

**Groundwater nitrate trends reflect stable isotope classification
and legacy nitrogen accumulation**

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Abbreviations: GWMA, Groundwater Management Area; SWV, southern Willamette Valley; N, nitrogen; CAFO, Confined Animal Feeding Operation; NUE, nutrient use efficiency; MCL, maximum contaminant level for public water supplies

Core Ideas:

- Nitrate concentrations increased over time (2006-2024) in an Oregon groundwater management area well network.
- Insights from stable isotope-based well classification helped identify nitrate trends and patterns.
- Legacy nitrogen accumulation instead of current fertilizer application is reflected in well nitrate trends.
- Setting expectations based on the role of legacy and well classification is important to communicate to managers.

ABSTRACT (206/250 words)

Groundwater nitrate contamination is a challenging problem facing many areas across the globe, in part due to difficulties reducing nitrogen leaching to groundwater and lags in the response of groundwater nitrate levels to changing land management. Monitoring of nitrate concentrations combined with dual stable isotopes of both nitrate and water can provide insights into trends and drivers of nitrate levels. From 2006-2024, annual nitrate concentrations were measured in the Southern Willamette Valley Groundwater Management Area where nitrate contamination is a concern for the state of Oregon. Increasing nitrate concentrations in the 36-well monitoring

network was observed using a Regional Mann-Kendall trend analysis ($p < 0.001$), with 53% of the individual wells showing an increase in concentration. During the monitoring period, nitrate concentrations did not directly track estimated annual fertilizer inputs but instead reveal potential lags in the response in nitrate concentrations to cumulative N surplus. The stable isotope-based well classifications provided insights: higher nitrate concentrations and consistent increases in nitrate were observed where the well classification indicated leaching of N from the surface or multiple processes affecting nitrate concentrations levels. These findings reinforce the challenges of reducing nitrate concentrations in contaminated groundwater and illustrate how dual-isotope approaches may inform site-specific nitrogen management recommendations to improve groundwater quality.

Plain language Summary (711/1000 characters):

Nitrate contamination of groundwater is a problem in rural areas across the US and the globe. The State of Oregon designated the southern Willamette Valley groundwater management area in 2004, due to concerns about nitrate concentrations in groundwater. We use dual stable isotopes of nitrate and water, combined with detailed land use and nitrogen input data to examine trends in groundwater nitrate concentrations in a long-term groundwater monitoring network in this area. We found that nitrate concentrations continue to increase in the area, despite decreasing fertilizer inputs, and can be explained specific well characteristics and continued release of legacy nitrogen within soils and the ecosystem.

64 Caption: Groundwater nitrate concentrations have increased in the Southern Willamette Valley
65 Groundwater Management Area. While most wells did not cross the GWMA trigger level (7 mg-
66 N/L), six wells increased, most of which were leaching wells. Meanwhile, only two wells
67 decreased below the trigger level, both of which were stable wells.



INTRODUCTION

Nitrate is a common drinking water contaminant across the globe (Aguilar et al., 2007; Buckart, 2002; Jalali, 2005; Pennino et al., 2017; Spalding & Exner, 1993; Thorburn et al., 2003; Wang et al., 2023). It is highly water soluble and when nitrogen (N) is available in excess, nitrate accumulates and is easily transported into surface- and ground-water resources (Pennino et al., 2020; Sebilo et al., 2013). Nitrate in drinking water sourced from groundwater is a prominent issue, as nearly 1.5 million people across the conterminous United States (US) are consuming groundwater from wells that have nitrate concentrations above 10 mg nitrate-N L⁻¹ (Ransom et al., 2022). High concentrations of nitrate in drinking water are linked to methemoglobinemia or blue-baby syndrome in children, which is an acute and potentially fatal condition where tissues are deprived of oxygen (Comly, 1987). To protect infants from this risk, a 10 mg nitrate-N/L maximum contaminant level in drinking water was established by the U.S Public Health Service and the 1974 Safe Drinking Water Act (Fan & Steinberg, 1996; U.S Dept. of Health, 1962). In addition, high nitrate concentrations in drinking water can increase risk of colorectal cancer, thyroid diseases, low birth weight, and the risk of spontaneous preterm births (Jensen et al., 2023; Lin et al., 2023; Schullehner et al., 2018; Sherris et al., 2021; Ward et al., 2018). Given these consequences of elevated nitrate consumption, approaches are needed to help understand and address local and regional nitrate issues in drinking water, particularly in domestic wells that are not subject to the Safe Drinking Water Act's standards and particularly in domestic wells not covered by the Safe Drinking Water Act's standards and requirements.

Leaching of non-point sources of nitrogen (N) from agriculture is a primary factor for nitrate accumulation in groundwater (Harter et al., 2017; Pennino et al., 2020; Ransom et al., 2022). Inputs of N fertilizers accelerated as an important component of agricultural production after discovery of the Haber-Bosch process and subsequent production of synthetic fertilizer (Erisman

et al., 2008). Substantial increases in annual N fertilizer inputs have been observed in the US through mid-1970s and inputs remain high but stable, supporting increasing agricultural production and improved nutrient use efficiency (NUE) (Cao et al., 2018). In 2017, 68% of N inputs to the conterminous US originated from agricultural activities through fertilizer use, livestock waste and biological N fixation (Brehob et al., In Review). High inputs and surplus of N can increase concentrations of nitrate in drinking water sources (Basu et al., 2022; Fried, 1991; Murphy & Sprague, 2019; Pennino et al., 2020; Schlesinger, 2009; Van Meter, Byrnes, et al., 2023). The proportion of N that does leach into the groundwater is dependent on factors such as NUE in crops, precipitation and/or irrigation, hydrogeological features that impact water flow rates and residence times, and redox conditions which control N transformations (DeSimone et al., 2015; Hansen et al., 2017; Quemada et al., 2013; Rivett et al., 2008). However, understanding which factors might be important for a particular location or region, and developing effective approaches to reduce N concentrations in water resources, remains a complex challenge.

Within Oregon's Willamette River Basin (WRB), 78% of N input to the landscape originates from agricultural activities, largely from the application of synthetic fertilizer (Compton et al., 2020). Field-level nitrate leaching has been measured in a wide range of crop types in the agricultural valley (Compton et al., 2021; Feaga et al., 2010; Weitzman et al., 2022; Weitzman et al., 2024). A detailed four-year leaching study in an irrigated corn field found that 44% of applied N was removed by crop harvest, and 29% of applied N leached below 3.0 meter, with the remainder accumulating in the soil (Weitzman et al., 2022). An average of 19% of annual watershed inputs were exported from tributaries of the WRB's Calapooia River, where 41% was removed by crop harvest on average, and approximately 40% of N inputs remaining within the

landscape each year (Lin et al., 2018). Potential fates of this remaining N include storage in soil and groundwater, or emissions to the atmosphere via denitrification or ammonia volatilization (Houlton et al., 2013; Schlesinger, 2009). While fertilizer is primarily applied early in the growing season, most nitrate leaching occurred in the wet fall and winter seasons, even in irrigated crops (Compton et al., 2020; Weitzman et al., 2024). Recent efforts identified a disconnect between annual N inputs and river export in the Willamette Basin, suggesting that storage of N within soils or groundwater is occurring (Metson et al., 2020). The impact of this accumulation of N within the landscape across the WRB on groundwater should be better understood to help address the nitrate issue in groundwater.

The unique combination of domestic wells in rural land raises the risk of nitrate contamination of drinking water in these areas (Hoppe et al. 2014). The State of Oregon has regional hotspots where many groundwater monitoring wells and domestic wells have nitrate concentrations above 10 mg nitrate-N L⁻¹ (DeSimone et al., 2015; Hoppe et al., 2014), the maximum contaminant level set by the EPA for public water supplies through the Safe Drinking Water Act. The goals of Oregon's Groundwater Quality Protection Act of 1989 (ORS 468B.150 – 468B.190) are “to prevent contamination of groundwater resources, conserve and restore groundwater, and maintain the high quality of Oregon's groundwater resource for present and future uses.” To achieve these goals, the Oregon Department of Environmental Quality's (ODEQ) groundwater program consists of technical assistance, minimal statewide coordination, and implementation of groundwater conservation and restoration activities in three Groundwater Management Areas or GWMA's (ODEQ, 2009, 2011): Southern Willamette Valley (SWV-GWMA), Northern Malheur County, and the Lower Umatilla Basin. Within the SWV-GWMA,

ODEQ established a long-term well monitoring network in 2006 to measure nitrate concentrations in the SWV-GWMA wells, and track progress toward these water quality goals.

This study examines the long-term trends (2006-2024) from ODEQ's groundwater nitrate monitoring network the SWV-GWMA. To understand potential sources of nitrate and water within the wells, dual stable isotopes of water and nitrate were added to the monitoring program in 2012 and 2016, respectively. The isotopic insights led to categorizing wells based on nitrate and isotopic dynamics, which included 5 well type classifications: **stable** wells with very consistent behavior over time, **mixing** between multiple N and water sources, **dilution** of nitrate by a seasonal water source, wells where **leaching** likely caused the nitrate dynamics, and wells where **multiple** processes occur (Weitzman et al., 2021). This work has helped ODEQ refine its monitoring program, but the question remains in tracking how the establishment of the SWV-GWMA has helped improve groundwater quality in the area. This study aims to assess long-term trends in nitrate concentrations and to analyze how agricultural nutrient management, alongside well classification indicators of sources and processes, accounts for variations in well nitrate concentrations throughout the monitoring period.

