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Review

Mercury sequestration by rainforests: The influence of microclimate and different successional stages

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HIGHLIGHTS

- Global climate change could increase mobilization of mercury to the atmosphere.
- Litterfall transfers mercury from the atmosphere to forest soils.
- Mercury in tropical forest soils and litter is 10 times higher than in temperate zones.
- Scenarios affecting the global mercury cycle must consider the role of tropical rainforests.

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ABSTRACT

Mercury (Hg) concentrations in tropical forest soils and litter are up to 10 times higher than those from temperate and boreal forests. The majority of Hg that has been stored in tropical soils, as the forest is left intact, could be trapped in deeper layers of soil and only small quantities are exported to water bodies. The quantitative approach to the Hg cycle in tropical forests is uncommon; the South America Atlantic Forest indeed is a hotspot for species conservation and also seems to be for the Hg's cycle. This study reports on a biannual dynamics of Hg through different species assemblage of different successional stages in this biome, based on 24 litter traps used to collect litterfall from 3 different successional stages under a rainforest located at Brazilian Southeast. The mean Hg litterfall flux obtained was 6.1 ± 0.15 μg ha^{-1} yr^{-1}, while the mean Hg concentration in litter was 57 ± 16 ng g^{-1} and the accumulation of Hg via litterfall flux was 34.6 ± 1.2 μg m^{-2} yr^{-1}. These inventories are close to those found for tropical areas in the Amazon, but they were lower than those assessed for Atlantic Forest biome studies. These low concentrations are related to the remoteness of the area from pollution sources and probably to the climatic limitation, due to the altitude effects over the forest's eco-physiology. The mercury fluxes found in each different successional stage, correlated with time variations of global radiation, suggesting a mandatory role of the forest primary production over Hg deposition to the soil.

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1. Introduction

Brazil holds two of the most important forested biomes on Earth, the Amazon and the Mata Atlântica forests. The later biome is considered a hotspot because of the combination of high biodiversity and continuous loss of territory (Myers et al., 2000). The fate of tropical forests in Brazil and elsewhere is highly important because they are efficient carriers of chemical compounds among different biosphere reservoirs (Malhi and Phillips, 2004). Additionally, when their high potential for nutrient losses is considered (Jordan et al., 1980), biogeochemical cycles play a crucial role for the maintenance of forest's homeostasis. The larger leaf surface area of tropical forests is a key step to their nutrient cycles, since it facilitates the adsorption of several substances, linking atmosphere and soil compartments through various processes, such as the uptake and sinking of CO_2 (Waring and Running, 2007) and other gases, unfortunately among them, atmospheric pollutants.

The faster dynamic found in the tropics, due to high temperature, rainfall and solar radiation, is an evidence of the important role played by these ecosystems in recycling elements at local, regional and global scales (Larcher, 2000). The incorporation of trace elements by plants such as Rb, Sc, Sr, As, Br, Cd, Cr, Hg, Sb and lanthanides supports this connection even if the element is not an essential plant nutrient (Aidid, 1988). In recent decades a growing body of literature has shown the damage to the biota caused by the association of Hg to organic matter and forests' structure and functioning may play a key role in this association (Roulet et al., 1998). With a well-known trophic biomagnification and worldwide distribution, Hg is considered a global pollutant (Schroeder and Munthe, 1998) with severe legal restrictions to its use in many countries as indicated by UNEP in the Minamata convention (Schroeder and Munthe, 1998).

In the Brazilian Amazon Basin, for example, local people and top predators show high Hg concentrations in muscle, blood, hair, and feathers (Malm et al., 1990). The contamination of humans and other living organisms by Hg may not be related just to past or present anthropogenic sources such as colonial and present day gold mining and others economic activities (Nriagu et al., 1992; Bastos et al., 2006), but it may be associated with the remobilization of deposited Hg from natural and anthropogenic by the natural cycling processes of elements within the forest (Lacerda et al., 2012). High Hg concentrations have been found in tropical soils, even in the most remote areas. Reported values can reach up to 400 ng g^{-1} in French Guyana and in parts of the Brazilian Amazon and have been associated with the typical paedogenesis of these tropical soils (Lechler et al., 2000; Roulet et al., 1998; Oliveira et al., 2001). However, the difference between the concentrations of Hg in the upper (<20 cm) and in deeper (>30 cm) layers of soil provides evidences of an additional atmospheric contribution (Oliveira et al., 2001). Measurements made since the beginning of the Industrial Revolution indicate that this additional Hg load from atmospheric deposition has increased continuously and is positively correlated with human activities, even when tropical regions are considered (Hylander and Meili, 2003; Lacerda and Ribeiro, 2004; Fiorentino et al., 2011; Pérez-Rodríguez et al., 2015; Chakraborty et al., 2016). Following atmospheric deposition, the Hg stocked in tropical soils has three possible fates: 1. immobilization in soils (mainly in deeper layers); 2. re-emission to the atmosphere, especially during forest burn or volatilization (mainly after the exposition of the soil surface due to the suppression of the forest (Almeida et al., 2009), and 3. leaching from the soil profile.

In forested areas, Hg air-soil deposition occurs through dry and wet precipitation, and/or by throughfall and litterfall. Wet deposition by rain and throughfall resultant from leaves rain-wash is responsible for removing approximately one quarter of all Hg captured by the canopy (Rea, 1999). The larger proportion interacts with leaves and epiphylls and can be incorporated by stomata. In Eco chambers experiments used to measure exchange of Hg concentrations under light and dark conditions, Stamenkovic and Gustin (2009) suggested that the nonstomatal pathway (epidermal entrance) might also be an important route of foliar accumulation of atmospheric Hg. Although it is not yet well defined whether the Hg in litterfall direct correlates with the *in situ* atmospheric Hg concentration (Hanson et al., 1995), there is a consensus that litterfall is the most important mechanism of Hg transfer from the canopy to forest soils (Frescholtz et al., 2009; Grigal, 2002). Studies in the Brazilian Atlantic Rain Forest has shown considerably higher Hg concentrations in litterfall when compared to Amazon forests (Oliveira et al., 2005; Silva-Filho et al., 2006; Teixeira et al., 2012) and even higher than temperate and boreal forests (Grigal, 2002). Specific surveys in leaves from ten different tropical trees show that Hg concentration can vary up to six times, depending on the species. Methodological differences have been dismissed as the cause of such variations (França et al., 2004). Different authors (Ericksen et al., 2003; Frescholtz et al., 2009; Silva-Filho et al., 2006) suggest these differences are caused by different variables such as leaf area, lifetime; foliar trichomes; leaf epicuticular waxes; stomatal density, and roughness, which may lead to different photosynthetic activity and absorption/adsorption processes.

This work contributes to a better understanding of the Hg biogeochemical cycle in tropical forests by providing new data on Hg concentrations in litterfall and the respective fluxes in the Brazilian Atlantic Forest from three different successional stages using canopy closure as the classification parameter. In the same site, physicochemical and biological data were collected to test the relationship of the forest's heterogeneity and the ecophysiological attributes of the canopy with Hg cycling. Simultaneously, micrometeorological data were recorded during two years to infer more precisely about the local environment.

2. Materials and methods

2.1. Site description

The area of study is located at the Serra da Mantiqueira, a mountain range located in Southeastern Brazil, among the three most industrialized Brazilian states: Minas Gerais, Rio de Janeiro and São Paulo. The study sites are located inside the Itatiaia National Park at an altitude of 2000 m (Fig. 1). The dominant ecotype found in the area is the evergreen *mountain rainforest*. Three successional stages were selected for data gathering conducted over