

Altered organic matter dynamics in rivers and streams: ecological consequences and management implications

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Received: 15/02/2016

Accepted: 05/05/2016

ABSTRACT

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Scientists have spent decades measuring inputs, storage and breakdown of organic matter in freshwaters and have documented the effects of soil uses, pollution, climate warming or flow regulation on these pivotal ecosystem functions. Large-scale collaborative experiments and meta-analyses have revealed some clear patterns as well as substantial variability in detritus dynamics, and a number of standardized methods have been designed for routine monitoring of organic matter inputs, retention and breakdown in different conditions. Despite the knowledge gathered, scientists have been relatively ineffective at convincing managers of the importance of organic matter dynamics in freshwaters. Here we review the existing information of the role of organic matter as a) an element structuring freshwater habitats, b) a source or sink of nutrients, c) a food resource for heterotrophs, d) a source of pollution, e) a modulator of the fate of pollutants, f) a source of greenhouse gases, g) a potential source of environmental problems, and h) a diagnostic tool for ecosystem functioning. Current knowledge in some of these points is enough to be transferred to management actions, although has seldom been so. Some other points, such as the interactions between organic matter and emerging pollutants, offer interesting research questions.

Key words: Detritus, large wood, litter, freshwaters, management.

RESUMEN

Alteraciones en la dinámica de la materia orgánica en ríos y arroyos: consecuencias ecológicas e implicaciones para la gestión

Los científicos han pasado décadas midiendo las entradas, la acumulación y la descomposición de materia orgánica en aguas continentales y han documentado los efectos de usos del suelo, de la contaminación, del calentamiento climático o de la regulación de caudales en estas funciones ecosistémicas fundamentales. Experimentos de colaboración a gran escala y meta-análisis han revelado algunos patrones claros, así como gran variabilidad en las dinámicas detríticas; también se han diseñado un buen número de métodos estandarizados para la determinación rutinaria de las entradas, retención y descomposición de materia orgánica en distintas condiciones. A pesar de dichos esfuerzos, los científicos hemos sido relativamente ineficaces a la hora de convencer a los gestores de la importancia de las alteraciones en la dinámica de la materia orgánica en aguas continentales. Aquí revisamos la información existente sobre el papel de la materia orgánica como a) un elemento estructurador de los hábitats acuáticos, b) una fuente o sumidero de nutrientes, c) un recurso alimenticio para los heterótrofos, d) una fuente de contaminación, e) un modulador del destino de otros contaminantes, f) una fuente de gases de efecto invernadero, g) una fuente potencial de problemas ambientales y h) una herramienta para diagnosticar el funcionamiento de los ecosistemas. El conocimiento existente en alguno de dichos campos es suficiente para ser transferido a acciones de gestión, aunque raramente lo ha sido. Otros puntos, como las interacciones entre materia orgánica y contaminantes emergentes, ofrecen preguntas de investigación interesantes.

Palabras clave: Detritus, madera, hojarasca, aguas continentales, gestión.

ORGANIC MATTER IN FRESHWATERS, A GROWING RESEARCH FIELD

Detritus, or dead organic matter (hereafter OM), is a very abundant but generally poor-quality food resource in most ecosystems (Moore *et al.*, 2004). Freshwater scientists have since long acknowledged the pivotal role of OM in stream and river ecosystems, and the importance of organic inputs of terrestrial origin, especially in forested streams where shading by the riparian vegetation limits primary production (Kaushik & Hynes, 1971; Vannote *et al.*, 1980), but also in other lotic systems (Hill & Webster, 1983).

Riverine detritus is diverse in nature, and it is commonly categorized by its size (Fig. 1). Dissolved organic matter (DOM), defined usually as the fraction not retained by filters of 0.2-0.45 μm pore size, can be derived either from the basin, especially soil leachates (Fiebig, 1992), or from autochthonous producers (Kaplan & Bott, 1989), and is often the largest pool of OM in running waters (Karlsson *et al.*, 2005). Although DOM tends to be dominated by recalcitrant forms such as hu-

mic substances (Battin *et al.*, 2003), it can be an important energetic resource for heterotrophic microbes (Bano *et al.*, 1997). Fine particulate organic matter (FPOM), constituted by particles in the range of 0.45 μm to 1 mm, is a poorly known fraction of OM, despite its importance as a food source for stream collectors (Bundschuh & McKie, 2015). It includes fragments of leaves and other materials, pollen, algal cells, and faeces of invertebrate consumers (Bonin *et al.*, 2000; Kendall *et al.*, 2001; Joyce & Wotton, 2008). Coarse particulate organic matter (CPOM) is the fraction larger than 1 mm, usually dominated by leaves, but which also includes other plant material such as bark, twigs, fruits and flowers (Pozo *et al.*, 1997), plus coarse particles of animal origin, which, although less abundant, can be extremely important for riverine consumers such as trout (Baxter *et al.*, 2004). Finally, large wood (LW) is the fraction of detritus made up by large branches, logs and trees (thicker than 10 cm and longer than 1 m), that can be extremely abundant in some streams and rivers, playing a major geomorphic role (Nakamura & Swanson 1993), in

