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Pyrogenic Carbon Erosion: Implications for Stock and Persistence of Pyrogenic Carbon in Soil

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Pyrogenic carbon (PyC) constitutes an important pool of soil organic matter (SOM), particularly for its reactivity and because of its assumed long residence times in soil. In the past, research on the dynamics of PyC in the soil system has focused on quantifying stock and mean residence time (MRT) of PyC in soil, as well as determining both PyC stabilization mechanisms and loss pathways. Much of this research has focused on decomposition as the most important loss pathway for PyC from soil. However, the low density of PyC and its high concentration on the soil surface after fire indicates that a significant proportion of PyC formed or deposited on the soil surface is likely laterally transported away from the site of production by wind and water erosion. Here, we present a synthesis of available data and literature to compare the magnitude of the water-driven erosional PyC flux with other important loss pathways, including leaching and decomposition, of PyC from soil. Furthermore, we use a simple first-order kinetic model of soil PyC dynamics to assess the effect of erosion and deposition on residence time of PyC in eroding landscapes. Current reports of PyC MRT range from 250 to 660 years. Using a specific example-based model system, we find that ignoring the role of erosion may lead to the under- or over-estimation of PyC MRT on the centennial time scale. Furthermore, we find that, depending on the specific landform positions, timescales considered, and initial concentrations of PyC in soil, ignoring the role of erosion in distributing PyC across a landscape can lead to discrepancies in PyC concentrations on the order of several 100 g PyC m^{-2}. Erosion is an important PyC flux that can act as a significant control on the stock and residence time of PyC in the soil system.

Keywords: soil carbon stabilization, erosion, fire, persistence, pyrogenic carbon

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INTRODUCTION

Fires and Production of Pyrogenic Carbon

Fire is a major environmental perturbation and driver of biogeochemical processes across a diversity of landscapes worldwide. Globally, over 400 million hectares are burned annually (Andela et al., 2017), and in the US alone, wildfires consume over 2.6 million hectares per year in over 74,000 wildfires (National Interagency Fire Center, 2015). The amount and properties of organic matter

(OM) left behind in and on soil post-fire are controlled by the amount and composition of fuel and the duration and temperature of the fire (Dyrness and Norum, 1983; Kasischke et al., 2008). Depending on burn severity, or the impact of the fire on the ecosystem, fires also control nutrient availability, water infiltration, soil pH (Certini, 2005), and OM stocks in soil (González-Pérez et al., 2004; Keeley, 2009). Moreover, fires can lead to the formation of pyrogenic carbon (PyC) from the incomplete combustion of biomass and soil organic matter (SOM) (Schmidt and Noack, 2000; Masiello, 2004; Preston and Schmidt, 2006). Pyrogenic carbon is a broad term for fire-altered materials that includes a continuum of materials such as soot, charcoal, lightly charred biomass, and biochar, or intentionally charred material for agricultural and carbon (C) sequestration purposes (Masiello, 2004; Bird et al., 2015; Lehmann and Joseph, 2015).

A growing body of literature now demonstrates that PyC is a major component of the global C cycle (Lehmann et al., 2008; Preston, 2009; Bird et al., 2015). PyC makes up 2.5–5% of global soil organic C (IPCC, 2013; Bird et al., 2015) and up to 30% of C in some soils (Skjemstad, 1996; Skjemstad et al., 1999), making it important not just for accounting of global soil C stocks but also for how the soil system plays an important role in regulation of global climate (Lehmann et al., 2008). In soil, PyC has an overall longer mean residence time (MRT, centuries to millennia) (Hammes et al., 2008; Lehmann et al., 2008), compared with non-pyrogenically altered OM (decades to centuries) (Torn et al., 1997; Schmidt et al., 2011). Current estimates of the MRT of PyC in the soil are considerably shorter than previously reported estimates (on the order of millennia), as several studies have demonstrated that some PyC is degraded on shorter (months to years) time scales in both laboratory (Nguyen et al., 2009; Whitman et al., 2014) and field studies (Soucémarianadin et al., 2015). Recent observations have indicated that current estimates of PyC residence times may be inaccurate due to failures in accurately quantifying lateral redistribution of PyC in the terrestrial ecosystem and its riverine transfer to the ocean (Rumpel et al., 2006; Jaffé et al., 2013; Masiello and Louchouarn, 2013).

Effect of Fire and PyC on Soil Erosion

Elevated rates of post-fire soil erosion are typically observed after wildfires (Certini, 2005; Carroll et al., 2007; Shakesby, 2011). The extent to which fires lead to soil erosion and the nature of the eroded material vary depending on fire type (i.e., crown fire, ground fire), the environment where the fires occur, and post-fire climatic conditions (Certini, 2005; Shakesby, 2011). One of the main controls on the type of fire is the ecosystem type (Kozlowski and Ahlgren, 1974; Brown and Smith, 2000), which dictates the type and quantity of vegetation available for charring into PyC along with climatic variables responsible for controlling vegetation growth and fire conditions. During fires, typically only the top few (2–5) centimeters of soil are directly and significantly impacted by the high temperatures (DeBano, 2000). Charring intensity, or the integral of the duration and maximum temperature reached during combustion of organic matter (Pyle et al., 2015), at the soil surface controls the properties of the PyC formed during the fire, where PyC formed at higher temperatures (above ∼350°C) can be more persistent in soil (González-Pérez et al., 2004; Zimmerman, 2010). Generally, this PyC formed at higher temperatures (above ∼350°C) has a higher skeletal density and is more porous (Brewer et al., 2014), making it more susceptible to erosional transport than low temperature PyC.

Fire also changes the physical properties of soil with implications for lateral movement of water and PyC. Fires can lead to destabilization of topsoil, reducing aggregation and aggregate protected C, increased soil hydrophobicity, which can lead to increased erodibility of soil post-fires through both water and wind-driven erosion processes (Shakesby and Doerr, 2006; Johnson et al., 2007; Ravi et al., 2007; Al-Hamdan et al., 2012; Miller et al., 2012; Araya et al., 2017). Albalasmeh et al. (2013), for example, showed that low severity fires can have a lasting impact on soil aggregate stability. Moreover, low to moderate temperature, ground-level fires (soil temperatures reaching ∼175–250°C) can lead to the formation of a hydrophobic layer at or just below the soil surface, or increases in any pre-existing soil hydrophobicity, resulting in decreases in infiltration rates (DeBano, 2000; Shakesby and Doerr, 2006; Mataix-Solera et al., 2011). This decrease in infiltration and altered hydrologic flow paths though the soil matrix can lead to increases in overland flow (Hortonian flow, see **Figure 1**, Shakesby and Doerr, 2006). In combination with the loss of soil-stabilizing vegetation during fire, this increase in overland flow can drive increased erosion rates and sediment export in fire-affected landscapes (Shakesby et al., 1993).

EROSION AND PyC PERSISTENCE IN SOIL

Over the last couple of decades, our understanding of how PyC becomes stabilized in, or is lost from, the soil system has advanced considerably. However, many of these calculations and measurements of PyC stabilization have not considered erosion. In the following sections, we discuss historical and modern ideas about PyC persistence within soil and the role of erosion as a loss and stabilization mechanism.

