



The role of sediments in the carbon and pollutant cycles in aquatic ecosystems

O papel dos sedimentos nos ciclos de carbono e poluentes em ecossistemas aquáticos

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Abstract: Aim: Anthropogenic modifications in the landscape are accelerating biogeochemical cycles and causing unbalances in terrestrial and aquatic ecosystems with still unknown impacts on biotic and abiotic processes. Therefore, there has been increasing scientific interest in the links between human activities and ecosystems functions. **Methods:** Here we review the role of aquatic sediments in the carbon and pollutant cycle. **Results:** We briefly explore the historical context, origin, and composition of the sediments, as well as the factors that influence the processes of carbon and contaminants cycling and the role of sediments in the greenhouse gases emissions in aquatic ecosystems. **Conclusions:** Aquatic sediments can help to understand the terrestrial and aquatic ecosystem changes, once they are good sentinels, reflecting key biogeochemical processes over time.

Keywords: biogeochemical cycles; freshwater sediments; organic carbon mineralization; contaminants; anthropogenic activities.

Resumo: Objetivo: Modificações antrópicas na paisagem estão acelerando os ciclos biogeoquímicos e promovendo desbalanços entre ecossistemas terrestres e aquáticos de maneira sem precedentes, com impactos ainda desconhecidos nos processos bióticos e abióticos. Desta forma, é crescente o interesse científico nas relações entre atividades humanas e funções ecossistêmicas. **Métodos:** Neste trabalho, foi realizada uma revisão do papel dos sedimentos aquáticos nos ciclos do carbono e de poluentes. **Resultados:** Neste trabalho exploramos brevemente o contexto histórico, a origem e composição dos sedimentos, bem como os fatores que influenciam os processos de ciclagem do carbono e dos contaminantes, e o papel dos sedimentos nas emissões de gases de efeito estufa em ecossistemas aquáticos. **Conclusões:** Sedimentos aquáticos podem ajudar a compreender as mudanças nos ecossistemas terrestres e aquáticos, uma vez que são considerados bons sentinelas, capazes de refletir processos biogeoquímicos chave ao longo do tempo.

Palavras-chave: ciclos biogeoquímicos; sedimentos de água doce; mineralização do carbono orgânico; contaminantes; atividade antrópica.



1. Introduction

Sediments are crucial for environmental research due to its relationship with eutrophication processes, chemical pollution, sedimentation and silting in aquatic ecosystems (Forsberg, 1989). These issues have become increasingly recurrent, especially in large urban centers and rural areas, and affect both natural (*e.g.*, streams, rivers, ponds and lakes), and artificial systems (*e.g.*, reservoirs for water supply and hydropower generation) (Apitz, 2012). These problems are challenging because they involve not only aquatic ecosystems, but also the processes that occur in the drainage basin scale. On the other hand, this situation shows the need for suitable solutions and alternatives for the management of aquatic systems, avoiding and minimizing the impacts at spatial and temporal scales. In order to better understand the processes taking place in the aquatic sediments, the following topics will be briefly discussed: the historical context, origin, and composition of the sediments, as well as the factors that influence the processes of organic matter in this compartment; the contributions of the sediments for CH₄ and CO₂ emissions to the atmosphere and their importance in natural and artificial environment transformations; and the importance of sediments in terms of aquatic ecosystems pollution. Lastly, some final considerations and perspectives for future studies will be presented.

2. Aquatic Sediments: a Brief Historical Context

Sediments of aquatic ecosystems have been studied for many years to characterize their properties for physical, chemical, biological, geological and cultural purposes (Apitz, 2012). Many analytical methods used for sediments have been adapted from soil and mineral exploration studies (Mudroch & Macknight, 1994). In the beginning, the absence of adequate methods and equipment was a limiting factor for its systematic study, which only became effective after the invention of dredgers and profile collectors. Historically, sediment investigations for limnological purposes only began in 19th century in order to better understand the matter and energy flows in aquatic ecosystems (Mudroch et al., 1996). The first study involving aquatic sediments date back to the 1862. It was performed by Hampus von Post and was focused on describing the characteristics of Swedish lakes sediments (Von Post, 1862). Later on, in the 20th century, Naumann described the metabolism in the sediments of temperate lakes

(Naumann, 1930), while Hummel performed the first investigations in the tropics, describing biogeochemical processes in the sediments of Indonesian lakes (Hummel, 1931). Currently, sediments are part of an important scenario of environmental issues related to greenhouse gas (GHG) emissions, the degradation of water resources, such as eutrophication, chemical pollution and silting processes, and their role in the carbon cycle at regional and global scales (Apitz, 2012).

