Received: 4 March 2024 | Revised: 15 May 2024 | Accepted: 16 May 2024

DOI: 10.1111/gcb.17354

Global Change Biology WILEY

OPINION

Into the unknown: The role of post-fire soil erosion in the carbon cycle

Antonio Girona-García[1] | Diana Vieira[2] | Stefan Doerr[3] | Panos Panagos[2] | Cristina Santín[1,3]

[1]Biodiversity Research Institute (IMIB), CSIC-University of Oviedo-Principality of Asturias, Mieres, Spain

[2]European Commission, Joint Research Centre (JRC), Ispra, Italy

[3]Centre for Wildfire Research, Swansea University, Swansea, UK

Correspondence
Antonio Girona-García, Biodiversity Research Institute (IMIB), CSIC-University of Oviedo-Principality of Asturias, Mieres, Spain.
Email: a.girona@csic.es

Funding information
Ministerio de Ciencia, Innovación, y Universidades/Agencia Estatal de Investigación, Grant/Award Number: RYC2021-031262-I; Consejo Superior de Investigaciones Científicas (CSIC), Grant/Award Number: 20208AT007; European Union, through NextGenerationEU/PRTR funds; Grant/Award Number: RYC2021-031262-I; Natural Environment Research Council, Grant/Award Number: UK-FDRS (NE/T003553/1); Horizon 2020 Framework Programme, Grant/Award Number: 101003890

Abstract

Wildfires directly emit 2.1 Pg carbon (C) to the atmosphere annually. The net effect of wildfires on the C cycle, however, involves many interacting source and sink processes beyond these emissions from combustion. Among those, the role of post-fire enhanced soil organic carbon (SOC) erosion as a C sink mechanism remains essentially unquantified. Wildfires can greatly enhance soil erosion due to the loss of protective vegetation cover and changes to soil structure and wettability. Post-fire SOC erosion acts as a C sink when off-site burial and stabilization of C eroded after a fire, together with the on-site recovery of SOC content, exceed the C losses during its post-fire transport. Here we synthesize published data on post-fire SOC erosion and evaluate its overall potential to act as longer-term C sink. To explore its quantitative importance, we also model its magnitude at continental scale using the 2017 wildfire season in Europe. Our estimations show that the C sink ability of SOC water erosion during the first post-fire year could account for around 13% of the C emissions produced by wildland fires. This indicates that post-fire SOC erosion is a quantitatively important process in the overall C balance of fires and highlights the need for more field data to further validate this initial assessment.

KEYWORDS
carbon sequestration, prescribed fires, pyrogenic carbon, soil organic carbon, wildfires

1 | INTRODUCTION

Wildland fires have been a natural perturbation in many ecosystems for millions of years and currently burn around 774 million hectares annually (Chen et al., 2023), an area almost equivalent in size to Europe. Their extent and severity are on the rise in many forested regions of the world, often causing substantial socio-economic and environmental impacts (Jones et al., 2022). They also play an important role in the global carbon (C) cycle, releasing annually ~2.1 Pg ($1\ Pg = 10^{15}\ g$) of C into the atmosphere in the form of CO_2, other greenhouse gases and aerosols (van Wees et al., 2022). Their net effect on the C cycle, however, goes beyond emissions and involves many other interacting processes that are yet neither fully understood nor quantified. They, for example, alter vegetation growth and productivity (Pausas & Keeley, 2014), change soil respiration (Zhou et al., 2023) and transform organic carbon from vegetation and soils into the more environmentally persistent pyrogenic carbon (PyC; Bird et al., 2015; Coppola et al., 2022).

A potentially significant, but currently unexplored mechanism by which fire affects the C cycle is through its impact on soil erosion, which is often not considered (e.g. see recent review on fire impacts in the terrestrial C cycle by Hudiburg et al., 2023). Wildland fires can trigger and greatly increase soil erosion by water in the first months or years after fire (Figure 1), up to several orders of magnitude as compared to pre-fire conditions (Shakesby & Doerr, 2006; Vieira et al., 2023). This enhanced post-fire erosive response is driven by the loss of protective vegetation and litter cover and the alteration of the soil's structure and its wettability (Shakesby & Doerr, 2006). The degree to which these vegetation and soil properties are affected by fires is related to burn severity (Keeley, 2009). During the erosion and transport of soil by water, some of the soil C is mineralized and released into the atmosphere or transported to water bodies, but another fraction is buried in depositional sites and, thus, largely protected from further degradation (Berhe et al., 2007; Borrelli et al., 2018; Lugato et al., 2016). Therefore, if the burial and associated stabilization of eroded C at depositional sites, together with the recovery of soil organic carbon (SOC) in the eroded landscape, exceed the C losses during mobilization, soil C erosion acts as a C sink mechanism (Berhe et al., 2007). For agricultural land and unrelated to wildfire, the global significance of the erosion-induced terrestrial C sink has already been explored, and it has been estimated that around 26% of the eroded soil C worldwide could act as a sink (Van Oost et al., 2007; Van Oost & Six, 2023). However, there are opposing perspectives on this potential, and it has also been argued that soil erosion in agricultural lands could act as a C source instead (Lal, 2019; Lugato et al., 2018).

In contrast to erosion on agricultural land, the wider role of fire-enhanced soil erosion as a potential C sink mechanism has yet to be assessed. It could be of global significance for at least three key reasons. First, wildland fires are widely distributed around the Earth, with many fire-prone landscapes exhibiting substantial topography, and thus erosion-prone terrain such as the fire-prone regions of western North-America or much of the Mediterranean region (Bowman et al., 2020; Krawchuck et al., 2009). Second, post-fire erosion by water most readily entrains the exposed top layer of soils, which contains the highest concentration of organic C (Johnson et al., 1995). Indeed, topsoils (to 30 cm depth) in fire-prone regions are estimated to store around 460 Pg C (Pellegrini et al., 2022), which roughly equals the amount of C stored globally in vegetation (450 Pg; Friedlingstein et al., 2023). Finally, in recently burnt landscapes, an important part of the C in the highly erodible surface soil is PyC, which comprises a range of fire-derived organic compounds, resulting from the incomplete combustion of fuel biomass, and includes soil organic matter (SOM) that has been pyrolyzed, charcoal pieces from burned vegetation and, also, small charred organic particles accumulated within the ash on the ground. PyC is highly susceptible to be transported by water erosion, as well as carbon-enriched (on a mass basis) and substantially more resistant to environmental degradation than the original biomass it is derived from. These factors enhance its potential to become a C sink following post-fire erosion and burial (Santín et al., 2016).

