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Key Points:

- Soil carbon models overlook petrogenic organic carbon (OC) contributions to soil and thus may underestimate soil carbon stocks
- Understanding the role of petrogenic OC alongside biospheric carbon is vital for assessing soil carbon dynamics
- Cross-disciplinary research is needed to study the transport and stability of petrogenic OC in soil systems

Supporting Information:

Supporting Information may be found in the online version of this article.

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The Known Unknowns of Petrogenic Organic Carbon in Soils

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Abstract Intensifying effects of global climate change have spurred efforts to enhance carbon sequestration and the long-term storage of soil organic carbon (OC). Current soil carbon models predominantly assume that inputs of OC are biospheric, that is, primarily derived from plant decomposition. However, these overlook the contribution of OC from soil parent material, including petrogenic organic carbon (OC_{petro}) from OC-bearing (meta-)sedimentary bedrock. To our knowledge, no soil carbon model accounts for the inputs of OC_{petro} to soils, resulting in significant gaps in our understanding about the roles OC_{petro} plays in soils. Here, we call for cross-disciplinary research to investigate the transport and stability of OC_{petro} across the bedrock–soil continuum. We pose four key questions as motivation for this effort. Ignoring the inputs of OC_{petro} to soils has significant implications, including overestimating biospheric carbon stocks and turnover times. Furthermore, we lack information on the role that OC_{petro} may play in priming microbial communities, as well as the impacts of land management on OC_{petro} stocks.

Plain Language Summary Some soils store carbon not just from plants but also from the rocks beneath them. This rock-derived carbon, called petrogenic organic carbon (OC_{petro}), comes from certain types of bedrock (e.g., shale). Most current models of soil carbon focus only on plant-derived carbon, ignoring the role of OC_{petro}. This oversight could mean we are underestimating the total carbon stored in soils, especially in deeper layers. Furthermore, the geologic age of OC_{petro} means that it may significantly impact ^{14}C signatures of soil OC, and hence apparent carbon turnover times. Additionally, we still don't fully understand how OC_{petro} might affect soil microbes or how land management practices influence this type of carbon. To address these gaps, researchers need to explore how OC_{petro} moves from bedrock into soil and how stable it is once there. This requires collaboration between scientists studying soils, rocks, and ecosystems. Answering key questions about OC_{petro}'s behavior could improve our understanding of soil carbon and help us manage soils more effectively for climate change mitigation. Including OC_{petro} in soil carbon models is a critical step toward better predictions of soil carbon storage and its role in the global carbon cycle.

1. The Absence of OC_{petro} in Soil Carbon Cycle Models

Soils constitute one of the most substantial terrestrial reservoirs of carbon. They harbor in excess of 1,500 Pg of organic carbon (OC; Scharlemann et al., 2014), a pool more than twice the size of that currently held in the atmosphere. Efforts to enhance both carbon sequestration and the long-term storage of soil OC have enriched our understanding about the different pools and transfers of OC within soils (Wang et al., 2023). Whilst there is no single soil carbon model applicable for all land-use contexts, most if not all are based on the principle that the major input of OC to soils is biospheric in origin and driven by photosynthetic carbon fixation (Janzen, 2004; Noë et al., 2023). Predominantly, this includes litter and plant residues, root exudation, the inputs of animal wastes (e.g., farmyard manure) and decomposition products of plants or organic matter present as microbial residues and necromass. Evidently absent from soil carbon models, and arguably the wider discourse within soil science, is the OC which is inherited from the underlying soil parent material during soil formation.

The roles that soil parent materials play in storing photosynthetically-derived (i.e., biospheric) OC is emerging (Evans, 2025; Moreland et al., 2021; Tye et al., 2022). However, some parent materials also act as sources of OC to soils. Here, we specifically refer to geogenic or petrogenic organic carbon (hereafter, OC_{petro}) from OC-bearing (meta-)sedimentary bedrock such as shale. Observations of the upward conveyance of rock-derived minerals and,

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in this case, OC_{petro} along the bedrock–soil continuum are not uncommon (e.g., Kalks et al., 2021; Riebe et al., 2017). Although not all bedrock contains OC_{petro}, many geoscientists have demonstrated the prevalence of petrogenic OC across both terrestrial and marine environments (Blair & Aller, 2012; Copard et al., 2007). Moreover, recent research has shown the potentially large influence that OC_{petro} can have on our calculations of soil OC turnover and stability in soils (Grant et al., 2023; Williams & Lawrence, 2025).