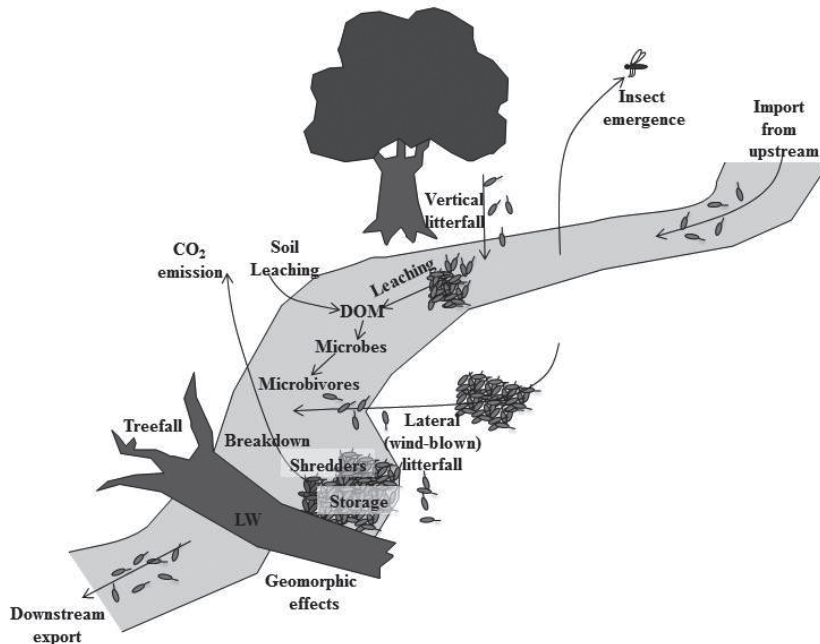


Figure 1. Main components and pathways of OM in stream ecosystems. *Principales componentes y vías de transformación de la materia orgánica en ecosistemas fluviales.*

addition to being an important trophic resource (Collier & Halliday, 2000; Eloisegi *et al.*, 2007).

A large number of now classic papers studied the inputs (Fisher & Likens, 1972), characteristics (Webster *et al.*, 1990), retention (Ehrman & Lamberti, 1992), storage (Smock, 1990), transformations and breakdown (Petersen & Cummins, 1974) of OM, its relevance for channel form and dynamism (Gurnell *et al.*, 2000), for river ecosystem functioning (Lepori *et al.*, 2005), as well as the potential use of breakdown as an indicator of functional integrity of streams (Gessner & Chauvet, 2002; Young *et al.*, 2008). The scientific literature dealing with OM has risen in the last decades (Fig. 2), including a number of review papers (e.g., Tank *et al.*, 2010), as well as some books (Gregory *et al.*, 2003). In these, researchers have documented how riverine OM and its breakdown are affected by land uses (Ferreira *et al.*, 2015; 2016), pollution (Niyogi *et al.*, 2001), climate warming (Ferreira & Canhoto, 2014) or flow regulation (Ponsatí *et al.*, 2014), among other human impacts, and their dynamics show a great variability (Pozo, 2005). Large-scale collaborative experiments

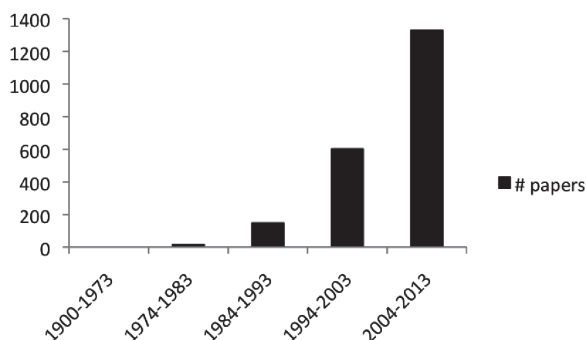


Figure 2. Number of papers published on OM breakdown in streams according to the ISI Web of Science in June 2014, with the following search criteria: Topic: ((stream or river) AND (“organic matter” or litter) AND (decomposition or breakdown)); Field: Environmental Sciences and Ecology; Document type: Article. The total output was 2095 papers. *Número de artículos publicados sobre la descomposición de materia orgánica en ríos según el ISI Web of Science en junio de 2014, según los siguientes criterios de búsqueda: Tópico: ((río o arroyo) Y (“materia orgánica” o hojarasca) Y descomposición)); Campo: Environmental Sciences and Ecology; Tipo de documento: Artículo. El número total de artículos fue de 2095.*