There is a large body of studies quantifying soil erosion rates after fires (Girona-García et al., 2021; Shakesby, 2011 and references therein) but only a very small fraction of these has addressed C redistribution, leaving an important gap in the understanding of the effects of wildland fires on local to global-scale C dynamics. Here, we explore the magnitude of soil C erosion by water after wildland fires and its potential to act as a C sink based on an assessment of the available peer-reviewed studies on soil C erosion after wildland fires and estimations based on the data extracted from these and related studies. To illustrate its quantitative importance at continental scale, we also perform a modelling exercise estimating the magnitude of post-fire SOC erosion by water in Europe following the wildfires that occurred in 2017. We focused on soil erosion by water as dominant eroding agent compared to wind. For example, wind erosion in agricultural soils has been observed to be an order of magnitude lower than water erosion (Panagos et al., 2017).

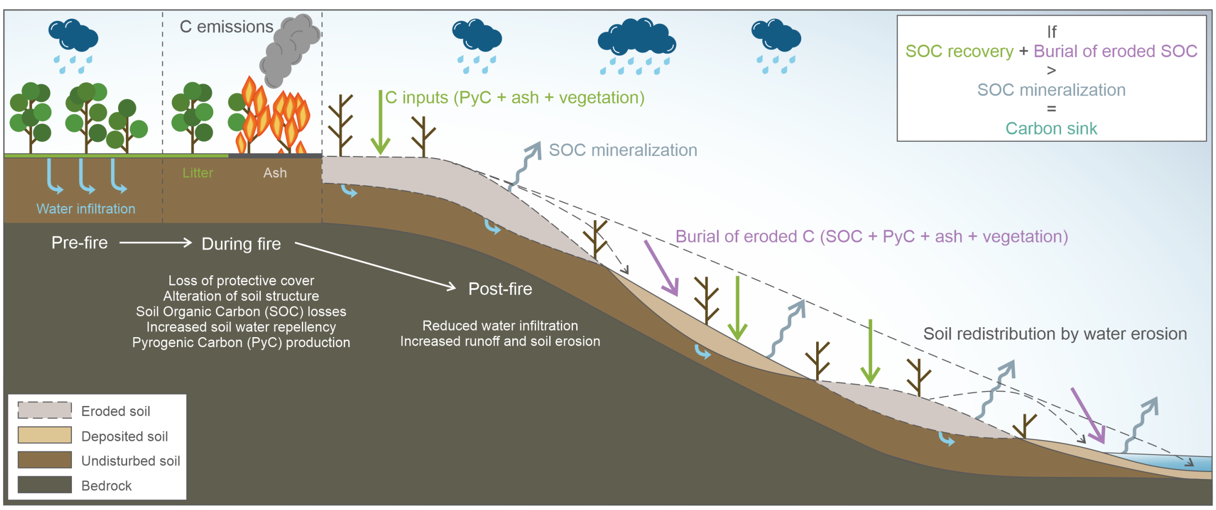

FIGURE 1 Representation of fire-induced changes in the soil that lead to enhanced erosion and interacting processes in the post-fire soil erosion response that determine its potential to act as a C sink. Note that these processes occur at different times and scales.

2 | THE MAGNITUDE OF SOC EROSION AFTER WILDLAND FIRES

The direct field assessment of post-fire soil and SOC erosion rates has only been addressed to date in 15 peer-reviewed articles containing 31 case studies, published between 2000 and 2023 and covering semi-arid, temperate, and continental climates in the USA, Portugal, and Spain (Table S1). These publications have quantified soil erosion rates at hillslope- (using bounded sediment barriers) and catchment- (using traps at the outlet) scales (Table S1). Most of these studies were not aimed at assessing C fluxes and dynamics, but at examining erosion rates to evaluate the effects of pre- or post-fire management, for example, erosion mitigation (Fernández, 2022; Prats et al., 2012, 2014, 2016, 2019, 2021), ploughing (Malvar et al., 2016) or logging (Malvar et al., 2017); however, they also quantified SOC (or SOM) contained in the eroded sediments as additional information, including, as controls, areas where treatments were not applied.

The data retrieved from the 31 case studies (Table S1) indicate that on average the eroded soil during the first post-fire year, period in which most of post-fire erosion usually happens, amounted to $5.4 \pm 7.1\,\mathrm{Mg\,ha^{-1}}$ (mean ± SD), from which $0.6 \pm 0.9\,\mathrm{Mg\,ha^{-1}}$ corresponded to SOC (Figure 2a), representing 12 ± 9% of the total eroded sediments. These figures show a large variability, which is a common trait of post-fire soil erosion rates, explained by the differences in soil type, rainfall regimes, and burn severity (Girona-García et al., 2021). These values also show the magnitude of the increase of soil erosion rates after fires as compared to unburned forests. As an example, in forested catchments with minimal disturbance of the Sierra National Forest (USA), soil erosion rates were $26 \pm 6\,\mathrm{kg\,ha^{-1}\,year^{-1}}$ over a period of 7 years, from which $0.2–4.4\,\mathrm{kg\,ha^{-1}\,year^{-1}}$ (0.9%–17% of the total eroded sediments) corresponded to eroded C (Stacy et al., 2015).

To put these values into perspective with other erosion-inducing disturbances, a comparison against those estimated by Van Oost et al. (2007) for global erosion in agricultural lands is provided in Figure 2. The average soil erosion rate in agricultural lands is $13.2 \pm 5.0\,\mathrm{Mg\,ha^{-1}\,year^{-1}}$, which is almost three times the average soil erosion rate for burned areas estimated here, and SOC erosion rates are of $0.156 \pm 0.095\,\mathrm{Mg\,ha^{-1}\,year^{-1}}$. However, the proportion of eroded SOC per total eroded sediment yield after fires (12 ± 9%) is an order of magnitude higher than in agricultural lands (1.2 ± 0.6%), as these soils tend to have lower C contents compared to vegetated wildland soils.