MATERIALS AND METHODS

Study Area

The SWV-GWMA is part of the WRB, within Lane, Linn, and Benton counties. The SWV-GWMA covers ~ 600 km² of lowlands and was established as a groundwater management area in 2004 to address the high nitrate concentrations in domestic groundwater wells. The SWV-GWMA has a strongly seasonal climate, with cool, wet winters and warm, dry summers. The area receives approximately 1020-1270 mm of annual precipitation, of which ~ 80% occurs from October to March (Uhrich & Wentz, 1999). Mean monthly air temperatures range from 3°C-5°C

in January to 17°C-20°C in August (Uhrich & Wentz, 1999). Approximately 93% of the SWV-GWMA area is covered by agricultural land, producing pasture, hay, grass seed, orchard crops, and blueberries (LCOG, 2008; Metson et al., 2020).

Groundwater flows northward aligned with the flow direction the Willamette River, following the contour of the land (Herrera et al., 2014). Groundwater within the shallowest aquifer of the SWV-GWMA moves through an upper sedimentary unit that is highly permeable and porous, and has high well yield (Conlon et al., 2005). Groundwater is primarily recharged by direct infiltration of valley precipitation (Hinkle, 1997), with evidence of seasonal Willamette River hyporheic flow in some wells (Weitzman et al. 2021). Approximately 32% of the 26,593 people living in the 2020 Census (Murray et al., 2025).

Well Monitoring Network and Nitrate Measurements

The SWV-GWMA monitoring network includes a combination of privately-owned domestic wells (DW, n = 15) and groundwater monitoring wells (GW, n = 21) installed by ODEQ. Over the years, ODEQ has modified the number of monitoring wells and the sampling frequency of wells due to resource availability. Brief descriptions of the wells are shown in Table S1. Initially, all wells were sampled quarterly. Since 2015, all wells were sampled annually in May/June of each year to capture the maximum nitrate concentrations during the year, while only a few were sampled on a quarterly basis. Occasionally, if a well could not be sampled in annual May/June sampling, it would be sampled in the next quarterly sampling in August. To be included in this analysis, wells needed to be consistently sampled in May or August from 2009 to 2020, but the number included in each analysis described below varied based on sampling duration (Table S1). The majority of well sampling began in 2005 (n= 1) and 2006 (n = 31), while some wells that were added to the monitoring well network in 2007 (n = 2) and 2009 (n = 2) for a total of 36

wells (Table S1). ODEQ quantified nitrate in groundwater samples using the analytical method SM 4500-NO₃⁻ F (APHA, 1998).

Analyzing Nitrate Trends

To study nitrate trends in the SWV-GWMA monitoring wells (Table S1), trend analyses were conducted on the yearly nitrate concentration data collected by the ODEQ. A Mann-Kendall trend analysis (McLeod, 2022) was conducted for each well, and regional Mann-Kendall trend analysis (Julian & Helsel, 2021) was conducted for wells grouped by well classification (Table 1) (Weitzman et al., 2021). Wells with decreasing nitrate trends had a negative Tau, and wells with increasing nitrate trends had a positive Tau. Two significance levels are presented here, $\alpha = 0.05$ (often used for scientific research) and $\alpha = 0.2$, based on the 80% confidence interval ODEQ uses to complete water quality trend analyses for rivers and streams across the state and within the Northern Malheur County GWMA and the Lower Umatilla Basin GWMA (ODEQ, 2025).

Well Classifications

Wells were grouped by existing well classifications based on stable isotope data (Weitzman et al. 2021) to examine the relationship between well classification and nitrate trends in the SWV-GWMA (Table 1). Well classes were determined using dual water and nitrate isotope measurements from wells in this SWV-GWMA network. The isotopic data indicated water and nitrate sources and processes that influence groundwater nitrate pollution (Weitzman et al., 2021). Weitzman et al. (2021) divided the wells into 5 different categories: Stable, Dilution, Mixing, Leaching, and Multi-Process (Table 1). In stable wells, nitrate concentrations and isotope values did not change over time, indicating a consistent source of N over time, and a long residence time of water. In dilution wells, nitrate concentrations from a single nitrate source varied with shifting water sources, and the diluting water source was generally found to be the

Willamette River. In mixing wells, two nitrate sources with distinct N and water isotopic signatures impacted the well, shifting in correlation with different nitrate sources. Leaching wells had a consistent source of nitrate, varying nitrate concentrations, and varying water isotope values uncorrelated with nitrate concentration, indicating strong connection with the isotopic variation in precipitation falling within the site, with short water residence time within the wells. Leaching wells likely reflect areas that may have a strong connection between management and nitrate concentrations. Lastly, multi-process wells were complex, with multiple water sources, N sources, and N processes. Weitzman et al (2021) did not find wells where denitrification was evident but proposed a categorization framework for wells if they met those conditions. In this analysis, we included additional isotopic data collected after the publication of Weitzman et al. (2021), and reclassified wells if warranted (Figure S2).

Table 1: Well classifications used in this analysis based on Weitzman et al. (2021) using nitrate concentration, $\delta^2\text{H-H}_2\text{O}$ and $\delta^{15}\text{N-NO}_3^-$. For each well, these parameters were categorized as “stable”, “variable” and/or “correlated” depending on parameter variance over time, and correlation with other indicated parameters. See Weitzman et al. (2021) for more details.

Well Classification	Nitrate Concentration [N]	$\delta^2\text{H-H}_2\text{O}$ Water Source	$\delta^{15}\text{N-NO}_3^-$ Nitrate Source	Number of Wells	Well Classification Description
Stable	Stable	Stable	Stable	8	Nitrate source and water source are stable over time.
Dilution	Variable	[N] correlated	Stable	5	Source of nitrate is constant over time, but concentrations are diluted by lower concentration water.
Mixing	Variable	[N] Correlated	[N] Correlated	5	Mixing of two nitrate sources that each have distinct nitrate and water isotopic signatures.
Leaching	Variable	Variable, not [N] Correlated	Stable	11	Soil nitrate that is moving through soil with precipitation.
Multi-Process	Variable	Variable, not [N] correlated	Variable, not [N] correlated	7	Multiple processes possible, e.g. mixing, denitrification, dilution, and leaching.

Comparing “Beginning” and “Ending” Nitrate Concentrations

In addition to trend analysis, we focused on well nitrate concentrations at the beginning (2006-2009) and ending (2021-2024) of their monitoring history and classified them based on nitrate thresholds of concern for public health. Nitrate concentration categories were based on Oregon’s groundwater quality protection trigger level of 7 mg nitrate-N L⁻¹ (ODEQ, 2025) and the national nitrate MCL in drinking water of 10 mg nitrate-N L⁻¹. Each well’s beginning and ending three-year average nitrate concentrations was classified into one of three different categories: < 7, 7-10, and > 10 mg nitrate-N L⁻¹. The beginning group was compared to the ending group for each monitoring well. Only the 36 wells that were included in the monitoring program in 2009 or earlier and continued to be monitored through 2024 were included in this study. Therefore, the average of the first three years (“Beginning”) varied between wells: one well based on the 2005-2007 average, 31 wells based on the 2006-2008 average, two wells based on the 2007-2009 average, and two wells based on the 2009-2011 average. The average nitrate concentration in the last three years (“Ending”) were calculated from 2022-2024 for all wells.

Land Cover Controls

To investigate the influence of land cover on nitrate concentrations in the last three years, the means and standard error for each crop percentage was calculated for the wells within the three Ending nitrate concentration groups. A Wilcoxon rank sum test was used to determine if the median of crop percentages were significantly different among nitrate concentration groups. Additionally, a Mann-Kendall trend analysis was completed on each crop type for temporal trends within a group. These non-parametric approaches are appropriate for land use data that may not meet normality assumptions. We used $\alpha = 0.05$ to determine significantly increasing or decreasing trends in this analysis.

Estimating Nitrogen Inputs in Well Influence Zone

To investigate the potential role that fertilizer application may have on nitrate well trends, we used two approaches, a bottom-up approach using crop cover and recommended fertilizer rates, and a top-down approach using fertilizer sales data for the SWV-GWMA counties, modified approach from Compton et al. (2020) and (Lin et al., 2018)

For the bottom-up approach, overlying crop data from 2008-2023 was analyzed around each well. Each well was geocoded into ArcGIS Pro and crop data was imported from the U.S. Department of Agriculture (USDA) CroplandCROS (USDA, 2022) as rasters for each year from 2008 to 2023. For each year and well, we tabulated the area of each crop type within the 500 m radius circle with a total of 85 possible crop types to estimate the amount of fertilizer applied each year. These annual fertilizer inputs were used to look for trends in potential fertilizer use. The 85 different crop types were categorized into 14 groups (Table S3). For these 14 groups, we estimated fertilizer application rates using Oregon State University Extension and previous publications recommended fertilization application rates in the Willamette Valley (Lin et al., 2018). Total applied fertilizer for the circle was calculated multiplying the recommended rates with the crop area in each of the 14 groups within the circle and summing for each year. A Mann-Kendall trend analysis was used on estimated total applied fertilizer within the 500 m radius zone of influence.

