



Editorial: From Fires to Oceans: Dynamics of Fire-Derived Organic Matter in Terrestrial and Aquatic Ecosystems

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Keywords: fire-derived carbon, pyrogenic carbon, methods, decomposition, stocks, terrestrial and aquatic ecosystems

Editorial on the Research Topic

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INTRODUCTION

Fire is a global phenomenon, which has contributed to create the Earth's landscapes for several millions of years. Fire can greatly impact the carbon (C) cycle, and it can act in opposite directions, depending on which timescale one considers. On the one hand, over short timescales, a vast amount of organic C is rapidly oxidized and emitted as gases and aerosols during burning, in a much more intense and faster process than respiration. Depending on the magnitude of the fire, the CO₂ released by burning can be very relevant in terms of net ecosystem CO₂ exchange with the atmosphere. On the other hand, over longer timescales, fire can actually contribute to CO₂ drawdown. Due to the incomplete combustion of the fuel biomass, fire not only releases C to the atmosphere but it also converts a substantial fraction of the vegetation C into pyrogenic organic matter also named charcoal, black carbon, or pyrogenic carbon (PyC). This fire-derived organic matter is more resistant to environmental degradation than unburnt biomass and can act as a long-term C sink. Some remains for centuries to millennia in the environment, not statically but changing form and moving between terrestrial and aquatic pools. The relics of fire, in the form of PyC, are present in all compartments of the Earth: In the air, soils, marine and fresh water sediments, rivers, and the oceans...

Despite its global importance, our understanding of the dynamics of fire-derived organic matter is limited. Simple questions like “how much,” “how fast,” or “how old” remain only partially answered. There are diverse reasons for these gaps in our knowledge. To start with, not all fire-derived organic matter is born equal. PyC is not a single, chemically well-defined organic compound, but a large continuum of different materials, from slightly charred plant material to soot. It is therefore difficult to estimate its initial production and to quantify and characterize this type of organic matter in environment matrices. Another reason is the spatial heterogeneity of the fire phenomenon and the myriad ways and forms fire-derived organic matter can be produced, deposited, and stored in the environment. The processes leading to mobilization of fire-derived organic matter within land, from land to rivers, and from rivers to the ocean also need to be further clarified.

OPEN ACCESS

Edited by:

Alexandra V. Turchyn,
University of Cambridge,
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Reviewed by:

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Specialty section:

This article was submitted to
Biogeoscience,
a section of the journal
Frontiers in Earth Science

Received: 07 December 2018

Accepted: 08 February 2019

Published: 27 February 2019

Citation:

Abiven S and Santín C (2019)
Editorial: From Fires to Oceans:
Dynamics of Fire-Derived Organic
Matter in Terrestrial and Aquatic
Ecosystems. *Front. Earth Sci.* 7:31.
doi: 10.3389/feart.2019.00031

This research topic explores these different questions in our understanding of fire-derived organic matter, from the characterization and quantification of PyC components, to the transformation and mobilization processes taking place on land and in rivers and oceans. The studies compiled here provide novel and, often, unexpected results. They all answer some of the questions posed and, more importantly, provide scope for many more.

IDENTIFICATION AND CHARACTERIZATION OF PYC

Fire-derived organic matter differs physically and chemically from all other types of organic matter. Identifying its specificities is a major part of ongoing research. The first step is usually to detect it in the environment, in different forms and associated with different matrixes. Zimmerman and Mitra describe the current methodological hurdles we are facing. They note that many of the terms and methods used to quantify and characterize PyC do not match. They recommend linking the reported values to the method applied and propose implementation of a new “ring trial” study that cross-compares the most recently developed methods and examines a wider set of samples, including biochar. They also pose the interesting question of why quantities of PyC and total organic C in waters and soils are, in many cases, directly correlated.

While complex laboratory methods are useful to understand in detail the characteristics of PyC, quick and inexpensive methods are also fundamental in order to explore the inherent high variability of PyC materials. In their study, Belcher et al. propose charcoal reflectance as an indicator of how different fire behavior may lead to PyC with different physical and chemical properties. They found that the total heat released during combustion positively correlates with charcoal reflectance and with its resistance to degradation. This method can be a useful tool to reconstruct fire history and to predict PyC residence in the long term.

PYC ON-SITE: PRODUCTION AND STORAGE IN SOILS

Our knowledge about PyC production and its relationships with different ecosystem properties such as vegetation cover or fire type or behavior is still very limited. Using an adventurous field approach, Miesel et al. quantify immediate impacts on PyC and total ecosystem C stocks of wildfires of various severities in a Californian mixed-conifer forest. Fire resulted in a net ecosystem gain in PyC of around 1t PyC ha⁻¹, but they did not find any difference of PyC production with fire severity.