In spite of this emerging empirical work, no soil carbon model to the best of our knowledge has yet comprehensively considered the inputs of OC_{petro} to soils, reflecting a larger void in our understanding of carbon dynamics across the bedrock–soil continuum. Without accounting for OC_{petro} inputs into soil systems, we (a) risk overestimating biospheric carbon stocks and turnover times; (b) remain unaware of the roles that OC_{petro} may play in priming microbial communities within the subsoil and catalyzing enhanced microbial respiration (X. Chen et al., 2022; Y. Chen et al., 2022); and (c) are ignorant of the potential effects of land management practices on the stability of OC_{petro} within soils. Combined, these hamper our efforts to develop valid and accurate models (including long-term forecasts) of soil OC, and our ability to design robust land-use policies in pursuit of Net Zero carbon emissions. In this Perspective, we are calling on the geoscience community to undertake concerted cross-disciplinary efforts to study the transport and stability of OC_{petro} across the bedrock–soil continuum.

2. The Presence and Role of OC_{petro} as a Topic of Broader Relevance to the Geoscience Community

The geologic cycling of OC_{petro} has seen a flurry of research following studies that reveal considerable amounts of OC_{petro} are reburied in new sedimentary strata (e.g., Galy et al., 2008). With contributions across disparate geoscience disciplines including palynology, organic petrology and geochemistry, OC_{petro} has been detected in many modern soil and sedimentary environments (Blattmann et al., 2018). In particular, the popularization of radiocarbon measurements and thermal methods (e.g., ramped pyrolysis) have succeeded in providing quantitative constraints on the abundance of OC_{petro}, disentangling it from the typically larger "biospheric" OC component (e.g., Hilton & West, 2020). Its prevalence in surface environments indicates that a fraction of OC_{petro} released from bedrock embarks on a journey from the geosphere to the pedosphere and eventually back into the geosphere along sedimentary source-to-sink pathways (Figure 1). This, in turn, implies that a portion of OC burial operates in a CO_2 neutral manner, and it is therefore important to distinguish this from the burial of fresh biospheric OC to accurately assess carbon sequestration (Galvez et al., 2020). Daines et al. (2017) introduce a general concept on OC_{petro} cycling operating through geologic time, with greater reburial during the Archean and Proterozoic owing to a lower oxygen content in the atmosphere, and relatively little OC_{petro} reburial during times similar to modern-day oxygen levels that lead to a high degree of oxidation. With its oxidation, not only is CO_2 released, but O_2 is also consumed, resulting in an interplay of OC_{petro} cycling with, and responding to, atmospheric chemistry (Canfield, 2021; Nabhan & Canfield, 2023). Episodes of accelerated OC_{petro} cycling contributing to substantial CO_2 release to the atmosphere have been suggested during times of deglaciation that exposed reactive OC_{petro} to rapid oxidation (Blattmann, 2022) as well as release during greenhouse conditions that prevailed during the Paleocene-Eocene Thermal Maximum (e.g., Hollingsworth et al., 2024; Lyons et al., 2019). Throughout the vast expanse of geologic time, a fraction of OC_{petro} also appears to undergo exhumation and reburial over multiple cycles (Galy et al., 2008; Sparkes et al., 2020). Recalcitrant, more highly condensed (graphitized) forms of OC_{petro}, are thus stable enough to withstand repetitive cycling through the geosphere–pedosphere domains.

