Warming-related increases in soil CO₂ efflux are explained by increased below-ground carbon flux

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Methods

The CAO LiDAR was operated at 50 kHz, with a maximum half-scan angle of 17 degrees and 50% overlap between adjacent flight lines to ensure canopy penetration (Asner et al. 2008, 2009). The LiDAR data were analyzed using a physical model to derive top-of-canopy and ground digital elevation models (DEM), which were then used to determine vegetation height (DEM and vegetation height errors: 0.12 m ± 0.14 m and 0.7 m ± 0.2 m, respectively).

For radiocarbon analyses, samples were combusted in presence of CuO and Ag, purified, and reduced to graphite in an H₂ environment with a Fe catalyst (Vogel et al. 1984). The ¹⁴C content was determined on the graphite targets (Vogel 1992), with radiocarbon data being reported as Δ¹⁴C, which is the difference in parts per thousand from the ¹⁴C to ¹²C ratio of oxalic acid standards. Data were corrected for fractionation effects, where δ¹³C was measured using a Thermo Finnegan Delta V IRMS at the UH Hilo Analytical Laboratory (Stuiver and Polach 1977).
To further elucidate the role of temperature on SOC storage and flux, we fractionated soils from our surface (0-10 cm) depth using a sodium poly-tungstate (SPT) density separation method that divided bulk soils into SPT soluble, light (<1.6 g mL\(^{-1}\)), intermediate (1.6 – 2.4 g mL\(^{-1}\)) and heavy fractions (> 2.4 g mL\(^{-1}\)). We observed no trends in the distribution of various density fractions with MAT (Figure A1). And while we observed a strong increase in the age of the fractionated carbon with increasing fraction density (Figure A1), we observed no pattern of decreasing MRT with increasing MAT for any of the fractions (Figure A2).

Finally, we synthesized and compared radiocarbon-based estimates of MRT for acid insoluble carbon, fractionated through acid hydrolysis, and for paired bulk soils (Figure A3). We found that the radio-carbon age for the acid insoluble fraction is strongly related to the radiocarbon age of carbon in bulk soils. Presumably, this relationship, spanning dozens of soils and most soil orders from across the Earth, would hold across our MAT gradient where many variables are strongly controlled. These data indicate that the lack of a pattern for MRT for bulk soil SOC would translate into a lack of a pattern for acid insoluble carbon – typically defined as the most stable carbon in soil – for our research site. It also indicates that the lack of an MAT pattern for our density fractionated (0-10cm) soils (Figure A2) is robust.
Figure A1. Effects of mean annual temperature (MAT) on the mean residence time (MRT) of density isolated soil organic carbon (SOC) fractions (upper panel; Means) and density isolated SOC fraction size (lower panel; Means) for 0-10 cm soil depths. No error bars are provided as analyses were performed on one composite sample per site. The upper panel shows that sequential fractionation was successful at isolating fractions with different MRTs. For the lower panel, regression analyses revealed that none of the relationships between MAT and fraction size were significant (n= 9).
Figure A2. Effects of mean annual temperature (MAT) on the mean residence time (MRT) of soil organic carbon (SOC) fractions (Means) for 0-10 cm soil depths. No error bars are provided as analyses were performed on one composite sample per site. Regression analyses revealed that none of the relationships between MAT and MRT were significant (n= 9), indicating that the MRT of the various density isolated SOC fractions is unrelated to MAT.
Figure A3. The relationship between mean residence time (MRT) for bulk soil organic carbon (SOC) and MRT for acid insoluble carbon (AIC) for three studies where both were measured.

Data was assembled from a wide range of research sites (forest, agriculture, grassland) and mean annual temperatures (MAT; -2 to 22 degrees C): red triangles represent data from Fissore et al. (2009) for 0-20 cm depth soils; dark blue circles represent data from Paul et al. (2001) for soils sampled at three depths (0-20, 25-50, and 50-100 cm); the dark green square represents data from Jenkinson and Rayner (1977) for soil sampled from 0-23 cm; the light green squares represent data from Paul et al. (1997) for soils sampled at four depths for one site (0-10, 10-20, 20-30, 30-45 cm) and one depth for a second site (0-15 cm); and the light blue triangles represent data from Shawel et al. (2000) for three soil depths (0-18, 18-30 and 30-60 cm). Across depth, vegetation cover type, management and MAT, >73% of the variation in AIC MRT is explained.
by the MRT of bulk SOC, indicating that bulk soil MRT is a robust indicator of how the most
stable fraction is soil behaves in response to environmental variables including MAT (n=47). For
our study, the bulk SOC MRT data would suggest that the lack of temperature sensitivity would
also extend to individual fractions, as we have shown for surface (0-10cm) density isolated
fractions (Fig A1).

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