High N retention in Mediterranean catchments enhanced by water management practices

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Abstract
The share of nitrogen (N) that is exported to the sea or accumulated on land (N retention, *sensu lato*) involves different environmental processes; coastal eutrophication and anoxia in the first case; the acidification of soils, the emission of ammonia and greenhouse gases, and the pollution of aquifers in the latter. Nevertheless, the factors involved in N retention are still poorly constrained, particularly in arid and semi-arid systems. The present study evaluates the N fluxes of 38 catchments on the Iberian Peninsula with contrasting climatic characteristics (temperate and Mediterranean), land uses, and water management practices. The contribution of physical and socio-ecological factors in the retention of N was partitioned, and the link between N retention and water regulation was explored. We hypothesize that the extreme flow regulation performed in the Mediterranean enhances the high N retention values associated with arid and semi-arid regions. Our 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, and notably in arid and semi-arid areas. Increased water demands will likely lead to a higher flow regulation, and the situation may resemble that of Mediterranean Iberian Peninsula catchments. High N retention and the associated environmental risks must therefore be considered as an important consequence of water regulation practices, and must be adequately managed.

Key Words
irrigation, Mediterranean climate, reservoirs, river basin, water regulation

Introduction

Globally, the input of biologically available nitrogen (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. Here we focus on one aspect of the complex biogeochemical cycle involved, i.e. the share of N retained on the terrestrial and freshwater systems (herein considered 'N retention' as in Howarth et al. 1996) versus the fraction that is conveyed to the marine compartment (N export). The proportion of N that is exported to the sea or accumulated on land involves different environmental processes. Large amounts of N in 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. On the other hand, high exports of N to coastal waters can induce coastal eutrophication, harmful algal blooms, and episodes of anoxia. Despite these implications, the functioning of retention processes is still poorly understood, particularly in arid and semi-arid regions. Retention may be linked to climatic features (e.g., Behrendt and Opitz 2000; Schaefer and Alber 2007) and to socio-ecological factors such as land and water use (Caraco and Cole 2001; Pacheco and Sanches Fernandes 2016), but the contribution of each factor remains 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 experience temperate climate, while in the east and mid-southern regions rivers present typical Mediterranean conditions. Contrasting climatic characteristics are matched by different land uses and water management practices. Second, rivers in southern Europe have been traditionally less studied than those in northern European countries. This paucity of data is particularly marked in the case of the Mediterranean region. 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 climate change (IPCC, 2014). In many of these arid and semi-arid regions, as has occurred in semi-arid catchments of the Iberian Peninsula during the past decades, an intensification of agriculture and the expansion of irrigation facilities are foreseen. Under those circumstances, better knowledge of what physical and human-related factors regulate the retention of N in Iberian watersheds may be very helpful to understand future N trends in many other regions of the world.

In a previous study, Lassaletta et al. (2012) assessed the fate of N within the Ebro River catchment (NE Spain) and hypothesized that water management practices had a major influence in N retention. The Ebro River is a case of extreme human intervention with over 95% of the watershed area under some type of regulation, but far from being unusual, 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 on the cycling and transport of N in a semi-arid basin in Central Asia. These authors found that water diversions and the high recirculation ratios related to irrigation facilities deeply modified the river export of N. The role of constructed reservoirs and ponds, particularly when they are located in agricultural landscapes, was also found to be substantial for river nutrient delivery by Powers et al. (2015).

Here we aim to explore the link observed between N retention and water flow regulation. The study estimates 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 climatic features and water management strategies, and we argue about the singularities of Mediterranean (or broadly, semi-arid) versus temperate rivers and the need to consider these singularities when planning effective N management measures.

Methods

N fluxes and retention

To describe the N fluxes entering the territory, we used the NANI approach (Howarth et al. 1996; Billen et al. 2011). The approach considers anthropogenic N input fluxes associated with: (1) synthetic fertilizer application (2) biological N fixation, (3) net atmospheric deposition, and (4) net import of food and feed. The methodology and data sources are similar (updated) to those presented in Lassaletta et al. (2012). The output flux comprises the export of N at the outlet of the river. The riverine export of N to coastal waters was calculated using data on river flow and water quality provided by several water authorities from Spain and Portugal. Annual N fluxes were obtained for the 2000-2010 period using flow-adjusted concentrations, following the methods described in Romero et al. (2013). To allow comparisons between catchments, all N fluxes were re-scaled per square kilometre dividing the flux by the area of the corresponding river basin. Once all input and output fluxes are computed, a retention value can be derived as the difference between total inputs and riverine outputs at the coastal zone. Used in this way, the term retention encompasses a fraction of N that may be removed by subsequent denitrification processes within the soil or freshwater compartments, and another fraction stored in the landscape as vegetal biomass or soil or sediment organic matter. River basins are assigned to two different groups (Mediterranean or temperate) depending on their corresponding climatic features.

