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Water management practices exacerbate nitrogen retention in Mediterranean catchments

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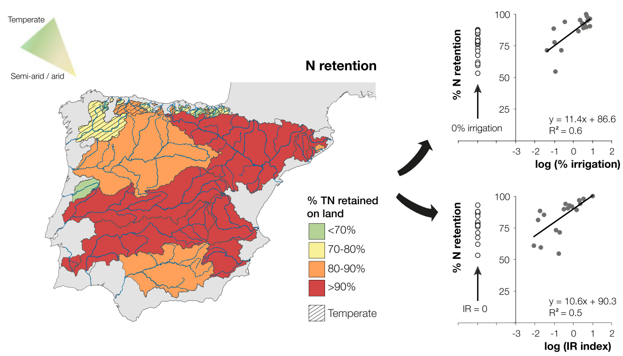
HIGHLIGHTS

- The study describes the fluxes and retention of N within 38 Iberian catchments.
- We compare the N fluxes in contrasting temperate and Mediterranean basins.
- We hypothesise that N retention is tightly related to water management practices.
- The numerous reservoirs and channels in semi-arid basins enhance retention values.
- Above a certain threshold of water regulation, N retention is consistently >85–90%.

GRAPHICAL ABSTRACT



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ABSTRACT

Nitrogen (N) retention *sensu lato* refers to all processes preventing new reactive nitrogen brought into watersheds through agricultural or industrial activities to be exported by river systems to the sea. Although such processes protect marine systems from the threat of eutrophication and anoxia, they raise other environmental issues, including the acidification of soils, the emission of ammonia and greenhouse gases, and the pollution of aquifers. Despite these implications, the factors involved in N retention are still poorly controlled, particularly in arid and semi-arid systems. The present study evaluates the N fluxes of 38 catchments in the Iberian Peninsula with contrasting climatic characteristics (temperate and Mediterranean), land uses, and water management practices. This diversity allows addressing the contribution of physical and socioecological factors in N retention, and more specifically, exploring the relation between N retention and water regulation. We hypothesise that the extreme flow regulation implemented in the Mediterranean enhances the high N retention values associated with arid and semi-arid regions. The results show that reservoirs and irrigation channels account for >50% of the variability in N retention values, and above a certain regulation threshold, N retention peaks to values >85–90%. Future climate projections forecast a decrease in rainfall and an increase in agricultural intensification and irrigation practices in many world regions, most notably in arid and semi-arid areas. Increased water demand will likely lead to greater flow regulation, and the situation in many areas may resemble that of Iberian Mediterranean catchments. High N retention and the associated environmental risks must therefore be considered and adequately addressed.

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1. Introduction

Nitrogen (N) is a key element for plant growth, and as such it plays a central role in the world's agricultural production and in the capacity of the planet to feed human populations (Sutton et al., 2011). Such a pivotal role sparked intense research on its sources and potential supply, and led to the discovery of the Haber-Bosch process in the early years of the 20th century. The Haber-Bosch process has allowed a great increase in crop yields worldwide (Smil, 2001; Erisman et al., 2008; Gruber and Galloway, 2008), but it has remarkably altered the N budget in most of the terrestrial and aquatic compartments involved, at one stage or another, in the N cycle (Galloway et al., 2003; Rockström et al., 2009).

Globally, the input of biologically available N to terrestrial ecosystems has more than doubled in the past century (Gruber and Galloway, 2008). The ecological significance of such an enormous increase is far-reaching and has been thoroughly reviewed in a number of studies (the European Nitrogen Assessment provides a comprehensive summary; Sutton et al., 2011). We here focus on one aspect of the complex biogeochemical cycle involved, i.e. the proportion of reactive N brought into watersheds through anthropogenic activities that is eliminated to the atmosphere or retained on land during its cascading travel through the soil, aquifers and river network before reaching the sea. Specifically, we account for the percentage of N that remains in the terrestrial and freshwater systems (herein considered 'N retention' *sensu lato*, as in Howarth et al., 1996), and the fraction that is conveyed to the marine compartment.

The proportion of N that is exported to the sea or accumulated/eliminated on land involves different environmental issues. Large amounts of N on terrestrial compartments are related to shifts in community structure and function, the acidification of soils and freshwater lakes, the emission of ammonia and greenhouse gases, and high nitrate concentrations in streams and aquifers (e.g. Henriksen and Brakke, 1988; Schulze, 1989; Crabtree and Bazzaz, 1993; Spalding and Exner, 1993; Bowman et al., 1995; Camargo and Alonso, 2006; Grizzetti et al., 2011). On the other hand, high exports of N to coastal waters can induce coastal eutrophication, harmful algal blooms and eventually episodes of anoxia (e.g. Nixon, 1995; Cloern, 2001; Beman et al., 2005; Howarth et al., 2011; Romero et al., 2013).

