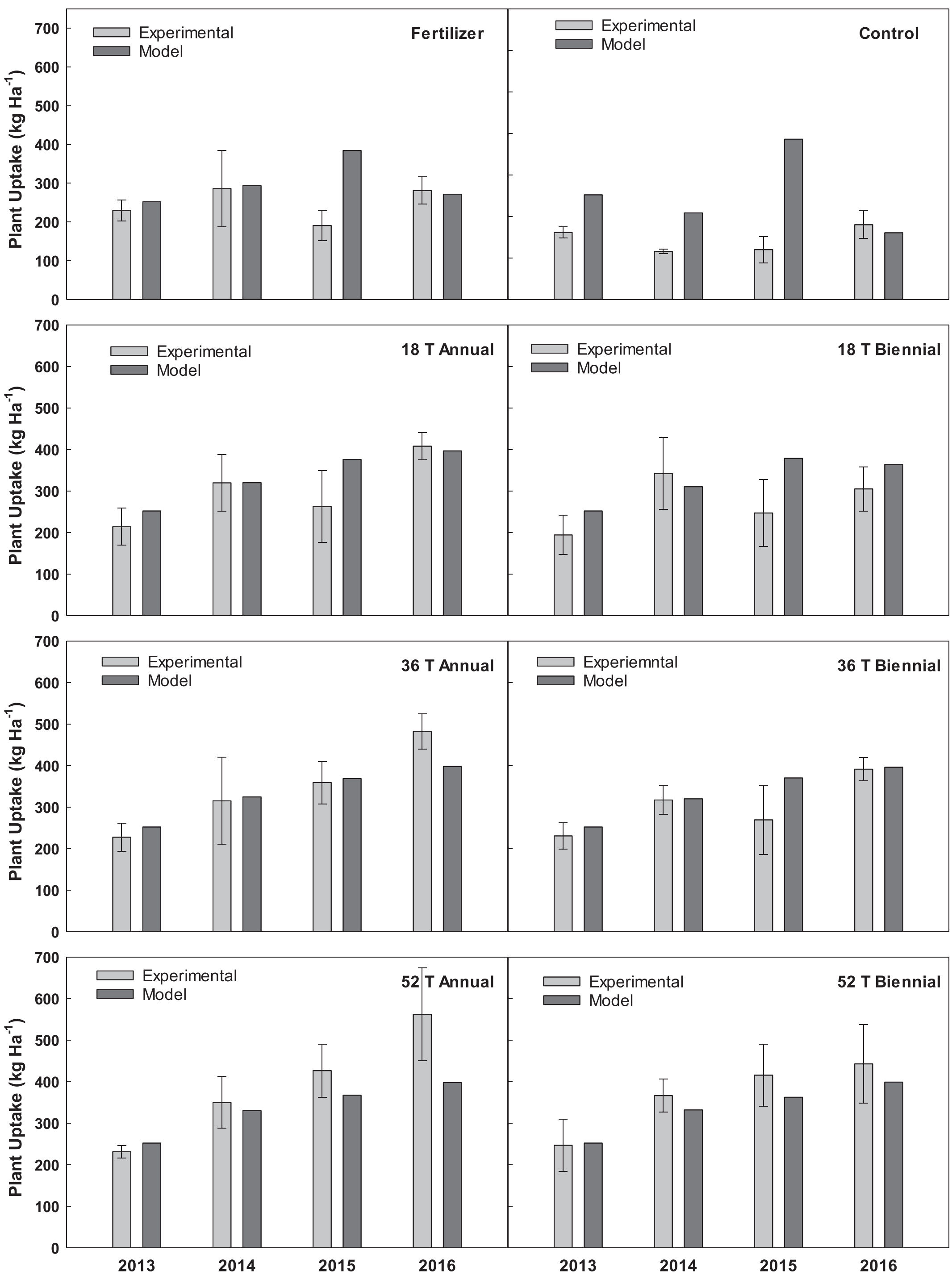


**Fig. 2.** Plant nitrogen uptake for each treatment over the 4 years. The crop rotation is wheat, potato, barley, and sugar beet for 2013, 2014, 2015, and 2016, respectively. The error bars represent one standard deviation.

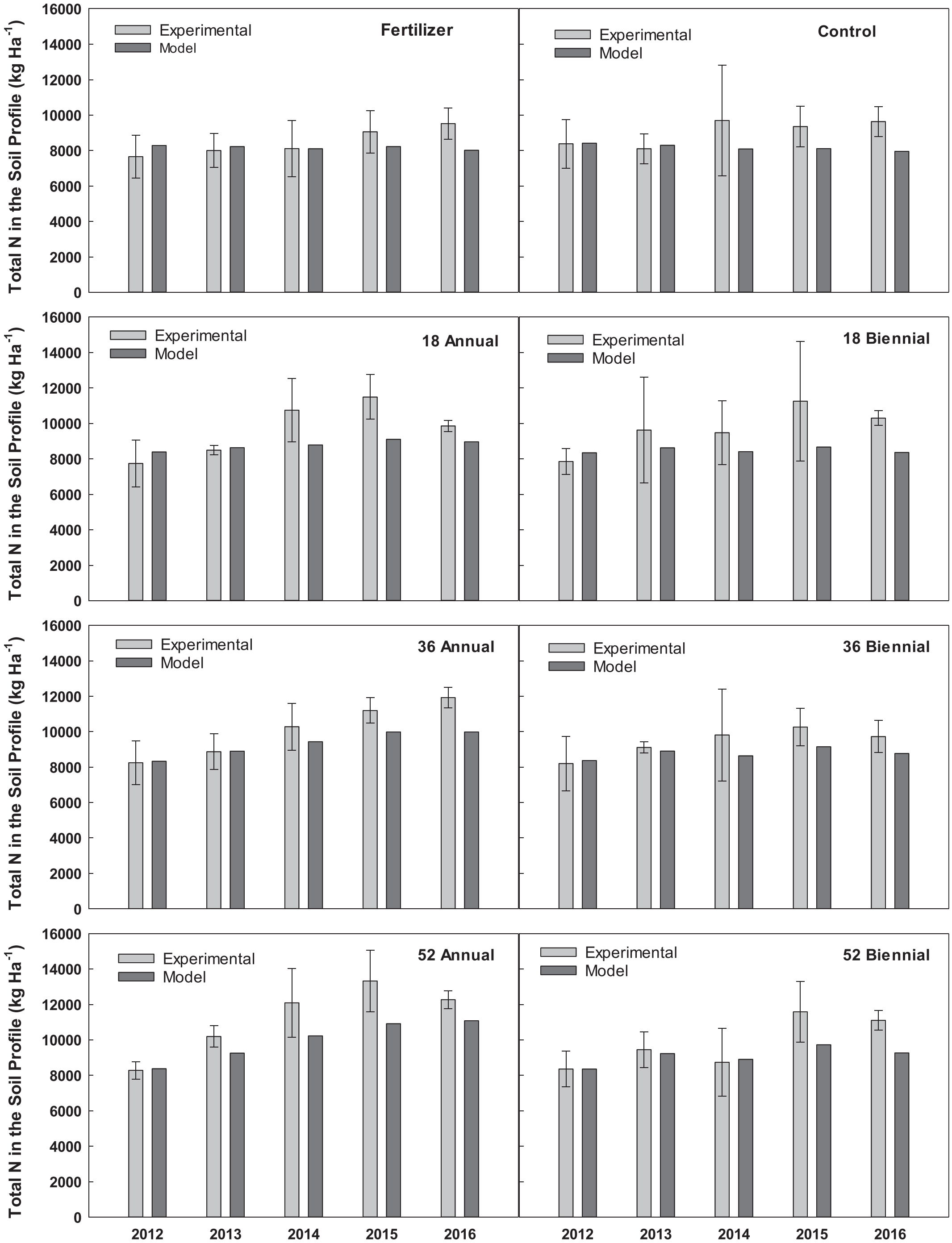


**Fig. 3.** Experimental and model results for Total N in the soil profile. The crop rotation is wheat, potato, barley, and sugar beet for 2013, 2014, 2015, and 2016, respectively. The error bars represent one standard deviation.