As a top-down approach to estimate N inputs, the data from the EPA's National Nutrient Inventory (Brehob et al., In Review) was downscaled for StreamCat using the StreamCat methods (Hill et al. 2016). Farm fertilizer, human waste generated, atmospheric deposition, livestock manure, and crop N-fixation, within the GWMA catchments are included in the total N inputs. In order to incorporate a locally-derived metric of the N left behind on the field after

farming, annual N surplus was determined by multiplying agricultural inputs by the 41% NUE (Lin et al., 2018).

To investigate the influence of confined animal feeding operations (CAFOs) on domestic wells, the general location of CAFOs were located from a data request from Oregon Department of Agriculture. Using Google imaging, four CAFOs were identified to be near monitored wells. Three wells were within 1km of a CAFO.

RESULTS

Well Nitrate Trends Over Time

From 2006-2024, the overall well nitrate concentrations increased significantly across the SWV-GWMA monitoring well network (Figure 1a; Table 2). As determined from Mann-Kendall analysis, nitrate concentrations in individual wells increased in 53% of wells and decreased in 22% of wells (Figure 1c, p-value < 0.2). Nitrate concentrations did not significantly change in 25% of the wells (Figure 1c). Of the wells that increased, 39% were drinking water wells, while 86% of the decreasing wells were drinking water wells. The total number of wells with concentrations above 7 mg nitrate-N L⁻¹ increased from 11 to 15 in the 36 well monitoring network (Figure 2). At the end of the sampling period, 16% of all wells in the monitoring network had concentrations greater than the public water supply MCL of 10 mg nitrate-N L⁻¹, and 22% had concentrations above the Oregon GWMA trigger level of 7 mg nitrate-N L⁻¹ (Figure 2).

Changes over time were strongly related to the well classification and well nitrate concentrations at the beginning of the monitoring period. The average nitrate concentrations in the first 3 years will be referred to as “Beginning”, and last 3 years, which will be referred to as “Ending”. Nitrate concentrations in wells beginning with > 10 mg nitrate-N L⁻¹ (8 wells)

generally stayed the same (7 wells, 87%), while one well decreased in nitrate concentrations (13%) (Figure 2). Only 3 wells had nitrate concentrations that began between 7 and 10 mg nitrate-N L⁻¹, two increased and the other decreased. Most wells (25) started with concentrations below 7 mg nitrate-N L⁻¹, while 19 remained below this threshold over time, and the remaining 6 wells increased (Figure 2).

Well classification helps explain the nitrate concentrations and the trends over time in that well classes had distinct patterns and trends from each other. Leaching, multi-process and dilution wells had increasing nitrate trends, and stable wells had decreasing nitrate trends (Table 2). All wells classified as stable ended with nitrate concentrations < 7 mg nitrate-N L⁻¹ along with most of the wells classified as dilution. The wells that ended above 10 mg nitrate-N L⁻¹ were all leaching, mixing, and multi-process wells, and only one leaching well ended with concentrations < 7 mg nitrate-N L⁻¹ (Figure 2).

Figure 1: a) Box plot of annual (May) nitrate concentrations from 2006 to 2024 in 36 SWV-GWMA wells (n = 36, center line in the box is median, the whiskers are the 5th and 95th percentiles, and the box spans the 25th and 75th percentiles). GWMA trigger level is 7 mg nitrate-N L⁻¹; Drinking water MCL is the EPA maximum contaminant level (MCL) for public drinking water supplies of 10 mg nitrate-N L⁻¹. b) Percentage of wells with statistically significant increasing or decreasing nitrate trends (p-value < 0.05) and wells that are not significantly changing (based on Mann-Kendall analysis of individual well trends). c) Same as (b) but using a p-value < 0.2.

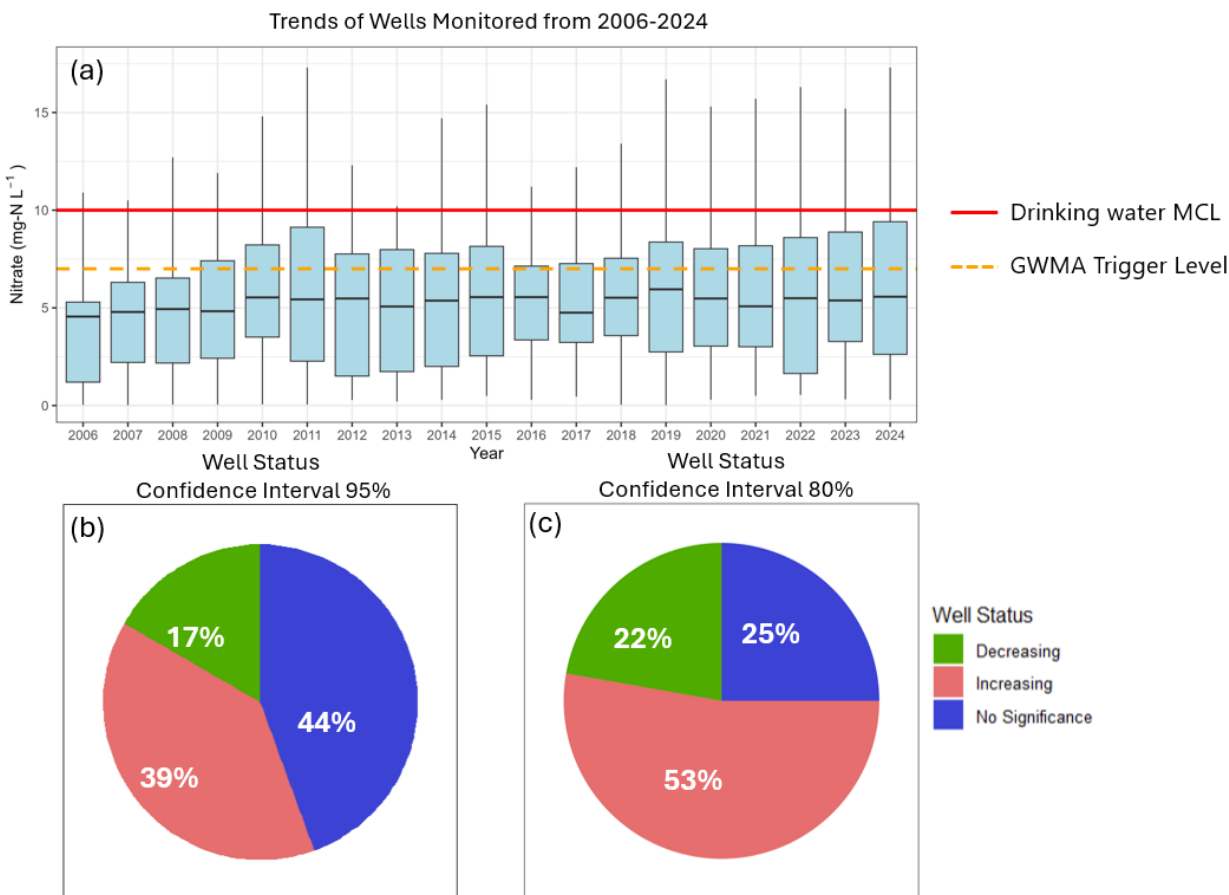


Figure 2: Stacked bar chart illustrating the number of wells that show a significant nitrate concentration trend or no significant trend ($\alpha = 0.2$), stacked by well classification.

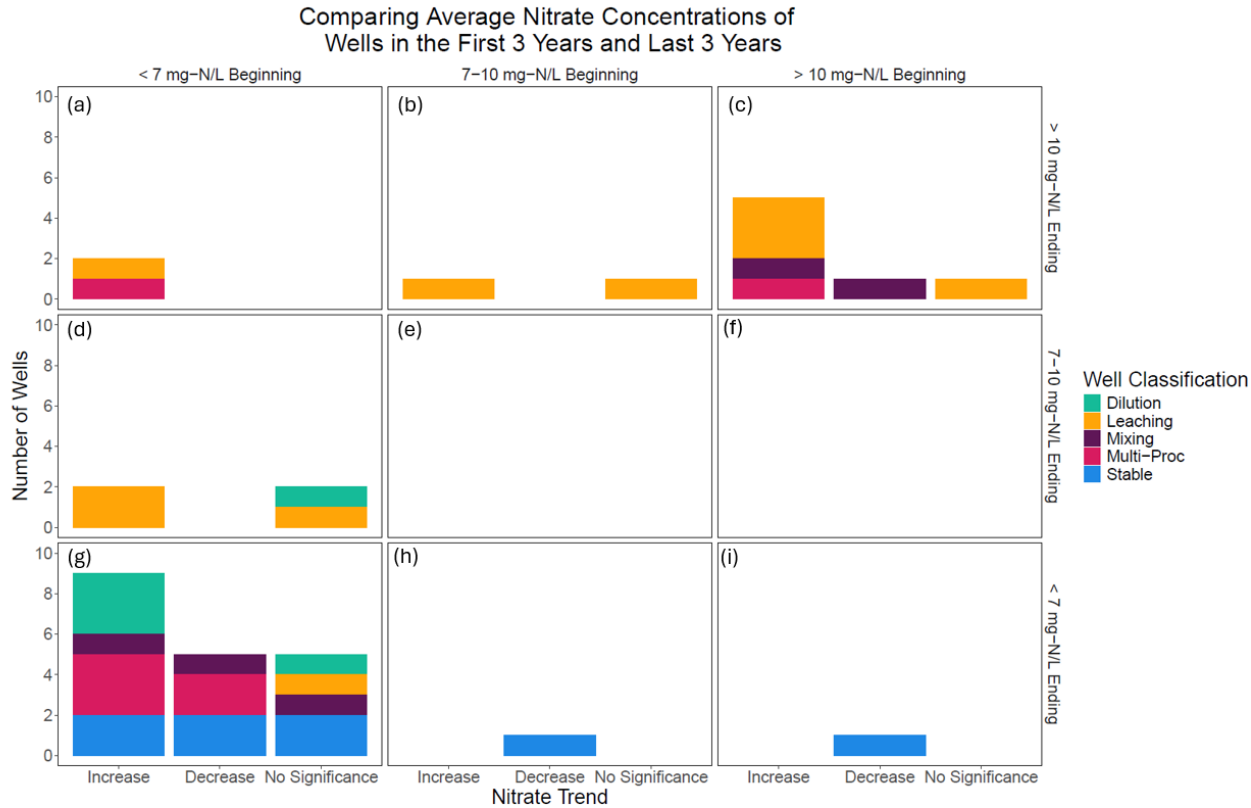


Table 2: Regional Mann-Kendall of Well Nitrate concentrations from 2006-2024 and fertilizer application from 2008-2024. Column “Variable” distinguishes whether the result is from well nitrate or estimated fertilizer. Column “tau_SK” is the tau from the Regional Mann-Kendall, a negative tau indicates a decreasing trend while a positive tau indicates an increasing trend and column “p-value” indicates the significance of the trend.