(Woodward *et al.*, 2012) and meta-analyses (Ferreira *et al.*, 2016) have revealed some clear patterns, and a number of standardized methods have been designed for routine monitoring of OM inputs, retention and breakdown in different conditions (Graça *et al.*, 2005; Arroita *et al.*, 2012; Tiegs *et al.*, 2013).

Nowadays there is consensus among scientists on the importance of OM dynamics for the ecological integrity of river ecosystems. Nevertheless, scientists seem to have been ineffective at convincing managers of the consequences of altered OM dynamics in freshwaters, and few management actions focus directly OM. Here we review the existing information of the role of OM as a) an element structuring freshwater habitats, b) a source or sink of nutrients, c) a food resource for heterotrophs, d) a source of pollution, e) a modulator of the fate of pollutants, f) a source of greenhouse gases, g) a potential source of environmental problems, and h) a diagnostic tool for ecosystem functioning. Our objective is to analyse the gap between scientists and managers regarding OM in streams and rivers, and to detect fields in which scientific information could be transferred into management actions, as well as fields in which more knowledge is necessary before trying such a transfer. We do not intend the review to be exhaustive, as there is a vast amount of information on OM in streams and rivers. We rather provide specific examples of the type of research performed and of their possible management implications.

OM AS AN ELEMENT STRUCTURING FRESHWATER HABITATS

One of the fields related to OM in streams and rivers in which there has been more active exchange of ideas between scientists and managers is the role of LW as a key factor structuring river habitats (Gregory *et al.*, 2003). LW can at times accumulate in rivers in huge jams (Fig. 3; Boivin *et al.*, 2015) whose effects were mentioned in early books on geomorphology (Lobeck, 1939). Nevertheless, it was much later, with the reviews by Keller and Swanson (1979) on its geomorphic

effects, and the more comprehensive review by Harmon *et al.* (1986), that river scientists began considering LW as a key component of unimpaired river ecosystems. LW was shown to shape channel form and control river dynamism (Piégay & Gurnell, 1997), to slow down flow and retain sediments and OM (Roberts *et al.*, 2007), to increase the number and depth of pools (Abbe & Montgomery, 1996), to provide refuge for salmonids and other organisms (Scealy *et al.*, 2007) and to control island formation in large rivers (Gurnell *et al.*, 2001). More recently, it has been shown that LW can also be a key habitat for microscopic organisms of the biofilm, to the point that the amount of LW promotes biofilm abundance and consequently enhances ecosystem functioning (Baldwin *et al.*, 2014). All these functions can be compromised by changes in riparian vegetation, which affect the phenology and amount of LW inputs to streams (Díez *et*

al., 2001). Therefore, the reciprocal interactions between channel form and dynamics of riparian vegetation strongly affect river geomorphic processes (Corenblit *et al.*, 2007).

The important geomorphic and ecologic roles of LW, together with the evidence that human actions had strongly reduced its abundance in many streams and rivers (Elosegi & Johnson, 2003; Wohl, 2014), led to many restoration projects in which logs were added into the channels, initially to improve fish habitat (Hunt, 1993), but later on with more objectives in mind, from general improvement of river geomorphology (Kail *et al.*, 2007) to promoting retention of OM and sediments (Flores *et al.*, 2011; Elosegi *et al.*, 2016). These projects are constrained by the generally negative perception of LW in streams and rivers in most countries, where woody debris is considered to be an alien, non-aesthetic and dangerous element in river channels (Piégay *et*



Figure 3. A large LW dam formed naturally in Urdallu Stream (Urumea River basin, Navarre). It stores a large amount of carbon and promotes the upstream retention of large volumes of sediment and leaf litter. Photo Jorge González-Esteban. *Una gran presa de madera formada de manera natural en el arroyo Urdallu (cuenca del Urumea, Navarra). Almacena gran cantidad de madera y produce la retención aguas arriba de un gran volumen de sedimento y hojarasca. Foto Jorge González-Esteban.*

al., 2005). Despite these societal constraints, LW is being increasingly used in river restoration projects (Bernhardt *et al.*, 2005a; Roni *et al.*, 2015), which although often based on wrong scientific ideas and poorly monitored (Palmer *et al.*, 2010), show in general a strong interaction between managers and scientists, as exemplified in the many practical guides available for LW reintroduction (e.g., Brooks, 2006; Opperman *et al.*, 2006).