Following with the comparison with agricultural lands, the SOC stocks for the uppermost 0–2 cm reported in Van Oost et al. (2007) for these soils were of approximately $5.30 \pm 2.93\,\mathrm{Mg\,ha^{-1}}$, so the yearly SOC erosion rates described in the previous paragraph account for 3 ± 1% of these stocks. In the case of the post-fire studies (Table S1), the SOC stocks in the topsoil (0–2 cm in depth) right after fire were of $6.6 \pm 3.1\,\mathrm{Mg\,ha^{-1}}$ (Figure 2b), showing that, potentially, 8 ± 11% of these stocks could be eroded during the first post-fire year based on the abovementioned SOC erosion rates ($0.6 \pm 0.9\,\mathrm{Mg\,ha^{-1}}$). Notwithstanding that agricultural and post-fire erosion are not fully comparable due differences in the nature of the disturbance, soil characteristics, and duration of soil availability (Shakesby & Doerr, 2006), this exercise shows the quantitative relevance of post-fire C erosion.

3 | POST-FIRE SOC EROSION RATES AT EUROPEAN SCALE

During the 2017 European wildfire season, 633,429 ha of forests, grasslands, and shrublands were burnt, leading to 21.2 ± 8.5 million Mg of soil losses over the first post-fire year as estimated using the RUSLE soil erosion model (Vieira et al., 2023). In the current study, we have built on the successful previous application of this modeling framework to Europe; the only geographic region for which

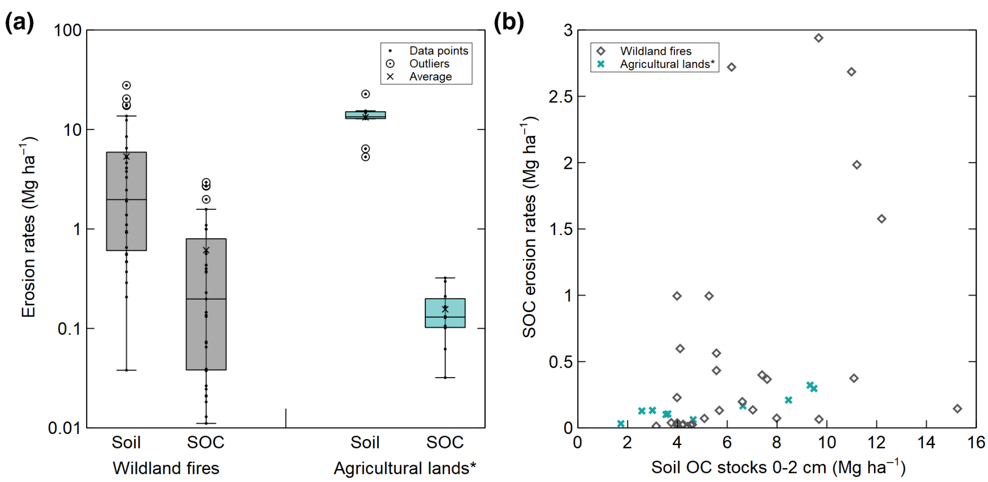

FIGURE 2 Soil and soil organic carbon (SOC) erosion rates after wildland fires and in agricultural lands at log scale (a); SOC erosion rates in relation to soil OC stocks (0–2 cm deep) after fire and in agricultural lands. *Soil and SOC erosion data obtained from Van Oost et al. (2007).

a modelling framework has been built and tested. This allowed applying SOC content ratios derived from our compiled database (Table S1) to estimate SOC erosion rates after the 2017 European wildfires (Text S2). We focused our analysis on the first post-fire year because this is the time period in which most of the post-fire erosion is expected to happen (Girona-García et al., 2021; Shakesby & Doerr, 2006; Vieira et al., 2023) and provided the greatest data availability. Our modelling exercise estimates that 2.5 million Mg of SOC were eroded (at a rate of 3.9 Mg ha^{-1}) during the first post-fire year (Figure 3). This highlights the relevance and magnitude of this process at large scales, especially when compared to soil and SOC erosion rates across other land uses. SOC erosion in European agricultural lands, which cover 187 million ha, has been estimated to amount to 10 million Mg y^{-1} (Lugato et al., 2016). Comparing those results to our model outputs, SOC losses in burned forest, shrubland, and grassland areas after the 2017 fires were equivalent to ~25% of those in European agricultural lands, which occupy 300-fold more surface (Lugato et al., 2016). It is, however, important to note that soil erosion in agricultural lands is a widespread and recurring process that is rarely limited by soil availability, while enhanced post-fire erosion is limited to the so-called window of disturbance (Prosser & Williams, 1998), which is usually greatest in the first year after fire, although it can span many years in cases where vegetation recovery particularly slow or where the ecosystem does not naturally recover and no mitigation measures have been applied (Girona-García et al., 2021; Vieira et al., 2023). Furthermore, on steep slopes, sediment exhaustion can limit the supply and, thus, the associated C erosion potential following fire (Shakesby, 2011).

4 | THE POTENTIAL OF POST-FIRE EROSION AS A SOIL CARBON SINK

The data presented here show that post-fire soil erosion by water mobilizes a substantial amount of SOC, both in relative terms (per surface area) and absolute terms (total eroded amount). The long-term fate of this mobilized SOC will determine whether post-fire SOC erosion by water can be considered a C sink (Figure 1). Several studies indicate that the mobilized SOC, which is mainly eroded from ridgetops and steep slopes (Blake et al., 2009; Campo et al., 2022; Novara et al., 2011), is either stored in depositional areas within the catchment (Galanter et al., 2018; Novara et al., 2011) or enters the stream network (Blake et al., 2009), where it can then be either buried in alluvial deposits (Cotrufo et al., 2016) or transported into the oceans (Jones et al., 2020). At the depositional sites, the mobilized SOC can be buried and stabilized through physical and chemical mechanisms, slowing its turnover rates and, thus, enhancing its role as a C sink (Billings et al., 2019; Doetterl et al., 2016). In addition, during transport by overland flow at the watershed scale, there can be an enrichment of stabilized SOC compounds, what can also facilitate the preservation of the deposited organic matter (Rumpel et al., 2014).