Variable	Well Classification	Number of Wells	Number of Observations	tau_SK	p-value	slope
Well Nitrate	Mixing	5	84	-0.10	0.22	-0.03
Well Nitrate	Dilution	5	84	0.21	0.01	0.04
Well Nitrate	Multi-Process	7	115	0.27	< 0.01	0.14
Well Nitrate	Stable	8	136	-0.21	< 0.01	-0.05
Well Nitrate	Leaching	11	182	0.31	< 0.01	0.12
Well Nitrate	All Wells	36	601	0.11	< 0.01	0.04
Fertilizer Application	Dilution	5	79	-0.09	0.28	-0.47
Fertilizer Application	Mixing	5	79	-0.08	0.36	-0.75
Fertilizer Application	Multi-Process	7	108	-0.34	< 0.01	-4.43
Fertilizer Application	Stable	8	128	-0.17	0.01	-1.75
Fertilizer Application	Leaching	11	172	-0.19	0.001	-2.32
Fertilizer Application	All Wells	36	566	-0.18	< 0.01	-1.92

Trends in land cover and fertilizer inputs over time

Crop-based estimates of fertilizer applied within 500 m of wells decreased across all the wells according to the regional Mann-Kendall, based on changing crop types since fertilizer recommendations per a crop type were constant (Table 2). Within well classes, changes were not significant for dilution and mixing wells (Table 2, $p\text{-value} > 0.2$). Data on fertilizer in the SWV-GWMA suggest that N fertilizer applied to agricultural lands has varied substantially since 1987 with a notable decrease in inputs since 2012 for both the bottom up and top-down approaches (Figure 3, Figure 4). The slight decline in fertilizer application does not seem linked to the increasing temporal trends in nitrate concentrations in the well monitoring network (Table 2) but instead may be more linked to the accumulated legacies in Figure 3b.

Land use surrounding wells (within 0.5 km of the wells) can influence well nitrate concentrations. Agricultural land is the dominant land cover near all wells. Wells surrounded by more natural lands, such as wetlands, open water, and forests, tend to have lower nitrate concentrations ($p\text{-value} < 0.05$, Figure 5). Wells surrounded by higher levels of agricultural lands have higher nitrate concentrations (Figure 5). Agricultural lands could be sources of N and natural lands could be important N sinks in the SWV-GWMA.

Figure 3: Top-down approach to calculate nitrogen inputs (a) and legacy normalized by agricultural land area (b) from 2006-2017 for the catchments within the SWV-GWMA shown as kg N ha⁻¹ yr⁻¹. Data from EPA's National Nutrient Inventory (Brehob et al. In review).

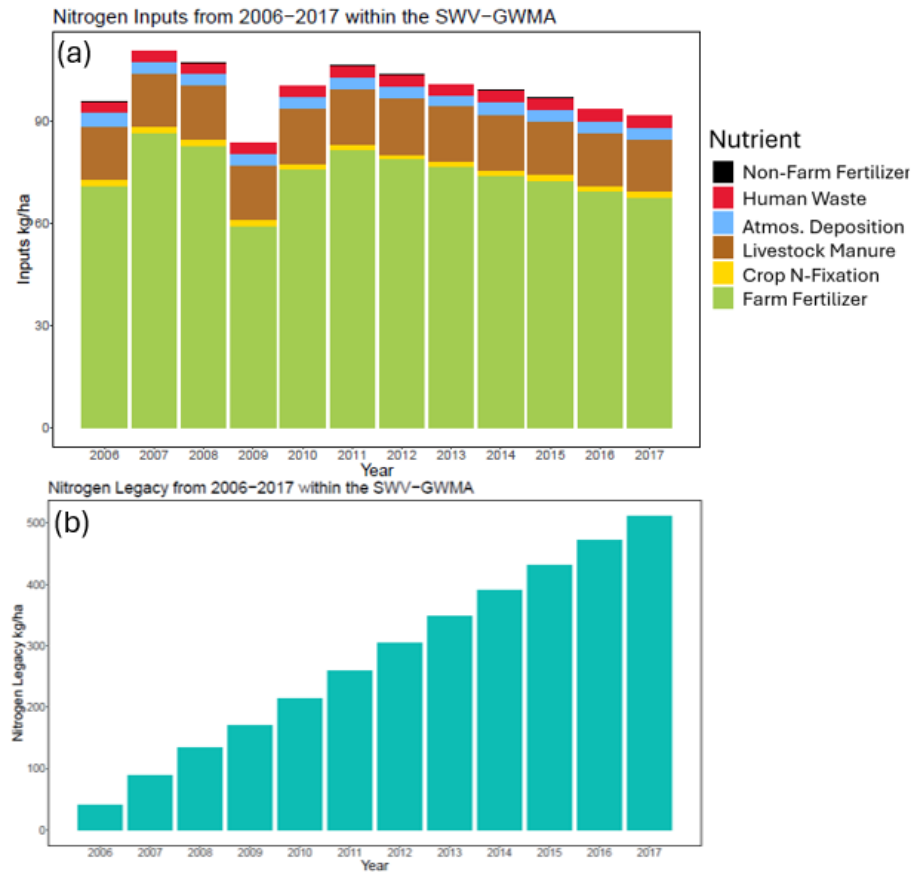


Figure 4: Estimated fertilizer applications based on cropland data layer and recommended nitrogen farm fertilizer applications for all agricultural land within the SWV-GWMA from 2008-2023. Crop recommendations changed throughout the SWV-GWMA because crop types changed. This nitrogen farm fertilizer approach is termed the “bottom up” approach in the text. Table S3 contains the low and high crop recommendations from Oregon State University Extension and crop data layer agricultural cropland cover. Green line is the lower end of fertilizer recommendations, red line is the higher end of fertilizer recommendations, blue line is the average between the lower and higher end of fertilizer recommendations.