3. Origin and Composition of Aquatic Sediments

Sediments are essentially unconsolidated materials, products of modification of rocks, soils, and organic matter that have undergone weathering, transportation, transformation and deposition near the Earth's surface or in water bodies (Figure 1). Depending on their origin, sediments may contain particles of different sizes, shapes, mineral and chemical compositions (Mudroch & Macknight, 1994). When they are transported to aquatic ecosystems, by runoff, these particles settle in a differentiated way according to their nature. Generally, the coarsest material, such as sands (> 62.5 µm – < 2 mm) and pebbles (> 4 mm – < 64 mm), settle near the banks of lakes and in river gutters. Thinner particles, such as silts (3.9 – 62.5 µm) and clay (< 3.9 µm), lodge themselves in deeper, lower-flow areas such as lake bottoms. Over time, this material tends to accumulate in the systems in proportions ranging from a few millimeters to many centimeters per year (Mudroch et al., 1996).

When sediments begin to integrate the aquatic ecosystems, they also interact with the biota and provide habitat and substrate for a wide variety of organisms. It is estimated that sediments of freshwater ecosystems (*e.g.*, lakes, rivers, groundwater, and floodplains) shelter around 100,000 species of macroinvertebrates, 10,000 species of algae and more than 20,000 species of protozoa and bacteria (Palmer et al., 1997, 2000). These organisms, in turn, contribute to the sediment degradation, which, contain many organic and inorganic substances that will later be available to sediments and water column, subsidizing the trophic chains of aquatic ecosystems (Fenchel et al., 2012). Over time, sediments also receive contributions from allochthonous materials, mainly composed of terrestrial material originating from the drainage basin, which is transported by effluents and rainwater; and autochthonous species, composed of