Instead of being stored at depositional sites, the eroded SOC can also be mineralized during mobilization, leading to a net loss of C to the atmosphere (Figure 1). During the transport phase, soil aggregate breakdown releases occluded SOC, becoming more exposed to oxygen, water, and to decomposers whose activity is favored by the incorporation of readily available SOC, enhancing the mineralization

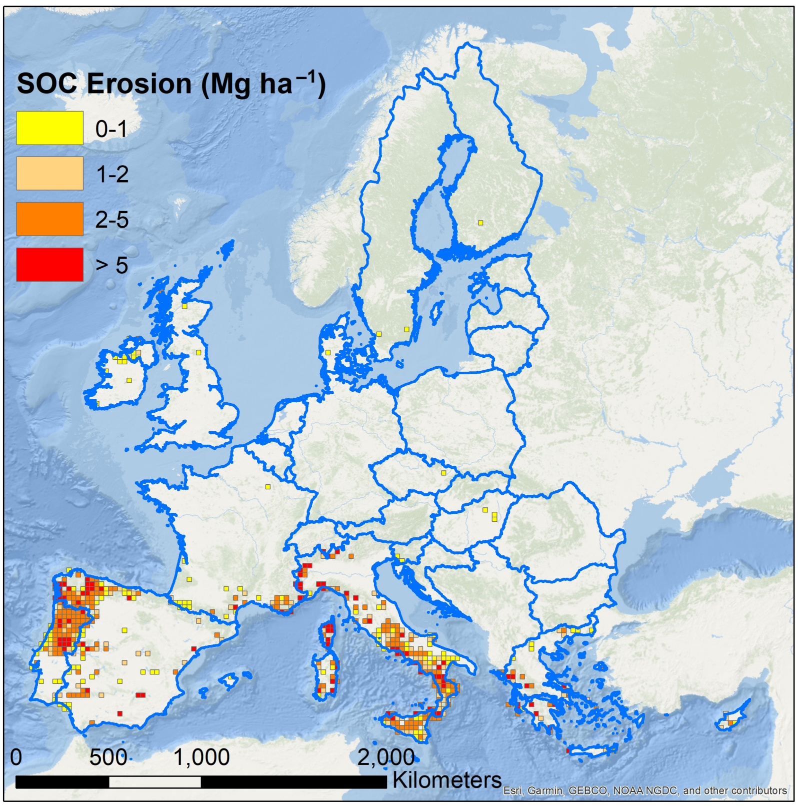

FIGURE 3 Estimated soil organic carbon (SOC) erosion for the first post-fire year after the 2017 wildfires in Europe. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

of more stable forms (De Nijs & Cammeraat, 2020). This mineralization is also conditioned by the duration and length of the transport until the SOC is ultimately deposited within the terrestrial ecosystems or in water bodies (Berhe & Kleber, 2013; Cotrufo et al., 2016). There are no data on the magnitude of SOC mineralization during its transport by post-fire water erosion, but data from agricultural lands show a wide range, accounting for 0%–43% of the eroded SOC (Xiao et al., 2018). This variability in mineralization rates is related to the complexity of the erosive processes, the source and stability of the transported C, and the site-specific environmental conditions (Doetterl et al., 2016).

In the case of fire-affected areas, the production of PyC also plays a fundamental role in the ability of post-fire SOC erosion to act as a C sink (Abney et al., 2017). PyC is produced in substantial quantities, estimated to account for around 11% of the global biomass carbon stocks affected by fire, and most of it remains on the ground after the fire (Jones et al., 2019). In addition, it is highly susceptible to water erosion, as it is not attached to minerals and has a low density (Masiello & Berhe, 2020). Moreover, its enhanced chemical recalcitrance makes it a more persistent C store than unburnt SOC (Santín et al., 2016).

When evaluating the capacity of post-fire SOC erosion by water to act as a C sink, the recovery of SOC at the eroding sites is the other key factor to take into account, in addition to the long-term fate of the mobilized SOC discussed above (Figure 1). At the hillslope scale, erosion acts as a net atmospheric sink when the lateral SOC losses are compensated by the incorporation of new organic inputs from vegetation, charred remains, and ash. However, it is worth considering that extreme erosion rates, which can often happen after wildfires (Girona-García et al., 2021), could also have a detrimental effect on the recovery of the net primary production and therefore, act as a C source (Van Oost & Six, 2023). This may be particularly relevant for areas with high fire recurrence that burn repeatedly before the ecosystem has fully recovered to its pre-fire status, which may result in an alternate state with shifts in vegetation type (and its implications for biomass build up and SOC of varying amount and composition) and even SOC exhaustion. At landscape scale, it becomes increasingly complex to assess this mechanism as SOC is heterogeneously distributed across landforms, where the site-specific conditions may also vary and therefore have different C storage capacities and dynamics. Wildland fires add another layer of complexity to this process, because the degree of burn severity is often highly heterogeneous at landscape scale, thus differentially influencing the erosion pathways and the amount and type of carbon that is being redistributed (Fernández, 2023; Shakesby, 2011). To assess the potential for C sequestration at larger scales, SOC exports to riverine systems also need to be considered. For agricultural landscapes, it has been estimated that 53%–95% of the eroded SOC is deposited in a limited area (14%–35%) within the catchment (Van Oost et al., 2007). This type of data is not available for burned landscapes, but the riverine exports of PyC to the oceans amounts to 34 ± 26% of the produced annually by wildland fires (Jones et al., 2020), what suggest that overall more than half of PyC produced may either be deposited or mineralized within the catchment.

The capacity for SOC erosion to act as a sink is also heavily dependent on the temporal scale in which this process is studied (Lal, 2019). Studies in agricultural lands reporting SOC erosion as a C source have considered short timescales (0.5 ± 0.7 years), whereas it has been observed to act as a sink at longer timescales (91 ± 1098 years; Van Oost & Six, 2023). These findings suggest that the erosion-induced sink increases with the duration of the disturbance, as it has been estimated that for two decades of disturbance 26% of the eroded SOC acts as a sink, but that fraction increases to 58%–100% over 100 years of continued erosion (Van Oost & Six, 2023). Thus, for agricultural lands, erosion could represent a C source initially, becoming a C sink around four decades after the beginning of the disturbance (Van Oost & Six, 2023). This increase in the sink potential of erosion is mainly associated with the lower SOC reposition rate at initial stages of the erosional disturbance, as compared to the rates at which it is being laterally eroded and/or mineralized. However, this is also one of the more controversial arguments for erosion to act as C sink, because other authors have estimated that the C losses produced during its transport would largely offset the sink effect (Lugato et al., 2018). This ongoing debate calls for further research to assess this potential at longer timescales (Lal, 2019).

