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A framework model for investigating the export of phosphorus to surface waters in forested watersheds: Implications to management

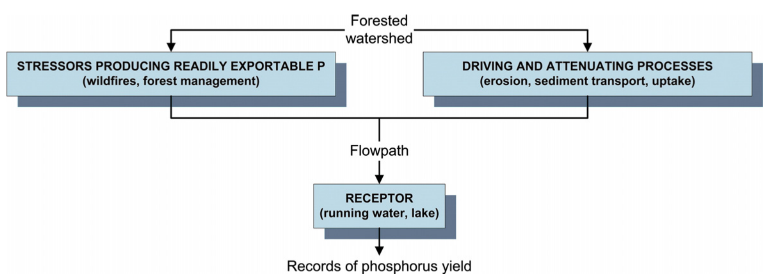
R.M.B. Santos [a], L.F. Sanches Fernandes [a,d], M.G. Pereira [a,b,e], R.M.V. Cortes [a,f], F.A.L. Pacheco [c,g,*]

[a] Centre for the Research and Technology of Agro-Environment and Biological Sciences, Vila Real, Portugal
[b] Dom Luiz Institute, University of Lisbon, Campo Grande, 1749-016 Lisbon, Portugal
[c] Chemistry Research Centre, Vila Real, Portugal
[d] Department of Engineering, University of Trás-os-Montes and Alto Douro (UTAD), Ap. 1013, 5001-801 Vila Real, Portugal
[e] Department of Physics, UTAD, Portugal
[f] Department of Forestry Sciences and Landscape Architecture, UTAD, Portugal
[g] Department of Geology, UTAD, Portugal

HIGHLIGHTS

- Framework model of phosphorus yields in forested watersheds
- Consequences of wildfires and forest management to the quality of surface water
- The role of lakes
- Rainfall intensity / pathway length promote leaching / retention of P in catchments
- Management measures to prevent eutrophication and comply with the WFD

GRAPHICAL ABSTRACT



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ABSTRACT

The present study was developed in four sub-basins of rivers Cávado and Douro, located in the North of mainland Portugal. The goal was to identify main stressors as well as driving and attenuating processes responsible for the presence of phosphorus in masses of surface water in those catchments. To accomplish the goal, the basins were selected where a quality station was present at the outlet, the forest occupation was greater than 75% and the phosphorus concentrations have repeatedly exceeded the threshold for the good ecological status in the period 2000–2006. Further, in two basins the quality station was installed in a lotic (free-flow water) environment whereas in the other two was placed in a lentic (dammed water) environment. The ArcMap GIS-based software package was used for the spatial analysis of stressors and processes. The yields of phosphorus vary widely across the studied basins, from 0.2–30 $kg \cdot ha^{-1} \cdot yr^{-1}$. The results point to post-fire soil erosion and hardwood clear cuttings as leading factors of phosphorus exports across the watersheds, with precipitation intensity being the key variable of erosion. However, yields can be attenuated by sediment deposition along the pathway from burned or managed areas to water masses. The observed high yields and concentrations of phosphorus in surface water encompass serious implications for water resources management in the basins, amplified in the lentic cases by potential release of phosphorus from lake sediments especially during the summer season. Therefore, a number of measures were proposed as regards wildfire combat, reduction of phosphorus exports after tree cuts, attenuation of soil erosion and improvement of riparian buffers, all with the purpose of preventing phosphorus concentrations to go beyond the regulatory good ecological status.

* Corresponding author.
E-mail address: fpacheco@utad.pt (F.A.L. Pacheco).

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1. Introduction

Land use changes in forested watersheds, namely those related to hardwood cuttings or wildfires, have been documented as factors responsible for hydrologic disturbances and degradation of water quality caused by excessive inputs of nutrients such as phosphorus (O'Driscoll et al., 2014; Shakesby, 2011; Smith et al., 2011; Tong and Chen, 2002). Phosphorus is considered the limiting factor of freshwater aquatic systems, because its availability in surface waters determines primary production and consequently eutrophication. The risk of eutrophication related to nutrient exports from harvested or burned areas is recognized (Blake et al., 2010; Ferreira et al., 2008; Hutton et al., 2008; Lane et al., 2008; Shakesby, 2011; Smith et al., 2011), as is the impact of eutrophication on aquatic species, especially on ecologically sensitive species like salmonids or freshwater pearl mussels (Correll, 1998; Santos et al., 2015a; Varandas et al., 2013). The concentrations of nutrients endanger the aquatic species whenever they exceed the thresholds for good ecological status. The risk of exceeding the limits can be amplified whenever land use changes correspond to land use conflicts (Pacheco et al., 2014; Valle Junior et al., 2014a, 2014b, 2015).

Tree cuts relate to the phosphorus problem because this nutrient may leach to surface waters in the course of organic matter decay, namely by decomposition of foliage and branches (brash), unwanted stems, stumps and dead roots (harvest residue), left on site after crop thinning or felling which are added to the soil at the same time that nutrient uptake is reduced (Hutton et al., 2008; O'Driscoll et al., 2014). To avoid this leakage, it has been defended the cut and removal of whole trees from the harvested site in a single operation (Nisbet et al., 1997; O'Driscoll et al., 2014). Whole tree removal is crucial because phosphorus concentrations in the foliage or brash are much higher than in the trunks (O'Driscoll et al., 2014). For example, in the study of a Sitka spruce forest Carey (1980) reported 46 kg $P \cdot ha^{-1}$ in foliage or branches and 14 kg $P \cdot ha^{-1}$ in the trunks. Similarly to harvesting, the burn of forest biomass also increases phosphorus concentrations at the soil surface, through total or partial combustion of litter and vegetation (Certini, 2005; Shakesby, 2011).