Historical Perspective

Historically, PyC was thought to be a highly recalcitrant form of soil C that is inherently resistant to microbial decomposition. The presumed chemical recalcitrance of PyC was attributed to its chemical structure including large linkages of condensed aromatic structures (Skjemstad et al., 1999), as well as it forming chemical and physical associations with soil minerals (Lehmann et al., 2005; Brodowski et al., 2006). This idea of chemical recalcitrance prevailed for decades, even though there was evidence for the breakdown of PyC from the beginning of the twentieth century (Potter, 1908). This presumed inherent recalcitrance of PyC was even used to support arguments that PyC storage in soil might be part of the "missing C sink" because it seemed so environmentally stable (Lehmann, 2007). At the same time, the ability of PyC to persist in the soil longer than non-PyC OM, has also contributed to the widespread research

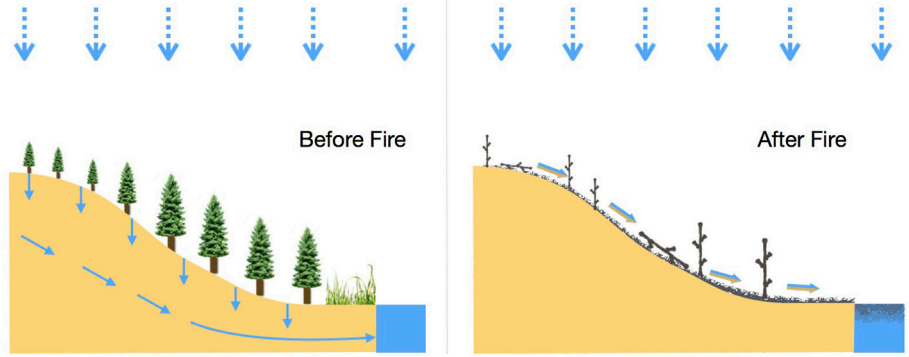

FIGURE 1 | On the hillslope scale, fires alter dominant hydrologic flow regimes in soil, reducing infiltration and subsurface flow of water, and increasing surface runoff.

on the potential of PyC to serve as an agricultural amendment (biochar) with the main aim of increasing soil C stocks and decreasing C turnover (i.e., improving a soil's potential to sequester atmospheric CO_2; Lehmann et al., 2008); however some other types of biochar can be utilized to improve soil productivity (Lehmann and Joseph, 2015). However, recent works showed PyC can become decomposed or lost from soil rather quickly, on the scale of months to years (Nguyen et al., 2010; Zimmerman, 2010; Zimmermann et al., 2012; Zimmerman and Gao, 2013).

There is now a major paradigm shift occurring in our understanding of PyC dynamics in the earth system. **Figure 2** shows how published estimates of PyC MRT have decreased over the last few decades. Some earlier studies reported MRT estimates over thousands of years, but around 2008, a gradual shift in viewpoints happened as evidence for rapid decomposition and mobilization became apparent (**Figure 2**). Some of the most recent research suggests that the rate of PyC decomposition is tightly controlled by environmental conditions and its persistence in soil is a property of the ecosystem (Schmidt et al., 2011).

Stability and Turnover of PyC

PyC can become stabilized or lost from soil through similar processes that control the fate of bulk or non-pyrogenic carbon, including biotic and abiotic decomposition, leaching, and erosion (Rumpel et al., 2006; Major et al., 2010; Zimmerman, 2010). Current estimates of PyC MRT range from weeks to months to millennia (Bird et al., 2015). Lehmann et al. (2008) suggested that PyC MRT in soil could range between 700 and 9,000 years. However, other studies have argued that PyC has considerably shorter MRT in soil (**Table 1**). For example, Hammes et al. (2008) found a PyC turnover time of 239 years in a Russian steppe site, and similarly, Boot et al. (2015) found a similar MRT for PyC of 300 years. Overall, laboratory incubation derived estimates of loss of PyC are typically higher (1.5–20% PyC mass loss per year) than field studies (0.08–15% PyC mass loss per year), even though field studies include other forms of loss other than microbial decomposition (e.g., erosion and leaching, **Table 1**). Much of the variation in field and laboratory studies is due to the range of different processes that control PyC persistence in soil, and laboratory studies are commonly conducted under ideal decomposition conditions, which are more reflective of near maximum potential breakdown rates of PyC. Below, we present a discussion on the role of erosion in controlling the dynamics of PyC in the soil system.

Erosion as a Driver of C Dynamics in Soil

Interest in the role of erosion on soil C and PyC dynamics and biogeochemical cycling of essential elements has increased over the last two decades. In particular, research has focused on the potential for erosion to constitute a net sink for atmospheric CO_2, on the order of 0.12–1.5 Gt C y^{-1} (Stallard, 1998; Lal, 2003; Berhe et al., 2007; Battin et al., 2009; Regnier et al., 2013; Doetterl et al., 2016). In upland, eroding landform positions (shoulder positions), erosion leads to losses of SOM through direct removal of soil mass (Berhe et al., 2008; Harden et al., 2008; Berhe, 2012; Nadeu et al., 2012; Stacy et al., 2015; McCorkle et al., 2016). About 70–90% of the eroded topsoil material is redistributed downhill or downstream, and this material is not exported out of the source watersheds but instead is deposited in toeslope and footslope landform positions (Gregorich et al., 1998; Stallard, 1998; Lal, 2003). Erosion leads to stabilization of at least some of the eroded SOM in depositional landforms through new and reconfigured associations of the eroded SOM with soil minerals (Sharpley, 1985; Lal, 2003, 2004; Berhe, 2012; Berhe and Kleber, 2013). During the transport phase of erosion, eroded material is exposed to breakdown mechanisms and for non-pyrogenic C, over 20% of the OM transported from eroding landform positions is assumed to be lost via oxidative decomposition during or after transport (Jacinthe and Lal, 2001). Erosion is a particularly important flux for PyC in soil when it stays on surface layers (Rumpel et al., 2006) at least on the order of months, if not longer (Boot et al., 2015; Faria et al., 2015), because this leaves PyC vulnerable to weathering forces of wind and water. However, current research has focused on hillslope- and plot-scale erosion of PyC (Rumpel et al., 2006, 2009; Abney et al., 2017; Pyle et al., 2017), so its redistribution at the watershed and larger scales remains largely unknown.

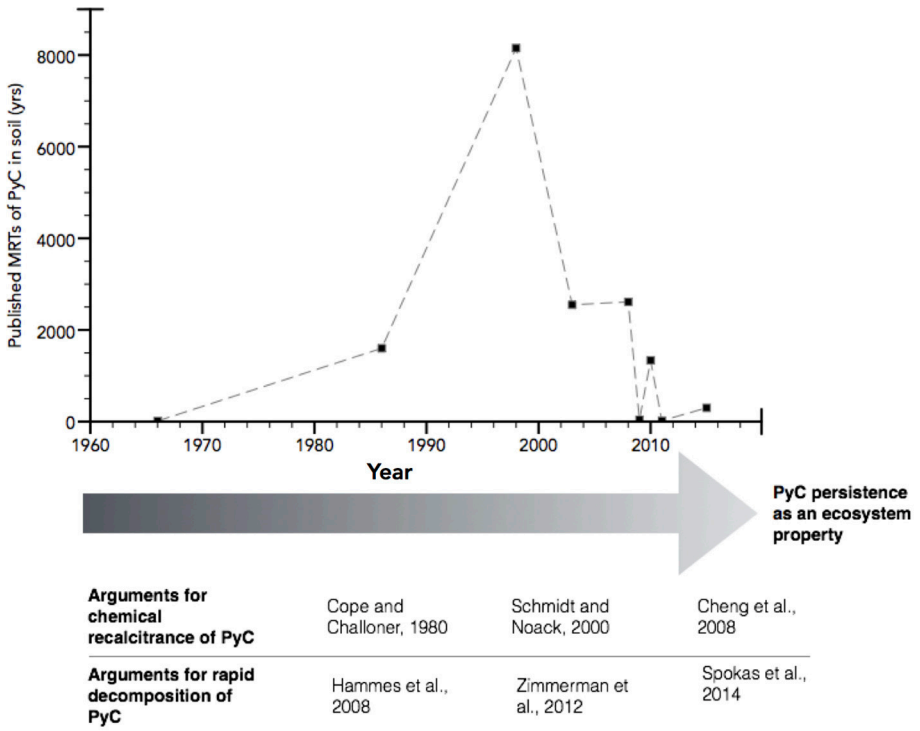

FIGURE 2 | This timeline of estimated MRTs of PyC and key papers illustrates the changing paradigm on controls of PyC persistence in the soil system. The estimate for char age from Cope and Chaloner (1980) was not included in the average of 300 million years, because it was not an estimate of turnover time, but it does reflect the view that PyC would reside in soil for very extended periods of time. Also, note that the x-axis is not numeric.

