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Climate-dependent topographic effects on pyrogenic soil carbon in southeastern Australia

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ABSTRACT

The interactive effects of climate and topography on the composition, distribution and storage of soil organic carbon (SOC) remain unclear. This is particularly true for pyrogenic carbon (PyC) which is considered long-lasting in soil environments. With a goal to characterize how PyC responds to climate-dependent erosion and deposition processes, two hillslopes from SE Australia, differing in climate (MAP: 549 vs. 815 mm) and vegetation but with similar topography were selected for this study. We examined the colluvial soils that include A and B horizons on eroding (convex) and depositional (convergent) areas within each hillslope. Mid-infrared measurements with a partial least squares regression model were adopted to quantify the size and distribution of SOC fractions (i.e., particulate organic carbon (POC) fraction, humus organic carbon (HOC) and resistant organic carbon (ROC; representing PyC fraction) along the two hillslopes. These SOC fractions were examined with respect to climate, topographic position and soil depth. Total SOC was dominated by HOC (44 to 88%) followed by PyC (7 to 37%) and POC (0 to 37%). Effects of topography on inventories of PyC were more strongly expressed in the drier hillslope (eroding vs. depositional: 0.39 vs. 1.73 kg m^{-2}) than the wetter hillslope (eroding vs. depositional: 1.14 vs. 2.46 kg m^{-2}), which also illustrates that climatic effects on soil PyC differ between eroding and depositional hillslope areas. In contrast, relative contributions of PyC to SOC showed less systematic variation with topography (6.9–36.8% in eroding soils vs. 6.9–37.3% in depositional soils) and climate (6.9–36.8% at drier site vs. 6.9–37.3% at wetter site), which together with other laboratory and field data suggest that erosion may not preferentially transport PyC over other organic carbon forms or that erosional PyC flux may not be large enough to alter SOC concentration and distribution into fractions. Our results highlight the importance of considering topography in understanding SOC pools in general and PyC specifically under different climates.

1. Introduction

Soil organic carbon (SOC) constitutes the largest carbon pool in terrestrial ecosystems and is sensitive to changes in climate, plant productivity and various anthropogenic stressors (Lehmann and Kleber, 2015; Schmidt et al., 2011). Despite huge research efforts into understanding the quantity, composition, and stability of SOC, there remain many unknowns (Stockmann et al., 2013). Soil organic carbon is made of diverse compounds (Cotrufo et al., 2016b; Schmidt et al., 2011), and SOC is thus typically conceptualized and mathematically modeled as being composed of several pools with characteristic turnover rates (Manzoni and Porporato, 2009). Among the SOC fractions, this study is particularly focused on pyrogenic carbon (PyC), i.e. charcoal or black carbon (Preston and Schmidt, 2006).

Pyrogenic carbon is resistant to breakdown and can persist in soil for centuries to millennia, which contrasts with particulate organic carbon which may turnover in days to months (Bird et al., 2015), and therefore may create a long-term soil carbon sink (Cusack et al., 2012; Preston and Schmidt, 2006). Primarily a product of wildfire (Santín et al., 2015), PyC is widely distributed in soils, sediments and water, and can contribute > 40% of the total SOC in temperate grasslands and boreal forests (Cotrufo et al., 2016b; Cusack et al., 2012; Preston and Schmidt, 2006; Schmidt et al., 2001). While this carbon fraction has been considered biologically inert and chemically resistant component of SOC (Masiello, 2004; Preston and Schmidt, 2006; Skjemstad et al., 1996), recent studies provide evidence that PyC could be more reactive than previously thought and is potentially susceptible to microbial degradation (Singh et al., 2012; Soong and Cotrufo, 2015). The recent global synthesis by Reisser et al. (2016) revealed that environmental controls on the concentrations and abundances of PyC in soils are