data was made possible by primarily adjusting residue and humus pools, organic matter decay rates and C:N ratios. The information from the total N in the soil profile (Fig. 3) was important in deciding the correct C:N ratios and humus pool ratios to obtain reasonable N mineralization rates (Fig. 4). The N mineralization rates were then fine-tuned by adjusting the organic matter decay rates. Most of the soil organic matter was transferred to the slow humus pool to match the measured low soil mineralization (Table A.6). Cassity-Duffey et al. (2018) measured mineralization rates from the manured soil (52 T Annual treatment) and the control soil (no chemical fertilizer or manure) in an adjacent study with the same treatments. Their results indicate a relatively large $Q_{10}$ for manured soil (5.1) compared to the control soil (1.7) at low temperatures (−14 to 4 °C). In the temperature range −14° to 30 °C, the $Q_{10}$ was 2.7 and 2.0 for the manured and control soil, respectively (Cassity-Duffey et al., 2018). These differences in mineralization rates between manure-amended soil and unamended soil could explain some of the differences between simulated mineralization and experimental mineralization as the model parameters are same regardless of treatment (Fig. 4). Even though there were differences, RZWQM2 simulated soil N mineralization effectively (Fig. 4, Table 3). When comparing the trend for the average difference from the fertilizer treatment for the experimental and simulated results, the Pearson correlation coefficient was 0.94 ($Prob > |r| = 0.0019$) indicating the responses to treatment were very similar. The increase in the experimental N mineralization

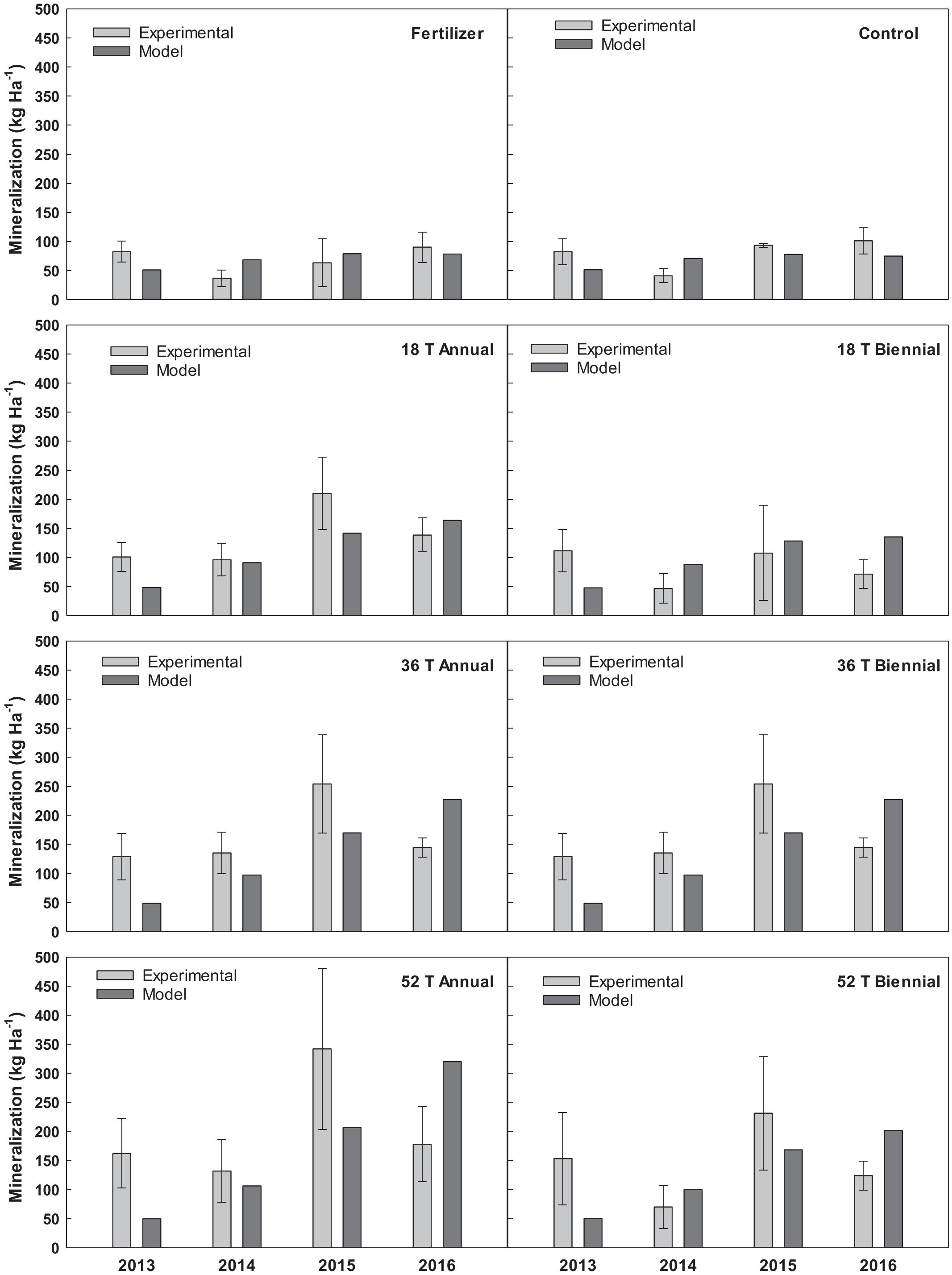


**Fig. 4.** Experimental and model results for $NO_3$-N mineralized. The experimental N mineralized represents the top 30 cm of the soil profile. The crop rotation is wheat, potato, barley, and sugar beet for 2013, 2014, 2015, and 2016, respectively. The error bars represent one standard deviation.

for the 18 T Annual, 36 T Annual, and 52 T Annual treatments compared to the fertilizer treatment was 118, 172, and 223%, respectively, and for the corresponding simulated N mineralization it was 54, 85, and 130%, respectively. The increase in experimental N mineralization for the 18 T, 36 T and 52 T biennial treatments compared to the fertilizer treatment was 28, 129, and 120%, respectively and 39, 58, and 78% for the respective simulated treatments. The average N mineralization for the experimental control treatment was 18% higher than the fertilizer treatment and −0.5% lower for the simulated control treatment. Mahal et al. (2019) suggested that ammonia fertilizer may suppress soil organic matter mineralization because of its effect on microbial activity which could be one possible explanation for greater mineralization in the experimental control treatment compared to the fertilizer treatment. The overall calibrated PBIAS and RRMSE for N mineralization was 12.09% and 0.59, respectively, and the validated PBIAS and RRMSE was 13.62% and 0.47, respectively (Table 3). Those results are in the acceptable range according to Moriasi et al. (2007). The calibration for soil mineralization was successful in this study even though Probert et al. (2005) stated that it would be “naïve” to expect that methods used to model N mineralization of plant residues would apply to manures, especially when the manure can be a combination of feces, urine, bedding material, feed refusals, and soil as was the case in this study.

