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Factors affecting agricultural nitrogen removal in riparian strips: Examples from groundwater-dependent ecosystems of the Po Valley (Northern Italy)

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ABSTRACT

The role of riparian ecosystems in mitigating the effects of diffuse agricultural sources is recognized in several regulatory measures and public policy initiatives in many parts of the world. This study aimed to evaluate the N buffering capacity of semi-natural riparian zones associated with spring-fed lowland streams, also known as “fontanili”, representing the most important groundwater-dependent ecosystems in Northern Italy. Monitoring parcels were set up in nine riparian sites selected to cover a range of different soil properties and hydrogeological settings, and to sustain the evaluation of the main drivers affecting their N removal efficiency. Subsurface water level, nutrient concentrations and the main hydro-chemical parameters were monitored along transects of piezometers installed from crop fields to the spring channels. On selected samples from two sites stable isotopes of the water molecule were also determined. Median NO_3^- input concentrations from adjacent cropland to the riparian sites ranged from 0.10 to 21 mg N L^{-1}, with maximum values exceeding the drinking water limit recorded during the summer and winter fertilization periods. Highly variable groundwater nitrate patterns were found in the riparian areas, including short nitrate plumes extending from the adjacent cropland into some riparian zones, or in others, small patches where NO_3^- declined at variable distance from the stream. Some chemical indicators (e.g., NO_3^-/Cl^- ratio, O_2, DOC) suggested that NO_3^- attenuation was mostly due to the denitrifying activity occurring in the subsurface aquifers in specific conditions (hot spots and moments), although, in some cases, physical processes such as dilution also contributed. The overall N removal efficiency was greater than 90% in four sites, 74%, 34% and 30% in three sites, and zero in the remaining two sites. Useful predictors of the nitrate removal capacity were factors linked to the water residence time, such as the hydraulic conductivity, the soil texture and the slope of the riparian profile, together with the water table depth and soil organic carbon. A combination by standardized averaging of these five factors supported a clear discrimination of sites with zero or low N removal effectiveness from those with high efficiency.

1. Introduction

The use of nitrogen fertilizers and energy production through fossil fuel combustion have dramatically altered the nitrogen cycle by increasing the release of reactive nitrogen (Galloway et al., 2008). The excess of nitrogen (N) moves easily through the different environmental compartments causing a “cascade” of environmental changes that negatively impact both people and ecosystems (Galloway et al., 2003). The contamination of surface and ground waters by N compounds is a widespread phenomenon all over the world (UNEP and WHRC, 2007) with heavy impacts on the ecological quality and ecosystem services.

In Europe, the achievement of good ecological status in water bodies, required by the Water Framework Directive (EC, 2000), demands the rapid adoption of effective and verifiable measures to reduce nutrient loading to surface waters and groundwater. With regard to pollution from diffuse sources, the measures are oriented, on the one hand, to the development of technologies

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and methods to reduce losses from agriculture and, on the other hand, to the promotion of procedures and/or regulations encouraging farmers to adopt such methods.

Over the last decades there has been increasing evidence that biogeochemical processes occurring naturally in riparian ecosystems – i.e., the vegetated areas adjacent to rivers and wetlands – and in the riverbed are able to modulate the concentrations of nutrients exported downstream (Mulholland, 2004; Sabater et al., 2003). The use of riparian buffers is considered a bioremediation strategy that is supported by the adoption of several regulatory measures and public policy initiatives in many parts of the world (EC, 2009, 2013; Lee et al., 2004). In the European Community, the Water Framework Directive (EC, 2000), the Nitrates Directive (EC, 1991), and the Common Agricultural Policy—CAP (EC, 2009, 2013) promote, support and impose practices to improve water and environmental quality through the establishment, restoration, maintenance and protection of both riparian buffers and perimetral and/or interfield vegetated linear structures. Usually, regulations and incentive programs place great emphasis on the installation of new buffer areas (Lovell and Sullivan, 2006 and references therein). However, realizing policies for protecting existing natural and seminatural riparian zones is regarded to be less expensive than installing new buffers or restoring degraded ones (Mayer et al., 2007; USDA-NRCS, 2003). On a watershed scale, the evaluation of the riparian areas with significant potential to control diffuse pollution, in addition to other ecosystem services, is suggested as a management practice to implement for protecting riparian areas (U.S. EPA, 2005).