In addition to LW, other components of detritus such as leaf litter and fine organic sediments can be important habitats for river organisms, at least for some invertebrates (Holomuzki & Hoyle, 1990; Boulton & Foster, 1998), but so far there are few examples of management actions focusing specifically on them (Kemp *et al.*, 2000), maybe because these components lack the stability of LW.

OM AS A SOURCE/SINK OF NUTRIENTS

A large fraction of the nutrients in many forests are stored in OM (Whittaker *et al.*, 1979; Attiwill & Adams, 1993), and thus, litter breakdown has long been known to represent an important source of nutrients to forested stream and river ecosystems (Gosz *et al.*, 1973). Many papers measured the contribution of OM to stream nutrients, either by leaching (Wallace *et al.*, 2008) or by mineralization (Johnson *et al.*, 2013). Although some authors reported decreased con-

centration of nutrients in stream water shortly after peak leaf fall (Mulholland, 1992), and other modelled the relationship between decomposition and dissolved nutrients (Lin & Webster, 2014), the overall effect on long-term nutrient availability or export is likely minor and probably only significant in oligotrophic streams. For instance, based on results by Pozo *et al.* (1998) and Molinero & Pozo (2004, 2006), dissolved nitrogen generated by leaf decomposition represents less than 1% of the dissolved nitrogen exported by streams of the Agüera basin, both under deciduous forest and eucalyptus plantations. For phosphorus, the equivalent ratio is lower than 5%. Other types of OM can be more important sources of nutrients, as, for instance, salmon carcasses, which enrich both streams and riparian areas alike (Helfield & Naiman, 2006). It is also likely that the massive insect emergence in some rivers produces a net transport of nutrients to nearby areas, as has been described in some midge lakes (Gratton *et al.*, 2008).

In addition to being a source of nutrients, OM also plays a role on the uptake and immobilization of dissolved nutrients by microbial decomposers (Mulholland *et al.*, 1985; Molinero *et al.*, 1996; Webster *et al.*, 2003), on their long-term storage in LW and other refractory organic materials (Hyatt & Naiman, 2001), and on key processes such as denitrification, which occurs in the interphase between oxidized and reduced sediments, and thus, is often spatially linked to de-

Table 1. Main findings on the storage, breakdown rate and CO₂ production associated to leaf litter in north Iberian streams depending on nutrient status. *Principales hallazgos sobre la acumulación, tasa de descomposición y producción de CO₂ asociados a la hojarasca en arroyos ibéricos en función de su nivel trófico.*

	Oligotrophic		Mesotrophic
Decomposition of eucalyptus leaves	slow		fast
Eucalyptus litter standing stock		similar	
CO ₂ production	high		high
Decomposition of alder leaves	fast		fast
Alder litter standing stock		similar	
CO ₂ production	high		high
Decomposition of leaves of intermediate quality	moderate		fast
Intermediate litter standing stock		similar	
CO ₂ production	moderate		fast

caying OM (Hill, 1996). As an example, the decomposition rate of nutrient-poor leaves such as those of eucalyptus is strongly dependent on dissolved nutrients, being low in nutrient-poor waters and fast, close to that of alder leaves, in nutrient-rich waters (Pozo *et al.*, 1998) (Table 1). Furthermore, the replacement of native riparian vegetation by eucalyptus plantations reduces the inputs of organic N and P to streams, but higher leaf retention at eucalyptus sites, related to phenology of inputs and hydrology, results in a benthic storage of N and P similar to that at deciduous sites (Moliner & Pozo, 2004). Therefore, managing OM could potentially have important consequences for the flux of nutrients in streams and rivers. Other example was shown by Bernhardt *et al.* (2005b), who suggested that as the riparian forests mature instream nitrogen processing is enhanced as a consequence of greater abundance of LW and other OM, which enhances nutrient retention and creates patches of active denitrification. Therefore, by promoting the maturity of riparian forests and the abundance of instream LW, managers might reduce the downstream flux of nutrients. Acuña *et al.* (2014) showed that restoring instream LW in a basing draining to a drinking-water reservoir could be economically profitable in terms of enhanced ecosystem services, including nutrient retention. Ultimately, instream processes can dampen the effects of upland disturbances on nutrient export (Bernhardt *et al.*, 2003).

Despite the above information, to our knowledge managers rarely use OM as a way to control nutrients in stream and river ecosystems. A notable exception is the experimental addition of fish carcasses to recover natural nutrient regimes in rivers subject to strong declines in salmon runs, which proved to be more effective than adding nutrient pellets (Wipfli *et al.*, 2010).