Reservoirs and water regulation indices

We collected data on the number of dams and reservoirs per catchment, and their maximum (potential) and mean (live) water storage capacity, and we used these data to calculate the Impounded Runoff (IR) Index developed by Batalla et al. (2004). The IR is computed as the live storage capacity divided by the mean annual runoff of the river. Additionally, we calculated the Indirect Alteration (IA) Index presented by Belmar et al. (2013). The IA is a function of the percentage of irrigated land, the number of dams, and the regulatory capacity. The two indices are derived from variables associated with the main hydrologic pressures in the basin, and offer synthetic information on the degree of intervention in the watersheds.

Results

On average, the NANI for the whole peninsula is 3,121 kg $N \cdot km^{-2} \cdot y^{-1}$. NANI values on the Iberian Peninsula are very similar to those of other basins in the Mediterranean region (southern France, Italy, Greece), but significantly lower than those of central Europe, typically ranging 5,000-2,0000 kg $N \cdot km^{-2} \cdot y^{-1}$ (Billen et al. 2011). Average N fluxes per group of rivers are included in Table 1. Riverine export to coastal seas represents, for the whole Peninsula, only 9% of the total NANI inputs. Temperate basins present an average retention of 74%, in agreement with the 70-80% retention that is commonly specified in the literature (Howarth et al. 2006; Billen et al. 2011), while average retention in the Mediterranean is 92% (Table 1).

Table 1. Population (inhab·km^{-2}), N fluxes (kg N·km^{-2}·y^{-1}) and N retention (%) for the two groups of rivers (MED = Mediterranean, TEMP = temperate) and for all the Iberian catchments (*All*) in the study. Data are area-weighted averages.

	MED	TEMP	*All*
Population density	56	65	*57*
Synth. Fertilizers	2441	1199	*2360*
Biological N Fixation	340	786	*369*
Total Production	1582	1528	*1578*
Animal Feed Demand	1492	2580	*1563*
Human Food Demand	329	380	*332*
Net Import	239	1433	*317*

	MED	TEMP	*All*
NO_x Deposition	287	425	*296*
NH_3 Deposition	-222	-210	*-221*
Net Atm. N Deposition	65	215	*75*
NANI	3085	3632	*3121*
River export	242	941	*287*
Retention	92%	74%	*91%*

We used the IR index as a proxy for the impact of reservoirs and we plotted it against the percentage of retention in the catchments. Removing those rivers that did not have any reservoirs at all (IR=0), the two variables fitted well to a logarithmic relationship (Fig. 1). Interestingly, rivers with IR<0.5 showed a variable percentage of retention (53-89%), but all rivers with IR>0.5 presented retention values over 90%. We calculated the same relationship using the percentage of irrigated land (to account for the effect of irrigation channels), and obtained similar results: those catchments with at least 1% of irrigated surface systematically present retention values above 85% (Romero et al., 2016).

