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Hedgerows reduce nitrate flux at hillslope and catchment scales via root uptake and secondary effects

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ABSTRACT

Agricultural contamination of groundwater with nitrate (NO_3^-) is one of the most widespread and pressing environmental issues. The preservation and planting of hedgerows around agricultural fields can reduce NO_3^- flux, but the efficacy of hedgerows depends on the amount of NO_3^- in soil and groundwater, hydrological flowpath and timing, and biogeochemical conditions surrounding and below roots. Quantifying these parameters is a major challenge, usually requiring involved and destructive fieldwork. Here, we present a new analytical method to characterize NO_3^- stratification using water chemistry sampled during piezometer slug tests. We tested this method with a network of wells in a hillslope intersected by an oak hedgerow during high- and low-water conditions, respectively spring and autumn. We found that hedgerows had a strong seasonal effect on near-surface NO_3^- dynamics in the proximity of the root system, reducing annual hillslope-level fluxes by 26 to 63%, comparable to NO_3^- removal from cover crop techniques. Hedgerow root uptake accounted for two-thirds of this reduction, with the remaining third attributable to secondary effects, potentially hedgerow-induced microbial retention or denitrification due to increased organic carbon and heterogeneous redox conditions in the rooting zone. However, a simple scaling exercise suggested that at the catchment level, hedgerow NO_3^- removal has a smaller effect (ca 1–10% reduction of annual flux), due to the large legacy of NO_3^- in the aquifer from past fertilizer application. These results suggest that while hedgerows cannot immediately solve problems of past groundwater contamination, protection and reestablishment of hedgerow networks could substantially accelerate recovery of groundwater quality on decadal timescales.

1. Introduction

Groundwater and surface water nitrogen pollution from human activity is one of the most urgent environmental issues, incurring social, economic, and ecological costs valued at 0.3 to 3% of the global gross domestic product (0.2 to 2.3 trillion USD annually; Bodirsky et al., 2014; Sutton et al., 2013). Excess agricultural fertilizer is the primary cause of groundwater contamination by nitrate (NO_3^-; Bonton et al., 2012; Howden et al., 2011; Koh et al., 2010; Kurtzman et al., 2013, 2016; Thorburn et al., 2003). One approach for reducing groundwater contamination while maintaining agricultural yields is the planting or protection of hedgerows, i.e. lines of shrubs or trees around cultivated fields. The association of trees with arable land in the form of hedgerows is a widespread and ancient practice that results both spontaneously and from active management of rural landscapes (Forman and Baudry, 1984). In addition to decreasing nutrient loss and erosion (Angima et al., 2002; Nair et al., 2007), hedgerows provide secondary benefits including habitat for wildlife, a source of wood for fuel and forage, wind breaking, and aesthetic value (Barr and Petit, 2001; Droppelmann et al., 2000). Studies in the USA, Europe, and Africa have demonstrated that agroforestry can protect or rehabilitate water resources across a wide range of climatic and cultural contexts (Nair et al., 2007; Radersma et al., 2004; Reisner et al., 2007). Despite their benefits, many hedgerows have been removed to increase field size and facilitate agricultural machinery. This occurred in western France from the 1960s to the 1980s during the *remembrement* (regrouping) of agricultural fields (Baudry et al., 2000). The simultaneous increase in fertilizer inputs and removal of hedgerows during this period resulted in widespread degradation of surface and groundwater (Aquilina et al., 2012; Abbott et al., 2018). Recent studies have highlighted the ecosystem services provided by hedgerows (McKenzie et al., 2013; Thomas et al., 2016), and since 1997, European legislation actively promotes hedgerow restoration (Baudry et al., 2000; Garcia-Feced et al., 2015; Ghaffar and Robinson, 1997; Morelli, 2013).

While hedgerows can reduce NO_3^- concentration in near-surface groundwater (Grimaldi et al., 2012), the relative importance of uptake

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and removal processes underlying this effect remains uncertain. Hedgerows could influence NO_3^- flux via three non-exclusive mechanisms. First, shrubs and trees in hedgerow networks directly take up NO_3^- to fulfill their nutrient needs (Chapin, 1980; Sabater et al., 2003). Second, the presence of perennial plants and lack of tillage create soil conditions favorable for denitrification by allowing the accumulation of soil organic matter and the development of soil structure where anoxic microsites can develop (Constantin et al., 2010; Grimaldi et al., 2012; Singh et al., 2017). Third, evapotranspiration can modify soil and near-surface groundwater hydrology, routing NO_3^- rich soil water and groundwater to root networks and hedgerow-influenced soils (Ghazavi et al., 2011; Thomas et al., 2012). To identify how these three phenomena interact to regulate NO_3^- movement and removal, both hydrology and biogeochemistry of the near-surface groundwater surrounding hedgerows need to be characterized.

Near-surface groundwater chemistry is typically characterized by sampling water from shallow wells or piezometers (e.g. Kolbe et al., 2016; Lockhart et al., 2013; Martin et al., 2004; Pfeiffer et al., 2006; Houben et al., 2018). One of the limits of this sampling method is that water within the well casing may not be representative of groundwater in the surrounding soil and substrate, particularly if there is limited circulation in the well and water has been stagnant. To mitigate this effect, sometimes piezometers are emptied prior to sampling, though there is no standard procedure for the duration or timing of pumping. Furthermore, samples from a screened piezometer represent a mixture of water sources, and for groundwater with a chemical gradient, as one would expect to find near a hedgerow, this complicates interpretation of an instantaneous sampling. Groundwater stratification can be characterized by installing multiple piezometers at different depths, but this disturbs the soil profile, is costly, and does not necessarily resolve the issue of unidentified contributing area for each of the clustered piezometers (see Houben et al., 2018 for a quantitative comparison of methods).