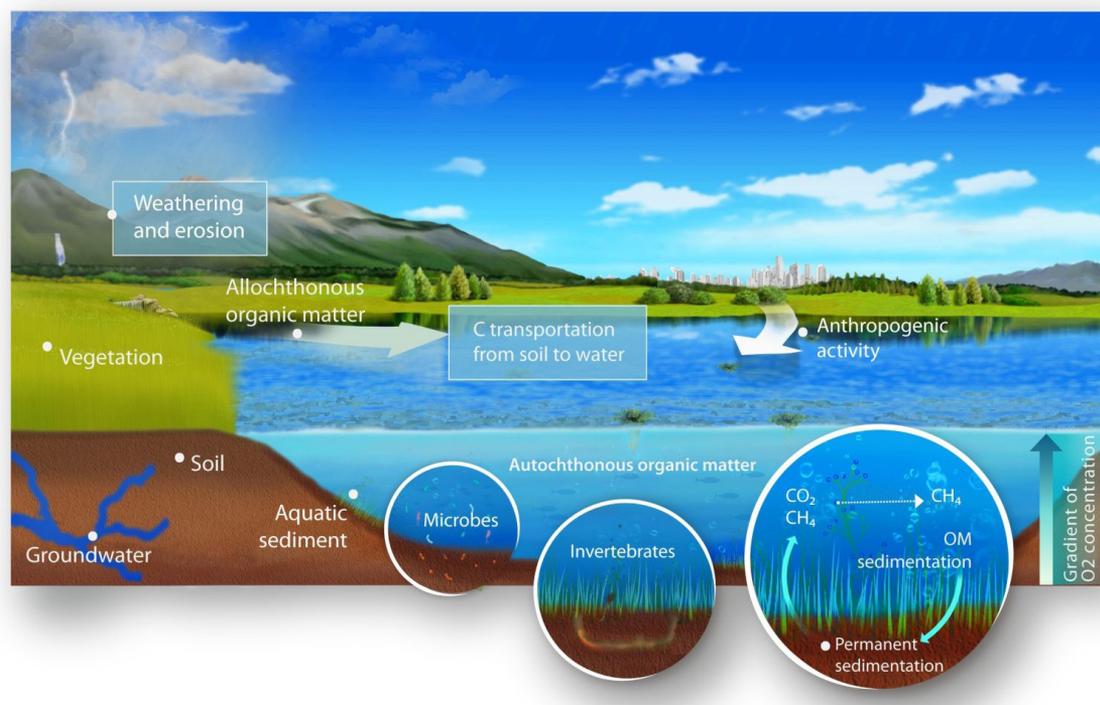


Figure 1. In the landscape, sediments are formed by unconsolidated materials, products of alteration of rocks, soils, and organic matter that have undergone weathering, transportation, transformation and deposition in terrestrial and aquatic ecosystems. Aquatic sediments can receive large amounts of allochthonous organic matter, mainly composed of terrestrial materials; and autochthonous organic matter, composed of algae, plants, and other animals originating from the aquatic environment itself. Once in the sediments, the organic matter of different origins and forms, can present three main destinations: 1 - be mineralized by microorganisms and invertebrates in the sediments and then returned to the water column as CO_2 and CH_4 ; 2 - to undergo resuspension of the sediments and to be mineralized in the water column; or 3 - be permanently sedimented, functioning as a carbon stock in the sediments. All these factors also depend on external factors such as morphological characteristics, hydrological conditions and water residence time in aquatic ecosystems, as well as anthropogenic activities.

algae, plants and other aquatic animals originating from the system itself (Figure 1).

As in the water column, the sediments also have a vertical zoning. In the vast majority of aquatic ecosystems, they are structurally formed by two main layers: i) superficial layer, also called a recent or biological layer; and ii) deep layer, also called permanent layer. The surface layer is in direct contact with the water column. It usually has only a few millimeters to centimeters, where oxygen and a greater amount of organic matter, nutrients, and benthic organisms are present, and therefore, it is considered the biologically active layer. The main processes of organic matter degradation mediated by the biota in the sediments are: resuspension, bioturbation and fractionation (benthic macroinvertebrates), photosynthesis (cyanobacteria, algae, and aquatic plants – when light is available), and decomposition (fungi and bacteria); besides the transformation by the biota,

chemical and physical processes may also take place, such as ionic dissociation and diffusion (Forsberg, 1989). In the deep layer, sediments are more compact, where conditions of anoxia prevail. In this layer, the processes of ions solubilization are more frequent; there is a low content of organic matter and few organisms that are composed mainly of anaerobic bacteria and fungi (Fenchel et al., 2012).

4. Organic Matter Mineralization in Aquatic Sediments

Mineralization is the process of converting organic matter into inorganic matter, generating soluble compounds, gases, and energy (Magonigal et al., 2005). It is essential to sustain life, as it promotes the cycling of matter and energy in ecosystems. In aquatic sediments, mineralization is a complex process mediated by several factors such as: quantity and quality of organic matter reaching the sediments, availability of electron

acceptors (*e.g.* oxygen, nitrate, iron, manganese and sulfate), structural characteristics of sediments (granulometry, water content, porosity, density), trophic conditions of the system, depth and mixing regime of the water column, temperature, pH, concentrations of inorganic carbon and biota (Forsberg, 1989; Fenchel et al., 2012). The following is an overview of each of these processes.

4.1. Quantity and the quality of the organic matter

In aquatic ecosystems, sediment receive large amounts of autochthonous organic matter (OM) (from the Greek: auto {self} + khthon {earth}), composed of algae, plants, and other animals originating from the aquatic environment itself; and allochthonous (from the Greek: allos {others} + khthon {earth}), composed of terrestrial material. OM can also present two essential forms: particulate organic matter (POM) and dissolved organic matter (DOM). The organic matter present in aquatic ecosystems is mostly composed of proteins, lipids, carbohydrates, humic substances (*e.g.*, humic and fulvic acids), plant tissues (rich in cellulose and hemicellulose) and animals, and other acids of different molecular weights (Benner, 2003). Generally, POM is composed of refractory materials, derived from the decomposition of aquatic macrophytes and lignocellulosic terrestrial residues; while DOM, besides being also refractory (Mayorga et al., 2005; Guillemette & Del Giorgio, 2011), has more labile and soluble materials such as colloids and humic substances (Killops & Killops, 2005). This OM can undergo transformations along the water column of the aquatic environments, and once in the sediments, this OM of different origins and forms, can present three main destinations: 1 - be mineralized by microorganisms in the sediments and then returned to the water column as CO₂ and CH₄; 2 - undergo resuspension of the sediments and to be mineralized in the water column; or 3 - be permanently sedimented, functioning as a carbon stock in the sediments (Cardoso et al., 2013, Mendonça et al., 2016). The relative importance of each of these processes is system-specific and can influence its role as a sink or source of carbon to the atmosphere (Mendonça et al., 2012a).