In the case of wildland fires, the duration of the erosional disturbance might be shorter compared to agricultural lands, as erosion rates usually peak during the first post-fire year and gradually decline until vegetation recovers, which can take from months to several years (Shakesby & Doerr, 2006). However, it is worth noting that SOC erosion rates in that relatively shorter period are an order of magnitude higher after wildland fires than in agricultural lands. Apart from the intrinsic ecosystem and site characteristics, the duration of the post-fire erosional disturbance can be shortened by the application of mitigation treatments (Vieira et al., 2023). In addition, further fire-induced erosional processes could be triggered over time with recurrent fires, and fire frequency is expected to increase with climate change in many regions around the world (Senande-Rivera et al., 2022).

While sufficient data are still lacking to thoroughly assess the potential for the eroded SOC to act as a C sink in burned areas, we can broadly estimate its magnitude in relation to the C emissions during wildland fires. Following our estimations of 3.9 Mg SOC ha^{-1} eroded during the first year after the 2017 fires in Europe, and assuming that 26% of that eroded SOC could act as a C sink (based on the average estimated by Van Oost et al., 2007 for agricultural lands), 1.01 Mg ha^{-1} of C could be sequestered in the short-term in the soils of these burned areas. Considering that 7.7 Mg ha^{-1} $year^{-1}$ of C were emitted during the 2017 wildfires in Europe (generated using the Copernicus Atmosphere Monitoring Service Information (CAMS), 2024), our estimations suggest that the C sink ability of SOC redistributed by water erosion alone during the first post-fire year would account at least for around 13% of the C emissions produced by wildland fires. This figure, to which wind erosion is likely to add, indicates that post-fire SOC erosion could be a quantitatively significant actor in the global C cycle and calls for further research on this topic. This should include the effects of successive erosional events, the recovery of the net primary production, and the burial and stabilization of SOC and PyC. Additional and more detailed field data from diverse fire-prone regions, and including both water and wind erosion, are required for informing models and reduce the uncertainties in the estimations of C balances in burned areas, thus allowing to identify to what degree post-fire SOC erosion and burial acts a C sink at the global level.

AUTHOR CONTRIBUTIONS

Antonio Girona-García: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; visualization; writing – original draft. **Diana Vieira:** Conceptualization; formal analysis; investigation; methodology; resources; software; validation; writing – review and editing. **Stefan Doerr:** Conceptualization; funding acquisition; investigation; writing – review and editing. **Panos Panagos:** Conceptualization; investigation; resources; writing – review and editing. **Cristina Santín:** Conceptualization; funding acquisition; investigation; methodology; writing – review and editing.

ACKNOWLEDGMENTS

Antonio Girona-García is recipient of the Grant RYC2021-031262-I funded by MICIU/AEI/10.13039/501100011033 and by "European Union NextGenerationEU/PRTR"; and was also funded by the Spanish Research Council (Consejo Superior de Investigaciones Científicas, CSIC) through the project 20208AT007. Stefan Doerr was supported by Natural Environment Research Council grant UK-FDRS (NE/T003553/1) and the project FirEURisk, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement no. 101003890.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from Zenodo at https://zenodo.org/records/11207872.

ORCID

Antonio Girona-García https://orcid.org/0000-0001-7003-8950
Diana Vieira https://orcid.org/0000-0003-2213-3798
Stefan Doerr https://orcid.org/0000-0002-8700-9002
Panos Panagos https://orcid.org/0000-0003-1484-2738
Cristina Santín https://orcid.org/0000-0001-9901-2658

REFERENCES

Abney, R. B., Sanderman, J., Johnson, D., Fogel, M. L., & Berhe, A. A. (2017). Post-wildfire erosion in mountainous terrain leads to rapid and major redistribution of soil organic carbon. *Frontiers in Earth Science*, *5*, 99. https://doi.org/10.3389/feart.2017.00099

Berhe, A. A., Harte, J., Harden, J. W., & Torn, M. S. (2007). The significance of erosion-induced terrestrial carbon sink. *Bioscience*, *57*, 337–346. https://doi.org/10.1641/B570408

Berhe, A. A., & Kleber, M. (2013). Erosion, deposition, and the persistence of soil organic matter: Mechanistic considerations and problems with terminology. *Earth Surface Processes and Landforms*, *38*(8), 908–912. https://doi.org/10.1002/esp.3408

Billings, S. A., Richter, D. B., Ziegler, S. E., Prestegaard, K., & Wade, A. M. (2019). Distinct contributions of eroding and depositional profiles to land-atmosphere CO_2 exchange in two contrasting forests. *Frontiers in Earth Science*, *7*, 36. https://doi.org/10.3389/feart.2019.00036

Bird, M. I., Wynn, J. G., Saiz, G., Wurster, C. M., & McBeath, A. (2015). The pyrogenic carbon cycle. *Annual Review of Earth and Planetary Sciences*, *43*, 273–298. https://doi.org/10.1146/annurev-earth-060614-105038

Blake, W. H., Wallbrink, P. J., Wilkinson, S. N., Humphreys, G. S., Doerr, S. H., Shakesby, R. A., & Tomkins, K. M. (2009). Deriving hillslope sediment budgets in wildfire-affected forests using fallout radionuclide tracers. *Geomorphology*, *104*, 105–116. https://doi.org/10.1016/j.geomorph.2008.08.004

Borrelli, P., Van Oost, K., Meusburger, K., Alewell, C., Lugato, E., & Panagos, P. (2018). A step towards a holistic assessment of soil degradation in Europe: Coupling on-site erosion with sediment transfer and carbon fluxes. *Environmental Research*, *161*, 291–298. https://doi.org/10.1016/j.envres.2017.11.009

Bowman, D. M. J. S., Kolden, C. A., Abatzoglou, J. T., Johnston, F. H., van der Werf, G. R., & Flannigan, M. (2020). Vegetation fires in the Anthropocene. *Nature Reviews Earth and Environment*, *1*, 500–515. https://doi.org/10.1038/s43017-020-0085-3

Campo, J., Cammeraat, E. L. H., Gimeno-García, E., & Andreu, V. (2022). Soil and organic carbon redistribution in a recently burned Mediterranean hillslope affected by water erosion processes. *Geoderma*, *406*, 115539. https://doi.org/10.1016/j.geoderma.2021.115539

Chen, Y., Hall, J., van Wees, D., Andela, N., Hantson, S., Giglio, L., van der Werf, G. R., Morton, D. C., & Randerson, J. T. (2023). Multi-decadal trends and variability in burned area from the fifth version of the global fire emissions database (GFED5). *Earth System Science Data*, *15*, 5227–5259. https://doi.org/10.5194/essd-15-5227-2023