Despite these implications, the functioning of retention processes is still poorly controlled, particularly in arid and semi-arid regions. Retention may be related to climatic and hydrological features (Behrendt and Opitz, 2000; Howarth et al., 2006; Lepistö et al., 2006; Schaefer and Alber, 2007) or to socioecological factors such as land and water use (Caraco and Cole, 2001; Pacheco et al., 2015; Pacheco and Sanches Fernandes, 2016), and a number of general principles have been proposed at the global scale regarding the role of specific discharge and mean temperature (Billen et al., 2010). Yet, at smaller scales, the contribution of each factor remains largely uncharacterised.

River catchments in the Iberian Peninsula are particularly suitable to test the importance of physical and socio-ecological factors in the retention of N. First, Iberian catchments can be divided into two different groups with distinct climatological features: rivers in the north and the north-western façade present temperate climates, while in the east and mid-southern regions rivers present typical Mediterranean conditions. These contrasting physical characteristics are matched by different land uses and notably by different water management practices (Álvarez-Cabria et al., 2016), and thus allow an assessment of the various factors involved in retention and export processes. Second, partly as a result of the delayed implementation of monitoring networks, rivers in Southern Europe have been traditionally less studied than those in Northern European countries. This paucity of data is particularly pronounced in the Mediterranean regions, where stream flows are low and irregular, and they are very frequently omitted in large-scale studies. Third, arid and semi-arid regions represent a large fraction of the Earth's land, and they are predicted to increase as a consequence of global warming (IPCC, 2014). In many of these regions, as has occurred in semi-arid catchments of the Iberian Peninsula during the past few decades, intensification of agriculture and expansion of irrigation facilities are foreseen (water withdrawals for irrigation are projected to increase by 11% from 2005 to 2050; Bruinsma, 2009). Under these circumstances, better knowledge of what physical and human-related factors operate on the retention of N in Iberian watersheds may be very helpful to understand future N trends in many other world regions.

In a previous study, Lassaletta et al. (2012) discussed the relevance of land management and flow regulation for the fate of N within the Ebro River catchment (NE Spain). The study presented an overall N budget in the basin and detailed N calculations in different sub-catchments, and hypothesised that agricultural and water management practices had a major influence on N retention. The Ebro River is a case of extreme human intervention, with over 95% of the watershed area under some type of regulation (Liquete et al., 2005; Lorenzo-Lacruz et al., 2012). Far from being unusual, however, this situation is found in many other streams around the world. In the same vein, Törnqvist et al. (2015) addressed the influence of irrigated agriculture to the cycling and transport of N in the semi-arid Amu Daria River basin in Central Asia. These authors found that the water diversions, recirculation, and changes in flow-paths related to irrigation facilities deeply modified the river export of N. The role of reservoirs and ponds, another example of human intervention in river networks, was also found to be substantial in river nutrient delivery by Powers et al. (2015), particularly when reservoirs were located in agricultural landscapes.

This study aims to explore whether the relation observed between N retention and water flow regulation, and specifically the patterns described for the Ebro River by Lassaletta et al. (2012), hold for other rivers with similar features, and if the opposite is true in rivers with substantially different characteristics. To ease comparisons with Lassaletta et al. (2012), we assessed the fluxes of N by means of the Net Anthropogenic Nitrogen Input (NANI) approach (Howarth et al., 1996). The NANI accounts for four main reactive N input types, namely fertilisers, biological fixation, atmospheric deposition and the net import of food and feed. This can be easily calculated and underlines the importance of human activities, which is particularly convenient for our objectives.

The study reviews the N fluxes in 38 catchments of the Iberian Peninsula, accounting for all N inputs and outputs, and finally working out the export to the sea and the retention of N within the basins. We discuss differences in the retention of N in light of different hydrological features, agricultural practices, and water management strategies, and we discuss the singularities of Mediterranean (or broadly, semi-arid) versus temperate rivers and the need to consider these singularities when designing and planning effective N management measures.

2. Materials and methods

2.1. Land fluxes

We have selected 38 river basins situated in areas in a Mediterranean or temperate climate including enough information to estimate nutrient fluxes at the river mouth (2000–2010 period). To describe the N fluxes entering the territory, we used the NANI approach. The method has been successfully applied in a number of studies (Howarth et al., 1996; Billen et al., 2009a; Hong et al., 2013; Goyette et al., 2016), notably in the European Nitrogen Assessment (Sutton et al., 2011). The approach considers all the anthropogenic "new" N input fluxes associated with: (1) synthetic fertiliser application, (2) biological N fixation, (3) net atmospheric deposition and (4) net import of food and feed. The output flux comprises (5) the export of N at the outlet of the river.

Once all input and output fluxes have been computed, a retention value can be derived as the difference between total inputs and riverine outputs at the coastal zone. We are well aware that used in this way, the