Post-fire Erosion

Fire increases the susceptibility of soils, particularly surface soils, to erosion by changing soil physical and chemical properties (Certini, 2005). For example, the development of soil hydrophobicity post-fire can reduce water infiltration, increasing topsoil susceptibility to runoff (DeBano, 2000). The presence of PyC in litter and surface soil can also increase the rates of bulk erosion, as fire-affected biomass tends to have lower density, compared to uncharred biomass and litter, making it easier to transport by both water- (Rumpel et al., 2006) and wind-driven (Beyers et al., 2005; Shakesby, 2011) erosional processes. In many ecosystems, erosion preferentially transports carbonaceous topsoil material, compared to mineral constituents of soil, leading to C enrichment in eroded sediments compared to soil in source slopes (Avnimelech and McHenry, 1984; Stacy et al., 2015).

Similarly, Rumpel et al. (2006) found evidence for selective transport of PyC during interrill erosion due to its lower density and concentration on the soil surface. One study found that interrill sediment erosion was doubled in a burned watershed compared to a neighboring unburned watershed, along with increases in runoff velocity due to increased bare ground coverage (Pierson et al., 2008, 2013). The relative extent of interrill compared with rill erosion depends upon local landscape and precipitation conditions, where higher precipitation intensity and steeper slopes can drive increased rill formation (Moody et al., 2013). The relative role of rill and interrill erosion can control the mobility of PyC throughout a landscape, as rill erosion likely would not preferentially transport PyC and would result in transport of bulk soil material (Schiettecatte et al., 2008), while sheet or interrill erosion can preferentially transport smaller, lighter, and organic-rich material (Wang et al., 2010).

Atmospheric and Aeolian Transport of PyC

The atmospheric component of the global PyC cycle has received considerably more research focus than soil PyC, largely due to the interest in air pollution associated with soot and other aerosols released to the atmosphere during fires (Seiler, 1980; Campbell et al., 2007), and their implications for global climate change and public health (Highwood and Kinnersley, 2006; Bond et al., 2013). Fossil fuel combustion and biomass burning produce the majority of atmospheric PyC, which has a relatively short residence time (up to months) in the atmosphere (Chapin et al., 2006; Preston and Schmidt, 2006), and an even shorter (<week) in the lower atmosphere (Parungo et al., 1994).

Dry and wet deposition of PyC from the atmosphere is a global process that transports 2–10 Tg PyC per year, to both land and ocean depositional settings spanning thousands of km (Parungo et al., 1994; Jurado et al., 2008; Bond et al., 2013). From the soil surface, soot and smaller PyC constituents can be rapidly transported post-fire (**Figure 3**), depending on local wind and precipitation conditions, such that dry climates are

TABLE 1 | Examples of decomposition rates measured in laboratory and field studies, as converted to percent mass loss of PyC per year.

%PyC mass loss in a year	Type of experiment	Source of PyC	Method to measure PyC	Citation
LABORATORY EXPERIMENTS				
2	Incubation, at tropical conditions	Mulga (*Acacia aneura*)	^{13}C direct polarization NMR spectroscopy, hydrogen pyrolysis	Zimmermann et al., 2012
10–20	Incubation, temperature change from 4 to 60°C	Laboratory generated corn (*Zea mays* L.) char at 350°C	^{13}C direct polarization NMR spectroscopy	Nguyen et al., 2010
4–20		Corn char at 600°C		
2.3–15		Oak (*Quercus* spp.) char at 350°C		
1.5–14		Oak char at 600°C		
0.02–4.89	Three simulations of PyC loss via decomposition ranging from 2 to 2,000 years	N/A	N/A	Foereid et al., 2011
0.38	Laboratory incubation–O horizon	Laboratory generated char from ponderosa pine (*Pinus ponderosa*)	Chemo-thermal oxidation at 375°C	Hatten and Zabowski, 2009
0.24	A1 horizon			
0.08	A2 horizon			
0.7	Laboratory incubation: average over 8.5 years	Ryegrass (*Lolium* spp.)	^{14}C labeled biochar	Kuzyakov et al., 2009
0.25	Average PyC loss between years 5 and 8			
FIELD EXPERIMENTS				
1	Field chronosequence: first 30 years after production	Field burning of maize (*Zea mays* L.)	^{13}C CPMAS NMR spectroscopy, FTIR	Nguyen and Lehmann, 2009
3.2	Field chronosequence: first 5 years after production		Manual identification	
1.1	Field experiment in native savannah	Mango trees (*Mangifera indica* L.)	Mixing model from δ^{13}C of PyC and field soil	Major et al., 2010
0.25	Field experiment	Natural PyC in chernozem	BPCA	Hammes et al., 2008

The range of reported loss rates for incubation experiments (1.5–20%) is considerably higher than field experiments (0.08–15%). Several of these reported loss rates are different between lengths of experiments, indicating non-linear decomposition and breakdown kinetics for PyC. The difference between field and laboratory experiments is largely due to laboratory experiments being more representative of optimal or maximal decomposition conditions. Moreover, several of the laboratory studies use laboratory generated PyC, this is critical to control and account for the variation in PyC found in the field and in the case of wildfires.

more susceptible to post-fire wind erosion (Shakesby, 2011; Pereira et al., 2015). Few studies have focused on wind-driven erosion, atmospheric transport, and terrestrial deposition of PyC post-fire, due to both methodological difficulties and widespread assumptions that it is a very small flux or only a site-specific phenomenon (Wondzell and King, 2003; Shakesby, 2011). However, it is likely that smaller, low-density PyC, or PyC produced by higher temperature fires (Brewer et al., 2014), could be rapidly transported significant distances, particularly with the loss of vegetation and breakdown of soil structure post-fire (Beyers et al., 2005).

Stabilization of Eroded PyC via Burial

The stabilization of PyC can occur through post-erosion burial of a fraction of the eroded PyC in depositional landform positions, similar to non-pyrogenic C (Berhe et al., 2007; Berhe and Kleber, 2013; Doetterl et al., 2016). PyC-rich material eroded from hillslopes can get stabilized in deep soil layers of downhill or downstream depositional landform positions with repeated erosion/deposition events, especially if it is buried at >1 m depths, as was observed in char-rich Paleosols in Nebraska (Chaopricha and Marín-Spiotta, 2014; Marín-Spiotta et al., 2014). This deep-soil stabilization can also be driven by aeolian-derived deposits burying an existing soil (Chaopricha and Marín-Spiotta, 2014; Marín-Spiotta et al., 2014), via anthropogenic burial, such as the Terra Preta soils of the Amazon (Glaser et al., 2000; Glaser, 2002), or via charring of roots at depth during high intensity fires (Kyuma et al., 1985). The burial of PyC reduces PyC exposure to microbes, air, and extracellular enzymes, which are major drivers of decomposition.