Information about immediate fire effects is indeed important, but knowledge of the residence of PyC in the longer term is essential in its role as a durable carbon sink. Preston et al. quantify the PyC (>2 mm charcoal) stocks and characteristics in boreal forest soils using a fire chronosequence (24–2,355 years since fire). They find that charcoal stocks are highly variable (50–5,527 kg ha⁻¹) but, generally, they decrease with time since

fire. Importantly, old charcoal is more aromatic and, therefore, more relevant in terms of long-term C storage. From this C sequestration perspective, both PyC stocks and their residence times need to be quantified. Based on a unique set of soils from five European long-term bare fallows, Lutfalla et al. provide the first direct comparison between the persistence of PyC and total soil organic C in temperate arable soils. They find that soil PyC content decreased more rapidly than expected, with the mean residence time of PyC being just 1.6 times longer than that of total soil organic C.

At the global level, Reisser et al. compile all published data on soil PyC. They find that PyC represent on average 13.7% of the global soil organic C pool, making it one of the largest groups of identifiable soil compounds. They estimate global PyC stock at 200 Pg for the uppermost 2 m of soil. For this global database, soil properties (clay and pH) are better predictors of PyC content than climate or frequency of fire.

PyC is not only important from a C cycle perspective, but it also affects ecosystem properties. Pingree and DeLuca review our current knowledge about the functions of wildfire-produced PyC in terrestrial ecosystems. They discuss the implications of its C-rich, N-poor nature, and its high surface area. They particularly review our knowledge about the “charosphere,” the soil near PyC, with its enhanced microbial activity and implications for soil functioning.

PYC DEGRADATION PROCESSES

While initially PyC was considered inert, it is now well-established that part of it can suffer degradation in the short term. Ascough et al. carried out a 1-year litterbag field experiment in the tropical rainforests of northeast Australia. Their results show that all types of PyC studied partially degraded. Depositional environment characteristics, in particular oxygen availability and protection from sunlight and rainwater, were the main drivers. Along the same lines, Stuart et al. investigate the environmental parameters influencing early-stage PyC dynamics in a subtropical forest. Their study points not to biological decomposition but to losses by volatilization and leaching as the main drivers in the first months of PyC degradation.

One obvious ecosystem process modifying the PyC pools is actually fire burning the charcoal produced in previous events. Doerr et al. observe that, in the boreal forest, fire can be indeed a significant removal mechanism for the PyC that remains on the ground. In their study, higher wildfire maximum temperatures result in higher PyC losses. Such losses also depend on the characteristics of the material, with wildfire charcoal being more readily consumed than slash-and-burn charcoal (which has a higher recalcitrance). Interestingly, fire also increased the recalcitrance of the remaining “twice-heated” PyC making it, therefore, more resistant to subsequent fires.

It is important to note that PyC degradation does not always imply PyC mineralization (and therefore net loss). A good example of this is PyC leaching. In this process, some of the solid PyC retains its pyrogenic nature but becomes soluble in water (but see Wagner et al. for more details about PyC solubility).

Bostick et al. assess the solubility of PyC by characterizing “new” and “old” leachates from laboratory charcoals. They observed that up to 7% of the PyC can be lost in the dissolved forms in about a year, with the chemical characteristics of the leached PyC differing from those of the original solid PyC material.

PYC MOBILIZATION: THE IMPORTANCE OF LEACHING AND EROSION

The two main mechanisms described in the literature for PyC mobilization are leaching and erosion. In this research topic, Santos et al. quantify losses by leaching, as dissolved PyC, from two spodosols: one in a site burnt 100 years ago and one with no evidence of burning for the past 250 years. While soil PyC stocks are larger in the burnt site, they do not detect any differences in the dissolved PyC concentrations between the two sites (~3% total organic C pool). This result may indicate that the release of dissolved PyC is a continuous, long-term process, or alternatively, that there are other PyC sources, such as atmospheric deposition, that should also be considered.

In addition to leaching, erosion is a key but still poorly understood mechanism in PyC fluxes. Abney and Berhe present a synthesis of available data to compare the magnitude of the water-driven erosional PyC flux with other important pathways of PyC loss from soil, including leaching and decomposition. Depending on the topography, timescale, and initial concentrations of PyC in soil, ignoring the role of erosion in distributing PyC across a landscape can lead to discrepancies of several 100 g PyC m⁻². In a more specific study, Abney et al. assess the amount and types of soil organic C in different landform positions before and after a wildfire in California. Even if they observed an accumulation of PyC and soil organic C in the post-fire depositional positions 1 year after the fire, both of these C pools decreased 10 years after fire, indicating further erosion or decomposition.