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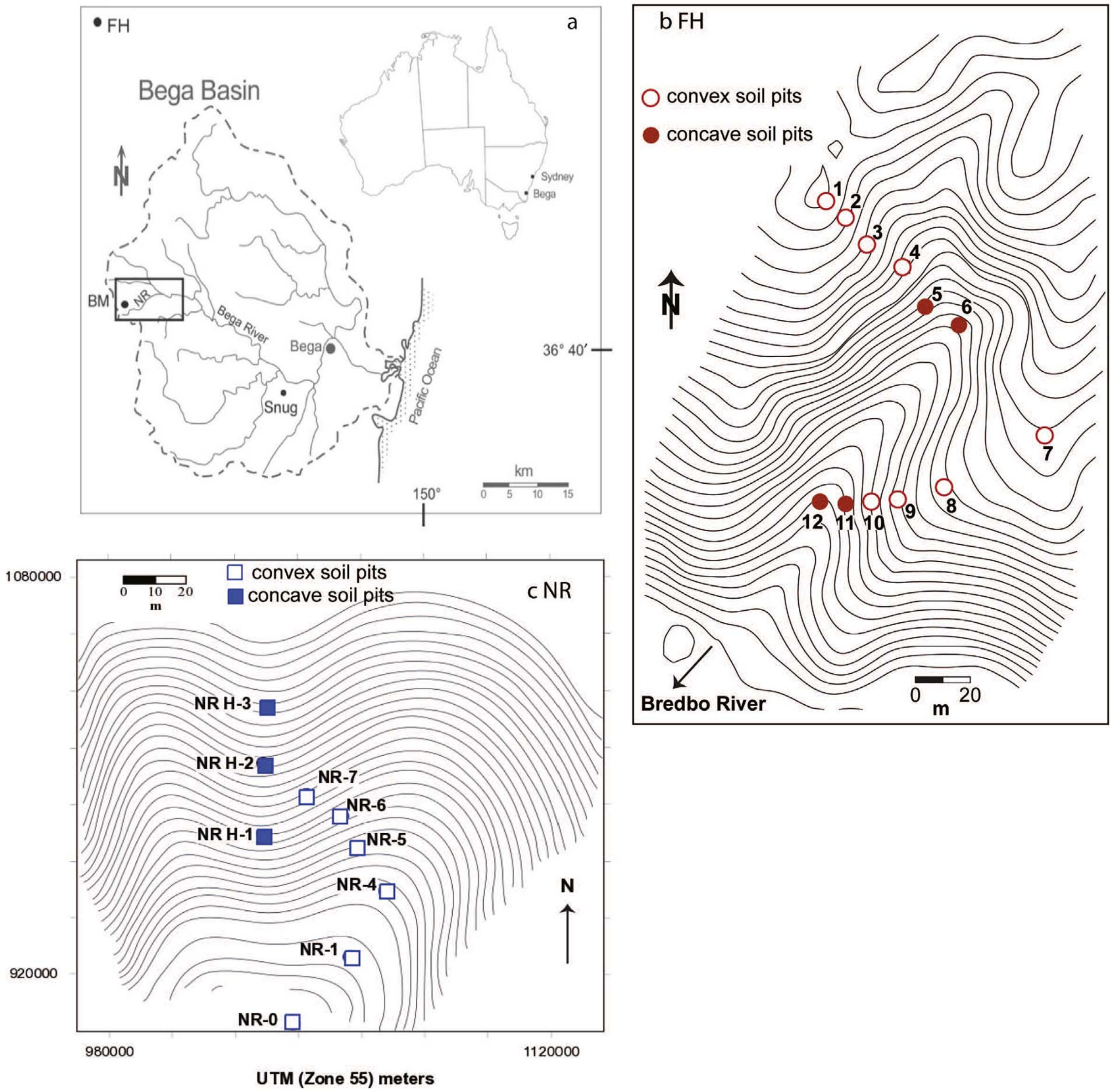

Fig. 1. Location of studied sites, Frog Hollow (FH), the drier and cooler site and Nunnock River (NR), the wetter and warmer site from Southeastern Australia. The figure is modified from Burke et al. (2009).

complex. For example, climate effects on PyC abundance were found to be minimal, and little connection between PyC abundance and fire regimes was found. Instead, PyC abundance was found to be positively correlated with soil clay content (Reisser et al., 2016).

Previous studies have shown that PyC distribution and stocks are strongly related to topographic positions (Kane et al., 2007, 2010); however, the extent to which PyC topographic trends are controlled by erosion is poorly known. Soil erosion mechanisms and severity are known to be sensitive to climate and vegetation (Marshall et al., 2017; Riebe et al., 2015). The mode and extent of PyC erosion are related to the same processes that detach and transport organic matter and mineral particles on the soil surface (Rumpel et al., 2009, 2006). However, Müller-Nedebock et al. (2016) observed that the selective transport of organic carbon by water erosion may be more related to the slope length and the characteristics of rainstorms had no significant impact on the selectivity of organic carbon erosion. Discrepancies thus exist between different studies and little is known about the interplay between climate, topography and PyC. Advancing our understanding of the topographic control of PyC is our goal in this contribution, and this goal can be most benefited by having a factorial study to investigate both topography and climate as independent variables.

These growing but confounding findings on the characteristics and environmental controls of soil PyC necessitates a better understanding of how soil PyC is distributed at watershed scales in different climates. This is important because field soil sampling is typically designed with consideration of topography, and thus knowing the variability of carbon distribution at a landscape scale is critical to determining and interpreting large-scale environmental controls on soil carbon data. This need is more acute because soil erosion has been identified as a dominant mechanism for the fate, transport and redistribution of PyC in the areas as affected by wildfire (Boot et al., 2015; Chaplot et al., 2005; Cotrufo et al., 2016b). For example, in Northern Laos where water erosion annually removed 0.69 t ha^{-1} of SOC from the upslope of steep hillslopes, PyC was preferentially redeposited at hillslope bottoms (Chaplot et al., 2005). An artificial rainfall irrigation study, conducted at a plot scale, showed water erosion via raindrop and runoff was capable of removing 7–55% of the initial PyC (Rumpel et al., 2009). However, Cusack et al. (2012) found no evidence that PyC is