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Historical tracking of nitrate in contrasting vineyards using water isotopes and nitrate depth profiles

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ABSTRACT

The European Water Framework Directive (EWFD) aims to achieve a good chemical status for the groundwater bodies in Europe by the year 2015. Despite the effort to reduce the nitrate pollution from agriculture within the last two decades, there are still many groundwater aquifers that exceed nitrate concentrations above the EWFD threshold of 50 mg L^{-1}. Viticulture is seen as a major contributor of nitrate leaching and sowing of a green cover was shown to have a positive effect on lowering the nitrate loads in the upper 90 cm of the soil. However, the consequences for nitrate leaching into the subsoil were not yet tested. We analyzed the nitrate concentrations and pore water stable isotope composition (δ^2H) to a depth of 380 cm in soil profiles under an old vineyard and a young vineyard with either soil tillage or permanent green cover in between the grapevines. The pore water δ^2H data was used to calibrate a soil physical model, which was then used to infer the age of the soil water at different depths. This way, we could relate elevated nitrate concentrations below an old vineyard to tillage processes that took place during the winter two years before the sampling. We further showed that the elevated nitrate concentration in the subsoil of a young vineyard can be related to the soil tillage prior to the planting of the new vineyard. If the soil was kept bare due to tillage, a nitrate concentration of 200 kg NO_3^--N ha^{-1} was found in 290–380 cm depth 2.5 years after the set-up of the vineyard. The amount of nitrate leaching was considerably reduced due to a seeded green cover between the grapevines that took up a high share of the mineralized nitrate reducing a potential contamination of the groundwater.

1. Introduction

At least since the EU council adopted the Nitrates Directive over two decades ago the members of the European Union commit themselves to reduce the nitrate pollution of European water bodies by agricultural sources (European Council, 1991). This goal was affirmed by the EU Water Framework Directive, whose integrated river basin management aimed to get the groundwater in Europe into a "good chemical status" by 2015 (European Council, 2000). The upper limit of 50 mg L^{-1} for nitrate in groundwater was confirmed by the Groundwater Directive (European Council, 2006). However, despite the efforts in the last two decades, many groundwater aquifers do not meet the quality standard of the EU due to elevated nitrate concentrations. In agriculturally intense catchments in the southwest of Germany, several groundwater monitoring wells show nitrate concentrations that exceed the threshold of 50 mg L^{-1} and at some sampling locations, there is even an increasing trend (LUBW, 2009). The situation of the groundwater quality only improves slowly around the Kaiserstuhl located west of Freiburg i. Br., Germany, even though the average nitrate surplus decreased between 1980 and 2005 from 24 to 11 kg N ha^{-1} and the average nitrate loads of leaching water declined from 57.9 mg L^{-1} in 1980 to 29.8 mg L^{-1} in 2005 (LUBW, 2008). Nevertheless, vine farming is seen as a relevant factor influencing high nitrate concentrations (Erhardt and Riedel, 2011). Under old vineyards in the study area, the nitrate-N concentrations in the upper 90 cm of soil are on average far below the control value of 90 kg N ha^{-1} defined by the Umweltministerium (2001). The concentration in the topsoil shows a decreasing trend for the monitoring period between 2001 and 2013 (LTZ, 2013). However, under young vineyards the nitrate-N concentrations are on average above the threshold in the first year (Erhardt et al., 2012). The elevated nitrate-N concentrations result from high Nitrate mineralization rates of organic matter developed in the previous vineyard and deeper soil tillage (e.g., land clearing and soil modification) as well as shallow soil tillage before and after planting (Erhardt et al., 2012; Rupp, 1988). These values decrease over the following years and approach the nitrate concentrations

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of old vineyards after about four years (Erhardt and Riedel, 2013). Thus, a possible nitrate leaching from vineyards is most likely within the first year after planting the grapevines. The concentration of nitrate under young vineyards can considerably be reduced by sowing a mixture of *Phacelia tanacetifolia* and *Fagopyrum esculentum* and *Sinapis alba* in between the rows of grapevines instead of keeping a bare soil due to tillage (Erhardt and Riedel, 2013). The green cover, sown in every second interrow one month after planting, did not have any consequences regarding the growth of the young vine plants in the first year (Erhardt and Riedel, 2012; Erhardt et al., 2013).

These studies dealing with an optimal nitrate supply of the grapevines in the topsoil, while keeping the contamination of groundwater by nitrate leaching low are promising. However, it is yet unknown if the lowered nitrate concentration in the upper 90 cm due to sowing in the interrows on a vineyard also positively influences the leaching of nitrate into the deeper soil eventually reaching the groundwater. Soil physical modeling, including pore water stable isotope data ($\delta\,^2$H) as a natural tracer for calibrating the soil water balance and travel times, was shown to enable tracing the water movement into deeper soil layers (Sprenger et al., 2015). Though, a practical application and a validation with another tracer have not been done so far. Based on the above mentioned experiences and knowledge gaps we test the following hypothesis in this study:

i.) The timing of the nitrate mineralization can be traced back by pore water $\delta\,^2$H data.
ii.) The risk of nitrate leaching into the subsoil is higher under young vineyards than under old vineyards
iii.) A permanent green cover reduces the nitrate loads in the subsoil.
iv.) Soil tillage in winter increases the risk of nitrate leaching.