The quantity and quality of OM that reaches the sediments results from a range of factors, such as the relative contribution of autochthonous sources (organic matter from primary production, usually more labile and easily degraded) and allochthons sources (terrestrial organic matter, more refractory

and of slower degradation). It is also a result of the processes that occur in the water column, such as the partial mineralization of organic matter by aquatic microorganisms (Cole, 1999), and photodegradation (Bertilsson & Tranvik 2000, von Wachenfeldt & Tranvik, 2008; Farjalla et al., 2009). It is important to highlight that all these factors, and consequently the quantity and quality of OM, are closely related to the hydrology of the systems, a strong driving factor controlling the runoff of terrestrial material and transformation in the OM, as well as the transformations that occur in their drainage basin (Aitkenhead et al., 1999).

4.2. Availability of electron acceptors

After undergoing transformations in the water column and reaching the sediments, the OM is degraded by several redox reactions. These reactions release decreasing amounts of energy, ranging from more oxidative (greater release of energy) to less oxidative (less release of energy), and take into account the availability of the electron acceptors in the system (Fenchel et al., 2012). In the superficial layer, the oxygen reduction reactions (aerobic respiration) prevail, until the oxygen is exhausted. Subsequently, reactions of nitrate reduction (nitrification), manganese reduction, iron reduction, sulfate reduction and methanogenesis occur. After the reactions, the final products of anaerobic mineralization (CH₄, HS⁻, Fe²⁺, Mn²⁺) can dilute and diffuse in the water column or diffuse into the upper layer of the sediment where they can be reoxidized by different types of bacteria. In general, electron acceptors do not have homogeneous distribution in the systems and are also closely related to the origins and formation of aquatic sediments.

4.3. Structural characteristics of the sediments – granulometry, water content, porosity and density

In the sediments there are many grading scales of particles, or grains, which range from clay (< 3.9 µm) to gravel or boulders (> 256 mm) (Mudroch & Macknight, 1994). The grain size is an important ecological characteristic, once it is related to the substrate complexity and benthic community distribution (Strayer et al., 1997). Further, the quantification of the different particle sizes (*i.e.*, granulometry) of sediment gives us information about its origin and biogeochemistry. More clayey sediments, for example, have a great capacity for ionic exchange and, therefore, play a fundamental role as chemical regulators

in the sediments and in the water body, directly influencing the nutrient concentrations and organic matter mineralization processes (Mudroch & Macknight, 1994).

Aquatic sediments have a great variety of size, geometric forms and chemical compositions (Mudroch & Macknight, 1994). In these systems, sediments tend to form aggregates, which are a combination of minerals, organic matter, air, water and microorganisms. In sediment aggregates, there are also voids between particles, which are called pores. They can be occupied by both water and air. In sediment aggregates, the interstitial water that occupies the pores of the sediments acts as a solubilizing fluid for several ions and salts, which are essential for the occurrence of many chemical reactions and the existence and performance of microorganisms. Also, this pore water can have significant amounts of soluble CO_2 and CH_4 (Mendonça et al., 2016; Van Dijk et al., 2016), which can potentially contribute to carbon diffusion to the water column (Van Dijk et al., 2016; Aben et al., 2017; Call et al., 2018). In addition to water, these aggregates can also have spaces occupied by gases (air) such as O_2 , an important electron acceptor that is poorly soluble in water (Fenchel et al., 2012). The density of pores in the sediment particles is also important. Sediments particles with fewer pores (more compact), for example, tend to be denser and to sediment more rapidly in water bodies, while those with more pores tend to remain suspended in the water column for longer periods.

4.4. Nutrient cycling and trophic conditions of the aquatic system

Organic and inorganic nutrients, among them, mainly carbon, nitrogen, and phosphorus, are almost continuously transported to aquatic ecosystems and later to sediments through sedimentation (Forsberg, 1989). Upon reaching the sediments, these nutrients can be readily transformed by chemical, physical and biological processes and made available to sediments and water column, or they can be immobilized (stored) in the sediments, which occurs, especially when sedimentation rates are higher than transformation rates (Mudroch & Macknight, 1994). This nutrient cycling is also dependent on external factors such as morphological characteristics, hydrological conditions and water residence time in aquatic ecosystems, as well as the relative contributions of different allochthonous and autochthonous sources of nutrients to sediments (Esteves, 2011).