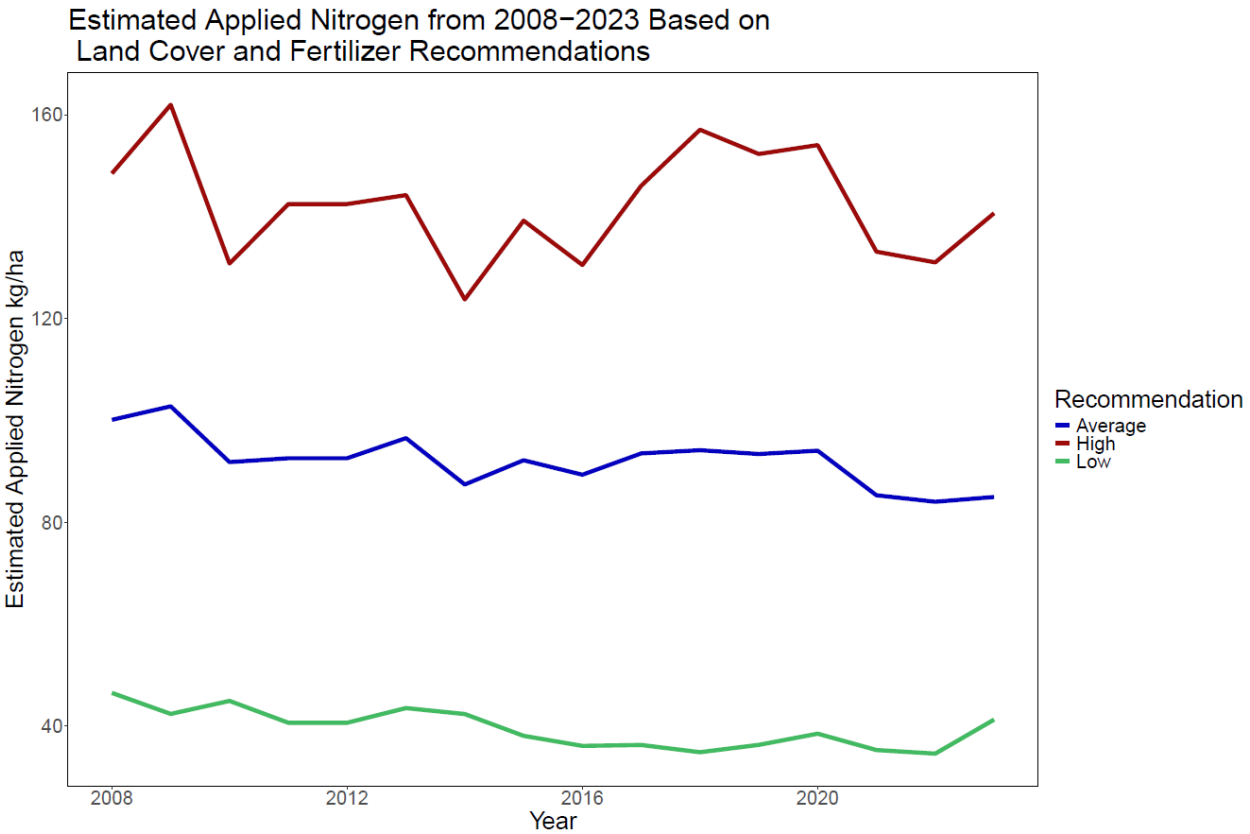
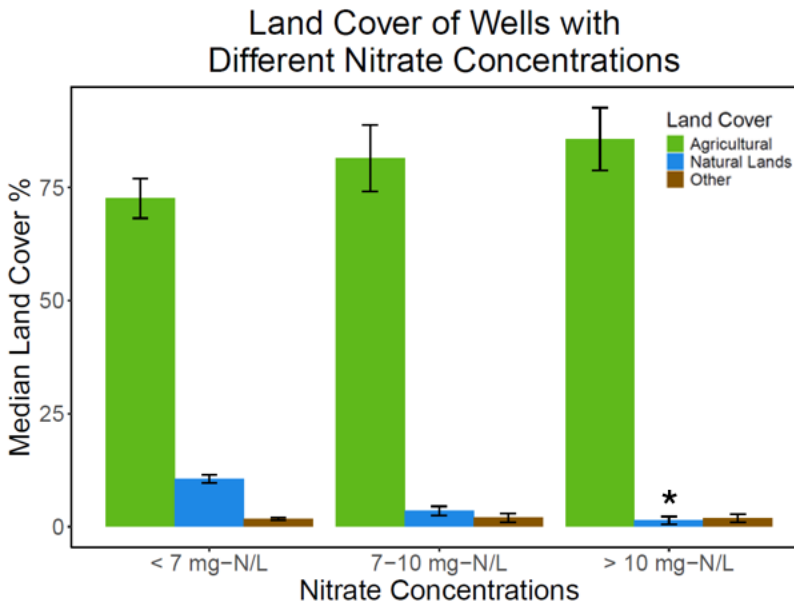


Figure 5: Median percentage of each land cover type within a half of km of each well categorized by ending nitrate concentration summed together. Error bars represent the sum of standard error of each land cover type. Agricultural lands include grasses and hay, miscellaneous crops, grains, squash, corn, legumes, mint, blueberries, and fruit and nut trees. Natural lands include wetlands, open water, and forest. Other lands are developed and fallow. Significant differences within land cover categories across nitrate concentrations are shown with an asterisk.



Isotopic Insights into Individual Well Case Studies

Wells classified as leaching, mixing, and multi-process generally tend to have increasing nitrate concentrations (Table 1, Figure S1b). A closer analysis of wells with distinctive nitrate trends and stable isotope data can highlight dominant processes influencing nitrate concentrations within each well class. Most wells had nitrate $\delta^{15}\text{N}$ values lower than 10 ‰, which is a threshold commonly used to indicate manure or human waste, and some very close to 0 ‰, which is the isotopic value of synthetic fertilizer ‰ (Figure S2). The lowest nitrate $\delta^{15}\text{N}$ values indicate synthetic fertilizer with little N processing (e.g. DW-11). Increasing $\delta^{15}\text{N}$ values indicate more N cycling and processing either within the soil (legacy N) or from an isotopically enriched N source (such as manure/human waste or septic). Nitrate $\delta^{15}\text{N}$ values above 10 ‰ signify an isotopically enriched source if they are associated with nitrate concentrations that

increase with $\delta^{15}\text{N}$ (e.g. DW-1525, DW-10, GW-11). In the case of DW-1525, both nitrate concentrations and $\delta^{15}\text{N}$ decreased with time, indicating the enriched source was dissipating. Leaching wells generally had lower $\delta^{15}\text{N}$ indicating a synthetic fertilizer, except for DW-10 that indicated a shift to an enriched N source that increased over time, and a CAFO was located within 1 km of DW-10 well. Other wells near a CAFO did not have high $\delta^{15}\text{N}$. Dilution wells were being diluted by hyporheic water from the Willamette River with, which has much lower nitrate concentration levels. Nitrate concentrations in multi-process wells appear to be controlled by both enriched N sources (shown by higher $\delta^{15}\text{N}$; GW-10, DW-1524) and loss of N through denitrification (shown by a linear relationship between $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$; GW-10, GW-7, GW-18, GW-8R).

In the SWV-GWMA monitoring network, CAFOs appear to have limited effect on groundwater nitrate. Of the three wells located near a CAFO, only DW-10, classified as a leaching well, had an increasing well nitrate trend with an enriched isotopic signature that indicated the CAFO could be a source. Well nitrate dynamics in GW-24 were related to dilution and had no significant trend. GW-12 was a mixing well that had an increasing nitrate trend, but low $\delta^{15}\text{N}$ hinted the increasing nitrate trend may be connected to fertilizer inputs. Collectively, these insights can help understand groundwater nitrate dynamics in wells and understand the sources of N to help improve management.

DISCUSSION

Improving nutrient-related water quality issues stemming from non-point sources has proven extremely challenging (Easton et al., 2025), with a small number of success stories emerging from the literature (Basu et al., 2022; Del Rossi et al., 2023; Gross & Hagy, 2017; Hansen et al., 2017). Addressing groundwater nitrate contamination is particularly difficult, with lag times and

legacy N accumulation and release hampering the ability to connect current management to changing water quality (Ascott et al., 2021; Meals et al., 2010; Van Meter et al., 2017). In the SWV-GWMA, nitrate concentrations continue to increase in the well network since establishment, reinforcing these challenges and revealing a lack of progress to resolve the issue. Increasing nitrate concentration trends across the well network, and the pattern of high concentration wells remaining above 10 mg nitrate-N L⁻¹, indicate that the GWMA goals “to prevent contamination of the groundwater resource, to conserve and restore this resource, and to maintain the high quality of Oregon’s groundwater resource for present and future uses ((DEQ, 2005) are not being met.

Trends in nitrate concentrations in Oregon’s SWV-GWMA

Nitrate concentrations significantly increased across all wells from 2006-2024 in the SWV-GWMA well monitoring network. Most wells (88%, 7 of 8) with high nitrate concentrations above 10 mg nitrate-N L⁻¹ remained above this level during the 17-year time period, and most wells (90%, 19 of 21) with nitrate concentrations below the GWMA trigger level of 7 mg nitrate-N L⁻¹ remained below this level over time (Figure 2). However, six wells moved above 7 mg nitrate-N L⁻¹ and were primarily leaching wells, while only two moved below that threshold over the monitoring period and were classified as stable wells. We used two different probability levels to track the individual wells, (p-value < 0.05 which is commonly applied in scientific research, and p-value < 0.2 which is the level reflecting Oregon DEQ’s procedures). Using the ODEQ probability value (< 0.2), nitrate concentrations increased in 53% of the monitoring wells, illustrating the continuing challenges in managing nitrate contamination since groundwater nitrate concentrations are increasing despite the Southern Willamette Valley being designated as a GWMA by the state of Oregon in 2004.

Using Stable Isotope-based Well Classifications to Understand Trends

In this study, stable isotopes provided valuable context for individual well behavior with respect to nitrate concentrations and trends across the monitoring network and may provide insights for improved management. While stable isotopes of nitrate have long been a tool for groundwater nitrate dynamics (Böhlke et al., 2002; Wassenaar et al., 2006; Yu et al., 2020), dual isotopes of both nitrate and water together can provide important new insights about the drivers (Grimmeisen et al., 2017; Hu et al., 2019; Hu et al., 2024; Weitzman et al., 2021). This approach is particularly useful identifying water and nitrate sources in areas where water isotopes vary spatially (Grimmeisen et al., 2017; Hu et al., 2019). In our study, well class based on the dual isotopes of water and nitrate linked wells with similar nitrate concentrations and trends.

Leaching, mixing, and multi-process wells tended to have increasing nitrate trends with nitrate concentrations above the MCL, while stable wells tended to have decreasing nitrate trends and nitrate concentrations below the MCL (Figure 2). This suggests isotopic temporal variance, and water and nitrate sources are an important component in understanding why certain wells have nitrate concentrations above the MCL. Leaching wells had highly dynamic water isotope values and nitrate concentrations, indicating a short residence time impacted by isotopic variation in precipitation. Water isotope values and nitrate concentrations were not correlated in leaching wells, and nitrate isotopes indicated a single source with values similar to legacy soil nitrate (Figure S2). Ten of the 11 leaching wells had nitrate concentrations above the GWMA trigger level, while seven were above the MCL. Based on the dynamic behavior of their nitrate concentrations and water isotopic values, these leaching wells are likely to respond to changes in N management, thereby helping managers identify areas where implementation of best management practices are better linked to improvements in groundwater nitrate contamination.