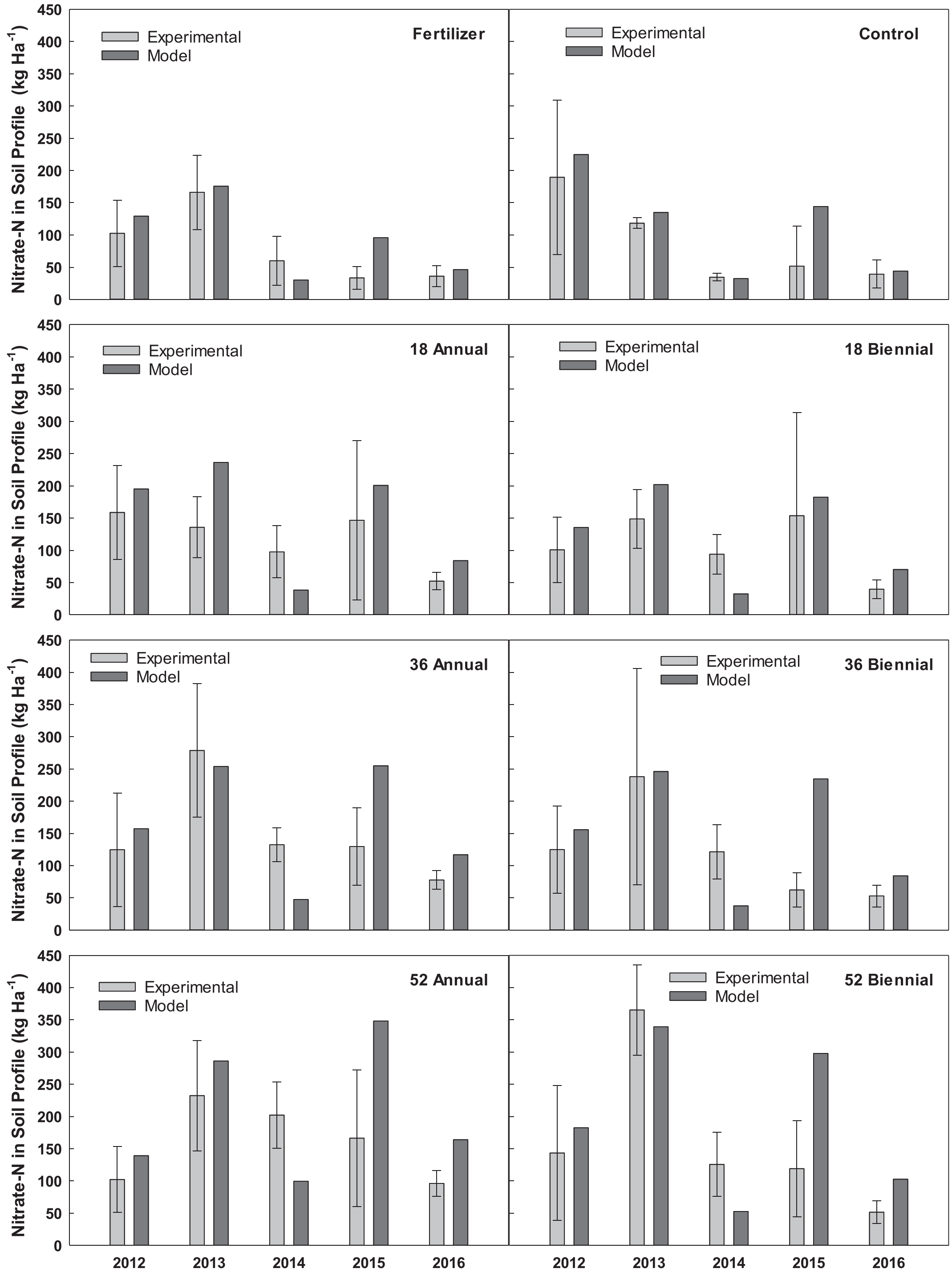


**Fig. 5.** Experimental and model results for $NO_3$-N in the soil profile for each treatment over the 4 years. These results represent $NO_3$-N in the soil profile in the soil sampled once a year after harvest and before the fall application of manure. The crop rotation is wheat, potato, barley, and sugar beet for 2013, 2014, 2015, and 2016, respectively. The error bars represent one standard deviation.

The calibration of RZWQM2 was acceptable for total soil N as PBIAS and RRMSE for the calibration treatments were 8.47% and 0.14, respectively (Table 3). RZWQM2 simulated total soil N in the acceptable range as PBIAS and RRSME were 11.23% and 0.14, respectively, for the validation treatments. More experimental total soil N was accumulated than was applied as fertilizer and manure for all treatments except for the 52 T Annual and the control treatment (Fig. 3). The 18 T Annual, 18 T Biennial, 32 T Annual, 32 T Biennial, 52 T Biennial, and Fertilizer treatments, accumulated a net of 593, 1480, 999, 337, 838, and 1085 kg N ha$^{-1}$, more than was applied, respectively, at the end of 4 years. The 32 T Annual, 52 T Annual, and 52 T Biennial treatments did not receive supplemental fertilizer after potatoes (crop year = 2014). RZWQM2 will mathematically balance the input nutrients with output nutrients and thus would not have results where simulated total soil N would be higher than applied total soil N. There is variation in the composition of the manure applied and a small amount of the soil is analyzed compared to the size of the entire research plot for total soil N, therefore, estimates from the analysis may have some error. Also, because of the high density of dairies in the Magic Valley, it is possible there is atmospheric deposition of nitrogen in particulate matter that was not accounted for in RZWQM2. An estimate of ammonia and nitrate-N in the rain and irrigation water was accounted for in the model input parameters, however, this estimate may not account for all the nitrogen deposition. Even with these problems, RZWQM2 simulated total soil N in the acceptable range (Table 3). When comparing the trend for the average difference from the fertilizer treatment for the experimental and simulated results, the Pearson correlation coefficient was 0.92 (Prob > $|r| = 0.0029$) indicating the responses to treatment were very similar. The increase in the experimental total N for the 18 T Annual, 36 T Annual, and 52 T Annual treatments compared to the Fertilizer treatment was 17, 21, and 38%, respectively, and for the corresponding simulated total N it was 10, 18, and 27%, respectively. The increase in experimental total N for the 18 T, 36 T and 52 T biennial treatments compared to the fertilizer treatment was 17, 13, and 17%, respectively and 6, 9, and 14% for the respective simulated treatments. The total N in the experimental control treatment was −2% of the fertilizer treatment and −0.3% for the simulated control treatment.

RZWQM2 overestimated the $NO_3$-N in the soil profile as PBIAS and RRMSE for the $NO_3$-N in the soil profile were −29.48% and 0.74 (Gupta et al., 1999; Moriasi et al., 2007), respectively, for the calibration treatments (Table 3). The PBIAS for the validation treatments was in the acceptable range (−18.73%) and the RRMSE was 0.61 (Table 3). The experimental range of soil $NO_3$-N in the profile was 33 to 365 kg ha$^{-1}$ (Fig. 5) depending on the manure treatment and crop planted, which made it difficult to calibrate, in other words, the calibration treatments represent the widest range of treatments – the control with no N added to the soil and the 52 T Annual manure treatment. N mineralization was measured over the growing season, whereas the N in the soil profile was a fall measurement, therefore the focus was on accurately calibrating RZWQM2 for N mineralization. It was a major challenge to simulate both soil parameters simultaneously, however, by calibrating RZWQM2 to slightly underestimate N mineralization, $NO_3$-N in the soil profile was closer to the acceptable range. It is not clear why RZWQM2 overestimated the $NO_3$-N in the soil profile so much in this study. Because RZWQM2 was calibrated for several soil nitrogen measurements, it is difficult to compare results to different model studies where only one or two measurements were used for calibration. Gersseler et al. (2012) used RZWQM2 to model the response of irrigated forage systems fertilized with liquid dairy manure and had difficulty in modeling mineral N contents in the soil profile during the cropping season and attributed it to inaccurate predictions of water movement in the different soil layers and lack of information on N mineralization. The increase in $NO_3$-N in the profile the last 2 years of the 4-year rotation for the high manure treatments (36–52 T Annual and Biennial, Fig. 5) indicated there may be an issue with RZWQM2 and high manure applications. The average calibrated and validated $NO_3$-N in the soil profile