The trophic conditions of aquatic ecosystems, in turn, are governed by the availability of these nutrients and influence directly the mineralization rates of organic matter in sediments (Fenchel et al., 2012). In sediments of oligotrophic ecosystems, for example, there is a lower primary production, which is mainly maintained by benthic algae. Due to these factors, more oxygen arrives and remains in the sediments, since it is not fully consumed in the water column, thus favoring aerobic mineralization processes (more energetic) in the sediments. However, because nutrients are also limiting for microorganisms, although there is more oxygen available to the sediments, mineralization rates may not be higher. On the other hand, in more eutrophic systems, where more nutrients are available, primary production is high, which is mainly maintained by macroalgae and phytoplankton. These organisms and others such as fish, invertebrates and zooplankton, in turn, use part of the nutrients and oxygen still in the water column limiting its reach in the sediments. With less oxygen reaching the sediments, there is a limitation of the more energetic mineralization processes (aerobic) and other organisms and electron acceptors, other than oxygen, begin to act in the process of mineralization of organic matter in the sediments, but with a lower energy balance. Because the anoxic condition prevails, production and emission of GHG gases, mainly CH_4 , become possible, once methane is only formed in the anoxic conditions. In turn, it has a global warming potential of almost 30 times higher than CO_2 .

4.5. Depth and mixing regime of the water column

The depth of aquatic ecosystems is also an essential factor for the organic matter mineralization in sediments. Deeper systems tend to have low mixing regimes (few water column mixing events throughout the year) and thermal and chemical stratification conditions during most of the year (Kalff, 2001). The thermal and chemical stratification of the water column may promote conditions of low temperatures and anoxia in hypolimnion and sediments. However, some studies have shown long lasting high temperatures in the sediments of some Amazonian lakes (Sanders et al., 2018). These conditions affect the organic matter mineralization rates, making them, in most cases, slower due to lower temperatures (Gudasz et al., 2010), and less energy efficiency due to anoxia conditions (Megonigal et al., 2005). Furthermore, a greater depth of the water column

means more chance that the organic matter will be partially or totally degraded by the organisms in the water column, which means before reaching the sediments. Shallow systems, on the other hand, mix many times a year, mainly due to their morphometrics and climatic conditions such as wind and precipitation. In these systems, the sedimentation rate tends to be lower, and the oxygenation of the sediments is constant. These conditions allow the arrival of organic matter in greater quantities and qualities (less degraded) in the sediments. More oxygenated sediments, in turn, favor the occurrence of mineralization processes with higher energy efficiency (aerobic processes).

4.6. Temperature

The temperature modulates many chemical and biological processes in ecosystems, including organic matter degradation processes (Kirschbaum, 2006; Fenchel et al., 2012) and metabolism of aquatic organisms (Yvon-Durocher et al., 2010). Recent studies have shown that elevations in temperature increase the organic matter mineralization rates in aquatic sediments of different tropical (Cardoso et al., 2014; Marotta et al., 2014) and temperate regions (Gudasz et al., 2010). It is also important to note that other factors such as nutrients and electron acceptors availability in the sediments can act synergistically with the temperature in the control of organic matter mineralization rates (Cardoso et al., 2014). In general, given a global warming scenario, this effect can have significant consequences for the carbon cycle at different scales, as more carbon would be available to the atmosphere than would be permanently stored in the sediments of the ecosystems (Gudasz et al., 2010; Sobek et al., 2011).

4.7. pH and inorganic carbon concentrations

pH is defined as the negative logarithm of the hydrogen ion concentration. Its scale varies between 0 and 14 and indicates acidity (between 0 and 7), neutral (7) or alkalinity (between 7 and 14) (Esteves, 2011). pH influences several chemical processes that occur in the water column and sediments, and its accurate measurement can provide valuable information about the biogeochemistry of the systems. pH variations, for example, may interfere in the concentrations of the different forms of inorganic carbon in the water column and sediments, which are CO_2 , H_2CO_3 , HCO_3^- , and CO_3^{2-} (Esteves, 2011). These different forms of inorganic carbon, in turn, are very important because they are buffer

substances, responsible for stabilizing sudden pH changes in the system. Furthermore, they determine the amount of inorganic carbon available for photosynthesis, provide a great binding capacity of ion connection HCO_3^- e CO_3^{2-} , and remove inorganic carbon from the water column through the precipitation of CaCO_3 aggregates (Kalf, 2001). In turn, it may influence the organic matter mineralization processes, sedimenting the final products of the redox reactions and avoiding their release into the water column and atmosphere (e.g., CO_2 ; Cole, 2013).