Another way of assessing PyC erosion is to study the sediment transported off-site. Saiz et al. quantify and characterize PyC using $\delta^{13}\text{C}$ HyPy in recent sediment (from farm dams) and burnt and unburnt soils in savanna ecosystems with different grass/tree covers. They observe that grass-derived PyC, compared with tree-derived PyC, is both preferentially produced and preferentially eroded. This higher mobility is probably related to its smaller particle size, which is also important to take into account for accurately reconstructing savanna fire regimes using PyC particles.

FROM LAND TO THE OCEAN

As explained earlier, a key characteristic in terms of PyC mobilization is its solubility in water, especially when considering long distance mobilization and transfer from terrestrial to aquatic environments. Wagner et al. investigate the apparent solubility of different dissolved PyC-type molecules by calculating octanol-water partition coefficients. Their approach reveals that only a minor proportion of the PyC molecules are truly soluble in water (those that are small aromatic structures with hydrophilic moieties), whereas large condensed structures, which are present

in large quantities, are not. The authors suggest that other dissolved organic molecules can mediate in PyC solubilisation, but their experimental approach is not able to confirm this hypothesis.

Marques et al. study the main processes behind the release and turnover of dissolved PyC (DBC) in the Paraíba do Sul River catchment (Brazil). Their results show a clear relationship between hydrology and river DBC concentrations. DBC is mainly mobilized from the upper soil horizons during heavy rainfall (wet season) and most of it is derived not from the sugar cane plantations that are the main vegetation cover today, but from relic charcoal produced decades ago during the slash burning of the Atlantic rain forest. They also found that a substantial (23–40%) part of this DBC is photo-oxidized in the river, but, interestingly, not in the estuary.

And, moving further into the ocean, Nakane et al. characterize the dissolved PyC (DBC) in surface waters of the North Pacific. They found that whereas the main input of DBC in coastal waters was fluvial, atmospheric deposition was the main source of DBC in open waters. Their results point to photodegradation and adsorption on to sinking particles as the main removal processes.

MOVING FORWARD: RESEARCH NEEDS AND CHALLENGES

This research topic provides new insights about the PyC dynamics in ecosystems, but also highlights the upcoming research needs and challenges. While progress is tangible regarding the nomenclature, characterization of PyC in different matrices still remains a frontier to our general understanding. New systematic ring trials, more specifications about the techniques and, maybe, new and more integrative methods are still needed in order to unify existing knowledge. This research topic indicates two main directions to be followed: methods that can characterize and quantify precisely PyC, so we understand better the mechanisms and processes of transformation within terrestrial and aquatic systems, and screening methods, cheaper and faster than the previous ones, in order to explore the PyC spatial heterogeneity.

Understanding the variability of PyC stocks and fluxes in the ecosystems is another important challenge to address. Our understanding of PyC residence time and quantities remains scarce. In particular, we still need to identify the drivers that lead to larger and older stocks of PyC. New methodological developments combining radiocarbon dating on PyC specific compounds, and quantitative estimations of PyC stocks in soils, sediments and dissolved organic carbon should help us to address this issue. Also, the spatial variability within the landscape is still largely unknown, like, for example, the identification of accumulation or preferential losses zones. This would help to identify intermediate pools and better connect the different processes leading from the fire to the oceans. This understanding is a pre-requisite for a third

challenge we identified here, which is the need to include PyC in models.

Up to now, modeling efforts have been very limited, and PyC has been often considered as a passive pool adjusted to explain model mismatches in the long term. As PyC emerges as a substantial contributor to total organic carbon, both in soils and waters, and a much more dynamic one than previously thought, it is now urgent to integrate it into mechanistic models, in order to test the validity of the processes, but also in earth system models, in order to constrain better soil, water and sediment carbon fluxes and budgets.

AUTHOR CONTRIBUTIONS

SA and CS contributed to the writing and editing of the publication.

ACKNOWLEDGMENTS

We thank all authors for their contributions and the reviewers for their valuable feedback. They all have made possible this Research Topic. We also thank Satish Myneni, Moritz F. Lehmann, and Francien Peterse for their editorial roles for some of the articles. Special thanks to Rob Bryant for proof-reading this manuscript.

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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