SIGNIFICANCE OF EROSIONAL REDISTRIBUTION OF PyC IN THE TERRESTRIAL ECOSYSTEM

As of yet, the relative rates of PyC erosion, compared with bulk SOM erosion at the plot, hillslope, or even watershed scale remain relatively unexplored, so the amount of PyC transported via erosion processes is largely unknown. Accurate quantification of the rates of PyC loss through biological (decomposition) versus physical (erosion, leaching) processes is necessary for fully understanding its role in the soil C pool, including its potential

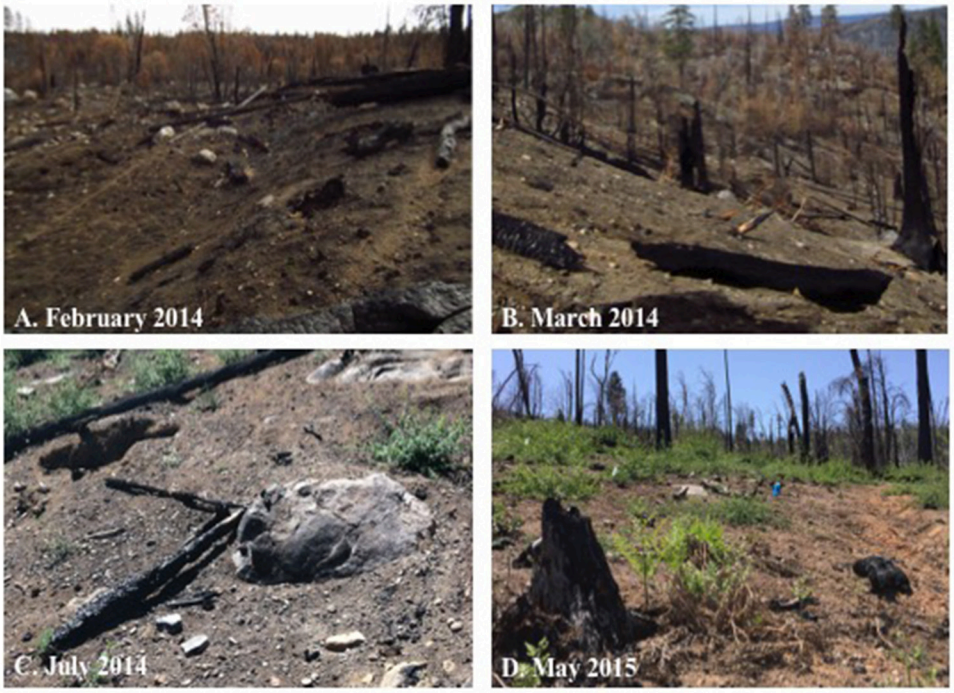

FIGURE 3 | Erosion in upland temperate forests is dependent upon precipitation and topography. This progression of photographs from the Rim Fire (2013, in Yosemite National Park and Stanislaus National Forest in California, USA) illustrates the significant loss of PyC post-fire in a high-severity burn area and post-fire vegetation regrowth (all photos, R. Abney). The Rim Fire began in August of 2013 and was contained in November of 2013, with the aid of snowfall. The picture in **(A)** (from February 2014, 3 month's post-fire) illustrates the significant PyC layer remaining after the first snowmelt. The picture in **(B)** from March 2014 is the remaining PyC after the first major rainfall post-fire. The soil color is considerably lighter (3–5/1 5YR dark gray compared with 2.5/1 5YR black), which is evidence of loss (erosion) of highly charred material (PyC). The pictures in **(C,D)** have considerably less PyC covering the soil surface and illustrate the beginnings of vegetation regrowth based on ocular assessment after the Rim Fire.

role as a C sink (Hammes et al., 2008). Due to recent research indicating that PyC is preferentially eroded (Rumpel et al., 2006, 2009), it is likely that it will be redistributed throughout the landscape differently than non-pyrogenic carbon, and this may have significant impacts on our understanding of its long-term persistence in soil, as is true for non-pyrogenic carbon (Berhe, 2012; Berhe et al., 2012).

Recent evidence suggests that PyC often interacts with the soil minerals and microbial community differently than some forms of non-pyrogenic C (Kuzyakov et al., 2009; Zimmerman, 2010; Zimmerman et al., 2011), which makes measuring the fluxes of PyC critical for quantifying global PyC stocks. Furthermore, understanding of the controls on the fluxes of PyC through soil is needed for generating more accurate and representative models of dynamics of the soil C pool and how the soil system controls global climate. Thus, improved understanding of PyC interactions in soil and its loss mechanisms are currently needed to elucidate the role of PyC in soil total C dynamics.

Erosion and Soil PyC Dynamics

The role of erosion in controlling the fate of PyC is likely more important than for non-pyrogenic SOM, as fire can significantly increase the rate of soil erosion, and prior research has demonstrated that PyC is highly erodible (Rumpel et al., 2006; Yao et al., 2014). The increased rate of soil erosion post-fire results from a combination of environmental changes, including: loss of the protective litter layer, exposure of surface soil to erosive forces (precipitation, wind), increased hydrophobicity of the subsoil (DeBano et al., 1998; DeBano, 2000; Benavides-Solorio and MacDonald, 2001; MacDonald et al., 2001), and a reduction in water infiltration and water holding capacity of the surface soil (Robichaud, 1997; DeBano, 2000; Doerr and Thomas, 2000; Carroll et al., 2007). Furthermore, the time that elevated rates of soil erosion are sustained is at least partially controlled by the extent of vegetation recovery post-fire, but is typically around a year (Baker, 1988).

Erosion, in turn, can indirectly affect vegetation and soil water status. Both fire and erosion are controlled by climate to various extents (Imeson and Lavee, 1998; Neary et al., 1999; Riebe et al., 2001). Watershed size and topography (Liu et al., 2003; Iniguez et al., 2008), in addition to the amount, intensity, and temporal distribution of precipitation can influence the rate of bulk SOM and PyC loss from or redistribution within an eroding watershed (Nearing, 1998; Cain et al., 1999; Rumpel et al., 2009). These relationships have been documented by many erosion prediction models, such as the Universal Soil Loss Equation (Wischmeier and Smith, 1965, 1978) and the Water Erosion Prediction Project

(WEPP) model, which were originally developed in agricultural soils (Laflen et al., 1991).

Important inferences can be drawn on factors that control PyC erosion based on available data and by extrapolation of what we know about erosion of non-PyC or bulk C. Below we briefly discuss how specific variables (i.e., the amount and nature of PyC available for transport, climate, geomorphology of the landscape) control how strongly erosion can regulate soil PyC dynamics.

The Erodible Nature of PyC

The amount and composition of PyC that is laterally distributed over the soil surface by erosion, at least in part, depends on the concentration, location, chemical composition, and physical size of the PyC. These variables are all products of complex interactions among the type and density of vegetation available to be combusted (i.e., fuel load), combustion conditions (e.g., temperature, duration, oxygen availability), and frequency of fire events (Schmidt and Noack, 2000; Masiello, 2004; Hockaday et al., 2006; Czimczik and Masiello, 2007; Knicker, 2007).

Transport of PyC is assumed to occur in erosion events immediately after fire when the land surface is covered by a layer of PyC, which can become quickly mobilized through the landscape via either wind- or water-driven erosion processes (Carroll et al., 2007; Pereira et al., 2015; Abney et al., 2017). The PyC on the soil surface is likely to be eroded before and more preferentially than mineral soil or mineral-associated PyC, except in the cases of landslides and other major mass wasting events. Additionally, the recently formed PyC would not have enough time to form stabilizing physical and chemical interactions with soil minerals prior to preferential transport, as these stabilizing interactions can take years to decades to form in natural settings (Faria et al., 2015). Over time, the PyC that is not transported by erosion is mobilized downward into the profile via dissolution, leaching, and biological processes that render it more susceptible to in-solution transport with flowing water (Güereña et al., 2015). However, the PyC that remains on the soil surface is exposed to wetting- and drying-cycles that are likely to render it more susceptible to leaching losses, although some research has indicated that the material left after leaching may be less easily decomposed (Naisse et al., 2015).