Copernicus Atmosphere Monitoring Service Information (CAMS). (2024). CAMS global biomass burning emissions based on fire radiative power (GFAS). https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-global-fire-emissions-gfas?tab=overview

Coppola, A. I., Wagner, S., Lennartz, S. T., Seidel, M., Ward, N. D., Dittmar, T., Santín, C., & Jones, M. W. (2022). The black carbon cycle and its role in the earth system. *Nature Reviews Earth and Environment*, *3*, 516–532. https://doi.org/10.1038/s43017-022-00316-6

Cotrufo, M. F., Boot, C. M., Kampf, S., Nelson, P. A., Brogan, D. J., Covino, T., Haddix, M. L., MacDonald, L. H., Rathburn, S., Ryan-Bukett, S., Schmeer, S., & Hall, E. (2016). Redistribution of pyrogenic carbon from hillslopes to stream corridors following a large montane wildfire. *Global Biogeochemical Cycles*, *30*, 1348–1355. https://doi.org/10.1016/10.1002/2016GB005467

De Nijs, E. A., & Cammeraat, E. L. H. (2020). The stability and fate of soil organic carbon during the transport phase of soil erosion. *Earth-Science Reviews*, *201*, 103067. https://doi.org/10.1016/j.earscirev.2019.103067

Doetterl, S., Berhe, A. A., Nadeu, E., Wang, Z., Sommer, M., & Fiener, P. (2016). Erosion, deposition and soil carbon: A review of process-level controls, experimental tools and models to address C cycling in dynamic landscapes. *Earth-Science Reviews*, *154*, 102–122. https://doi.org/10.1016/j.earscirev.2015.12.005

Fernández, C. (2022). Carbon loss in sediments and sequestration in vegetation after wildfire and mulching in a high-severity burned area in NW Spain. *Journal of Sustainable Forestry*, *42*(5), 206–517. https://doi.org/10.1080/10549811.2022.2045506

Fernández, C. (2023). Soil fire severity is more relevant than fire frequency in explaining soil, carbon and nitrogen losses and vegetation recovery after wildfire in NW Spain. *Journal of Environmental Management*, *327*, 116876. https://doi.org/10.1016/j.jenvman.2022.116876

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Bakker, D. C. E., Hauck, J., Landschützer, P., Le Quéré, C., Luijkx, I. T., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Anthoni, P., … Zheng, B. (2023). Global carbon budget 2023. *Earth System Science Data*, *15*, 5301–5369. https://doi.org/10.5194/essd-15-5301-2023

Galanter, A., Cadol, D., & Lohse, K. (2018). Geomorphic influences on the distribution and accumulation of pyrogenic carbon (PyC) following a low severity wildfire in northern New Mexico. *Earth Surface Processes and Landforms*, *43*, 2207–2218. https://doi.org/10.1002/esp.4386

Girona-García, A., Vieira, D. C. S., Silva, J., Fernández, C., Robichaud, P. R., & Keizer, J. J. (2021). Effectiveness of post-fire soil erosion mitigation treatments: A systematic review and meta-analysis. *Earth-Science Reviews*, *217*, 103611. https://doi.org/10.1016/j.earscirev.2021.103611

Hudiburg, T., Mathias, J., Bartowitz, K., Berardi, D. M., Bryant, K., Graham, E., Kolden, C. A., Betts, R. A., & Lynch, L. (2023). Terrestrial carbon dynamics in an era of increasing wildfire. *Nature Climate Change*, *13*, 1306–1316. https://doi.org/10.1038/s41558-023-01881-4

Johnson, M. G., Levine, E. R., & Kern, J. S. (1995). Soil organic matter: Distribution, genesis, and management to reduce greenhouse gas emissions. *Water, Air, and Soil Pollution*, *82*, 593–615. https://doi.org/10.1007/BF00479414

Jones, M. W., Abatzoglou, J. T., Veraverbeke, S., Andela, N., Lasslop, G., Forkel, M., Smith, A. J. P., Burton, C., Betts, R. A., van der Werf, G. R., Sitch, S., Canadell, J. G., Santín, C., Kolden, C., Doerr, S. H., & Le Queré, C. (2022). Global and regional trends and drivers of fire under climate change. *Reviews of Geophysics*, *60*, e2020RG000726. https://doi.org/10.1029/2020RG000726

Jones, M. W., Coppola, A. I., Santín, C., Dittmar, T., Jaffé, R., Doerr, S. H., & Quine, T. A. (2020). Fires prime terrestrial organic carbon for riverine export to the global oceans. *Nature Communications*, *11*, 2791. https://doi.org/10.1038/s41467-020-16576-z

Jones, M. W., Santín, C., van der Werf, G. R., & Doerr, S. H. (2019). Global fire emissions buffered by the production of pyrogenic carbon. *Nature Geoscience*, *12*, 742–747. https://doi.org/10.1038/s41561-019-0403-x

Keeley, J. E. (2009). Fire intensity, fire severity and burn severity: A brief review and suggested usage. *International Journal of Wildland Fire*, *18*(1), 116–126. https://doi.org/10.1071/WF07049

Krawchuck, M. A., Moritz, M. A., Parisien, M. A., van Dorn, J., & Hayhoe, K. (2009). Global pyrogeography: The current and future distribution of wildfire. *PLoS One*, *4*(4), e5102. https://doi.org/10.1371/journal.pone.0005102

Lal, R. (2019). Accelerated soil erosion as a source of atmospheric CO_2. *Soil & Tillage Research*, *188*, 35–40. https://doi.org/10.1016/j.still.2018.02.001

Lugato, E., Paustian, K., Panagos, P., Jones, A., & Borrelli, P. (2016). Quantifying the erosion effect on current carbon budget of European agricultural soils at high spatial resolution. *Global Change Biology*, *22*, 1976–1984. https://doi.org/10.1111/gcb.13198

Lugato, E., Smith, P., Borrelli, P., Panagos, P., Ballabio, C., Orgiazzi, A., Fernández-Ugalde, O., Montanarella, L., & Jones, A. (2018). Soil erosion is unlikely to drive a future carbon sink in Europe. *Science Advances*, *4*(11). https://doi.org/10.1126/sciadv.aau352

Malvar, M., Prats, S. A., & Keizer, J. J. (2016). Runoff and inter-rill erosion affected by wildfire and pre-fire ploughing in eucalypt plantations of north-central Portugal. *Land Degradation & Development*, *27*, 1366–1378. https://doi.org/10.1016/10.1002/ldr.2365