OM AS A FOOD RESOURCE FOR HETEROTROPHS

OM is a key food resource for riverine heterotrophs, both consumers and decomposers (Marcarelli *et al.*, 2011). These organisms use

organic matter as an energetic resource depending on its texture and chemical composition, including nutrient content and the amount of refractory and toxic substances (Casas *et al.*, 2013; Canhoto & Graça, 1995). The degradation of refractory compounds such as cellulose and lignin requires the action of specific enzymes that are lacking in many consumers. Therefore, detritus rich in these compounds is of low nutritional value and slow decomposition (Melillo *et al.*, 1984). Some DOM fractions are readily used by bacteria (Hall & Meyer, 1998), resulting in a “microbial loop” similar to that described in lentic ecosystems (Legendre & Rassoulzadegan, 1995). On the other hand, particulate OM is colonized by microbes, especially bacteria and fungi, but also *Archaea* (Manerkar *et al.*, 2008), to the point of controlling their biomass and activity (Artigas *et al.*, 2008). These microbes, in turn, are consumed by micro- and meiofauna (Gaudes *et al.*, 2009), and promote consumption by macroinvertebrates (mainly shredders but also collectors) through enhanced palatability (Hieber & Gessner, 2002). Therefore, the energy contained in OM spreads bottom up to the entire aquatic food web (Wallace *et al.*, 1997) and even to the surrounding terrestrial environment through aquatic-terrestrial trophic linkages such as spiders, bats and birds feeding on emerging insects (Baxter *et al.*, 2004; Kautza & Sullivan, 2015). Interestingly, in addition to the transfer of energy, these “reciprocal subsidies” (Nakano & Muramaki, 2001) also account for the transfer of contaminants from the aquatic to the terrestrial realms (Runck, 2007; Alberts *et al.*, 2013).

Many factors affect the importance of OM as a food resource. OM availability depends on the amount of inputs, which are a function of the type and maturity of riparian vegetation (Webster & Meyer, 1997), the mobility of leaves, which depends on species (Fig. 4), and the capacity of stream channels to retain and store OM over long periods (Flores *et al.*, 2011). The latter depends, among others, on channel complexity, and very especially on the amount of LW (Quinn *et al.*, 2007), which is the most retentive structure, especially at high flows (Larrañaga *et al.*, 2003). On the other hand, food quality depends mainly

on the composition of the riparian forest, as tree species can differ greatly on the nutritional quality of their leaves (Petersen & Cummins, 1974; Melillo *et al.*, 1984), but also on deposition site (Flores *et al.*, 2013), probably because it affects its stability and, thus, the capacity of microbes to colonize and condition the trapped material. Changes in riparian vegetation seem to affect decomposers less than detritivores (Ferreira *et al.*, 2015). Other environmental factors affecting the use of OM include hydraulics (Ehrman & Lamberti, 1992; Jones & Smock, 1991) as well as the concentration of nutrients in water (Gulis & Suberkropp, 2003).

The importance of OM as a food resource and the potential implications for ecosystem functioning of the amount and quality of OM stored in the channel have been stressed out in several research papers that directly manipulated OM inputs (Larrañaga *et al.*, 2006; Richardson, 1991) and suggest ways to manage stream and river ecosystems to enhance basal resources and consumers. These include controlling the cover, composition and maturity of riparian forests,

managing channel retention capacity, and so on. Nevertheless, we are not aware of management actions specifically focusing OM as food, with the exception of a few experiments introducing OM-trapping structures (Dobson *et al.*, 1995; Tiegs *et al.*, 2011).

OM AS A SOURCE OF POLLUTION

Excess OM inputs can have detrimental effects on freshwater ecosystems, including oxygen depletion, eutrophication, and problems associated with human health (Harper, 1992). There is an extensive body of literature dealing with the impacts, treatment and prevention of the effects of high biological oxygen demand (BOD) and chemical oxygen demand (COD, e.g., Sullivan *et al.*, 2010), and modelling their impact on oxygen concentration (e.g., Fornasini, 1991). BOD and COD have been incorporated into the water legislation such as the EU Water Framework Directive, and their inputs are now regulated in most of the world. On the other hand, the