Among the most important physical and chemical properties of PyC that make it susceptible to erosion are its low density compared with soil minerals (Brewer et al., 2014), its hydrophobic properties when formed at lower ($< \sim 250°C$) charring temperatures (Sander and Pignatello, 2005; Bodí et al., 2011), and its aromatic content and aromatic condensation (Preston and Schmidt, 2006). Generally, it is assumed that the low density ($<1\,Mg\ m^{-3}$) and hydrophobic properties of PyC allow for flotation and lateral transport of PyC with flowing water (Rumpel et al., 2006, 2009). The slow wetting and filling of the pores of PyC with water, however, should increase its density (Gray et al., 2014) and reduce its potential for flotation and transport with overland flow. Furthermore, the breakdown of PyC also depends on density of the PyC and on associations between PyC and non-pyrogenic SOM (Zimmermann et al., 2012; Pyle et al., 2017). The duration, intensity, and frequency of storm events also plays a significant role in controlling the wetting of PyC, as the hydrophobic properties of PyC can only delay wetting, not prevent it entirely (Bodí et al., 2011).

Climate and Hydrology

The process of water-driven soil erosion occurs though detachment of a soil particle which is transported and deposited away from the source location. During rain-driven erosion, the impact of raindrops breaks down aggregates on the soil surface which leads to transport of soil away from the point of impact, and gravity leads to the downslope mobilization of detached particles across the soil surface (Kinnell, 2005). With all other erosion-driving factors held equal, the intensity of precipitation is the leading driver of erosion and runoff (Renard et al., 1997). Large storms are generally thought to drive the major erosion events within a landscape; however, intermediate storms can also mobilize significant amounts of material over the course of a year (Wischmeier, 1962). In addition to intense storms, rapid snowmelt and rain-on-snow events are important drivers of rapid runoff (Pierson et al., 2001). The loss or reduction of vegetation cover due to fires creates the opportunity for raindrops to reach the soil surface at high velocity, without being slowed down by aboveground vegetation and overlying litter layers. Hence, the same amount or intensity of rainfall can mobilize more PyC, and bulk C, from soil post-fire than it would under unburned conditions if there is loss of vegetation or litter layers (Inbar et al., 1998; Beyers et al., 2005; Cerdà and Doerr, 2005; Pierson et al., 2008, 2009, 2013). Generally, low intensity precipitation events drive preferential transport of light carbonaceous material (higher enrichment ratios, higher concentration of C) (Schiettecatte et al., 2008; Wang et al., 2010). However, during high intensity or longer duration rainfall events, a mixture of mineral material along with SOM, including pyrogenic carbon, is mobilized from the soil surface or even deeper soil horizons (large rainfall events lead to scouring of the surface or river banks or creation of deep rills and gullies), as was observed by Stacy et al. (2015) and McCorkle et al. (2016).

Geomorphology of the Landscape

The geomorphology of a landscape can significantly impact the erosion of PyC. In particular, the steepness of a hillslope has a non-linear, direct effect on the amount of sediment transported by soil erosion, where increased gradient increases the mass of transported sediment (Montgomery and Brandon, 2002). Slope length and hillslope hydrology also likely play important roles on PyC transport, as they do in in non-fire impacted landscapes (Munro and Huang, 1997; Parsons et al., 2006; Istanbulluoglu et al., 2008), as moderate length slopes allow for the greatest transport of material, while shorter slopes are limited in space for runoff to build speed. Longer slopes have increased area for water to meet resistance and for particles to settle out, so the travel distance of particles is a function of their size.

Aspect of a hillslope can impact erosion due to its effects on plant growth, density, OM decomposition, with subsequent implications for fuel availability for fires and soil burning (Cerdà et al., 1995). The impacts of aspect on hillslope erosion can be compounded by delays in vegetation recovery, leading to longer-term enhanced erosion rates and continued loss of soil

nutrients, and weather-related events, which can cause different erosion rates on different aspects of the same hillslope (Cerdà et al., 1995; Pierson et al., 2008, 2009). Furthermore, the location within a landscape where PyC is formed or deposited can be critical for the long-term fate of the PyC. If PyC is produced on eroding landform positions (convex or linear positions such as summit, shoulder, or back/foot slope positions), then it is more likely to be transported laterally by wind or water erosion processes, or gravity driven diffusive mass transport, compared to PyC produced in depositional landform positions (concave or flat positions such as toeslopes, or alluvial and colluvial plains). However, if the PyC is either formed or deposited on depositional landform positions, then it is more likely to persist in the catchment longer and be stabilized in the depositional landform positions by forming physical and/or chemical associations with soil minerals, or to get buried by subsequent erosion/deposition events that bring sediment to the depositional position as has been found for non-pyrogenic carbon (Stallard, 1998; Berhe, 2012).

Interactions

The three drivers of PyC erosion, fire, geomorphology, and climate, also interact with each other to control rates of PyC erosion (**Figure 4**). For example, different combinations of steepness of a hillslope, size of watershed, and intensity of precipitation may lead to differing rates of erosion (Pierson et al., 2001). Generally, climate describes the expected precipitation events, but local scale variations in weather, such as exceptionally large precipitation events, can drive the formation of rills or gullies and large mass wasting events. Furthermore, landscapes with very steep slopes, which could predispose a landscape to mass wasting events, could further enhance these large movement events. As another example, long-term climate patterns impact the type and amount of vegetation available as fuel for fire, which could further impact the quality and quantity of PyC left behind after fire. The amount and nature, such as density and water content, of available fuel play an import role in determining the intensity of fire, which controls the resulting PyC properties, such as aromatic content and aromatic condensation, as demonstrated by laboratory studies (Mimmo et al., 2014; Pyle et al., 2015; Wiedemeier et al., 2015). This more condensed PyC produced at higher temperatures is more susceptible to flotation and theoretically more susceptible to erosive forces (Brewer et al., 2014).

Implications of Including Erosion as a PyC Flux Term

While the magnitude of PyC transported by soil erosion has not been fully determined, some estimate that this flux is on the order of 29–87 Tg PyC per year (Bird et al., 2015). Current evidence suggests that erosion is a significant driver of PyC redistribution in hillslopes (i.e., loss from soil profiles of eroding landform positions, that may or may not remain in the same catchment as input to the soil profiles of depositional landform positions; Rumpel et al., 2006, 2009; Abney et al., 2017). Environmental conditions post-fire and the nature of PyC lead to elevated rates of erosion and enrichment of PyC within the resulting eroded sediments (Pierson et al., 2008; Rumpel et al., 2009). The large flux of PyC to oceans (Jaffé et al., 2013) is further indication that there is considerable transport of dissolved and particulate forms of PyC within the terrestrial and to the aquatic system. An approach that considers the geomorphologic and biogeochemical cycling changes associated with fires is needed to quantify stock and erosional fluxes of PyC in fire-affected dynamic landscapes and to determine *how* and *why* erosional distribution of PyC could affect our understanding of the dynamics of both bulk SOM and PyC in the terrestrial biosphere.