Regardless of the stressor, phosphorus will trigger eutrophication and threat the aquatic system, only if this nutrient reaches the water masses and stays there in a speciation easily utilized by primary producers, such as orthophosphate (Monbet et al., 2009). The phosphorus present in decayed organic matter or in ash is prone to erosive and transport processes that increase the potential leaching of phosphorus, either in the dissolved or particulate forms (Lane et al., 2008). It is therefore critical to relate the phosphorus dynamics at the watershed scale with the process of soil erosion and sediment transport between the source areas (harvested or burned areas) and the receptors (streams or lakes). The RUSLE equation (Revised Universal Soil Loss Equation; Renard et al., 1997; http://www.iwr.msu.edu/rusle/) summarizes the main factors controlling soil losses by sheet and rill erosion. Specifically, it takes into account the erosive impact of rainfall intensity, soil type, vegetation cover, length and slope of the hillside, and support practices like contoured plantation, stone wall sedimentation or buffer strips (e.g., riparian vegetation). Sediment transport is driven by the same factors, although combined in different formulae (Van Rompaey et al., 2001). A large number of studies demonstrated and quantified the impact o soil erosion and sediment transport in the quality of surface waters. Some of these studies reported the combined effects of hydric erosion and wildfires, making a note that the largest erosion rates and nutrient losses tend to occur during the first rainstorms after the occurrence of the fires (Andreu et al., 2001; Shakesby, 2011). In some other cases, researchers highlighted the dominant influence of rainfall intensity in the phosphorus concentrations of water masses, although considering the role of other variables (Rodríguez-Blanco et al., 2013; Sharpley et al., 2008; Udawatta et al., 2011).

Despite the large number of papers addressing phosphorus dynamics in forested watersheds, there have been just a few attempts to assemble all intervening stressors and driving processes into a common standpoint that fully explains phosphorus yields across these catchments (e.g., Hutton et al., 2008). This study is a contribution to fill in this gap. The model approach adopted for the present work sticks to a methodology based on the concept of "pressure-pathway-receptor", as proposed by the European Union (EU, 2003) to attain Water Framework Directive (2000/60/EC) objectives. Specifically, the objectives of this study are threefold: (i) to identify stressors in forested watersheds that explain the presence of phosphorus in bodies of surface water, as well as factors that control soil erosion/sediment transport and phosphorus losses in those catchments; (ii) to correlate phosphorus yields with the aforementioned stressors and factors; (iii) to propose mitigation measures that keep surface waters in forested watersheds at the highest quality level, especially by bringing phosphorus concentrations below the limits of good ecological status.

2. Materials and methods

2.1. Study area

The study area (Fig. 1) comprises four watersheds located in mountainous regions of northern Portugal, essentially occupied by forests (>75% coverage). Two watersheds (Vilarinho das Furnas as well as Paradela and Alto Cávado) are headwater sub-basins of River Cávado catchment, while the other two (Olo and Arda) are tributaries of River Douro catchment. The streams draining the River Cávado sub-basins were dammed in three places and the stored water is now being turbinated for generation of electric power. According to the National Water Inventory, available at http://geo.snirh.pt/AtlasAgua/, the watershed areas range from 58.4 km^2 (Vilarinho das Furnas) to 215 km^2 (Paradela and Alto Cávado). As regards annual rainfall, a great disparity is observed among the watersheds. The Cávado River sub-basins receive larger amounts of rainwater, with a maximum of 3123 $mm \cdot yr^{-1}$ in Vilarinho das Furnas. The lowest precipitation approached 1000 $mm \cdot yr^{-}$and has been recorded in the Arda. Apart from being the watershed with the largest annual rainfall, Vilarinho das Furnas is also the basin where precipitation is more intense, considering the number of days with precipitation >20 mm in this (219) and the other catchments (157, 150 and 134, respectively for Paradela and Alto Cávado, Olo and Arda). Maximum altitudes are persistently higher than 1000 m.a.s.l. in all watersheds, but altitude ranges vary among them, from a minimum of 839 m in the Paradela and Alto Cávado and a maximum of 1241 m in the Olo. The climatic and geomorphologic parameters of the four basins are summarized in Table 1, which also depicts a characterization for soil type and land use/occupation. As regards land use/occupation, the Corine Land Cover survey of 2000 (http://www.eea.europa.eu) shows all basins covered by more than 75% of forest and semi natural areas (cf. also Fig. 1). The dominant classes are scrub/herbaceous vegetation as well as open spaces with little vegetation. In the forested areas, the broad-leaved and mixed forests are predominant (Fig. 2). More specifically, the Vilarinho das Furnas is covered by 57% of open spaces with little vegetation plus small percentages of broad-leaved forest (15%) and scrub/herbaceous vegetation (18%). This later type of vegetation cover dominates in the Olo (37%) as well as in Paradela and Alto Cávado (42%), but the Olo has also a considerable coverage by coniferous forests (24%). Finally, the Arda is mostly occupied by broad-leaved (37%) and mixed (31%) forests.

Wildfires and forest management practices were responsible for variable landscape changes in the four watersheds, considering the timeframe 2000–2006 (Table 2 and Fig. 3). The River Douro sub-basins underwent larger alterations than the River Cávado sub-catchments. The Arda experienced the largest modification (16.1% of basin area), being followed by the Olo (8.9%), Paradela and Alto Cávado (2.6%), and Vilarinho das Furnas (1.2%). On average, wildfires accounted