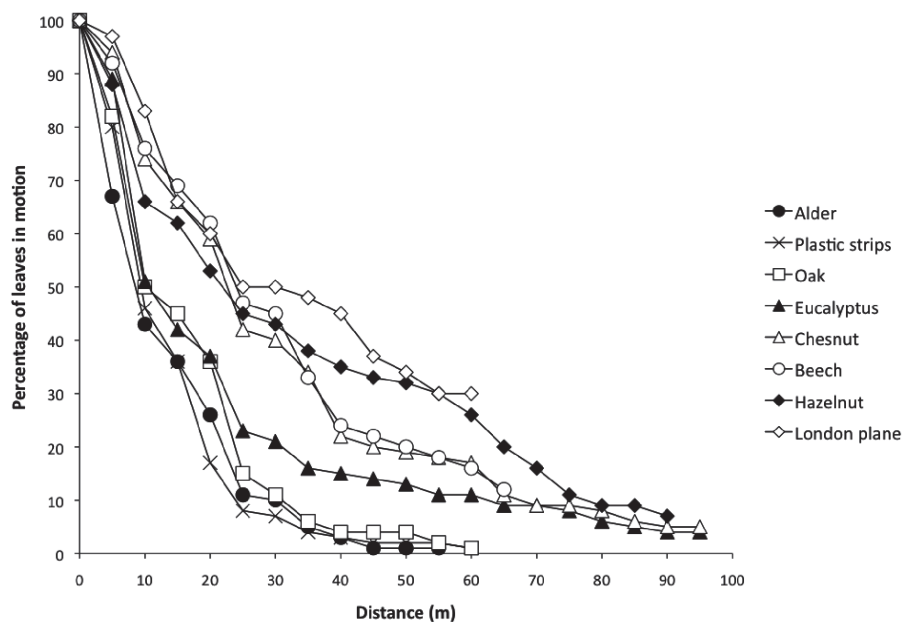


Figure 4. Distances travelled by plastic strips and different leaf species of the riparian vegetation in the Agüera Stream (northern Spain) at baseflow. Mean values are reported by Larrañaga *et al.* (2003). *Distancias recorridas por tiras de plástico y distintas especies de hoja de la vegetación riparia en el río Agüera (norte de España) en caudales basales. Los valores medios fueron publicados por Larrañaga et al. (2003).*

detrimental effects of excess OM in freshwaters led, among others, to consider OM as a pollutant, and to develop bioindication methods such as the Saprobian method (Lange-Bertalot, 1979), or specific diatom indices (Kelly & Whitton, 1995). Therefore, this is one aspect of OM in streams and rivers that is already well incorporated into management.

On the other hand, there is a growing concern on the environmental and health effects of a large range of organic substances, included in the so-called emerging contaminants (Loos *et al.*, 2009; Pal *et al.*, 2010). These include pesticides, pharmaceuticals and personal care products, natural and synthetic hormones, alkylphenols and other substances related to detergents, and perfluorinated compounds, among many others (Petrovic *et al.*, 2013). Many of these substances have very powerful biological effects, but their effects in nature are little known, especially in the case of complex mixtures, such as wastewater treatment plant (WWTP) effluents (Gros *et al.*, 2007). Clearly, there is a lot to learn on the fate and effects of these organic contaminants, and of their degradation products, which can in some cases be more harmful than the parent compounds (Schulze *et al.*, 2010). Therefore, there is an increasing number of calls for incorporating at least some of these contaminants into monitoring programs, as they represent a challenge for water resource management in the near future (Geissen *et al.*, 2015).

OM AS A MODULATOR OF THE FATE OF POLLUTANTS

OM modulates the fate of pollutants in multiple ways, including their storage, mobility, persistence, toxicity and bioaccumulation (Chapman *et al.*, 1998; Redman *et al.*, 2002; Eggleton & Thomas, 2004), as well as by controlling the main biogeochemical routes through its effects on the riverine chemical environment, especially on the redox potential (Kim *et al.*, 2008).

Dissolved, flocculated or particulate OM can adsorb multiple pollutants, as shown, for instance, by Stankus *et al.* (2011) for gold nanopar-

ticles or by Sounthararajah *et al.* (2015) for heavy metals. Similarly, dissolved organic carbon (DOC) and leaf leachates are known to interact with metal mobility (Guibaud *et al.*, 2000; Tsui *et al.*, 2008), and the organic content of sediments tends to increase the sorption of hydrophobic pollutants (Karickhoff *et al.*, 1979). Additionally, there are many papers showing an effect of OM on pollutant toxicity and bioaccumulation. For instance, Lambertson and Nilsson (2006) showed that OM is the main control of mercury toxicity in estuarine sediments, and Granier *et al.* (1999) showed that DOM modulates bioaccumulation of PCB by *Daphnia*.