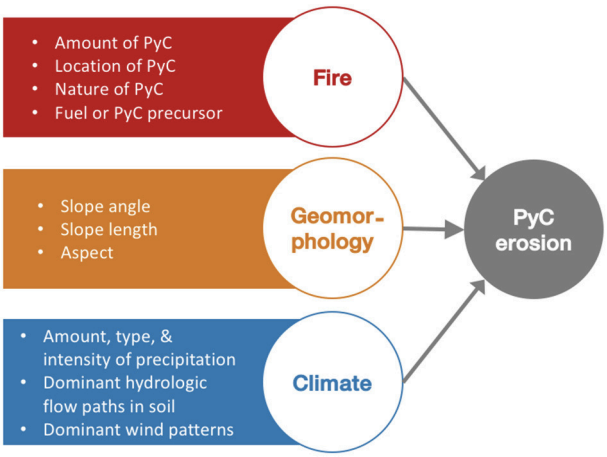

FIGURE 4 | Three main factors interact to control the erosion of PyC in any environment: landscape, climate, and hydrology, and the amount and nature of PyC produced from fire. These three factors interact with each other in both space and time to impact the fate of PyC.

Calculating Loss and MRT of PyC

One of the most common and simplest approaches to estimating PyC MRT is based on calculations of a loss rate from a given reservoir (i.e., soil) using simple one-pool box model approaches. Turnover time (T) is assumed to be equivalent to the inverse of the loss rate constant (k), with the assumption of steady state. Turnover time is imposed on a first-order kinetic model of PyC dynamics as:

$$T = 1/k \tag{1}$$

where,

$$dPyC/dt = I_{PyC} - k \times PyC \tag{2}$$

where T is turnover time (years), k is a loss rate constant (as a proportion of the PyC stock, yr^{-1}), PyC is stock of PyC in a soil pool (g/m^2), I_{PyC} ($g\ m^{-2}\ yr^{-1}$) is the rate of PyC input to the reservoir. This model assumes a single rate of loss of PyC that is solely comprised of decomposition, and a uniform input of PyC across the ecosystem. Below we argue for the role of erosion as a significant loss factor for PyC and demonstrate the error in MRT calculations when erosion is ignored using a specific case study.

Estimating MRT of PyC in Dynamic Landscapes

Ignoring the contribution of erosion to soil PyC stocks can lead to errors in both the stock as well as estimated turnover time of PyC in dynamic landscapes. Many fires occur in areas that are prone to erosion, but even if an erosional loss term of PyC is included, the role of erosion as a gain term (in depositional landform positions) is not yet accounted for within soil PyC budget models, and rarely accounted for in field studies (Abney et al., 2017). Not accounting for this gain of PyC can lead to major errors within our budget models of PyC and C within eroding landscapes. We have considered three landform positions or types in the following model: (1) a landform where no sediment material is being transported to or from that area; (2) an eroding landform position (e.g., shoulder, backslope), where erosion represents a loss term for PyC; and (3) a depositional landform position (e.g., toeslope or plain), where deposition of PyC eroded from upslope positions leads to input of PyC. Following works of Stallard (1998) and Berhe et al. (2008) on erosional redistribution of bulk SOM, here, a model for first order C kinetics was modified to assess the potential effect of erosion on PyC dynamics. The first-order loss rate constant (k) in the first order model (Equation 2) was replaced with two separate constants for decomposition (k_o) and erosional redistribution ($k_{e,}$), where $k = k_o + k_e$ as:

$$\mathrm{dPyC/dt} = I - (k_0 + k_e) \times PyC \tag{3}$$

where PyC = soil PyC stock (g m^{-2}); I = soil pyrogenic carbon inputs (g m^{-2} yr^{-1}); k_o = first-order loss of PyC by abiotic or biological decomposition (yr^{-1}); and k_e = first-order loss of PyC by erosion (yr^{-1}). This k_e term describes the different trajectories of PyC at eroding or depositional landform positions and accounts for additions or losses of PyC via erosional processes. Additionally, in the depositional landform position, there is both a loss of PyC initially deposited that is a function of the stock of PyC in that landform position (Equation 4). There is also an increase in PyC stock in the depositional landform position due to the input from erosion, k_e = first-order gain of PyC by erosion (yr^{-1}) which is a function of the PyC stock in the corresponding eroding landform position, PyC_{ero} = eroding soil PyC stock (g m^{-2}):

$$\mathrm{dPyC/dt} = I - (k_0 \times PyC) + (k_e \times PyC_{er}) \tag{4}$$

For our model calculations, we used published results from Hammes et al. (2008) where they measured PyC stock in chernozem soils at a steppe preserve in Russia as a case study. The soils were sampled twice over about 100 years, first between 1895 and 1903, and then in 1997 and 2004. The authors then used the difference in PyC stock (measured using the BPCA marker technique) of the soil between the two time periods and radiocarbon measurements of SOM to derive MRT of PyC in soil using a one PyC pool, first-order decay (i.e., linear, donor-controlled) model (Hammes et al., 2008). Though, this study does not account for any leaching or erosion of PyC that could have occurred between the two sampling points. In our calculations, we assumed the soils had initial soil PyC stock of 2.5 kg PyC/m^2 (Hammes et al., 2008) and a relatively low decomposition constant (k_o) for PyC of 0.4%/year, which approximates a turnover time of 250 years (Hammes et al., 2008). Then, we considered erosion or deposition as loss or gain terms, as shown in Equations (3) and (4). We calculated the stock of PyC in the non-erosion (flat) position by assuming that $k = k_0$ and that $k_e = 0$. For the eroding position k_e represents a loss term for PyC, while for the depositional position it represents a gain to the existing PyC stock. The depositional area has erosional inputs of PyC that maintain a higher PyC stock through the simulation. The eroding area has both erosion and decomposition acting together to remove PyC from the soil, so it has the lowest PyC stock at the end of the 150-year simulation (**Figure 5**).

This model scenario is an inherently simplified version of PyC dynamics within eroding hillslopes, and thus operates under several assumptions. This model assumes a single input of PyC, an initial even distribution and availability of PyC for erosional transport, and a landscape comprised of depositional and eroding landform positions. In real landscapes, landform positions can act as both eroding and depositional sites, such as flat locations that would serve as depositional sites can be susceptible to wind erosion (Pyle et al., 2017). However, depending on specific fire and environmental conditions, this model may still hold as a proximate estimation for the erosion

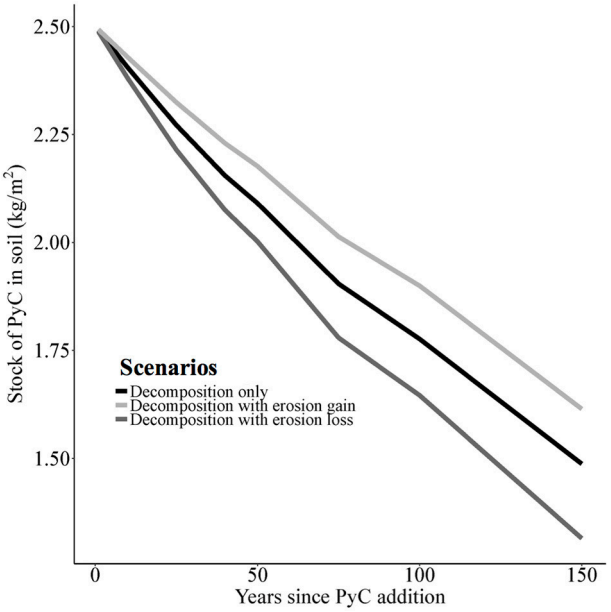

FIGURE 5 | The difference in PyC stock when erosion is considered as a loss (e.g., via transport out of a soil) vs. a gain (e.g., in depositional landform positions) in a model of PyC loss over 150 years can lead to around a 250 g difference in PyC stock per m^2 after 100 years. The assumed initial stock of PyC was 2.5 kg/m^2 (Hammes et al., 2008), and the base decomposition rate was derived from a 263-year turnover time (k_0 = 0.0038, from Equation 1). The rate of erosion was assumed to be 0.001 (K_e, from Equation 1), which equates to a 1,000-year turnover time. This model also assumes a single input of PyC into the soil. In reality, multiple fires would have occurred during the 150-year run of this model, suggesting that soil PyC stocks would not decline at this rate.