The recycling efficiency of OC_{petro}, as well as the loci and conditions that promote its oxidation, are the subject of current debate (e.g., Fox et al., 2020; Li & Li, 2024; Ruben et al., 2023). What has been missing to date is an understanding of the processes by which OC_{petro} transfers from the lithosphere to the pedosphere (i.e., across the bedrock–saprolite–soil continuum). Grant et al. (2023) make the case that OC_{petro} is not only a component of soil OC, but it is sufficiently abundant to warrant a paradigm shift in current conceptual models of soil carbon storage and turnover. Adding to the dynamic nature of soil OC, the degradation kinetics of OC_{petro} are also sensitive to temperature changes (Roylands et al., 2024; Soong et al., 2021). Merging geoscience and soil science perspectives on OC_{petro} cycling will advance our understanding of the carbon cycle amidst global climate change.

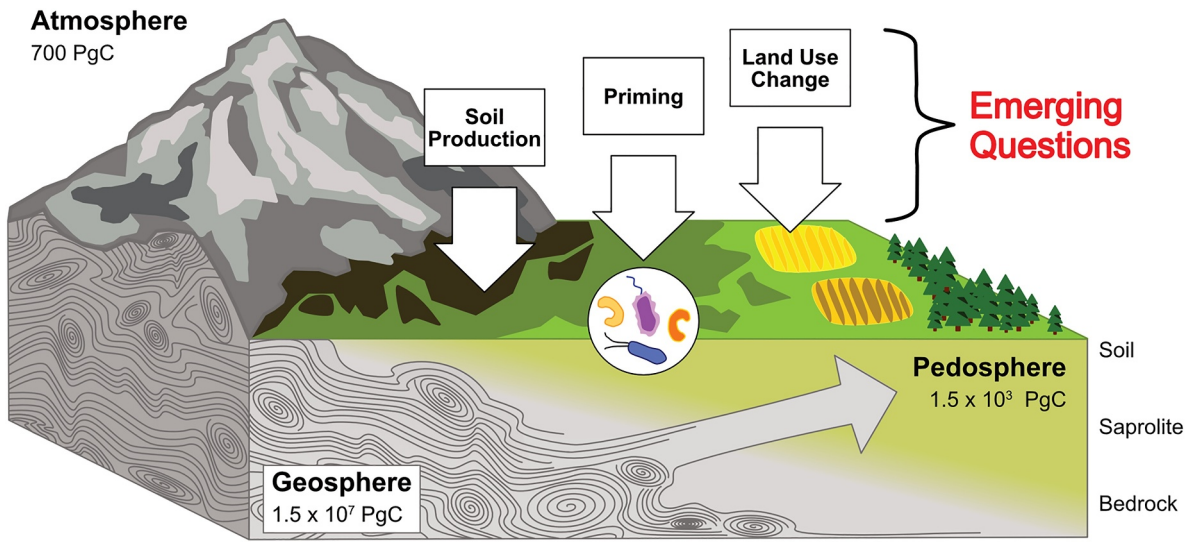

Figure 1. Petrogenic organic carbon from the geosphere is redistributed into the pedosphere via bedrock weathering and soil formation processes. The "known unknowns" discussed in this paper have roles in modulating both the rate at which this occurs, and the fate of the OC_{petro} in soils.

3. Emerging Questions on OC_{petro} Across the Bedrock–Soil Continuum

3.1. To What Extent Is the Input of OC_{petro} From Bedrock to Soil Limited by the Soil Production Function?

One of the most important yet understudied interfaces relevant to OC_{petro} is that marked by the transition between OC-bearing bedrock and the overlying soil profile. Across the bedrock–soil continuum, physical and chemical weathering processes transform consolidated bedrock into saprolite that supports the development of a progressively thickening layer of soil (Banwart et al., 2019; Evans et al., 2019). These processes transfer OC_{petro} from the parent material into the soil profile (Doetterl et al., 2015). The rate at which this occurs remains largely uncertain. Soil formation rates from bedrock are governed by many factors (Evans et al., 2019), one of which is a self-limiting mechanism (i.e., the soil production function) whereby soil formation slows as a soil progressively thickens. For example, a thickening soil can insulate the bedrock from diurnal temperature variations which are ultimately responsible for freeze-thaw weathering, a process particularly key for the frost-shattering of shale (Soulet et al., 2021). From this, we would hypothesize that the rate at which OC_{petro} is mobilized from bedrock to soil via weathering is similarly governed by the soil production function. Reconciling this relationship is important so that we can accurately integrate the inputs of OC_{petro} in soil carbon models. Moreover, new knowledge about the dynamics of the mobilization of OC_{petro} from bedrock to soils will also advance our understanding about the weathering of other key nutrients (e.g., N and P) from sedimentary rocks and their supply rates to soils (Zaharescu et al., 2019). This is especially pertinent given recent research showing, for example, that bedrock sources of nitrogen rival atmospheric nitrogen inputs (Houlton et al., 2018; Moreland et al., 2022).