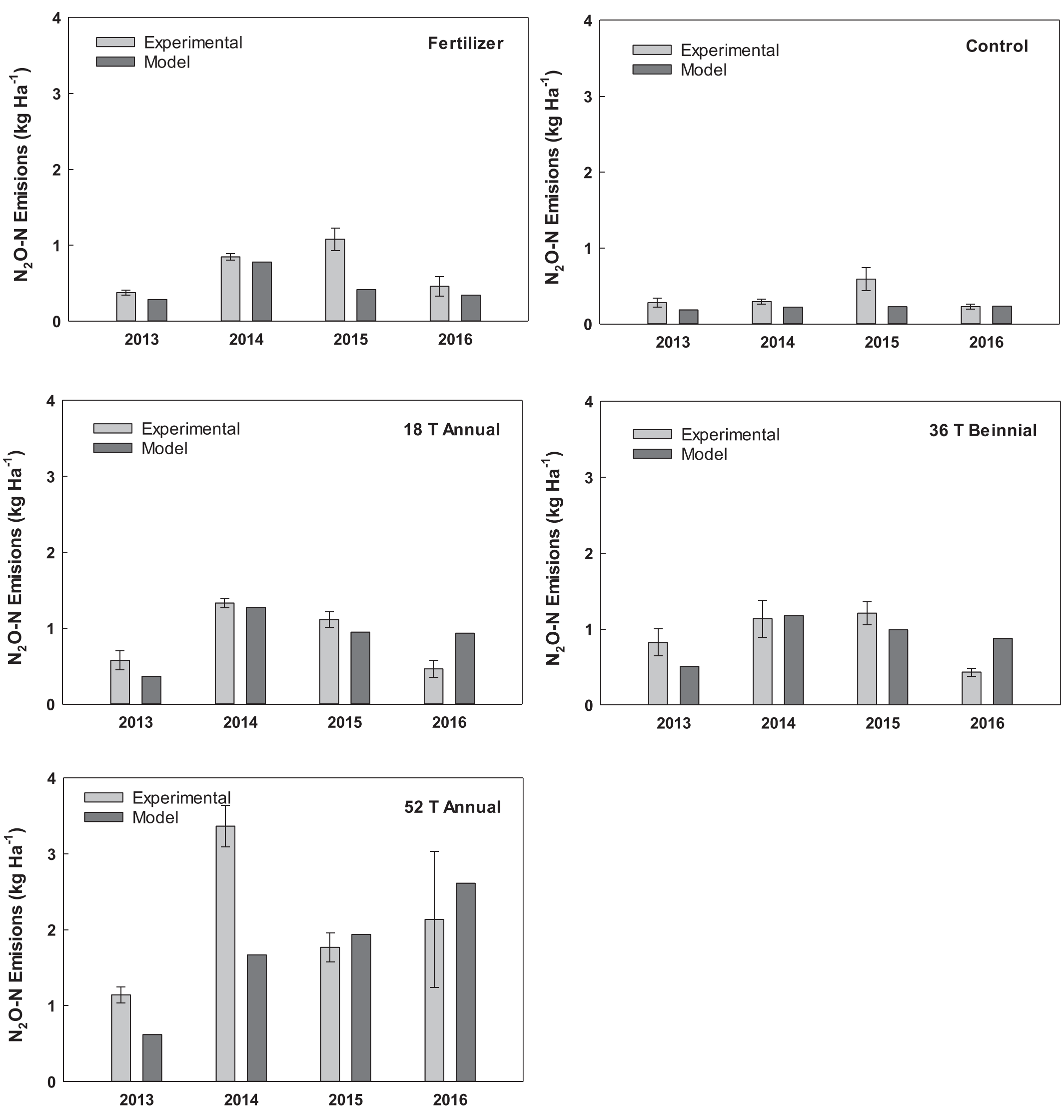


**Fig. 6.** Experimental and model N2O emissions for April thru October, except in 2016 it was May thru October. Using interpolated data for experimental N2O emissions. N2O emissions are total emissions for the season.

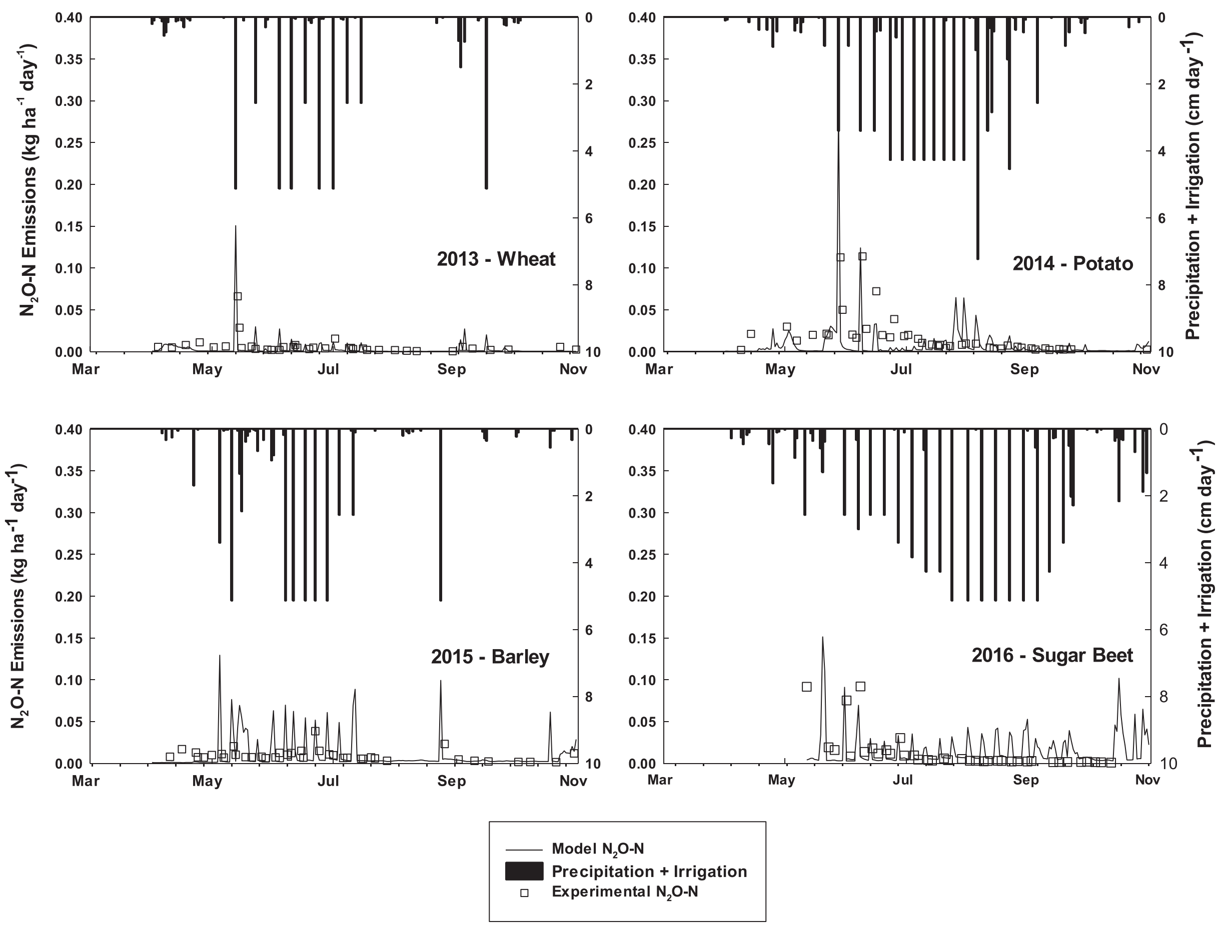


**Fig. 7.** This graph represents data from the 52 T Annual, the treatment with the most dramatic differences. The actual field measurements are used in this figure, in other words, not the interpolated data. The purpose of this graph is to demonstrate there may be peak time of $N_2O$ emissions that are not captured in the experimental measurements.