Connections to landscape N inputs

Fertilizer was the largest source of N inputs to the landscape, followed by manure, human waste, and N deposition. In 2008, Lane Council of Governments estimated that 90% of N inputs to the landscape comes from cropland, 6% from CAFOs and 4% from septic systems on rural land (LCOG 2008). These values align with the N budget (Lin et al., 2018) calculated for the nearby Calapooia River basin, where 90% of the N on farmland is from synthetic fertilizer, with a smaller input from N fixation and manure application. Thus, synthetic fertilizer was likely the largest source of groundwater nitrate in the well network, although individual wells are likely influenced by the mix of sources, including septic and manure that surround the well.

Connections to Current and Legacy Nutrient Management

Nutrient management practices and the establishment of more natural lands can reduce nitrate leaching into groundwater resources (Cui et al., 2018; Hansen et al., 2017; Quemada et al., 2013; Yu et al., 2019), and could improve groundwater quality in the area. Implementation of nutrient management practices may be complicated because groundwater management areas may need to be designated by a state agency or local committee (Exner et al., 2014) and voluntary compliance to adopting best nutrient management practices is preferred. In the SWV-GWMA, current inputs were the best predictor of nitrate leaching (Compton et al., 2021). Local field-level and watershed budgets indicated that approximately 30% of annual inputs remained within soils (Lin et al., 2018; Weitzman et al., 2022; Weitzman et al., 2024), pointing to legacy N accumulation with potential time lags in concentrations responses to declining inputs.

Accumulation of legacy pollution has impeded timely improvements in groundwater contamination in other areas (Tesoriero et al., 2019). Time lags between decreases in N inputs to the landscape and decreases in nitrate concentrations in groundwater create scientific and

perception challenges (Grimvall et al., 2000; Van Meter, Schultz, et al., 2023). For example, when fertilizer application was reduced by 50% in Woodstock during 2005, it took two years for similar reductions in both the nitrate concentrations of leaching pore water and total stored nitrate in the vadose zone (Rudolph et al., 2015). Additionally, Van Meter, Schultz, et al. (2023) analyzed 478 U.S watersheds and found a variety of time lags from when N inputs were decreased and to when N concentrations in drinking water decreased. Determining the exact lag time is difficult, because of variability in soil and geomorphological properties (Van Meter, Schultz, et al., 2023). In the SWV-GWMA, time lags between reduced N inputs and reductions in groundwater nitrate concentration will likely be different between well classes, but the length of those lags is unknown. Recently applied N fertilizer that is not taken up by plants or the soil biota can move preferentially through the deep soil and into the groundwater, while legacy N may be stored within soils for some time period (Weitzman et al., 2024). A reduction in fertilizer application can reduce nitrate concentrations in groundwater and could happen relatively quickly in areas with high preferential flow. Because leaching wells are more responsive and connected to surface inputs, the lag times may be shorter. Areas with leaching wells may be good places to assess lag times to better inform expectations for groundwater quality improvement.

Potential approaches to reduce groundwater nitrate

Basu et al. (2022) propose multiple practices to reduce the risk of nitrate leaching, such as (1) develop nutrient management, cover crops, and wetlands to minimize lag times, and (2) diverse monitoring approaches to track progress. The SWV-GWMA could benefit from exploring ways to increase NUE, which was only 57% across the Calapooia Basin (Compton et al., 2021). The NUE averaged 57% in a study of fourteen fields in the SWV-GWMA, but was highly variable, ranging from 0 to over 100% depending on the crop type and success (Compton et al. 2021).

Given this variability by crop and management, improving NUE is an important step in minimizing excess N available for leaching in the SWV-GWMA.

While nitrate contamination of groundwater is challenging to reverse, the few examples of successes provide important insights. Exner et al. (2010) calculated average nitrate concentrations in Nebraska's central Platte River valley at 26.8 mg nitrate-N L⁻¹ in 1988. After the Central Platte Natural Resources District enacted land management practices in 1988, such as banning the application of fall and winter commercial N fertilizer on all soil in 1992 and increasing the amount of N removed from fields, N concentrations have remained static in the primary aquifer beneath the bottomland and decreased in the primary aquifer beneath the terrace (Exner et al., 2010). Exner et al. (2014) compared nitrate trends in 17 different groundwater management areas (GWMAs) between 1987-2011 in Nebraska. They found nitrate trend reversal in 2 GWMAs, nitrate trend increases in 10 GWMAs, and no significant change in 5 GWMAs, concluding that GWMA designation and best management practices may simply slow down nitrate trend increases, and will not stop or reverse the trends completely in that large aquifer. Van Meter, Byrnes, et al. (2023) have similar conclusions based on estimates of N accumulation in groundwater in the Upper Mississippi Basin, suggesting that N in the subsurface will continue to impair drinking water quality for several future decades. Meanwhile, Hansen et al. (2011) conclude that regulation and policy can successfully cause groundwater nitrate trends to reverse. They found that nitrate trends in groundwater began to decrease in 1980 before Denmark's first Environmental Action Plan in 1985. Groundwater nitrate trends continued to decrease while additional action plans were initiated between 1987 and the present. Trend reversals of nitrate contamination into groundwater have been successful in Nebraska and Denmark after best management practices have been used. Basu et al. (2022) also show an example of reductions in

groundwater nitrate in Ontario with strong governmental oversight. These examples indicate that focused, direct management combined with monitoring can lead to reductions in groundwater nitrate concentrations, and that legacy N continues to challenge these efforts.

Improving NUE, as well as reducing overall inputs and surplus, can increase the N incorporation into the crop while also reducing excess N for leaching. Kirk et al. (2024) provided a targeted perspective for in-field vs. edge-of-field efforts to improve nutrient-related water quality based on spatial patterns of nutrient surplus and nutrient use efficiency. Other approaches to improve in-field nutrient management that have potential to optimize crop N use and minimize leaching include soil and tissue testing to optimize N fertilizer recommendations (Barker & Culman, 2020), incorporation of variable rate technologies and enhanced efficiency fertilizers (Xing & Wang, 2024), increased adoption of cover crop options (Popovici et al., 2023), and inclusion of irrigation water nitrate concentration loads in nutrient budgets (Weitzman et al., 2022).

Nitrogen storage and removal in the broader landscape can also help reduce nitrate leaching and groundwater contamination, even within this predominantly agricultural area. Denmark is enacting regulations that allow higher N application rate, while constructing wetlands and using additional cover crops on the fields in autumn and winter to reduce leaching during these vulnerable times (Hansen et al., 2017). In our study, open water, wetlands, and forests are generally more prominent around wells with nitrate concentrations below the MCL than other wells (Table S2, Figure 5). Wells with nitrate concentrations above the MCL are surrounded by more agricultural land than other wells and could be accumulating nitrate through N fertilizer application. Wells adjacent to open water could be diluted by hyporheic flow (diluting wells) and losing N due to riverine export during the wet fall and winter months when N uptake is low and

streamflow is greatest (Brooks et al., 2012; Compton et al., 2020). Wells adjacent to wetlands could be losing nitrate through denitrification in wetlands (Hansen et al., 2016), as was observed in some of the multi-process wells (i.e. GW-8R near a wetland). Wells near forests could have greater uptake by deeply rooted trees as water laterally passes through the vadose zone (Ma et al., 2022). Exploring the combined options of optimizing in-field nutrient management, together with conservation of N sinks within the landscape, could be considered in future plans to improve groundwater quality in the SWV-GWMA.

CONCLUSION

In the 17 years ODEQ has monitored groundwater conditions in the SWV-GWMA, well nitrate concentrations have increased, despite estimated decreases in fertilizer application. An analysis of nitrate and stable isotope trends for each well type, reveals that groundwater in certain well types (leaching, mixing, and multi-process) are more likely to have water nitrate concentrations above the MCL. Efforts to increase NUE and reduce surplus could help bring nitrate concentrations below the MCL. Legacy N could continue to contribute to groundwater nitrate concentrations, so changes in N management may not result in an immediate reduction in groundwater nitrate concentrations. The stable isotope classification suggests that the wells classified as leaching were dynamic and responsive and could possibly respond quickly to reductions to N inputs. Other areas (e.g., Denmark, Ontario, and Nebraska) have observed trend reversal in their groundwater nitrate since initiating efforts to reduce surplus and increase NUE. Lessons learned from these areas could be applied in Oregon to meet state goals.