4.8. Biota

Most organic matter mineralization occurs in the first 10 cm of sediment (Forsberg, 1989). This depth is composed of recent material and is, in most of the cases, the limit at which sediments can be altered by disturbances and mixing processes in the water column in shallow ecosystems, however variation may exist (Wetzel, 1983). This superficial layer is also considered as the most active layer due to the presence of benthic organisms. In relatively shallow systems with little suspended material in the water, the intense photosynthetic activity can also occur in the first mm to cm of sediment. This activity is mainly carried out by cyanobacteria, benthic algae and macrophytes (phytobenthos). Because of their photosynthetic activity, these organisms can promote diurnal changes in O_2 e CO_2 concentrations in the sediments and contribute to the partial diffusion of these gases to the water column (Fenchel et al., 2012).

Besides the primary producers found in this first centimeters of sediment, there are also some groups of protozoa, fungi, and viruses, which also help in the organic matter decomposition. Although their existence has already been mentioned in some studies, their ecological roles in the trophic sediment chains are still not well known (Fenchel et al., 2012). Benthic invertebrates, which use the sediment as a substrate and food, are on the surface and deeper layers of the sediments. They assist mainly in the mechanical degradation of organic matter, through the breaking of particles by mastication and digestion, as well as through the oxygenation of deeper layers of sediments through the tunnels they create by moving around. This as a great impact in the cycle of GHG gases, mainly methane, once this gas can be oxidized due to the oxygenation made by invertebrates when creating the tunnels. This process, in turn, may affect the concentrations of CO_2 in the sediments, as CO_2 is the product of the CH_4 oxidation process.

The most active and important community for the organic matter mineralization process along the entire sediment profile is the microbial community (Forsberg, 1989). It is a complex community with some microorganisms that exceeds many orders of magnitude ($> 10^9 \text{ cm}^{-3}$) the density found in the water column. It is composed of several groups with distinct functions and essentially heterotrophic activities (Fenchel et al., 2012). These organisms can perform the synthesis (chemosynthesis) and organic matter mineralization through respiration, denitrification, sulfate reduction, methanogenesis, and fermentation, which vary in their occurrence and intensity depending on the chemical and physical characteristics of the sediments. These processes, except for the sulfide and sulfate oxidation and nitrification processes, involve changes (consumption and production) in CO_2 concentration which, in turn, is potentially diffused to the water column.

5. Contribution of Sediment to CH_4 and CO_2 Emissions from Aquatic Ecosystems

In the landscape, carbon is transported in two main directions: laterally through an aquatic continuum towards the oceans, and vertically through gas exchange with the atmosphere (photosynthesis and respiration, in the case of CO_2), with permanent accumulation in soils and sediments (Regnier et al., 2013). Recent estimates calculate that freshwater ecosystems, on a global scale, receive about 5.1 Pg C annually from the drainage basin (Drake et al., 2018); of these, a portion returns to the atmosphere in the forms of CH_4 and CO_2 (ca. 3.88 Pg C) (Sawakuchi et al., 2017), another portion is retained in the sediments (ca. 0.6 Pg) (Battin et al., 2009), photosynthesis (ca. 0.3) and 0.95 Pg C returns to the oceans (Cole et al., 2007; Regnier et al. 2013).