Generally, the width of riparian strips is the principal design variable considered by watershed planners. This occurs even if the relationship between the lateral size of a buffer strip and the produced benefits is complex and dependent of the type of pollutants, and the characteristics and conditions of the site (Dosskey et al., 2008; Lin et al., 2002). Great efficiencies of nitrate removal have been measured in riparian strips, both extensive and narrow (e.g., Balestrini et al., 2011, 2008; Haycock and Pinay, 1993; Vidon and Hill, 2004a), and measurements at intermediate distances in the wider buffers have shown that most of the nitrate removal from subsurface flows occurred in a few meters. Moreover, some recent studies have emphasized the role of the so-called "hot spots and hot moments", i.e., small patches and short time periods that exhibit disproportionately high N removal rates compared to the surrounding matrix and the intervening time periods (Groffman et al., 2009; McClain et al., 2003). Several reviews and meta-analyses of the literature (e.g., Mayer et al., 2007; Zhang et al., 2010) agree on the multi-factoriality of dependencies associated with water decontamination potential in the riparian areas. Recently, Vidon and Hill (2006) developed a conceptual model for riparian zones in Ontario, Canada, that links landscape hydrogeological characteristics to riparian groundwater hydrology and nitrate removal efficiency.

In this paper, we propose as ecological tools for water protection from diffuse nitrate pollution, the boundary and linear vegetated elements associated with small spring-fed lowland water bodies, also known as "fontanili", which represent an Italian peculiarity in the European context. They are the most important groundwater-dependent ecosystem (GDE) within the river Po basin, and are located along the so-called "fontanili line" (50–200 m a.s.l.), which stretches for about 800 km varying from a few kilometers to over 50 km wide in a north-south direction (De Luca et al., 2013; Kløve et al., 2011). Generally, the "fontanili" are biotopes where groundwater emerges spontaneously mainly due to the decrease in the permeability of alluvial sedimentary deposits that are usually present in the transition zone between the northernmost part of the Po Valley (High Plain), mostly consisting of coarse materials, and the southern part (Low Plain), where materials are predominantly finer (Martinis et al., 1976). Since the Middle Ages groundwater outflow has been facilitated by the excavation of depressions and/or the installation of tubular artifacts drawing water from greater depths. For this reason, the "fontanili" can be defined as semi-natural water bodies capturing, collecting and conveying phreatic water for irrigation and reclamation purposes.

The overall goal of this study was to evaluate if the riparian strips of "fontanili" – covering a range of different hydrogeological settings – showed N buffering capacity. By tracing the spatial and temporal nitrate variation in groundwater we aimed at detecting where and when nitrate concentration decreased. In the meantime, we aimed at assessing the role of denitrification and/or the possible effect of physical processes in nitrate decline. Furthermore, we aimed at testing a series of possible key factors for N removal, and their combination, by comparing sites with low versus high removal effectiveness. An interpretation of the observed nitrate removal effectiveness of riparian areas, based on a series of explanatory variables, is provided. From this analysis, some predictors useful to identify the riparian areas with significant potential for diffuse pollution control were derived.

2. Material and methods

2.1. Study area

This study was conducted in riparian sites located in the typical flat agricultural plain of the Po River watershed (Northern Italy), at an altitude ranging between 80 and 130 m a.s.l., (Fig. 1). Agriculture and livestock together contribute ~80% of the total N load to the Po River basin, and have led to diffuse nitrate contamination of both surface and groundwater (Cinnirella et al., 2005).

The shallow phreatic aquifer of the Po Plain alluvial sequence comprises coarse gravel and sand, where the grain size decreases from N to S and from W to E. Accordingly, the permeability of the phreatic aquifer in the higher plain greatly exceeds that of the same formation in the lower plain. The water table depth varies from about 30 m in the northwest to 2–3 m in the southeast (Lombardy Region, 2006). The transition between the higher and the lower plain is marked by the numerous permanent outflows named "fontanili" (De Luca et al., 2013).

The climate is classified as temperate continental (mean annual temperature about 13 °C, mean precipitation about 800 mm), with cold winters and hot summers, spring and autumn being characterized by the highest precipitation.

In the Lombardy plain, where most study areas were located, intensive agriculture accounts for about 78% of the land cover. Dominant crops include maize and wheat (70%), and rice (11%) (Brenna et al., 2004). Corn fields are generally treated with large amounts of nitrogen fertilizer, usually urea or ammonium nitrate during sowing, usually in April, and in the cover phase. Irrigation techniques are mostly border irrigation, sprinkler irrigation and permanent floodings (Perego et al., 2012).

The hydrology of the area located north of the "fontanili" line strongly depends on irrigation. Large volumes of water taken from rivers are distributed to the fields through a network of mostly unlined canals, thus contributing significantly to the aquifer recharge by infiltration from both irrigation canals and irrigated areas. Despite the abundance and the density of the natural and artificial surface water network, riparian areas are rather limited in extent and width because of the intensive and unregulated exploitation of agricultural land.

This study was conducted at 9 riparian sites (Fontanin = F; Rile = R; Fontanone = CB; Mischia = M; Cavo Marocco = TV; Riazzolo = RZ; Uccello = U; Catanino = Z; Quattro Ponti = Q) where