Malvar, M. C., Silva, F. C., Prats, S. A., Vieira, D. C. S., Coelho, C. O. A., & Keizer, J. J. (2017). Short-term effects of post-fire salvage logging on runoff and soil erosion. *Forest Ecology and Management*, *400*, 555–567. https://doi.org/10.1016/j.foreco.2017.06.031

Masiello, C. A., & Berhe, A. A. (2020). First interactions with the hydrologic cycle determine pyrogenic carbon's fate in the earth system. *Earth Surface Processes and Landforms*, *45*, 2394–2398. https://doi.org/10.1002/esp.4925

Novara, A., Gristina, L., Bodí, M. B., & Cerdá, A. (2011). The impact of fire on redistribution of soil organic matter on a Mediterranean hillslope under maquia vegetation type. *Land Degradation & Development*, *22*, 530–536. https://doi.org/10.1016/10.1002/ldr.1027

Panagos, P., Ballabio, C., Lugato, E., Jones, A., & Borrelli, P. (2017). Condition of agricultural soil: Factsheet on soil erosion. EUR 29020, EN, Publications Office of the European Union, Luxembourg https://doi.org/10.2760/728794

Pausas, J. G., & Keeley, J. E. (2014). Evolutionary ecology of resprouting and seeding in fire-prone ecosystems. *New Phytologist*, *204*, 55–65. https://doi.org/10.1111/nph.12921

Pellegrini, A. F. A., Harden, J., Georgiu, K., Hemes, K. S., Malhotra, A., Nolan, C. J., & Jackson, R. B. (2022). Fire effects on the persistence of soil organic matter and long-term carbon storage. *Nature Geoscience*, *15*, 5–13. https://doi.org/10.1038/s41561-021-00867-1

Prats, S. A., González-Pelayo, O., Silva, F. C., Bokhorst, K. J., Baartman, J. E. M., & Keizer, J. J. (2019). Post-fire soil erosion mitigation at the scale of swales using forest logging residues at a reduced application rate. *Earth Surface Processes and Landforms*, *44*(14), 2837–2848. https://doi.org/10.1002/esp.4711

Prats, S. A., MacDonald, L. H., Monteiro, M., Ferreira, A. J. D., Coelho, C. O. A., & Keizer, J. J. (2012). Effectiveness of forest residue mulching in reducing post-fire runoff and erosion in a pine and a eucalypt plantation in north-central Portugal. *Geoderma*, *191*, 115–124. https://doi.org/10.1016/j.geoderma.2012.02.009

Prats, S. A., Martins, M. A. S., Malvar, M. C., Ben-Hur, M., & Keizer, J. J. (2014). Polyacrylamide application versus forest residue mulching for reducing post-fire runoff and soil erosion. *Science of the Total Environment*, *468-469*, 464–474. https://doi.org/10.1016/j.scitotenv.2013.08.066

Prats, S. A., Merino, A., González-Pérez, J. A., Verheijen, F. G. A., & de la Rosa, J. M. (2021). Can straw-biochar mulching mitigate erosion of wildfire-degraded soils under extreme rainfall? *Science of the Total Environment*, *761*, 143219. https://doi.org/10.1016/j.scitotenv.2020.143219

Prats, S. A., Wagenbrenner, J. W., Martins, M. A. S., Malvar, M. C., & Keizer, J. J. (2016). Mid-term and scaling effects of forest residue mulching on post-fire runoff and soil erosion. *Science of the Total Environment*, *573*, 1242–1254. https://doi.org/10.1016/j.scitotenv.2016.04.064

Prosser, I. P., & Williams, L. (1998). The effect of wildfire on runoff and erosion in native *Eucalyptus* forest. *Hydrological Processes*, *12*, 251–265. https://doi.org/10.1002/(SICI)1099-1085(199802)12:2<251::AIDHYP574>3.0.CO;2-4

Rumpel, C., Chaplot, V., Ciais, P., Chabbi, A., Bouahom, B., & Valentin, C. (2014). Composition changes of eroded carbon at different spatial scales in a tropical watershed suggest enrichment of degraded material during transport. *Biogeosciences*, *11*(12), 3299–3305. https://doi.org/10.5194/bg-11-3299-2014

Santín, C., Doerr, S. H., Kane, E. S., Masiello, C. A., Ohlson, M., de la Rosa, J. M., Preston, C. M., & Dittmar, T. (2016). Towards a global assessment of pyrogenic carbon from vegetation fires. *Global Change Biology*, *22*(1), 76–91. https://doi.org/10.1111/gcb.12985

Senande-Rivera, M., Insua-Costa, D., & Miguez-Macho, G. (2022). Spatial and temporal expansion of global wildland fire activity in response to climate change. *Nature Communications*, *13*, 1208. https://doi.org/10.1038/s41467-022-28835-2

Shakesby, R., & Doerr, S. (2006). Wildfire as a hydrological and geomorphological agent. *Earth-Science Reviews*, *74*(3–4), 269–307. https://doi.org/10.1016/j.earscirev.2005.10.006

Shakesby, R. A. (2011). Post-wildfire soil erosion in the Mediterranean: Review and future research directions. *Earth-Science Reviews*, *105*(3–4), 71–100. https://doi.org/10.1016/j.earscirev.2011.01.001

Stacy, E. M., Hart, S. C., Hunsaker, C. T., Johnson, D. W., & Berhe, A. A. (2015). Soil carbon and nitrogen erosion in forested catchments: Implications for erosion-induced terrestrial carbon sequestration. *Biogeosciences*, *12*, 4861–4874. https://doi.org/10.5194/bg-12-4861-2015

Van Oost, K., Quine, T. A., Govers, G., de Gryze, S., Six, J., Harden, J. W., Ritchie, J. C., McCarty, G. W., Heckrath, G., Kosmas, C., Giraldez, J. V., Marques da Silva, J. R., & Merckx, R. (2007). The impact of agricultural soil erosion on the global carbon cycle. *Science*, *318*, 626–629. https://doi.org/10.1126/science.1145724

Van Oost, K., & Six, J. (2023). Reconciling the paradox of soil organic carbon erosion by water. *Biogeosciences*, *20*, 635–646. https://doi.org/10.5194/bg-20-635-2023

Van Wees, D., van der Werf, G. R., Randerson, J. T., Rogers, B. M., Chen, Y., Veraverbeke, S., Giglio, L., & Morton, D. C. (2022). Global biomass burning fuel consumption and emissions at 500m spatial resolution based on the Global Fire Emissions Database (GFED). *Geoscientific Model Development*, *15*(22), 8411–8437. https://doi.org/10.5194/gmd-15-8411-2022