for the 52 T Annual treatment was 224 kg ha$^{-1}$ (range for the 4 years was 100 to 348 kg ha$^{-1}$) whereas the average $NO_3$-N in the soil profile using RZWQM2 default nutrient parameters was 535 kg ha$^{-1}$ (range for the 4 years was 343 to 785 kg ha$^{-1}$). The experimental average $NO_3$-N in the soil profile for the 52 T Annual treatment was 174 kg ha$^{-1}$ with a range of 96 to 232 kg ha$^{-1}$. On the other hand, for the control treatment, the calibrated and validated average $NO_3$-N in the soil profile was 87 kg ha$^{-1}$ and using default nutrient parameters it was 39 kg ha$^{-1}$ and the experimental average $NO_3$-N in the soil profile was 61 kg ha$^{-1}$. Because RZWQM2 underestimated $NO_3$-N in the soil profile using default nutrient parameters in the control treatment and overestimated it in the 52 T Annual, it was necessary to find common ground between the treatments when calibrating the model. The end results were that soil mineralization and total N in the soil were calibrated successfully, while $NO_3$-N in the soil profile was in the acceptable range for the validation treatments. Primarily $NO_3$-N in the soil profile was overestimated in the final 2 years of the rotation.

When comparing the trend for the average difference from the fertilizer treatment for the experimental and simulated results for $NO_3$-N in the soil profile, the Pearson correlation coefficient was 0.92 ($Prob > |r| = 0.0037$) indicating the response to treatments were very similar. The increase in experimental $NO_3$-N in the soil profile for the 18 T Annual, 36 T Annual, and 52 T Annual treatments compared to the Fertilizer treatment was 107, 148, and 210%, respectively, and for the corresponding simulated $NO_3$-N in the soil profile it was 56, 94, and 183%, respectively. The increase in experimental $NO_3$-N in the soil profile for the 18 T, 36 T and 52 T biennial treatments compared to the fertilizer treatment was 104, 69, and 132%, respectively and 34, 63, and 113% for the respective simulated treatments. The $NO_3$-N in the soil profile for the experimental control treatment −1.7% less than the experimental fertilizer treatment and the simulated control was −1.2% less than the simulated fertilizer treatment.

Two of the most important abiotic variables controlling the soil organic matter decomposition process are temperature and moisture and sensitivities or decomposition rates vary depending on the specific combination of temperature and moisture of the system (Sierra et al., 2015). In the agricultural system in southern Idaho, as the temperature increases in the summer, the soil water content often varies because the crops are irrigated, consequently, there are weekly or more frequent wetting/drying cycles in a growing season. Spring wheat and spring barley had 10 and 11 irrigations, respectively, while potato and sugar beet had 21 and 18 irrigations, respectively, over the growing season. Another factor is the Portneuf soil in southern Idaho has a high silt content (59 to 71%). Cotrufo et al. (2015) discuss how the dissolved organic matter in fine-textured soils can quickly become associated with the silt fractions in the mineral soil and microbes use the labile litter compounds more efficiently. These factors could be some of the reason the adjustments to organic matter decay rates and humus pool transfer coefficients were necessary in this study. More research is needed to better understand the interacting processes affecting organic matter decay rates to improve simulation of soil carbon and nitrogen cycling, especially in soils with heavy manure applications.

### 3.3. $N_2O$ soil emissions

After RZWQM2 was calibrated for total soil N and soil nitrogen mineralization, no further adjustments were made when comparing simulated and experimental $N_2O$-N emissions. RZWQM2 simulations of $N_2O$-N

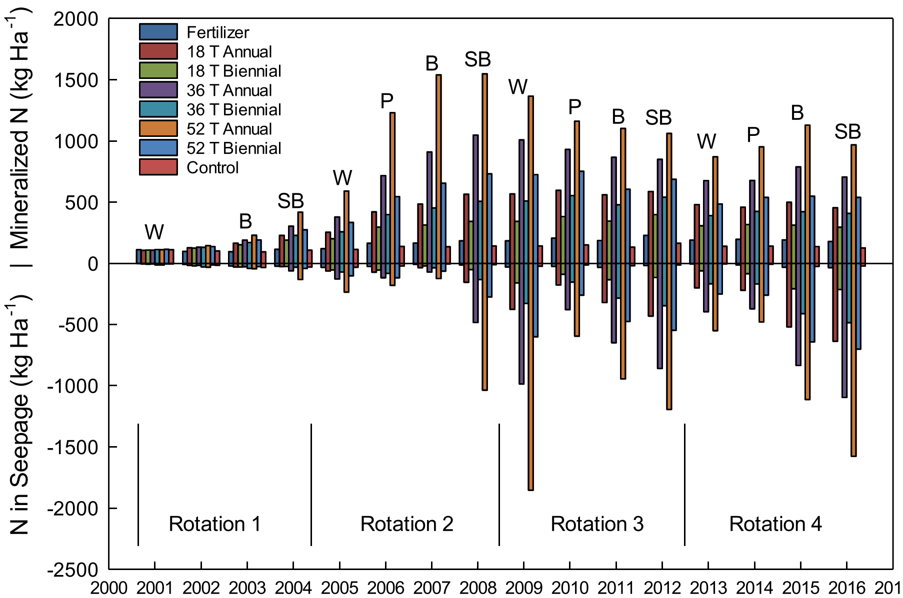


**Fig. 8.** Results of the 16-year simulation for mineralized N (positive values) and seepage of nitrate-nitrogen out of the profile (negative values) for the crop rotation wheat (W), potato (P), barley (B), and sugar beet (SB).

emissions were overall acceptable (Table 3). According to PBIAS, the present simulations tend to underestimate $N_2O$-N emissions for the fertilizer, control and 52 T Annual treatments, however, 18 T Annual and 36 T Biennial simulations closely agree with the experimental data (−1.10 and 1.45%, respectively, Table 3 and Fig. 6). RZWQM2 simulates $N_2O$-N emissions peaks usually when there are irrigations, whereas, the experimental data sometimes does not record them (Fig. 7). However, experimental $N_2O$-N emissions between the peaks are often higher than the simulated results (Fig. 7). Gillette et al. (2018) documented similar results of peak daily emissions from RZWQM2 that were higher than experimental measurements. The highest manure application treatment (52 T Annual) recorded the highest simulated and experimental $N_2O$-N emissions (1.71 and 2.10 kg ha$^{-1}$, respectively, Fig. 6). The experimental $N_2O$-N emissions for the 52 T Annual treatment were three and six times higher compared to the fertilizer and control treatments, respectively. The simulated $N_2O$-N emissions for the 52 T Annual treatment were 3.7 and 7.8 times higher than the fertilizer and control treatments, respectively. Experimental and simulated $N_2O$-N emissions for the fertilizer treatment were about twice as high as the control treatment (Fig. 6).