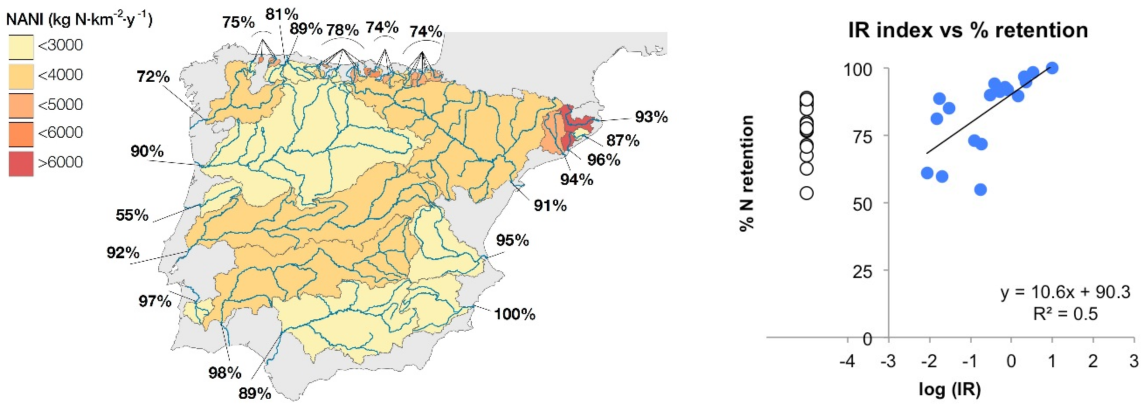

Figure 1. (left) Net anthropogenic N inputs in the 38 Iberian catchments, and the corresponding % N retention. The values at the top are averages for several rivers. (right) Percentage of retention in the watersheds versus the Impounded Runoff index (log IR). The white dots on the left represent the catchments without reservoirs (IR=0).

Discussion

Anthropogenic N inputs on the Iberian Peninsula, in either temperate or Mediterranean regions, are lower than the average values observed in most parts of Europe (Billen et al., 2011), but in contrast to other EU countries, the fluxes of N on the Iberian Peninsula have not stabilized over time. Atmospheric emissions and deposition of N oxides, for instance, have lately increased in Spain and Portugal (Fagerli and Aas 2008), and despite a reduction of the agricultural surface, the consumption of synthetic fertilizers and animal manure have increased during the past three decades, with only a recent stabilization (http://faostat.fao.org/; Lassaletta et al. 2012). High N retention values have serious implications in terms of N pollution of aquifers and freshwater streams, atmospheric emissions of greenhouse gases, and N accumulation in soils (e.g., Schulze 1995; Camargo and Alonso 2006; Grizzetti et al. 2011), and this is of particular concern in Mediterranean arid and semi-arid regions where freshwater is scarce and aquifers are a crucial resource.

Climatic differences between Mediterranean and temperate watersheds can only explain part of the divergence in the retention values. Temperatures in all Iberian basins are above the threshold of 10-12ºC considered as a breakpoint for the rate of denitrification (Schaefer and Alber 2007). Precipitation and runoff play a part, but we argue that their direct effects are much lower than their major indirect effect: a generalized flow regulation to manage water scarcity in Mediterranean basins. Flow regulation is intended to guarantee water supply for human and agricultural uses, and is performed through a dense network of dams and reservoirs, diversion canals for inter-basin water transfers and irrigation channels. Reservoirs, particularly those with a large storage capacity, can drastically increase the residence time of the water, favouring N assimilation by algae and denitrification processes within the sediments. Similarly, the ramification of flow paths caused by irrigation channels increases water residence time in the catchment and favours denitrification. Bartoli et al. (2012) suggested that the role of reservoirs and channels as N sinks in rivers where the flow is tightly regulated is essential, because the river no longer inundates the surrounding area and therefore natural denitrification spots such as riparian wetlands hardly operate.

The strong effect of reservoirs and irrigation channels stands out clearly in our results. The relationship between the Impounded Runoff Index and the % of N retention shows that when the regulatory capacity is limited, i.e. the storage capacity does not exceed the mean annual water yield and water stocked is effectively used on an annual cycle (IR<0.5), as occurs in temperate catchments, N retention is variable. In contrast, under multi-year regulatory strategies, i.e. the retention capacity exceeds the mean annual water yield (IR>0.5, and specially IR>1), N retention in the watershed is always >90%. Likewise, above a threshold of 1% of irrigated land, the retention in the catchments is >85%.

Conclusions

We believe the difference in N retention between temperate and Mediterranean catchments on the Iberian Peninsula is mostly related to water management practices, and notably to extreme flow regulation. Warm and dry conditions may favour higher denitrification rates in the Mediterranean, but this factor alone can hardly explain the large difference in retention. Our results show that reservoirs and irrigation channels account for >50% of the variability in N retention values. Further, above a certain flow regulation threshold, N retention peaks to values over 85-90%.

Future climate projections forecast a decrease in rainfall and increased evapotranspiration in many world regions, which will enhance water scarcity. Agricultural intensification and a net expansion of irrigation are also foreseen, particularly in arid and semi-arid systems (IPCC, 2014). Agricultural development entails an increase in N fertilizers, and the combination of increased water scarcity and higher water needs will certainly lead to flow regulation. The situation can therefore resemble the conditions observed in the Mediterranean catchments here studied, whose N dynamics were shown to be substantially affected by flow regulation infrastructures. High N retention and the environmental risks associated with it must be considered as an important consequence of water regulation practices, and must be adequately managed.

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