On the other hand, OM exerts strong effects on the riverine chemical environment, which, in turn, can affect the fate of pollutants. Especially important is the redox potential, which controls, among others, the nitrification and denitrification processes (Knowles, 1982), as well as the mobilization of metals and other toxicants (Kalbitz & Wennrich, 1998). Therefore, local OM accumulations can have important consequences for the fate of these toxic compounds. This has sometimes been transferred to management, such as in projects of riparian wetland restoration to enhance self-purification. Although the physico-chemical basis of the interactions among types of pollutants and different fractions of organic matter is beyond the scope of the present review (and beyond the knowledge of the authors), there is room to improve management. For example, managers may increase or reduce the inputs or retention of OM in a reach to enhance or reduce retention of toxicants. Or narrow the stream channel to increase flow velocity and flush OM and toxicants downstream. We are unaware of management measures along these lines.

OM AS A SOURCE OF GREENHOUSE GASES

Streams and rivers cover only a minute part of the Earth surface, and have traditionally been considered as biologically little reactive compared to terrestrial ecosystems. This fact, along with the lack of good metabolism data

for most rivers in the world, explains why river ecosystems are usually not incorporated into national greenhouse gas statistics. Nevertheless, it has recently been estimated that streams and rivers of the world transport, transform or store nearly 2.7 Pg of terrestrial organic carbon per year, a quantity that almost equals the size of the terrestrial carbon sink for anthropogenic emissions (2.8 Pg/y, Battin *et al.*, 2009). These figures would increase if we consider intermittent rivers and ephemeral streams, which are extremely abundant worldwide (Acuña *et al.*, 2014), and which can be very active at emitting greenhouse gases (von Schiller *et al.*, 2014). Furthermore, experimental evidence suggests that global climate change may enhance CO₂ evasion

by streams and rivers (Boyero *et al.*, 2011). Especially worrying from the point of global climate change are emissions of CH₄, associated to anaerobic decomposition of OM, which are common in freshwater ecosystems such as rice fields (IPCC, 2007) and reservoirs (Bastviken *et al.*, 2011), and which are caused in part to flooded plant and soil material (Barros *et al.*, 2011). On the other hand, LW can be an important C reservoir in headwater streams (Beckman & Wohl, 2014). We are not going to develop into detail the effect of rivers on global warming, which would be beyond the scope of the present review, but we want to stress out the fact that river management can play a role in the global management of greenhouse gases, and thus, should



Figure 5. An automatic rake to prevent OM entering the turbines in a small hydropower plant in Añarbe Stream, the Basque Country, Spain. *Una rejilla automática para evitar la entrada de materia orgánica a las turbinas de una pequeña planta hidroeléctrica en el arroyo Añarbe, País Vasco, España.*

be taken into account, from national accounting of emissions to carbon management plans.

OM AS A POTENTIAL SOURCE OF ENVIRONMENTAL PROBLEMS

OM can cause other serious environmental problems. For instance, POM can accumulate around water intakes installed in streams, lakes, and reservoirs, preventing efficient withdrawal of water for drinking, farming and power generation (Namihira *et al.*, 2009). In fact, many withdrawal schemes such as small hydropower plants have been forced to install rakes or other expensive devices to maintain their installations free from organic matter (Fig. 5). Similarly, floating logs can produce damages, clog bridges (Wu *et al.*, 2014; Lucía *et al.*, 2015) and increase flood hazard during spates (Ruiz-Villanueva *et al.*, 2014). They can also be a problem for river as well as coastal navigation (Doong *et al.*, 2011). Drifting wood causes an increasing number of problems in many regions such as Europe, because of the intense afforestation registered after the 1950s (Liébault & Piégay, 2002). The most common management measure is to remove logs fallen into stream and river channels and the thinning of riparian forests (Boyer *et al.*, 2003), but these are often expensive and of small efficiency. Other mechanisms such as log traps have been implemented experimentally in some rivers. We are not giving solutions here for such a complex problem, but clearly, managers should be aware of it. Although old bridges are extremely expensive to modify, when designing and building new bridges, engineers should take in account the oncoming wood loading regime, thus making them less prone to form log jams. Ironically, whereas most flood control programs still focus mainly on hard engineering measures such as channelization, the European Union is now promoting the introduction of LW in some streams as an experimental measure to enhance natural water retention and to reduce downstream peak flooding (<http://www.nwrm.eu/>).

OM AS A DIAGNOSTIC TOOL

Given the pivotal role of OM inputs, retention, storage and breakdown in stream and river ecosystem functioning, one would expect these variables to be incorporated into stream and river assessment tools. Indeed, they have been but, in our opinion, to a very limited extent.