inputs of PyC into a depositional landform position, particularly as recent research has demonstrated the preferential erosion of PyC on even apparently flat landscapes (Pyle et al., 2017). This model assumes only a single fire event to input PyC, but in many environments, it is likely that there would be more than a single input of PyC over the duration of 150 years. This model also assumes a linear and constant rate of erosion, which is not likely to occur in natural ecosystem. However, this model estimation demonstrates the possible order of magnitude error that might be found in post-fire erodible landscapes, assuming similar initial stocks and losses via erosion and decomposition. We found that, for the specific conditions we considered, not accounting for erosional redistribution of PyC can lead to almost 300 g PyC m^{-2} difference between the maximum gain of PyC stock from depositional of eroded material and minimum erosion loss scenarios over a 150-year simulation. Note that the model presented here is inherently simplistic by design, as it is aiming to demonstrate the role of soil erosion under three landform positions. In any given hillslope, the actual role of erosional redistribution depends on the nature of the landscape, rate of PyC input, and the environmental variables that control rate of PyC loss through decomposition, leaching, and/or erosion. For example, future models could be designed for specific environments to include additional fluxes of PyC that have yet to be well quantified, such as bioturbation, leaching, and subsequent fires, and likely control its stock and residence time in the soil.

The model presented above can also be used to determine the effect of erosion on mean residence times or persistence of PyC in soil. The more that erosion contributes to the k term as a loss of PyC, the larger the overall k term and the faster the turnover of PyC in a soil, since a portion of the PyC stock would be moved to downslope positions. Conversely, for depositional landform positions, the k_e adds to the soil profile's PyC stock, and because k_e would be negative in this case, it lowers the effective k term in Equation (1), leading to longer turnover times for PyC in soil profiles of depositional landform positions.

On the local scale, explicitly considering erosion as a loss or gain term (depending on the landform positions considered) for PyC in dynamic landscapes leads to considerable differences in MRT at different geomorphic landform positions. Across even a single hillslope, soil properties and controls on decomposition vary considerably. We calculated turnover times for eroding and depositional landform positions, by assuming a decomposition rate [k_0 from Equation 3 of 0.04%/year and an erosion rate of 0.01%/year (1,000-year turnover time from erosion processes alone)]. This calculation also assumes that PyC that is eroded and left in place is similarly impacted by decomposition, which is not necessarily true based on preferential erosion of PyC (Rumpel et al., 2009). Under natural conditions, a considerable proportion of PyC eroded in the short term (up to 1 year) post-fire is likely mobilized further through the landscape on longer (10 + years) timescales (Abney et al., 2017).

In this simple model, the erosion rate (k_e) was positive for the eroding landform position (indicating erosional loss of PyC from eroding landform positions and making net loss of PyC faster) and negative for the depositional landform position (indicates an addition of PyC and decreasing the net loss of PyC). This erosion rate was further divided into five different fractions, such that 0% indicates no erosion, or no erosion accounted for, and 100% indicates 100% of the 0.01% erosion rate accounted for within the model. We found that if 100% of this theoretical erosion rate is accounted for, then the difference in calculated turnover time is ∼150 years (**Figure 6**). If 50% of the erosional loss of PyC from a soil is accounted for, then the difference between the maximum turnover time with erosion as a gain and the minimum turnover time with erosion as a loss is ∼70 years. If the erosion rate were higher (i.e., the theoretical 100% erosion was a higher background erosion rate), then this difference in turnover time would be even greater. This difference in erosion indicates that over the scale of a landscape, local topographical differences that determine whether PyC is eroded or deposited over time can play a major role in the fate of that PyC, depending on the relative rates of loss, deposition, and burial of PyC.

This model only applies to the fate PyC that remains on the surface soils, which is the fraction that is likely to experience erosion. The fraction of soil PyC that is found in deep soil layers or gets buried overtime is not likely to experience significant lateral redistribution with erosion, and hence is not included in this discussion. Also, the importance of the role of erosion as a gain or a loss term is also dependent on the relative role of erosion in each landscape (**Figure 6**), as different landscape geomorphologies can lead to drastically different erosional rates and processes (section Geomorphology of the

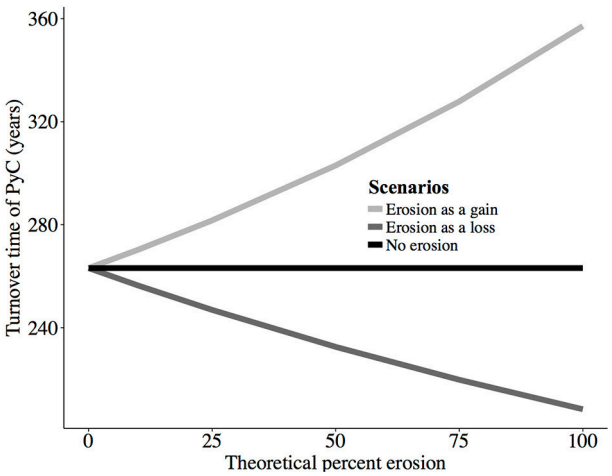

FIGURE 6 | The magnitude of difference in turnover time of PyC associated with discounting erosion as either an input (deposition of material) or loss (erosion of material) term can lead to an ∼150-year difference error in turnover time depending on the fractional amount of erosion occurring. The theoretical percent erosion is the percent of an erosion rate (K_e, from Equation 1) that is accounted for within this model from an assumed rate of erosion of 0.001 (1,000-year turnover time of PyC via erosion, a slow erosion rate). This erosion rate is added (deposition of material) or subtracted (erosion of material) from a base decomposition rate (k_0, from Equation 1) of 0.004, corresponding to a 250-year turnover time (Hammes et al., 2008). A theoretical percent erosion of 0% corresponds to no erosion contribution of input or output of PyC from a soil; whereas a theoretical percent erosion of 100% would lead to either an input (gain) of PyC into the soil or loss of PyC from the soil that would increase or decrease the turnover time of PyC by ∼70 years respectively.

Landscape). Furthermore, the intensity, type, and timing of post-fire precipitation play important roles in controlling the rate of PyC water-driven erosion (Hammes et al., 2008) and transport of other soil constituents (i.e., reactive minerals) that may influence the fate of PyC post-erosion and/or deposition.

Explicitly Considering Erosion in Global PyC Budgets

The role of erosion in redistributing PyC can also impact global models of PyC cycling and storage (Bird et al., 2015). The major global stocks of PyC are 1.05×10^{15} g PyC in the soil (Bird et al., 2015), 9.87×10^{18} g PyC in the ocean (Ziolkowski and Druffel, 2010), and 1.79×10^{22} g PyC in marine sediments (Masiello, 1998). The major fluxes of PyC are decomposition, which ranges from 0.25 to 20% loss per year depending on PyC properties and environment (**Table 1**), 1% loss per year from leaching and percolation (Major et al., 2010; Abiven et al., 2011), 7.4×10^{12} g PyC per year transported to oceans by rivers (Dittmar et al., 2012; Jaffé et al., 2013), and 0.02% loss of ocean PyC to sediment per year (Masiello, 1998).