However, these estimates can be conservative, since they consider the sediments only as carbon reservoirs, neglecting their important role in the flows (essentially CO_2) for the water column and atmosphere through the biogeochemical processes of organic matter mineralization (Battin et al., 2009). Mendonça and colleagues estimate a yearly OC burial of 0.15 (range, 0.06–0.25) Pg C in inland waters. However, the estimations are still very imprecise, mainly because the processes that lead to the organic matter mineralization in the water column and the sediments can vary spatially and temporally (Battin et al., 2009; Tranvik et al., 2009) and are also dependent on

many local factors, as discussed in previous sections of this manuscript (e.g. quantity and quality of organic matter, electron acceptors availability, structural characteristics of sediments, trophic conditions of the system, etc.). Furthermore, the carbon fractions that are emitted to the atmosphere and permanently stored in the sediments are also interfered by the increasing human interventions in the landscape, such as changes in land use and occupation (e.g., deforestation, soil fertilization, urbanization, sewage treatment) and climate change (e.g., global warming and changes in precipitation regimes) (IPCC, 2007, 2013; Roland et al., 2012), intensified mainly from the 20th century onwards (Sobek et al., 2003, Regnier et al., 2013).

Recent studies, for example, have pointed out that eutrophic environments tend to have high rates of mineralization, resulting in higher carbon emissions into the atmosphere and less accumulation of this element in the sediments (Bastviken et al., 2011; Pacheco et al., 2013). High carbon emissions have also been found in hydroelectric reservoirs, especially during the first years after flooding, when the mineralization of soil and flooded vegetation causes significant CO_2 and CH_4 emissions (Roland et al., 2010; Barros et al., 2011; Mendonça et al., 2012b). It is also estimated that elevations in global temperatures predicted for the next few years (2°C to 4°C , IPCC, 2007, 2013) could cause a significant increase in the carbon mineralization rates in the sediments, resulting in higher carbon emissions to the atmosphere, and contributing to the worsening of the greenhouse effect (Gudasz et al., 2010; Regnier et al., 2013; Raymond et al., 2013). In general, knowledge about CO_2 and CH_4 emissions from sediments becomes more and more essential for an accurate carbon cycle balance in aquatic environments, and also to support strategic planning for the management and conservation of these environments (natural and artificial) at local, regional and global scales.

6. Sediments as a Secondary Source of Pollutants

Water availability is a big challenge for humankind, especially due to water pollution. Chemicals are known as important agents of global change (Bernhardt et al., 2017). Industrial development and urbanization release a variety of pollutants into the environment, with still unknown consequences to organisms (Förstner & Wittmann, 1983; Filser, 2008; Cavalcanti et al., 2014). The urbanization process usually results in changes

in land cover, soil erosion, and waste production, which leads to a chemical load on the surrounding water bodies, altering the ecosystem and leaving records of disturbances in the sediments (Förstner & Wittmann, 1983). Several pollutants may be present in the sediments of aquatic ecosystems since many adsorb in this compartment, where they can stay for decades. Therefore, sediments act as a sink for pollutants (Salomons & Förstner, 1984). However, adsorbed pollutants can be released into the water column and incorporated by biota. In this way, sediments may work as secondary source of pollutants, depending on environmental conditions (Salomons & Förstner, 1984; Nizzetto et al., 2010). Thus, sediments are an essential tool to investigate water quality. It is possible to investigate past contamination, since sediments reflect the contamination accumulated over time, but also current contamination in surface layers, where the contaminants are more susceptible to be released to the water column again. Among the chemicals that occur in the aquatic environment, the most worrying are those that are susceptible to remobilization, bioaccumulation and biomagnification processes, such as heavy metals and organic pollutants (Salomon et al., 1995; Sobek et al., 2014).

Depending on the contaminant, the concentrations may be much higher in the sediments than in the water, which is constantly observed for heavy metals (Salomon et al., 1995). Heavy metals, such as cadmium and lead, are generally not removed from aquatic ecosystems by natural processes, suffering speciation and tending to accumulate in sediments (Förstner & Wittmann, 1983). Metals can be transferred through the food chain, eventually reaching humans, presenting a direct risk, being their environmental impact a major concern (Förstner & Wittmann, 1983). The introduction of metals into freshwater ecosystems has several sources, including natural and human-made. Metals are abundant elements in the Earth's crust, and mineral weathering processes are responsible for the natural introduction of metals into aquatic environments (Salomon et al., 1995). On the other hand, anthropogenic sources include smelting and combustion of fuels, where metals undergo atmospheric deposition, garbage leaching, and industrial, domestic and agricultural effluent discharges (Förstner & Wittmann, 1983; Salomons & Förstner, 1984). Therefore, sediment contamination by metals is a diffuse problem, which needs to be studied in a transdisciplinary way.