Some stream habitat assessment tools take into account the presence or the abundance of OM, and especially of LW. For instance, the IHF (Pardo *et al.*, 2002), which is designed to assess habitat diversity of Mediterranean rivers and can score up to 100 points, gives up to 4 points to the cover of leaf litter and up to 2 additional points to the presence of logs and branches. On the other hand, the RHS (Raven *et al.*, 1997) considers the abundance of LW, but the HQA, which is the tool derived to assess river condition, gives LW a maximum of 8 points from a total maximum of 100 points. Similarly, the US Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers (Barbour *et al.*, 1999) consider LW cover, but lump it with other “epifaunal substrate”, basically stable structures such as logs, rocks and undercut banks, in only one of the 10 elements it takes in account. Therefore, OM and LW seem not to be very prominent features of general habitat assessment protocols, probably because those who designed them were more concerned with other aspects of river habitats such as channelization or siltation.

Breakdown, on the other hand, has been by far the OM variable most often considered for assessment or diagnostic tools, probably because the seminal Gessner and Chauvet (2002) paper convinced breakdown scientist of the potential relevance of their work. In this context, the EU funded the research project RIVFUNCTION, whose aim was integrating ecosystem function (namely, OM breakdown) into river quality assessment and management, and there have been some national projects in the same line, such as IMPARIOS (Pozo *et al.*, 2011). Some of these projects produced reasonably standardized protocols to measure OM breakdown, including

leaves (Graça *et al.*, 2005), sticks (Arroita *et al.*, 2012), tea bags (Keuskamp *et al.*, 2013), cellulose strips (Tiegs *et al.*, 2013) and other materials (Kampfraath *et al.*, 2012). Scientists have also developed a number of metrics to analyse and score results, such as the ratio of breakdown rate in a reach compared to a “reference” reach (Gessner & Chauvet, 2002). Therefore, there is a broad range of techniques that can be adapted to a wide variety of environmental situations to assess ecosystem functioning. On the wrong side, breakdown rates have resulted to be highly variable among sites (Pérez *et al.*, 2011), making it necessary to define clear reference conditions for each case.

Coupled to these technical developments, a number of large collaborative research papers showed clear patterns in breakdown following environmental gradients. For instance, Boyero *et al.* (2011) measured decomposition in 22 streams spanning a large latitudinal range, and found breakdown rate to increase but the relative contribution of detritivores to decrease with temperature. Similarly, Woodward *et al.* (2012), in a pan-European experiment, showed breakdown to respond to nutrient concentration following a hump shape, which they attributed to nutrients accelerating microbial activity at low to medium concentrations, decreasing the role of shredders at large concentrations. On the other hand, Aristi *et al.* (2012) measured the breakdown of tongue depressors at 66 sites across the Iberian Peninsula, spanning a very large range of contamination and other types of environmental degradation. They found 50-fold variations in breakdown rates, which were related to temperature, phosphorus, catchment area, water quality and riparian buffer width.

The above papers are encouraging examples of the possibility of using breakdown to assess stream and river functional impairment. Indeed, a large number of breakdown papers claimed their results to be meaningful for this purpose (e.g., Friberg *et al.*, 2011; Hladyz *et al.*, 2011; Lecerf & Chauvet, 2008; Young *et al.*, 2008). Despite all these claims, managers did not adopt breakdown tools for routine monitoring of river ecosystems, with notable exceptions such as the

Waikato Regional Council in New Zealand (Collier & Hamer, 2014).

CONCLUDING REMARKS

Decades of research have made it clear that OM is a key element in streams and rivers, and its inputs, storage and breakdown are consequently pivotal ecosystem functions. Furthermore, today we have a clear understanding of the main environmental factors governing OM dynamics. As researchers produced an increasing volume of data, we have been able to progress from vague intuitions to the definition of clear patterns and the identification of some of the most important mechanisms behind these patterns. Equally important, researchers have narrowed down and clearly identified many of the remaining questions regarding OM in streams and rivers.

On the weak side, scientists have been little effective at convincing managers of the practical relevance of OM, and of the need to incorporate functional variables into river ecosystem assessment, as well as at putting streams and rivers in the global Carbon agenda. Rather than complaining about the little interest of managers into our scientific results, we should continue research to deepen in the mechanistic understanding of OM-related processes, such as movement and breakdown, investigate the interactions between OM and pollutants, and continue gathering data on OM in reference and impaired sites. Only this information will allow scientists moving from description to prescription. Of particular importance is to take advantage of the research opportunities linked to ecosystem manipulation, such as measuring the effects of restoration projects, and to increase our interactions with managers and stakeholders. Only then will OM reach its real importance in river management.

ACKNOWLEDGEMENTS

This work has been supported by the EU 7th Framework Programme Funding under Grant agreement no. 603629-ENV-2013-6.2.1-Globaqua.

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