580

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SUPPLEMENTARY MATERIAL

833 **Table S1: Information about each well included in the study, including the well classification based on the dual isotope**
834 **approach (Weitzman et al., 2021), nitrate and $\delta^{15}\text{N}$ -nitrate trends, and recent concentration and $\delta^{15}\text{N}$ -nitrate. Well ID is the**
835 **name of the well with DW representing wells used for drinking water while GW is groundwater monitoring wells not used for**
836 **drinking water. Well classification was determined using stable water and nitrate isotopes (Table 1; Weitzman et al., 2021).**
837 **Nitrate well trend and $\delta^{15}\text{N}$ trend are results from a Mann-Kendall trend analysis (p-value < 0.2). Earliest Nitrate (2005-2009)**
838 **is the first nitrate concentrations. Latest Nitrate (2020-2023) and Latest $\delta^{15}\text{N}$ (2020-2021) are the final nitrate concentrations**
839 **and $\delta^{15}\text{N}$ values from the ODEQ monitoring. Latest Nitrate values highlighted in blue indicate wells above GWMA trigger**
840 **level and latest nitrate values highlighted in yellow are above the MCL. DW-17 is the only site where the data record ended in**
841 **2020, every other site had nitrate data through 2024 and $\delta^{15}\text{N}$ data through 2023 or 2024. Wells in bold have a confined animal**
842 **feeding operation (CAFO) located within 0.5km of the well.**
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Well ID	Well Classification	Nitrate Trend	Earliest Nitrate (2005-2009)	Latest Nitrate (2020-2024)	$\delta^{15}\text{N}$ Trend	Latest $\delta^{15}\text{N}$ (2021-2024)	Start	End	Depth	Distance from CAFOS
			mg $\text{NO}_3\text{-N}$ L^{-1}	mg $\text{NO}_3\text{-N}$ L^{-1}		(per mil ‰)	Year	Year	Feet	km
DW-2	Dilution	I	0.7	0.3	NS	0.32	2006	2024	30	>1
GW-16		I	0.5	0.43	NS	5.38	2006	2024	27	>1
GW-17		I	0.33	2.62	NS	3.82	2006	2024	34	>1
GW-24		NS	5.92	5.68	NS	3.8	2006	2024	27	0.160
GW-5		NS	0.93	9.14	I	9.36	2006	2024	21	>1
DW-10	Leaching	I	5.13	12.3	I	14.21	2006	2024	60	0.365
DW-11		NS	6.21	5.63	D	1.78	2006	2024	29	>1
DW-13		I	5.22	8.36	D	4.15	2006	2024	58	>1
DW-17		NS	14.8	14.9	D	2.46	2007	2020	37	>1
DW-8		I	10.1	10.4	NS	6.51	2006	2024	30	>1
GW-1		I	9.35	11.3	NS	6.12	2006	2024	23	>1
GW-20		I	17	13.8	NS	3.11	2006	2024	23	>1
GW-21		NS	10.3	18.3	NS	2.37	2006	2024	23	>1

GW-22		NS	1.32	2.9	I	7.63	2006	2024	28	>1
GW-3		NS	22.1	31.6	D	4.48	2006	2024	23	0.630
GW-4D		I	4.66	9.41	NS	5.33	2006	2024	18	>1
DW-15	Mixing	D	4.98	1.93	NS	2.25	2006	2024	32	>1
DW-1525		D	35.9	14.3	D	13.35	2009	2024		>1
DW-1544		I	1.6	12.2	NS	3.33	2006	2024	39	>1
DW-7a		I	21.3	2.34	NS	2.93	2006	2024	34	>1
GW-12		I	0.92	17.3	NS	5.26	2006	2024	23	0.350
GW-19		NS	9.93	1.2	NS	0.954	2006	2024	23	>1
DW-1524	Multi-Proc	NS	0.03	14.3	NS	14.27	2009	2024	41	>1
GW-10		I	2.91	1.37	D	21.8	2006	2024	17	>1
GW-11		I	3.48	5.16	NS	0.435	2006	2024	24	>1
GW-18		I	2.5	15.2	D	2.77	2006	2024	20	>1
GW-4S		D	1.16	2.87	NS	16.74	2007	2024	12	>1
GW-7		I	0.93	5.04	D	5.06	2006	2024	23	>1
GW-8R		NS	4.66	0.364	NS	37.89	2006	2024		>1
DW-16	Stable	D	4.45	2.97	NS	1.03	2006	2024		>1
DW-3		I	5.32	5.79	NS	4.1	2006	2024	49	>1
DW-5		D	10.9	5.97	NS	5.38	2006	2024	37	>1
DW-6		D	1.36	5.57	NS	5.87	2006	2024	44	>1
DW-9		D	4.94	1.24	NS	1.59	2006	2024	39	>1
GW-13		I	3.26	6.74	NS	6.63	2006	2024	19	>1
GW-15		NS	4.68	4.55	NS	4.15	2005	2024	20	>1
GW-9		NS	0.7	5.11	NS	5.25	2006	2024	20	>1

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Table S2: Median and standard error in parentheses of crop type percentage within 500 meters of each well categorized by ending nitrate concentration. Values highlighted in orange indicate that the specific crop type percentage is significantly different while values highlighted in green indicate that the specific crop type percentage is not according to a Mann-Kendall analysis.

Crop Type	Ending Nitrate Concentration		
	< 7 mg nitrate-N L ⁻¹	7-10 mg nitrate-N L ⁻¹	> 10 mg nitrate-N L ⁻¹
	% of land area	% of land area	% of land area
Agricultural Lands			
All Grasses and Hay	61.3 (1.16)	70.5 (2.58)	72.7 (1.48)
Miscellaneous	6.36 (0.638)	7.7 (1.67)	3.03 (0.711)
Grains	2.41 (0.596)	1.14 (1.2)	4.4 (1.08)
Squash	0.935 (0.688)	0.148 (0.594)	1.5 (1.27)
Corn	0.526 (0.413)	0.854 (0.489)	2.77 (0.946)
Legumes	0.465 (0.35)	0.293 (0.245)	0.528 (0.897)
Mint	0.236 (0.388)	0.411 (0.192)	0.41 (0.457)
Blueberries	0.177 (0.121)	0.295 (0.0843)	0.147 (0.0405)
Fruit and Nut Trees	0.176 (0.0463)	0.118 (0.304)	0.235 (0.0384)
Natural Lands			
Wetlands	6.21 (0.462)	2.22 (0.744)	0.829 (0.47)
Open Water	3.29 (0.33)	0.117 (0.0162)	0.175 (0.0366)
Forest	1.05 (0.139)	1.11 (0.266)	0.354 (0.366)
Other			
Developed	0.523 (0.134)	0.265 (0.473)	0.413 (0.462)
Fallow	1.21 (0.134)	1.7 (0.473)	1.48 (0.462)

Table S3: Land cover types and associated N input for agricultural crops from the Cropland Data Layer Explorer CroplandCROS (USDA, 2022). Category is the combined crop group. Low and high N represent the low end, and the high end of the recommended nitrogen (N) application rates based upon the cited reference.

Category	Land Cover	Low N	High N	Reference
		kg N ha ⁻¹		
Forest	Deciduous Forest	0	0	(Lin et al., 2018)
Forest	Evergreen Forest	0	0	(Lin et al., 2018)
Forest	Forest	0	0	(Lin et al., 2018)
Forest	Mixed Forest	0	0	(Lin et al., 2018)
Forest	Shrubland	0	0	(Lin et al., 2018)
Developed	Developed/High Intensity	0	0	(Lin et al., 2018)
Developed	Developed/Low Intensity	0	0	(Lin et al., 2018)
Developed	Developed/Med Intensity	0	0	(Lin et al., 2018)
Developed	Developed Open Space	0	0	(Lin et al., 2018)
Legumes	Dry Beans	50	80	(Mansour et al., 2000)
Legumes	Chick Peas	50	80	(Mansour et al., 2000)
Legumes	Alfalfa	50	80	(Mansour et al., 2000)
Legumes	Lentils	50	80	(Mansour et al., 2000)
Legumes	Soybeans	50	80	(Schmidt)
Legumes	Vetch	0	0	(Hannaway & McGuir, 1982)
Corn	Corn	120	200	(Sullivan et al., 2017)
Corn	Sweet Corn	120	200	(Sullivan et al., 2017)
Grains	Flaxseed	100	150	(Hart et al., 2011)
Grains	Oats	100	150	(Hart et al., 2011)
Grains	Rye	100	150	(Hart et al., 2011)
Grains	Sorghum	0	100	(Armah-Agyeman et al., 2002)
Grains	Speltz	100	150	(Hart et al., 2011)
Grains	Spring Wheat	100	150	(Hart et al., 2011)
Grains	Triticale	100	150	(Hart et al., 2011)
Grains	Winter Wheat	100	150	(Hart et al., 2011)
Grains	Buckwheat	100	150	(Hart et al., 2011)
Grains	Barley	100	150	(Hart et al., 2011)
Fallow	Barren	20	40	(Lin et al., 2018)
Fallow	Fallow/Idle Cropland	0	0	(Lin et al., 2018)
Grass_Hay	Sod/Grass Seed	40	90	(Cook & McDonald, 2005)
Grass_Hay	Grassland/Pasture	44	88	(Pirelli et al., 2004)