Current global and smaller-scale literature is not fully accounting for the erosion of PyC and transformations of PyC during and after erosion throughout the global ecosystem, even though the stocks are in approximate steady state (Bird et al., 2015). This indicates that while preferential loss of PyC via erosion may serve as a significant loss mechanism for PyC, it is also likely acting as a stabilization mechanism of PyC for the budget to remain roughly in balance. Furthermore, uncertainties also remain concerning the role of erosional transport in physical breakdown and decomposition of PyC during erosional transport. In the landform position model presented here, the rate of decomposition during erosional transport was assumed the same as non-pyrogenic carbon, although there is considerable evidence that this is not likely the case (Santos et al., 2012; Whitman et al., 2014). Since this assumption would likely prove invalid and PyC decomposition during erosion is considerably lower, this would have important implications for the long-term stabilization of PyC. Moreover, this model also assumes a steady state of erosion and even distribution and formation of PyC across the landscape, which is not representative of the heterogeneous nature of fire. Finally, even though erosion of PyC from slopes represents a loss process, it serves the opposite role when the PyC is buried in depositional landform positions. If we assume that erosional redistribution, and subsequent burial of eroded PyC in depositional soil profiles can effectively reduce its decomposition rate, then the process of soil erosion can potentially be a stabilization mechanism for PyC in dynamic landscapes (Berhe et al., 2007; Berhe and Kleber, 2013). Future research should investigate the long-term fate of PyC that is eroded and buried, and the magnitude that this can serve as a mechanism for increased soil C storage.

The models presented here do not necessarily represent natural variation in timing and magnitude of fire, erosion, and future climates that may alter the global PyC cycle, particularly as large erosion and fire events are strongly controlled by local climatic conditions (Westerling et al., 2006). The loss of PyC from the soil is likely more episodic and variable in nature than these scenarios account for, and therefore this loss may be different than predicted by constant rate functions used in this model. Also, these calculations do not account for the decomposition or loss of PyC from groundwater or through leaching.

In addition to the limited knowledge of the controls on breakdown of PyC in the soil system, it is widely agreed that the laboratory-based incubation studies are over-estimating the rate of PyC decomposition due to the disturbance of the soil and since decomposition conditions are considered to be more optimal in the laboratory compared with field conditions. Many of the laboratory based estimates are over 10% PyC loss per year (Nguyen et al., 2010; Foereid et al., 2011), which is inconsistent with calculated PyC MRT measurements that range from several hundred years to several millennia (Hammes et al., 2008; Lehmann et al., 2008; Singh et al., 2012; Bird et al., 2015). It is also possible that erosional deposition and burial of PyC is a more significant process for the long-term stabilization of PyC than previously considered. If erosion is playing a significant role in the stabilization of PyC and if decomposition rates of PyC are consistently over-estimated, this could have major implications for global models of PyC cycling and storage (Bird et al., 2015). Parameterizing global stocks and fluxes of PyC is critical, because PyC could be serving a major role that has so far not been accounted properly in global C budgets (Lehmann, 2007; Santín et al., 2015).

While current box models, such as in Bird et al. (2015), suggest that erosion is playing a role in redistributing PyC and a role in burying it for longer-term storage within the soil system, these models are a simplification of the global PyC cycle that do not include quantitative inputs such as type of erosion, climate data, and topography, which are critical for determining the effects of erosion on PyC turnover times and persistence. What can conclusively be drawn from the model scenarios presented here is that the role of erosion of PyC should not be ignored as a factor controlling its long-term fate within the soil and that further research is needed to quantitatively describe and realize the variability in these systems.

Remaining Uncertainties in PyC Erosion and Recommendations for Future Research

The variation in the estimates of loss of PyC reflects both the spectrum of methodologies used to measure PyC and the lack of inclusion of erosion and other processes, such as leaching, as loss mechanisms. The dynamics of PyC within the soil system depends on prevalent environmental conditions, such as temperature, precipitation, land use, slope, aspect, and vegetation. Available data on the magnitude of loss of PyC from the soil by different processes is currently incomplete, and has a lot of uncertainty, making model parameterization very difficult (see **Table 1** for published magnitudes of fluxes of PyC). In particular, the rates of erosion and burial of PyC and the mechanisms and magnitude of the transport of PyC from land to water need further investigation (Bird et al., 2015; Santín et al.,

2016), particularly in ecosystems that are susceptible to erosion, such as upland temperate forests.

One of the major challenges in quantifying PyC fluxes within the environment is that no single analytical technique can measure the range of materials that make up PyC continuum, including soot, charcoal, and charred biomass (Masiello, 2004). Many different techniques (e.g., physical separation, nuclear magnetic resonance spectroscopy, mid-infrared spectroscopy, benzene polycarboxylic acid, mid-infrared spectroscopy, and partial least squares regression) are currently being used to measure PyC concentration and composition (Schmidt and Noack, 2000; Gustafsson et al., 2001; Masiello, 2004; Preston and Schmidt, 2006; Hammes et al., 2007; De La Rosa et al., 2008; Wiedemeier et al., 2013, 2015; Cotrufo et al., 2016), with varying degrees of accuracy for quantifying different types of compounds in the PyC continuum (Masiello, 2004; Hammes et al., 2007). Due to the variety of techniques currently used, and a lack of meaningful standardization methods for the different techniques, direct comparison of published results is extremely difficult. Many PyC-like, aromatic materials can be confounded with PyC in some of these techniques, further adding error to these analyses, along with some of them having varying degrees of sensitivity to aromatic condensation (Skjemstad et al., 1999). Hence, the data and arguments presented above are based on the most conservative results and least contradictory conclusions that we could draw from published literature.

In the simple decay model presented here (**Figure 5**), in the absence of new input, the soil's PyC stocks were declining considerably lower than the current PyC soil stock measurements would suggest. It is likely that the inferred or measured rates of PyC loss in soils are overestimating the effectiveness of microbial decomposition, especially for the studies generated from short-term laboratory experiments conducted under ideal climate and environmental conditions, especially since some research has indicated an initial priming effect with the addition of PyC (Zimmerman et al., 2011). In longer-term laboratory incubations and models, rates of PyC decomposition are considerably lower and are generally non-linear (Kuzyakov et al., 2009; Foereid et al., 2011), in contrast to the linear the model presented here. Future modeling efforts should focus on the temporal variability in inputs of PyC into the soil in addition to the role of erosion as both and input and loss process for PyC.

CONCLUSIONS

Interactions of environmental perturbations such as fire and erosion can play significant roles in regulating PyC and SOM persistence in dynamic landscapes. The synthesis of published results and the model presented here illustrates how not accounting for integrated dynamic decomposition and geomorphological processes can lead to significant errors in our current understanding of PyC dynamics in the terrestrial ecosystem. Specifically, not accounting for post-fire erosion could lead to significant differences in projected stocks and turnover times of PyC within the soil, depending on specific ecosystem properties such as erosion and decomposition rates. These differences in stock and turnover time vary based on landform position, rates and drivers of erosion, among other factors.

Understanding the long-term fate of terrestrial OM and PyC is critical for generating accurate models and to better manage these ecosystems to maximize soil C storage. Considering climate change, understanding the controls on the PyC cycle may become ever more critical for managing soil C cycle. This is particularly relevant as the relative roles of fire and erosion as controlling forces of the soil PyC cycle may act in different ways under altered climatic regimes and across different ecosystems and regions. PyC is an important component of the global C cycle that is being assessed for its potential to account for the missing C sink and biochar addition to soil is being discussed as one of many approaches that can be used to mitigate climate change (Lehmann, 2007). It is critically important for future research to focus on more quantitative understanding of the production, stocks and major loss processes for PyC from the soil, including decomposition, erosion, leaching, and consumption in subsequent fires. However, currently, the uncertainties in comparing loss rates from different ecosystems and measurement techniques make global synthesis difficult, in addition to uncertainties in current stock estimates. Moreover, major gaps remain in our understanding of the mechanisms and magnitude of PyC loss from the soil system, and it is likely that erosional redistribution of PyC post-fire plays a major role in controlling the fate of PyC in the soil system.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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