Science of the Total Environment 647 (2019) 301–312

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

An ounce of prevention is worth a pound of cure: Managing macrophytes for nitrate mitigation in irrigated agricultural watersheds

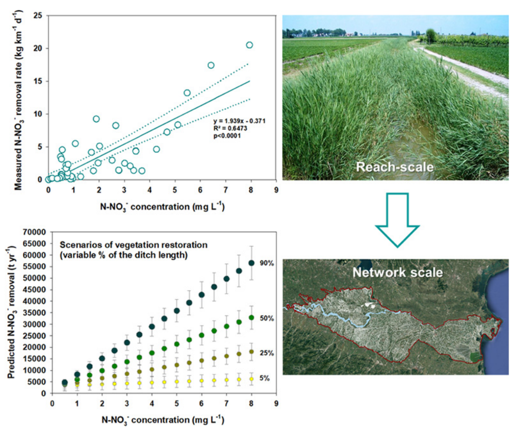
Elisa Soana [a,*], Marco Bartoli [b], Marco Milardi [a], Elisa Anna Fano [a], Giuseppe Castaldelli [a]

[a] Department of Life Sciences and Biotechnology, University of Ferrara, Via L. Borsari 46, 44121 Ferrara, Italy
[b] Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, Parco Area delle Scienze 33/A, 43124 Parma, Italy

HIGHLIGHTS

- The role of ditch networks in watershed-scale N-NO_3^- mitigation remains understudied.
- N-NO_3^- removal rates were scaled-up to the ditch network of the Po River lowlands.
- In-ditch denitrification was assessed in the context of agricultural N surplus.
- In-stream vegetation maintenance may efficiently control agricultural N excess.
- Predictive tools and management guidelines are needed to maximize ditch N removal.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 26 April 2018
Received in revised form 25 July 2018
Accepted 26 July 2018
Available online 29 July 2018

Editor: José Virgílio Cruz

Keywords:
Nitrate pollution
Ditch network
Denitrification
Vegetation management
Po River basin

ABSTRACT

Although ubiquitous elements of agricultural landscapes, the interest on ditches and canals as effective filters to buffer nitrate pollution has been raised only recently. The aim of the present study was to investigate the importance of in-ditch denitrification supported by emergent aquatic vegetation in the context of N budget in agricultural lands of a worldwide hotspot of nitrate contamination and eutrophication, i.e. the lowlands of the Po River basin (Northern Italy). The effectiveness of N abatement in the ditch network (>18,500 km) was evaluated by extrapolating up to the watershed reach-scale denitrification rates measured in a wide range of environmental conditions. Scenarios of variable extents of vegetation maintenance were simulated (25%, 50% and 90%), and compared to the current situation when the natural development occurs in only 5% of the ditch network length, subjected to mechanical mowing in summer.

Along the typical range of nitrate availability in the Po River lowlands waterways (0.5–8 mg N L^{-1}), the current N removal performed by the ditch network was estimated in 3300–4900 t N yr^{-1}, accounting for at most 11% of the N excess from agriculture. The predicted nitrate mitigation potential would increase up to 4000–33,600 t N yr^{-1} in case of vegetation maintenance in 90% of the total ditch length. Moreover, a further significant enhancement (57% on average) of this key ecosystem function would be achieved by postponing the mowing of vegetation at the end of the growing season.

The simulated outcomes suggest that vegetated ditches may offer new agricultural landscape management opportunities for effectively decreasing nitrate loads in surface waters, with potential improved water quality at

* Corresponding author.
E-mail address: elisa.soana@unife.it (E. Soana).

https://doi.org/10.1016/j.scitotenv.2018.07.385

the watershed level and in the coastal zones. In conclusion, ditches and canals may act as metabolic regulators and providers of ecosystem services if conservative management practices of in-stream vegetation are properly implemented and coupled to hydraulic needs.

1. Introduction

Denitrification, the reduction of nitrate (N-NO_3^-) to nitrogen (N) gases under anaerobic conditions, is globally considered the main biogeochemical process responsible for permanent removal of anthropogenic N along the terrestrial-freshwater-estuarine continuum. Understanding the relative contributions of terrestrial and aquatic compartments to denitrification, and its temporal and spatial variability, remains a significant challenge in biogeochemistry (Burgin et al., 2013; Duncan et al., 2013; Anderson et al., 2014). Furthermore, landscape science aimed at developing best management practices for improving water quality in agricultural watersheds could benefit from increased knowledge on denitrification (Dollinger et al., 2015; Kalcic et al., 2018). Several studies have highlighted that an internal generation of large N loads in irrigated landscapes impacted by intensive agricultural activities may not necessarily result in high export to downstream aquatic ecosystems and coastal zones (Bartoli et al., 2012; Castaldelli et al., 2013; Romero et al., 2016). Both plot-scale and basin-scale observations demonstrated that the landscape potential capacity to buffer N increases in relation to the density of small-size aquatic ecosystems (e.g. wetlands, reservoirs, drainage ditches and drains) (Lassaletta et al., 2012; Powers et al., 2015; Hansen et al., 2018), and the availability of dissolved inorganic N forms in surface waters is negatively correlated to the recirculation degree of irrigation water (Hitomi et al., 2006; Törnqvist et al., 2015). Indeed, water management practices aimed at guaranteeing a supply for agricultural uses (i.e. flow regulation, water diversions), deeply affect the N delivery patterns from the agro-ecosystems to the terminal water bodies. In particular, during the vegetative period, water volumes diverted from the main waterways are redistributed, together with associated solutes, on the landscape via extensive networks of canals and ditches where increased flow-path lengths and hydraulic residence time offer high opportunity for N processing and losses (Barakat et al., 2016; Mortensen et al., 2016).