In Fig. 7, on May 28, 2014 the $N_2O$-N emissions peaked (0.29 kg ha$^{-1}$) when there was a high minimum temperature (8.3 °C), a high maximum temperature (25.4 °C) and an irrigation of 3.4 cm. The range of the average minimum temperature for May from 2013 to 2016 was 5.7 °C to 7.0 °C and the range of the average maximum temperature at the same time was 20.7 °C to 22.0 °C. The high temperatures and irrigation occurred when the potato canopy was very open, later in the season when the crop canopy had closed there was less $N_2O$-N emissions with irrigations and warm temperatures (Fig. 7). These results demonstrate the effect of the interaction of temperature, irrigations, and crop canopy on $N_2O$-N emissions. Leytem et al. (2019) has a

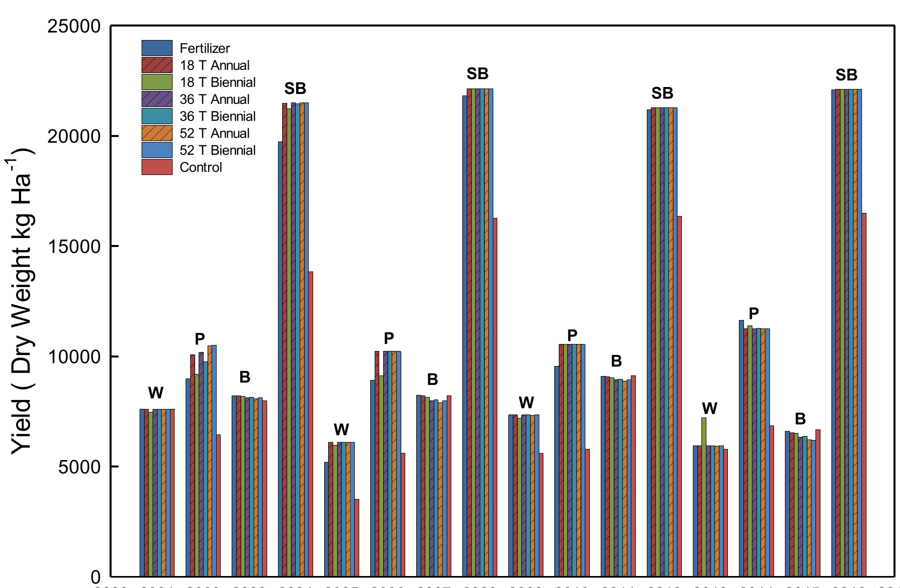


**Fig. 9.** Results of the 16-year simulations of crop yield for the rotation of wheat (W), potato (P), barley (B), and sugar beet (SB).

complete analysis and discussion of the $N_2O$-N emissions results from this study and other greenhouse gas emissions.

### 3.4. Simulated N budget

The nitrogen budget from all the RZWQM2 scenarios was balanced (Table 4, additions-losses ranged from −2.1 to 0.0). The nitrogen budget represents the average of the seasonal calculations from RZWQM2 simulations where the first season begins with the manure application in the fall of 2012 and ends with crop harvest in 2013 (333 days). The second, third and fourth seasons begin with the fall irrigation before applying manure and end with the harvest the following year including 361, 315, and 416 days, respectively. The budget indicates the average final inorganic nitrogen was similar to the initial inorganic nitrogen except for the 52 T Annual treatment where the inorganic nitrogen in the soil increased by 33 kg $ha^{-1}$. Nitrogen mineralized was higher in all manure treatments when compared to the fertilizer and control with annual treatments mineralizing more nitrogen than biennial treatments (Table 4). When comparing the annual and biennial treatments, the 18 T and 36 T Annual treatments increased average nitrogen mineralization by about 25 kg $ha^{-1}$ over the corresponding biennial treatment and in the 52 T Annual treatment the increase was 50 kg $ha^{-1}$ (Table 4). Denitrification increased in manure treatments compared to the fertilizer and control by a factor of 10 to 100 (52 T Annual) times. The loss of nitrogen from volatilization was similar for all treatments except the 52 T Annual was about 1.6 times higher than the fertilizer treatment and the control had zero volatilization (Table 4). The average nitrogen loss from seepage for the 52 T Annual treatment was 3.4 times the fertilizer treatment; 84.5 kg $ha^{-1}$ vs 25.1 kg, $ha^{-1}$, respectively (Table 4).

### 3.5. 16 and 24-year scenarios

The advantage of system models is that once they are calibrated and validated with available data, processes that could not be measured and long-term scenarios can be examined. One process, leaching or seepage of $NO_3$-N through the soil profile is of special interest for manure management in the Magic Valley of southern Idaho because of potential leaching into the East Snake Plain Aquifer and the nitrate priority areas.

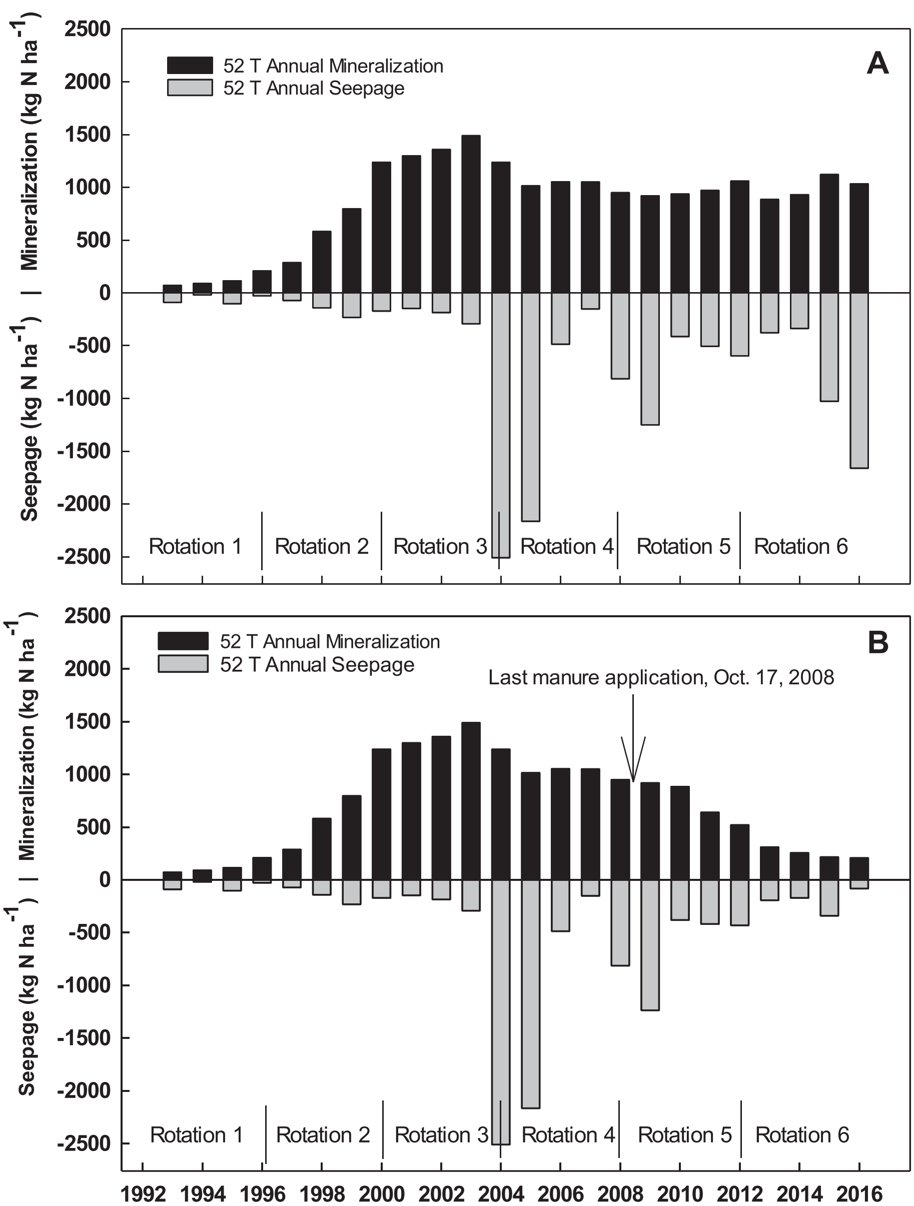


**Fig. 10.** Results of a 24-year simulation for mineralized N and nitrate-nitrogen seepage for the 52 T Annual treatment. Fig. A represents manure applied every year and Fig. B represents the 52 T Annual treatment where no manure or chemical fertilizer was applied after Oct. 2008. The crop rotation is spring wheat, potato, spring barley, and sugar beet repeated 6 times.