3.2. How Readily Is OC_{petro} Assimilated by Microbial Communities in Subsoils?

Controls on the short-to long-term stability of OC_{petro} mobilized from bedrock to soils remain unclear. We have only a sparse understanding about how OC_{petro} is assimilated by subsoil microbial communities (Bertassoli et al., 2016; Hemingway et al., 2018). On the one hand, OC_{petro} is largely comprised of "kerogen"—insoluble, nonhydrolyzable macromolecular material disseminated in sediments that is at least partially composed of condensed carbon structures with a high degree of aromaticity (Bouchez et al., 2010; Durand, 1980). This implies that it is difficult to break-down chemically, although the degree of stability likely depends on carbon composition and the degree of diagenetic and thermal alteration of the bedrock, as well as the microbial community structure, the availability of other essential nutrients such as nitrogen and phosphorus that may regulate microbial metabolism, and the redox conditions (Bukombe et al., 2021; Hicks et al., 2021; Kidinda et al., 2022, 2023; Manzoni et al., 2021). On the other hand, many sedimentary rocks bearing OC_{petro}, such as shale, are generally highly weatherable and can thus provide a large surface area for OC_{petro} mineralization. Like the rates of bedrock

weathering and soil formation, the mineralization of OC_{petro} may also be dependent on climatic variables; it has been suggested that OC_{petro} oxidation is generally rapid under warmer (Soulet et al., 2021) and wetter conditions, as found in tropical environments (Bukombe et al., 2021). Initially, the presence of OC_{petro} in an otherwise unmantled bedrock surface (i.e., before soil formation takes place) might provide the "kick-starter" carbon substrate - a "petrogenic OC supply" - for some microbial communities to stimulate ecological succession, although this may be dependent on other limiting nutrients such as N and P. While Petsch et al. (2001) found that a community dominated by Bacteria and Eukarya was able to directly assimilate kerogen from a weathering black shale, we are yet to gain a good understanding of the limiting factors that may promote or limit this assimilation in soils. Systematic studies of soil formation and development on different OC-bearing lithologies derived from different sources of organic matter (e.g., terrestrial, lacustrine, marine) and different thermal histories (i.e., from unconsolidated ancient sediments to metamorphosed graphitic rocks) are needed.

3.3. To What Extent Do Subsoil Priming Processes Directly or Indirectly Affect the Stability of OC_{petro}?

Attention is required to understand how OC_{petro} is affected by soil priming effects (Kuzyakov et al., 2000). Research has found that the supply of fresh organic matter (labile inputs such as litter inputs, root exudates, transport of DOC) can trigger the enzymatic activity of dormant microbial communities, leading to the mineralization of resistant OC pools (X. Chen et al., 2022; Y. Chen et al., 2022). Consequently, calls to study the vulnerability of resistant OC pools to priming effects are growing (e.g., Wu et al., 2024). So far, however, these have not included OC_{petro}. As a result, questions remain about the size and the type of fresh carbon inputs required to prime the mineralization of OC_{petro}, as well as the microbial communities capable of driving this priming effect, and the impact of OC_{petro} composition on the efficacy of priming. By extension, there may also be positive feedback processes. One such example is the production of CO_2 from microbial respiration which dissolves in soil pore water to create carbonic acid (Sánchez-Cañete et al., 2018). This carbonic acid, in turn, helps to promote bedrock dissolution and therefore the susceptibility of OC_{petro} to microbial oxidation.