Grass_Hay	Other Hay/Non Alfalfa	40	90	(Lin et al., 2018)
Squash	Pumpkins	120	200	(Sullivan et al., 2019)
Squash	Squash	120	200	(Sullivan et al., 2019)
Mint	Mint	175	250	(Hart, 2010)
Misc	Grapes	0	6	(Lin et al., 2018)
Misc	Greens	87	120	(Oregon Master Gardener)
Misc	Hops	75	150	(Gingrich, 1994)
Misc	Misc Veggies & Fruits	0	200	(Oregon Master Gardener)
Misc	Potatoes	150	250	(Sullivan et al., 2017)
Misc	Peppers	120	250	(Sullivan et al., 2017)
Misc	Sugar beets	128	200	(Shock & Feibert, 1996)
Misc	Other Crops	0	200	Range of all values
Misc	Garlic	120	200	(Sullivan et al., 2017)
Misc	Onions	120	200	(Sullivan et al., 2017)
Misc	Clover/Wildflowers	0	0	(Gardner, 1983)
Misc	Broccoli	150	200	(Sullivan et al., 2019)
Misc	Cabbage	150	200	(Sullivan et al., 2019)
Misc	Radishes	150	100	(Sullivan et al., 2019)
Misc	Turnips	150	200	(Sullivan et al., 2019)
Misc	Mustard	150	200	(Sullivan et al., 2019)
Misc	Canola	150	200	(Sullivan et al., 2019)
Misc	Cauliflower	150	200	(Sullivan et al., 2019)
Misc	Christmas Trees	0	150	(Hart et al., 2009)
Misc	Other Tree Crops	0	150	(Hart et al., 2009)
Misc	Walnuts	0	101	(Olsen, 2006)
Misc	Caneberries	20	80	(Hart, 2006)
Misc	Strawberries	30	90	(Hart et al., 1988)
Misc	Cranberries	40	60	(Hart et al., 2015)
Misc	Sunflowers	100	150	(Sullivan et al., 2019)
Orchard	Apples	0	109	(Righetti T, 1998)
Orchard	Cherries	0	109	(Righetti T, 1998)
Orchard	Peaches	0	109	(Righetti T, 1998)
Orchard	Pears	0	109	(Righetti T, 1998)
Orchard	Plums	0	109	(Righetti T, 1998)
Orchard	Prune	0	109	(Righetti T, 1998)
Wetlands	Herbaceous Wetlands	0	0	(Lin et al., 2018)
Wetlands	Wetlands	0	0	(Lin et al., 2018)
Wetlands	Woody Wetlands	0	0	(Lin et al., 2018)
Blueberries	Blueberries	100	260	(Hart et al., 2006)
Open_Water	Open Water	0	0	(Lin et al., 2018)

Figure S1: Trends for individual wells with significant declines (a) and Is (b) in nitrate concentrations (p-value < 0.2. Colors represent well classification as described in the legends.

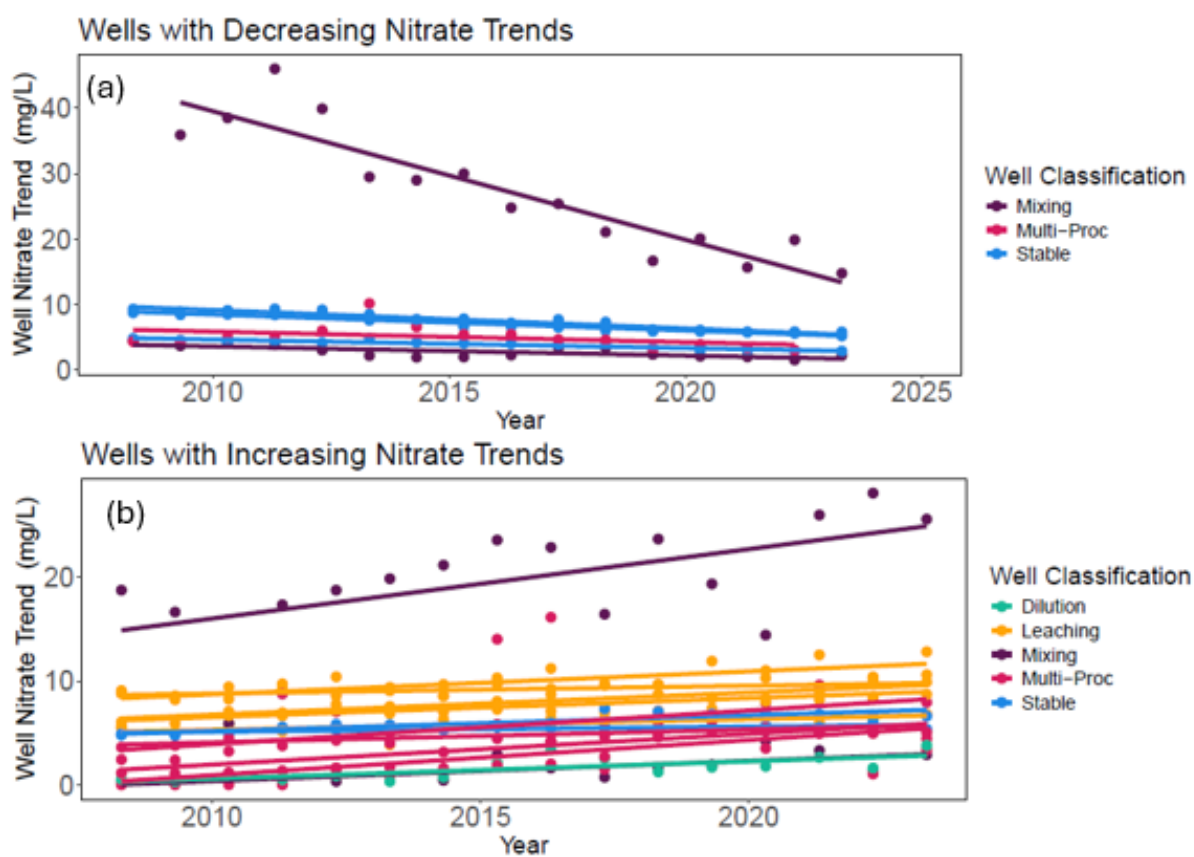
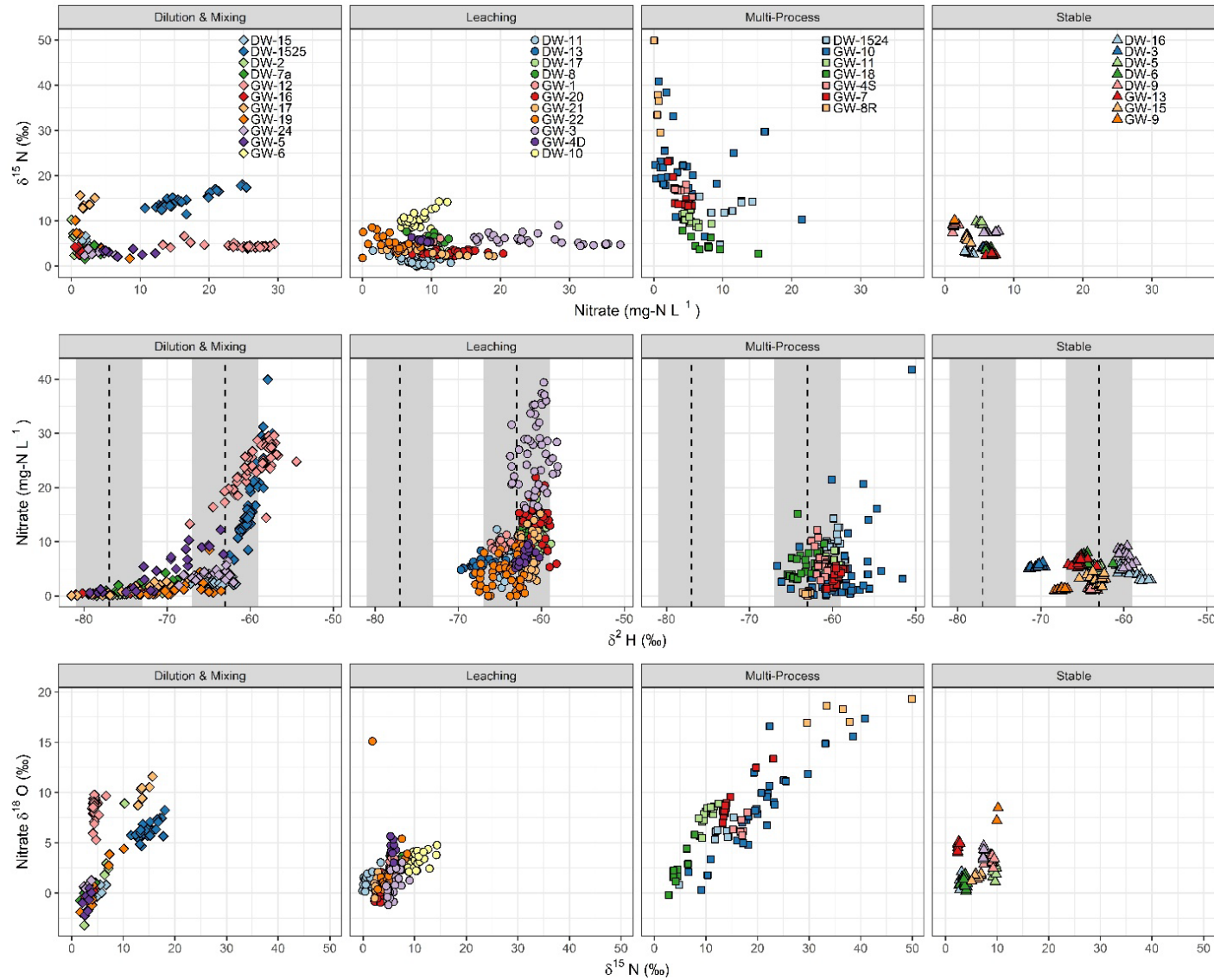


Figure S2: Isotope data used for classifying wells for the time period from 2012-2016, with well classes separated into columns from (Weitzman et al., 2021). Top row: Nitrate concentrations and nitrate $\delta^{15}\text{N}$ values for the SWV-GWMA wells. Middle row: Water $\delta^2\text{H}$ values and nitrate concentrations. The dashed vertical lines indicate the mean $\delta^2\text{H}$ values of the Willamette River (-77) and local precipitation (-63) with their variance indicated by the gray shading. Bottom panel: $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ of nitrate. Each well has a unique symbol shape and color as indicated in the top panel.



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