There are several ways to compare the seepage data, one is to compare corresponding annual and biennial treatments (for example, 18 T Annual vs 18 T Biennial). The results for the average nitrogen seepage over the 16-year period indicated the annual treatments were about two times the corresponding biennial treatment (Fig. 8). When comparing the annual manure application treatments, average nitrogen seepage for the 16 years increased 1.8, 1.7, and 3.0 times for the 36 vs 18, 52 vs 36, and 52 vs 18 T Annual, respectively (Fig. 8). The increase in nitrogen seepage for the annual treatments compared to the fertilizer treatment was 7.7, 15.1, and 23.5 times greater for 18, 36, and 52 T Annual, respectively. When biennial treatments were compared to the fertilizer treatment nitrogen seepage was 3.1, 7.0, and 10.6 times greater for 18, 36, and 52 T Biennial. The nitrogen seepage for the fertilizer treatment was 1.9 times higher than the control (Fig. 8). N seepage began to increase dramatically after rotation 2 with rotations 3 and 4 having the highest amount of N seeping through the soil profile (Fig. 8) following N mineralization rates exceeding 500 kg ha$^{-1}$ in rotation 2. Simulated average N uptake average for 16 years was similar for all the manure treatments, range = 302 to 326 kg ha$^{-1}$, therefore, the mineralization rates for the high manure treatments were much higher than the plant N uptake. According to the simulated N budget for the 16 years, mineralization increased with higher manure treatments as the average mineralization for the 52 T Annual treatment was 2.1 times higher than the 18 T Annual (409 kg ha$^{-1}$ vs 901 kg ha$^{-1}$, respectively). The 18 T Biennial and 36 T Biennial 16-yr average mineralization was 275 kg ha$^{-1}$ and 372 kg ha$^{-1}$, much closer to the amount of N required for maintaining crop yield. The 16-yr fertilizer treatment average mineralization was like the seasonal 4-yr simulated mineralization (128 and 106 kg ha$^{-1}$, respectively). Crop yield for 16-yr simulations for a given year was consistent among all treatments with the control having lower yields for most years (Fig. 9). Another source of N loss from the system was denitrification where the losses from the annual treatments were almost 3 to 4 times the biennial treatments (for example, the average 16-yr denitrification for 52 T Biennial it was 25 kg ha$^{-1}$ and for 52 T Annual it was 98 kg ha$^{-1}$). $N_2O$ emissions were also 2 to 3 times higher for annual treatments compared to biennial treatments (for example, for 52 T Annual $N_2O$ emissions = 17.4 kg ha$^{-1}$ and for 52 T Biennial $N_2O$ emissions = 5.4 kg ha$^{-1}$). When considering manure applications, biennial treatments would contribute less nitrogen to the groundwater and the atmosphere and high annual manure applications should be discouraged.

The purpose of the 24-yr scenarios was to simulate how much time it would take for the soil profile to recover from repeated high manure applications (52 T Annual, Fig. 10 A and B). The average N mineralization for rotation 6 in Fig. 10B was 992 kg ha$^{-1}$, whereas, it was 245 kg ha$^{-1}$, similar to 235 kg ha$^{-1}$ for 52 T Annual in the 4-yr simulation (Table 4). Consequently, the average losses for rotation 6 in Fig. 10A because of N uptake, denitrification, and seepage were 308, 192, and 850 kg ha$^{-1}$, respectively, and in Fig. 10 B those same losses were 280, 5, and 197 kg ha$^{-1}$, respectively. It is interesting to note the capacity of the soil profile to store nitrogen, in the 24-yr rotation the average final inorganic N in the soil profile for rotation 6 was 2025 kg ha$^{-1}$. If there are weather events during the year which would increase the amount of water going through the soil profile, the potential for leaching nitrogen with repeated high manure applications would be significant. The average precipitation for the 24-yr scenario was 26 cm (range = 13 to 45 cm), therefore, N seepage is unlikely to be caused consistently by high rainfall events. A closer look at the monthly seepage events indicates the highest N seepage occurs in the month of September (24-yr average for N seepage = 137.3 kg ha$^{-1}$, precipitation = 1.2 cm, and irrigation = 5.3 cm) especially when sugar beets are planted and a fall irrigation is necessary to keep the soil moist for digging sugar beets late in the season. The 24-yr average N seepage for the winter months (January, February, March, October, November, and December) when there is no irrigation was 36 kg ha$^{-1}$. Therefore, N seepage may be attributed to a combination of events; irrigation, the capacity of the soil to accumulate and store nitrogen, and possible, although seldom, high precipitation events. Cover crops may be useful to capture excess mineralized N and nitrogen in the profile in fields that have long term manure application. Another option would be to plant long-season crops to replace the short growing season grains.

## 4. Conclusion

Soil is key to filtering water contaminants and maintaining water quality for subterranean and surface waters (Clothier et al., 2008) and accurate models are helpful in predicting consequences of management practices over longer periods of time. RZWQM2 performed satisfactorily for all the soil, water, and plant parameters measured in this study. There is the possibility that the RZWQM2 may require more development to better estimate the soil nitrate – nitrogen portion of the model.

The 16 and 24-year scenarios introduce some interesting long-term research possibilities. The scenarios suggest there may be a pattern to nitrogen seepage and N mineralization and questions could be asked about how soil type, management practices, and environment influence nitrogen storage capacity. This study had a crop rotation where a short season crop (wheat and barley) was alternated with a long season crop (potato and sugar beet) so there could be different seepage and storage patterns with different crop rotations. Bingham and Cotrufu (2016) discuss the importance of understanding the factors that impact N sequestered in soils and how improving our understanding of N and C cycling and their effects on ecosystem structure and function will improve our understanding of saturation processes. A better understanding of long-term N storage and the factors that affect it will help us be better stewards of our environment (Bingham and Cotrufu, 2016).

Regarding nitrate priority areas in Idaho, the results from RZQWM2 suggests that applying manure annually might result in more nitrogen in the groundwater. In these areas, farmers may want to consider not applying manure at all or at least applying lower amounts at biennial or longer intervals.

## CRediT authorship contribution statement

Anita C. Koehn performed all RZWQM2 tasks, analyzed data, and wrote the manuscript.

David L. Borneberg provided supervision and many conversations and recommendations on all the phases of the manuscript.

Rob W. Malone provided instruction and suggestions for the calibration and validation of RZWQM2 and reviewing the manuscript.

April B. Leytem is the principal scientist on the long-term manure study and provided all the research data and provided suggestions to the manuscript.

Amber Moore is the principal scientist on the long-term study along with April Leytem and provided all the field research data.

Liwang Ma is the RZWQM2 scientist, made adjustments to the model code, reviewed the manuscript, and provided important suggestions to the manuscript.

Pat N. S. Bartling provided the training for the RZWQM2 and many helpful discussions on calibrating and validating the model, in addition to reviewing the manuscript.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Appendix A

**Table A.1**
The planting information and the fall soil sampling date for the scenarios in the RZWQM2 project. The number of plants for wheat and barley includes tillers and planting density was the same for both crops. The harvest data for potato is the vine kill date. The data from the fall soil sampling data is used to calculate the nitrate-N in the soil profile for model comparisons. Soil was sampled to a depth of 122 cm on 2013, 2014 and 2015 and in 2016 it was sampled to a depth of 90 cm.

| Crop | Planting date | Plants $Ha^{-1}$ | Harvest date | Fall soil sampling date |
|---|---|---|---|---|
| Wheat | Apr. 2, 2013 | 2,208,619 | Aug. 13, 2013 | Sept. 30, 2013 |
| Potato | Apr. 29, 2014 | 35,625 | Sept. 10, 2014 | Oct. 9, 2014 |
| Barley | Mar. 31, 2015 | 2,208,619 | July 29, 2015 | Sept 24, 2015 |
| Sugar Beet | May 9, 2016 | 82,200 | Oct. 11, 2016 | Nov. 15, 2016 |