3.4. To What Extent Does Land-Use and Management Impact OC_{petro} Across the Bedrock–Soil Continuum?

To date, most of the research on OC_{petro} has taken place in unmanaged or uncultivated environments, such as glacial chronosequences, where the impacts of land management practices on the stability of OC_{petro} are either minor or difficult to quantify (see Hilton and West (2020) and references therein). The vulnerability of biospheric soil OC to changes in land use and management has been thoroughly studied and reviewed (e.g., Beillouin et al., 2021; Smith et al., 2018), yet these efforts have ignored the dynamics of OC_{petro}. This omission in part reflects the difficulty of partitioning the oxidation of recently photosynthesized OC and ancient OC_{petro} (Tune et al., 2023). Nevertheless, some studies have developed methodologies that allow these OC fractions to be quantified. For instance, Vindušková et al. (2015) compare and evaluate information from a combination of isotopic, spectroscopic and thermal methods to show that OC_{petro} contributed up to 99% of the total OC in soils developed on a mine spoil heap. The authors state that a reliable method for quantifying the reintroduction of OC_{petro} into the modern OC cycle is needed, which is also relevant for evaluating the effectiveness of vegetation colonization strategies. For example, Zhang et al. (2023) report soil OC accumulation along a chronosequence of vegetation restoration, and show that an increase in microbial biomass with colonization over time can stimulate the decomposition of recalcitrant OC_{petro}. Although the conversion of croplands to grasslands or forest stands tends to increase soil OC stocks, deeper-rooted grass or tree species may enhance the susceptibility of OC_{petro} to oxidation by inducing bedrock weathering. The penetration and development of roots in bedrock has been shown to promote mineral dissolution (Wen et al., 2021) although the effects this has on the oxidation of OC_{petro} remains unknown and warrants further study (Tune et al., 2023).

4. Incorporating OC_{petro} Into Studies of the Soil Carbon Cycle

There are significant and fundamental knowledge gaps in our understanding of OC_{petro} and its role in the carbon cycle. Addressing these "known unknowns" is required so that we can advance efforts to understand the role of soils as a critical resource as well as to combat global climate change. Bridging these knowledge gaps represents an urgent challenge. In many high-latitude and high-altitude environments, bedrock weathering rates are accelerating due to climate warming, implying faster release rates of OC_{petro} into soil profiles (Zondervan et al., 2023). Meanwhile, in managed landscapes, accelerated soil erosion is grossly outpacing the production of

new soil, resulting in soil truncation, the exposure of soil parent materials at the land surface, and increased weathering rates of carbon-bearing bedrock (Evans et al., 2020). As bedrock containing OC_{petro} is introduced closer to surface soil horizons, the interactions and cycling of other nutrient cycles (e.g., N and P) have the potential to significantly modify the microbial decomposition of OC_{petro}, as well as the input of biospheric OC. How OC_{petro} exhumed from the geosphere modulated, and was itself modulated by, global biogeochemical cycles throughout geological history remains largely unexplored. Intuitively, soils must have played a crucial role given that they comprise the portal between the geosphere, the biosphere and the atmosphere; they represent the uppermost veneer of Earth's surface and are the primary source of terrigenous materials accumulating in marine sediments.

Conceptualizing soil and the underlying bedrock as a continuum, rather than two discrete layers of the Earth System, is needed to resolve some of the "known unknowns" in OC_{petro} research. In this context, the continued development of Critical Zone Research (Singha et al., 2024) constitutes an integrative solution to bring disparate geoscientific disciplines together to address the evidence needs.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

There was no data or software used in this manuscript.

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Erratum

The originally published version of this article contained typographical errors. Coauthor Jordon Hemingway's name has been corrected to include his middle initial. Coauthor Sebastian Doetterl's affiliation has been corrected to the following: Department of Environmental Systems Science, ETH Zurich, Zurich, Switzerland. This may be considered the authoritative version of record.

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