Most metals are essential for life, but all can be toxic if they reach high levels in organisms. On the other hand, some metals do not have a known biological function and are mentioned as non-essential, such as cadmium and lead (Förstner & Wittmann, 1983; Mason, 2013). Metals can cause lethal effects, but also sub lethal/chronic effects, such as reducing growth and fecundity, altering species composition, and decreasing population diversity and density (Moore & Ramamoorthy, 2012). Humans influence the cycle of these contaminants by increasing their fluxes (Mason, 2013), but also through acidification and eutrophication, which affect the behavior of metals and change natural paths from rivers to oceans (Salomons & Förstner, 1984). Also, anthropogenic activities release many other pollutants into the environment, and we know little about the simultaneous effects of mixtures on organisms. Thus, aquatic communities are continually exposed due to continuous discards.

The observed behavior of organic pollutants in aquatic ecosystems is not very different from metals, and it is a worldwide problem. Like metals, sediments also function as a reservoir for hydrophobic, recalcitrant, and dangerous pollutants. Many organic pollutants are considered persistent, since they have long half-lives in the environment, reaching years or even decades in the sediment. Depending on environmental processes, are also available for the biota by remobilization to the water column (Jones & De Voogt, 1999; Nizzetto et al., 2010; Perelo, 2010; Sobek et al., 2014).

Another group of pollutants that deserves attention is the microplastics. Although the literature about microplastics in freshwater sediments is limited to few studies, mainly in the shorelines (Wagner et al., 2014; Klein et al., 2015), the properties and ecological effects of microplastics showed by marine literature may be applied to freshwater ecosystems. Microplastics are easily ingested by biota and may cause adverse effects (Eriksen et al., 2013; Goldstein et al., 2013; Remy et al., 2015). Moreover, some studies already showed that microplastics might adsorb organic pollutants, supporting the bioaccumulation and transportation of these compounds (Andrady, 2011; Ryan, 2014).

As sediments integrate the contamination over time, this aquatic compartment presents a range of possibilities for investigating pollution over time, from the beginning to the present day. Thus, it is possible to observe the trends of the concentrations over time, which allows inferring about the use and

sources of the contaminants under investigation. This research field is called Paleolimnology (Last & Smol, 2006). For example, Cooke & Abbott (2008) investigate metal contamination in a lake in Peru. The authors found an increase in the metal concentration since 1925 but with the highest peak in the 1970s or 1980s according to each element studied. Then, the authors were able to infer about the industrialization period in that region (Cooke & Abbott, 2008). The tool is also valuable for organic pollutants. For instance, Feingold & Benoit (2018) studied lakes in the United States regarding contamination of DDT (dichloro-diphenyl-trichloroethane). DDT was widely used in World War II to prevent typhus in soldiers and later began to be used in agriculture. DDT was also used to control tropical diseases, such as malaria. However, due to its persistence, toxicology and bioaccumulation properties, DDT started to be banned worldwide (D'Amato et al., 2002). The authors found a peak of DDT concentration in the sediments during the large usage, however, due to banishment concentrations start to decrease over time (Feingold & Benoit, 2018).

7. Final Considerations

Anthropogenic activities are posing pressure on aquatic ecosystems, and research on aquatic sediments deserve more attention, since they can contribute to the management and mitigation of impacts in different scales. The understanding of the processes of transport, deposition, and metabolism of carbon and contaminants in aquatic sediments is of fundamental importance, especially considering the significant role of these processes in the ecological responses of the aquatic ecosystems. Much has been learned about the process in aquatic sediments in the world. However, it is necessary to invest in the knowledge of such processes in natural and artificial environments under different conditions (e.g., temperature, trophic conditions), covering longer periods of sampling, so that a complete scenario of ecosystems and their main environmental drivers can be created. Further, the knowledge about CO₂ and CH₄ emissions from sediments should be improved to support an accurate carbon cycle balance in aquatic environments, and to improve the management and the conservation of these environments (natural and artificial) at different spatial resolutions. Besides that, studies in tropical regions should be encouraged, since data regarding these areas are

still scarce. Therefore, sediment pollution should be a public health concern, since it can affect food from aquatic ecosystems, as well as drinking water. It is essential to invest in chemical removal and prevention techniques, such as reforestation of riparian zones with native species, investing in sewage treatment, restricting the use of fertilizers and pesticides in river basins, controlling the use of groundwater and implementation of environmental education and population participation to preserve water quality in ecosystems.

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