**Table A.2**
Percent organic matter for soil residue pool initiation and Soil Hydraulic parameters used in the RZWQM2.

| Horizon depth (cm) | % organic matter | % soil organic carbon | Soil hydraulic conductivity cm $hr^{-1}$ | Field capacity water content at 1/10 bar | Soil bulk density gr $cm^{-3}$ |
|---|---|---|---|---|---|
| 5 | 1.597 | 0.928 | 1.340 | 0.32 | 1.2 |
| 30 | 1.271 | 0.739 | 1.340 | 0.32 | 1.4 |
| 60 | 0.769 | 0.447 | 1.013 | 0.32 | 1.4 |
| 90 | 0.403 | 0.233 | 1.234 | 0.34 | 1.4 |
| 122 | 0.408 | 0.236 | 1.234 | 0.34 | 1.4 |
| 152 | 0.084 | 0.063 | 1.257 | 0.35 | 1.4 |

**Table A.3**
Residue pools and microbial population for defining the initial residue state in the RZWQM. The information is the same for all 8 treatment scenarios.

| Horizon depth (cm) | Slow residue (μg-C/g) | Fast residue (μg-C/g) | Fast humus (μg-C/g) | Intermediate humus (μg-C/g) | Slow humus (μg-C/g) | Aerobic heterotrophs (#org/g) | Autotrophs (#org/g) | Anaerobic heterotrophs (# org/g) |
|---|---|---|---|---|---|---|---|---|
| 0–15 | 100.0 | 2.10 | 113.50 | 543.0 | 10,377.0 | 401,813.09 | 6824.80 | 26,739.50 |
| 15–30 | 79.90 | 0.10 | 37.80 | 446.40 | 6119.0 | 81,665.30 | 2006.60 | 5438.70 |
| 30–60 | 117.20 | 2.50 | 19.0 | 424.50 | 3621.0 | 37,158.70 | 989.40 | 3193.0 |
| 60–90 | 22.10 | 1.40 | 25.90 | 261.10 | 1873.9 | 1126.80 | 488.60 | 1180.80 |
| 90–122 | 3.0 | 0.0 | 49.10 | 277.30 | 1889.20 | 6557.40 | 465.40 | 962.50 |
| 122–154 | 0.0 | 0.0 | 20.50 | 58.20 | 386.30 | 1315.10 | 378.10 | 198.40 |

**Table A.4**
Calibrated DSSAT parameters for wheat, barley, and potato in irrigated southern Idaho agriculture. The wheat and barley ecotypes are DS3585 and DSBA02, respectively.

| DSSAT parameter | Spring wheat – high latitude | Spring barley – high latitude | DSSAT parameter | Russet Burbank potato |
|---|---|---|---|---|
| P1V | 0.0 | 0.0 | G2 | 1000 |
| P1D | 0.0 | 0.0 | G3 | 17.0 |
| P5 | 726.2 | 750.0 | G4 | 0.2 |
| G1 | 52.0 | 45.0 | PD | 0.3 |
| G2 | 52.0 | 45.0 | P2 | 0.6 |
| G3 | 1.5 | 2.5 | TC | 17.0 |
| PHINT | 94.3 | 75.0 | | |
| PARUV | 3.25 | 2.65 | | |
| PARUR | 3.25 | 2.65 | | |
| RSFRS | 0.6 | 1.2 | | |
| GRNMN | 2.0 | 2.1 | | |
| GRNS | 2.3 | 2.2 | | |

P1V = Days at optimum vernalizing temperature required to complete vernalization.
P1D = Percentage reduction in development when photoperiod is 10 h less than the threshold relative to that at threshold.
P5 = Grain filling phase duration (degree C day).
G1 = Kernel number per unit canopy weight at anthesis (# $g^{-1}$).
G2 = Standard kernel size under optimum conditions (mg).
G3 = Standard, non-stressed dry weight (total, including grain) of a single tiller at maturity (g).
PHINT = Interval between successive leaf tip appearances (degree days).
PARUV = PAR conversion to dm ratio, before last leaf stage (g $MJ^{-1}$).
PARUR = PAR conversion to dm ratio, after last leaf stage (g $MJ^{-1}$).
RSFRS = Reserve fraction of assimilates going to stem (#).
GRNMN = Minimum Grain N (%).
Standard Grain N (%).
Potato:
G2 = Leaf area expansion rate in degree days.
G3 = Potential tuber growth rate.
G4 = currently not used in the model.
PD = Index that suppresses tuber growth during the period that immediately follows tuber induction.
P2 = Index that relates photoperiod response to tuber initiation.
TC = Upper critical temperature for tuber initiation.

**Table A.5**
Partitioning of biomass between roots and leaves at the end of each development phase for sugar beets in the HERMES management option and changes made to crop inputs. All other crop inputs and development phase parameters were the default settings.

| Sugar beets (HERMES) | | | | |
|---|---|---|---|---|
| Development phase | Roots | Leaves | Root N content | Specific leaf area |
| 1 | 0.53 | 0.43 | 0.5 | 0.002 |
| 2 | 0.53 | 0.43 | 0.6 | 0.002 |
| 3 | 0.53 | 0.43 | 0.6 | 0.002 |
| 4 | 0.53 | 0.43 | 0.7 | 0.002 |
| 5 | 0.53 | 0.43 | 0.7 | 0.002 |
| 6 | 0.53 | 0.43 | 0.8 | 0.002 |

Crop CO2 Method = 2, Hoffman.
Maximum Plant Height (cm) = 50.
Plant Biomass at ½ Max Height (kg ha$^{-1}$) = 400.
Maximum Leaf Biomass after Cutting (kg ha$^{-1}$) = 4; 0 = stem biomass.
CO2 Assimilation = 260.
Maximum effective rooting depth (cm) = 150.
Maximum Daily N Uptake = 10.

**Table A.6**
Intrapool transformation coefficients for organic matter pools used for all scenarios. These are the decimal fractions transformed from pool to pool. The slow residue pool to slow humus pool and fast residue pool to slow humus pool were added to allow the organic matter pools to be partitioned primarily to the slow humus pool.

| Source pool | Destination pool | Decimal fraction | Default values |
|---|---|---|---|
| Slow residue pool | Intermediate soil humus pool | 0.2 | 0.3 |
| Fast residue pool | Fast soil humus pool | 0.2 | 0.6 |
| Fast soil humus pool | Intermediate soil humus pool | 0.5 | 0.6 |
| Intermediate soil humus pool | Slow humus pool | 0.7 | 0.7 |
| Slow residue pool | Slow humus pool | 0.7 | 0.0 |
| Fast residue pool | Slow humus pool | 0.7 | 0.0 |

Nutrient System C:N ratios.
Slow Residue Pool 1 Partition Coefficient = 20 (Manure C:N ratio).
Fast Residue Pool 2 Partition Coefficient = 80.0 (Default).
Fast Soil Humus = 8.0 (based on SOC:N ratio).
Intermediate Soil Humus = 9.0.
Slow Soil Humus = 9.0.
All other parameters are the default values.

**Table A.7**
Organic matter decay rates used for all scenarios. Coefficients are for Arrhenius organic matter decay equation for organic matter pools. The units for the decay rates are nitrogen in moles L$^{-1}$ day$^{-1}$ (Ma et al. 2001).

| Decay "A" values | Decimal fraction | Default decimal fraction |
|---|---|---|
| Slow residue pool | $1.673\ 10^{-8}$ | $1.673\ 10^{-7}$ |
| Fast residue pool | $9.14\ 10^{-6}$ | $8.14\ 10^{-6}$ |
| Fast soil humus pool | $2.0\ 10^{-6}$ | $2.5\ 10^{-7}$ |
| Intermediate soil humus pool | $4.5\ 10^{-7}$ | $5.0\ 10^{-8}$ |
| Slow soil humus pool | $8.25\ 10^{-9}$ | $4.5\ 10^{-10}$ |

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