While the role of undisturbed headwater streams, wetlands and buffer zones in watershed N dynamics has been extensively investigated in the past (Peterson et al., 2001; Mayer et al., 2007; Passy et al., 2012; Hansen et al., 2018), the interest on agricultural ditches as effective N filters has been raised only recently (McPhillips et al., 2016; Veraart et al., 2017; Speir et al., 2017; Schilling et al., 2018). Although ubiquitous elements of human-impacted watersheds, and usually accounting for the greatest part of the total length of waterways, agricultural ditches still remain largely understudied compared to other aquatic ecosystems (Pina-Ochoa and Alvarez-Cobelas, 2006) and are scarcely included in restoration programs compared to wetlands and vegetated buffer strips (Dalgaard et al., 2014; Dollinger et al., 2015; Faust et al., 2018). The usually low habitat complexity of these modified waterways is a direct consequence of human-driven alterations and management practices (e.g. homogeneous morphology of the riverbed, channelization, burial, artificial flow regime, reduction of riparian vegetation, dredging). This condition has been traditionally associated with reduced efficiencies in organic matter processing and N removal compared to natural systems, leading to the belief that these systems act simply as conduits for N (Pinay et al., 2002; Beaulieu et al., 2015; Moore et al., 2017). However, multiple features of agricultural ditches may support a high mitigation potential towards N-NO_3^-: i) their being the first point of contact for diffuse and point N loads entering the hydrological network; ii) the occurrence of the three primary controls directly influencing occurrence and magnitude of denitrification, i.e. anoxic environment, availability of N-NO_3^- and organic carbon; iii) the tight terrestrial-aquatic coupling resulting from their extensive and capillary distribution across the landscape; iv) the high opportunity for N microbial processing due to long hydraulic residence time and large ratio between biological active surfaces and in-stream water volumes carrying excess nutrients; v) the shallow water depth that potentially supports the role of aquatic vegetation as "ecosystem engineer" in regulating biogeochemical processes and providing the development of denitrification hotspots, such as biofilms on submerged portions and oxic-anoxic niches in organic matter-rich sediments; vi) the frequent recirculation of water through the landscape, which maximizes the interaction among water and bioreactive surfaces, especially during spring and summer period when high water temperatures (up to >25 °C in temperate zones) enhance microbial processes (McClain et al., 2003; Hines, 2006; Marion et al., 2014; Soana et al., 2017). All the above-mentioned features make agricultural ditches and canals more similar to wetlands than to higher-order streams (Faust et al., 2018; Vymazal and Březinová, 2018).

Only a few attempts were made to assess the magnitude of catchment-scale denitrification in low-order waterways and drainage ditches, but modelling tools and geospatial approaches were often based on the up-scale of measurements of potential denitrification rates determined under optimal conditions of N-NO_3^- and organic carbon availability, not always reflecting the actual *in situ* activity (Oehler et al., 2009; Christopher et al., 2017; O'Brien et al., 2017). Moreover, the potential for water quality improvement exerted by vegetation in the ditch network has never been assessed at the watershed scale. In-stream vegetation is an important interface between croplands and surface water bodies, thus its presence and abundance are considered key elements in determining the potentiality of the canal network to provide ecosystem services in general (Bolpagni et al., 2013; Boerema et al., 2014; Dollinger et al., 2015), and water purification in particular, due to a complex synergistic action with bacterial communities (Pierobon et al., 2013; Taylor et al., 2015; Vymazal and Březinová, 2018). Nevertheless, aquatic vegetation is often considered only as a hindrance for water circulation by water management authorities, and thus regularly removed to preserve the hydraulic performance (Levavasseur et al., 2014).

The Po River catchment, the largest hydrographic system in Italy (652 km, >71,000 km^2, about a quarter of the national territory), is one of the most densely populated and agriculturally productive areas in Europe, but also a paradigmatic case study for N pollution, eutrophication and related implications for environmental policies (Viaroli et al., 2018; Martinelli et al., 2018). The plain zone (46,000 km^2), the largest Italian alluvial basin, is crossed by an extensive network of mostly artificial canals and ditches with irrigation, drainage, and flood control purposes. A comprehensive N budget has proven that the deltaic portion of the catchment, intensively cultivated and irrigated, acts as an effective N sink, buffering not only the N surplus leached from the croplands but also part of the N load generated by upstream agro-ecosystems and imported with drainage and irrigation water (Castaldelli et al., 2013). Multiple lines of evidences suggest that denitrification in vegetated ditches accounts for the majority of N losses during water transit through the hydrological network (Pierobon et al., 2013; Castaldelli et al., 2015; Soana et al., 2018).

Our hypothesis is that in highly hydraulic-regulated and simplified, agricultural watersheds, landscape management may deeply affect the balance between N sources and sinks and thus, at a widely variable