To quantify the NO_3^- removal capacity of hedgerows and address the methodological challenge of sampling piezometers, we developed a new protocol for sampling and analyzing water chemistry in shallow wells. We repeatedly sampled piezometer water chemistry during slug tests (where water in the well casing was emptied then allowed to refill) and used these curves to characterize gradients of NO_3^- in soil water and groundwater with reactive transport modeling. We tested this method for characterizing NO_3^- profiles with a network of shallow wells in a hillslope intersected by an oak hedgerow. We estimated how much of the observed NO_3^- removal was due to hedgerow root uptake, and quantified the potential impact of these processes on hillslope- and catchment-scale NO_3^- flux. Specifically, we were interested in the efficacy of hedgerows in reducing surface NO_3^- inputs from current agricultural activity and historical NO_3^-contamination of near-surface groundwater.

2. Methodology

2.1. Study site

The study site is located in a 4.4 km^2 agricultural catchment in western France (Fig. 1a and b, 48° 07′ N, 1° 43′ W). Agricultural regions in France have been hard hit by nitrogen pollution, with NO_3^- concentration in shallow groundwater often exceeding the recommended limit for drinking water (50 mg L^{-1}; Abbott et al., 2018; WHO, 2007). Since the 1950s, the region surrounding the research catchment has been subject to intense agriculture, with 90% of arable land cultivated for corn, wheat, and pastureland (Thomas et al., 2016). The research catchment has a mix of these land-use types and mean hedgerow coverage of approximately 2%. The climate is temperate with average monthly temperature ranging from 17.5 °C in July to 5 °C in December, mean annual precipitation of 720 mm, and potential evapotranspiration (PET) of 620 mm (Thomas et al., 2012). Soils are approximately 1.2 m thick in the uplands and 0.6 m thick in the lowlands (Ghazavi et al., 2008). The water table fluctuates seasonally from ca 2 to 4 m below the surface. Groundwater circulation is mainly constrained to a 30 to 100 m weathered layer, underlain by schist bedrock (Kolbe et al., 2016; Marçais et al., 2018).

2.2. Sampling design

We installed 7 piezometer wells along a 28-m transect extending from an agricultural pasture to a riparian zone (Fig. 1b). Hillslope monitoring was performed from September 1, 2005 to December 31, 2006. An oak hedgerow intersects the piezometer transect at the boundary between well-drained upland soils and waterlogged wetland soils (Fig. 1; Ghazavi et al., 2008). Piezometer wells were named in relation to the hedgerow (UP for upslope of the hedgerow and DW for downslope) followed by the distance from the hedgerow (Fig. 1, Table S1). Piezometers were 4.5 or 7.5 m deep, 68 or 112 mm in diameter, and screened along the deepest 2 or 4 m (Fig. 1, Table S1). The differences in piezometer depth were to account for the topographical gradient between upslope and downslope portions of the transect, and a consequence of accessibility (the truck-based drill was too heavy to reach the downslope sites, which were drilled manually).

To test how seasonal differences in hydrology and biogeochemistry affect hedgerow NO_3^- uptake and the applicability of this method, we carried out slug tests in June and October of 2006, corresponding to high- and low-water periods. The slug tests consisted of two phases (Fig. 2). First, we emptied the well with a portable pump (Koshin SE-25F) until the water level reached the bottom of the screened section of the piezometer, which took approximately 20 min. Second, we removed the pump and collected water samples as the well refilled with lateral flow from the surrounding aquifer and soil. We monitored water level with a pressure transducer and collected a sample every 30 to 60 s until the groundwater level stabilized. All samples were filtered to 0.45 μm with a polyvinylidene difluoride membrane (Millipore) and were stored at 4 °C in the dark until analysis within two weeks. Samples were analyzed for NO_3^-, chloride (Cl^-), and sulfate (SO_4^{2-}) by ion chromatography (Dionex DX 100).

2.3. Hydraulic properties

We determined saturated hydraulic conductivity following Hvorslev (1951). This analysis assumes a homogeneous, isotropic, infinite medium in which both the fluid and soil are incompressible. The Hvorslev formulation is:

$$K_s = \frac{R_w{}^2 \ln\left(\frac{L}{R_b}\right)}{2LT_l} \tag{1}$$

where K_s is the saturated hydraulic conductivity, R_w is radius of the well, L is height of screened part of the piezometer, R_b is radius of the borehole, and $T_l$is the time lag defined as:

$$T_l = \frac{h_t}{h_0} = 0.37 \tag{2}$$

where h_t is the variable water head measured during recovery period at time t, and h_0 is the water head at the time of maximum drawdown (t_0)—in this case, t at the end of the first phase. Saturated hydraulic conductivity (K_s) is determined using Eq. (1) and the time lag is graphically estimated using Eq. (2). Note that the difference between R_w and R_b is approximately 4 mm (the thickness of the casing). For each well, we calculated horizontal flow (discharge) with measured parameters using Eq. (3). Two-dimensional hydraulics of unconfined flow can be calculated analytically assuming that equipotential surfaces are vertical and flow is essentially horizontal (i.e. Dupuit assumptions; Bear, 1979). The two-dimensional flow in a homogeneous domain is approximated by a one-dimensional equation, which can be solved