Vieira, D. C. S., Borrelli, P., Jahanianfard, D., Benali, A., Scarpa, S., & Panagos, P. (2023). Wildfires in Europe: Burned soils require attention. *Environmental Research*, *217*, 114936. https://doi.org/10.1016/j.envres.2022.114936

Xiao, H., Li, Z., Chang, X., Huang, B., Nie, X., Liu, C., Wang, D., & Jiang, J. (2018). The mineralization and sequestration of organic carbon in relation to agricultural soil erosion. *Geoderma*, *329*, 73–81. https://doi.org/10.1016/j.geoderma.2018.05.018

Zhou, L., Liu, S., Gu, Y., Wu, L., Hu, H.-W., & He, J.-Z. (2023). Fire decreases soil respiration and its components in terrestrial ecosystems. *Functional Ecology*, *00*, 1–12. https://doi.org/10.1111/1365-2435.14443

DATA SOURCES

Abney, R. B., Kuhn, T. J., Chow, A., Hockaday, W., Fogel, M. L., & Berhe, A. A. (2019). Pyrogenic carbon erosion after the rim fire, Yosemite National Park: The role of burn severity and slope. *Journal of Geophysical Research: Biogeosciences*, *124*(2), 432–449. https://doi.org/10.1029/2018JG004787

Campo, J., Cammeraat, E. L. H., Gimeno-García, E., & Andreu, V. (2022). Soil and organic carbon redistribution in a recently burned Mediterranean hillslope affected by water erosion processes. *Geoderma*, *406*, 115539. https://doi.org/10.1016/j.geoderma.2021.115539

Faria, S. R., de la Rosa, J. M., Knicker, H., González-Pérez, J. A., & Keizer, J. J. (2015). Molecular characterization of wildfire impacts on organic matter in eroded sediments and topsoil in Mediterranean eucalypt stands. *Catena*, *135*, 29–37. https://doi.org/10.1016/j.catena.2015.07.007

Fernández, C. (2022). Carbon loss in sediments and sequestration in vegetation after wildfire and mulching in a high-severity burned area in NW Spain. *Journal of Sustainable Forestry*, *42*(5), 206–517. https://doi.org/10.1080/10549811.2022.2045506

Fernández, C. (2023). Soil fire severity is more relevant than fire frequency in explaining soil, carbon and nitrogen losses and vegetation recovery after wildfire in NW Spain. *Journal of Environmental Management*, *327*, 116876. https://doi.org/10.1016/j.jenvman.2022.116876

Gimeno-García, E., Andreu, V., & Rubio, J. L. (2000). Changes in organic matter, nitrogen, phosphorus and cations in soil as a result of fire and water erosion in a Mediterranean landscape. *European Journal of Soil Science*, *51*, 201–210. https://doi.org/10.1046/j.1365-2389.2000.00310.x

Malvar, M., Prats, S. A., & Keizer, J. J. (2016). Runoff and inter-rill erosion affected by wildfire and pre-fire ploughing in eucalypt plantations of north-central Portugal. *Land Degradation & Development*, *27*, 1366–1378. https://doi.org/10.1016/10.1002/ldr.2365

Malvar, M. C., Silva, F. C., Prats, S. A., Vieira, D. C. S., Coelho, C. O. A., & Keizer, J. J. (2017). Short-term effects of post-fire salvage logging on runoff and soil erosion. *Forest Ecology and Management*, *400*, 555–567. https://doi.org/10.1016/j.foreco.2017.06.031

Pierson, D. N., Robichaud, P. R., Rhoades, C. C., & Brown, R. E. (2019). Soil carbon and nitrogen eroded after severe wildfire and erosion mitigation treatments. *International Journal of Wildland Fire*, *28*, 814–821. https://doi.org/10.1071/WF18193

Prats, S. A., González-Pelayo, O., Silva, F. C., Bokhorst, K. J., Baartman, J. E. M., & Keizer, J. J. (2019). Post-fire soil erosion mitigation at the scale of swales using forest logging residues at a reduced application rate. *Earth Surface Processes and Landforms*, *44*(14), 2837–2848. https://doi.org/10.1002/esp.4711

Prats, S. A., MacDonald, L. H., Monteiro, M., Ferreira, A. J. D., Coelho, C. O. A., & Keizer, J. J. (2012). Effectiveness of forest residue mulching in reducing post-fire runoff and erosion in a pine and a eucalypt plantation in north-central Portugal. *Geoderma*, *191*, 115–124. https://doi.org/10.1016/j.geoderma.2012.02.009

Prats, S. A., Martins, M. A. S., Malvar, M. C., Ben-Hur, M., & Keizer, J. J. (2014). Polyacrylamide application versus forest residue mulching for reducing post-fire runoff and soil erosion. *Science of the Total Environment*, *468-469*, 464–474. https://doi.org/10.1016/j.scitotenv.2013.08.066

Prats, S. A., Merino, A., González-Pérez, J. A., Verheijen, F. G. A., & de la Rosa, J. M. (2021). Can straw-biochar mulching mitigate erosion of wildfire-degraded soils under extreme rainfall? *Science of the Total Environment*, *761*, 143219. https://doi.org/10.1016/j.scitotenv.2020.143219

Prats, S. A., Wagenbrenner, J. W., Martins, M. A. S., Malvar, M. C., & Keizer, J. J. (2016). Mid-term and scaling effects of forest residue mulching on post-fire runoff and soil erosion. *Science of the Total Environment*, *573*, 1242–1254. https://doi.org/10.1016/j.scitotenv.2016.04.064

Shakesby, R. A., Bento, C. P. M., Ferreira, C. S. S., Ferreira, A. J. D., Stoof, C. R., Urbanek, E., & Walsh, R. P. D. (2015). Impacts of prescribed fire on soil loss and soil quality: An assessment based on an experimentally-burned catchment in central Portugal. *Catena*, *128*, 278–293. https://doi.org/10.1016/j.catena.2013.03.012

SUPPORTING INFORMATION

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How to cite this article: Girona-García, A., Vieira, D., Doerr, S., Panagos, P., & Santín, C. (2024). Into the unknown: The role of post-fire soil erosion in the carbon cycle. *Global Change Biology*, *30*, e17354. https://doi.org/10.1111/gcb.17354