Our objective is to investigate the nitrate-N concentrations in parallel with pore water $\delta\,^2$H data in the soil down to a depth of 380 cm. The pore water $\delta\,^2$H measurements will be used to infer the water age in the soil to potentially relate an elevated nitrate signal at a certain depth to the time the isotopic signal of the water was introduced by the rainwater.

2. Methods

2.1. Study site

The study was conducted in the catchment of the groundwater aquifer Freiburger Bucht in the west of Freiburg i. Br., Germany, where the groundwater body showed a nitrate concentration above the legal limit of 50 mg L^{-1}. Vineyards are holding a relatively high share of 12% of the catchment area and are often established on terraces. The prevailing climate is temperate and for the years 2008–2013, the annual average air temperature was 10.5 °C and the annual rainfall was 722 mm. With about 17 frost days per year, snow does only occur occasionally. The studied soils are silty Pararendzina on deep Pleistocene loess. The soil profile is divided into a humus plowing horizon (Ap) in the upper 30 cm and a relatively uniform parent material below. Investigations were conducted in an old and a young vineyard, which are located in about 3 km distance from each other. The old vineyard was established in 1998. 70 kg N ha^{-1} of N-fertilization was applied by sulfate of ammonia in the years 2011–2013. Two different management practices were investigated: on the one hand, a permanent green cover in between the grapevines (OldGC), and on the other hand green cover with surface tillage and seeded green cover in every 2nd interrow, which shifted every other year (OldST). The young vineyard was planted in May 2011. No fertilization was done in 2011, but sulfates of ammonia were applied to add 30 kg N ha^{-1} in 2012 and 50 kg N ha^{-1} in 2013. Similar to the old vineyards, the management practice at young vineyards was studied. At one site, a permanent green cover with a mixture of *P. tanacetifolia* and *F. esculentum* and *S. alba* was sown in every second interrow one month after planting the vineyards (NewGC). In every other row a green cover was seeded four months after the planting of the grapevines. In this study, the latter interrows were not considered. At the other study site in the young vineyard, the soil was kept bare with surface tillage in the first year (NewST). An overview of the management practice and schedule for the years 2010–2012 at the four different sites is given in Table 1.

2.2. Soil sampling

Soil sampling was conducted on the 4th and 5th of November 2013 at the young and old vineyards, respectively. At each of the four study sites, soil cores with a diameter of 8 cm to a depth of 380 cm were drilled. Soil sampling was done in approximately 5 cm intervals and of each sample of approximately 265 cm^3 volume about 40 g were taken for the nitrate analysis and the remaining ca. 250 g were used to determine the $\delta\,^2$H of the pore water. The soil samples for the nitrate analysis were cooled after the sampling and stored frozen at −20 °C until analysis. The nitrate analyses were done according to LTZ (2001) and values of kg NO_3^--N ha^{-1} were obtained by assuming a bulk density of 1.3 in the upper 30 cm and 1.5 below 30 cm. Since a green cover was sown only in every second interrow, but only the interrow of the green cover was sampled in NewGC, an upscaling of the point sampling into space is not possible. The pore water $\delta\,^2$H analyses were done according to Wassenaar et al. (2008) as described in more detail by Sprenger et al. (2015). The measured isotopic signal is given as $\delta\,^2$H in [‰] relative to the Vienna Standard Mean Ocean Water (VSMOW). The precision for the pore water $\delta\,^2$H analyses is 1.16‰ and defined here

Table 1
Overview of the different management practices at the studied vineyards for the years 2010–2012.

Year	Date	Management practice	OldGC	OldST	NewGC	NewST
2010	Oct.	Vineyard removal			X	X
	8th Nov.	Plow (25 cm)			X	X
2011	27th April	Disc harrow (3 cm)			X	X
	29th April	Power harrow (7 cm)			X	X
	3rd May	Planting of vineyards			X	X
	3rd May	Mulching	X	X		
	4th May	Rotary hoe		X		
	21st May	Power harrow (7 cm)			X	X
	31st May	Sowing		X	X	
	15th June	Mulching	X	X		
	20th June	Power harrow (7 cm)				X
	4th July	Mulching	X	X		
	11th Aug.	Power harrow (7 cm)				X
	2nd Sept.	Power harrow (7 cm)				X
	24th Sept.	Mulching	X	X		
	29th Dec.	Disc harrow		X		
2012	26th April	Mulching	X	X		
	30th April	Power harrow (2 cm)			X	X
	2nd May	Power harrow (6 cm)		X		
	3rd May	Sowing		X		
	23rd May	Mulching			X	
	6th June	Mulching	X	X		
	15th June	Mulching			X	
	20th June	Power harrow (6 cm)				X
	26th June	Power harrow (6 cm)				X
	17th July	Mulching	X	X		
	18th July	Mulching			X	X
	5th Sept.	Mulching	X	X		