**Parent material and climate interact to control soil C dynamics through the development of poorly crystalline minerals**

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Abstract

Lorem ipsum…

**Parent material and climate interact to control soil C dynamics through the development of poorly crystalline minerals**

# 1 Key messages:

* Climate explains more variance in 14C at the soil surface; parent material explains more variance at depth
* Interaction of parent material and climate explains more variance in bulk soil and respired 14C than either factor alone
* Poorly crystalline mineral content is highly correlated with the difference between bulk soil 14C and respired 14Crespired

# 2 Introduction

* Climate change effects on soil C will determine whether or not soils continue to be a sink or will become a source in the coming decades
  + Understanding these effects requires understanding soil carbon persistence mechanisms
  + This study specifically looking at parent material, climate, and their interaction via weathering
* Climate most important explanatory factor for global variation in C stocks and 14C
  + Function of temperature and moisture effect on decomposition rates
* Mineral association attenuates these effects
  + Examples of decomposition rates different for different parent materials under the same climate conditions
  + Lab and field?
  + E.g….
* Mechanisms of mineral protection and specific minerals, i.e. beyond clay
  + Poorly crystalline minerals in particular
  + Develop from interaction of parent material and climate over time, i.e. weathering
  + Examples of mechanisms
* Bulk soil 14C as proxy for age
  + Larger pools that cycle more slowly dominate mass of bulk soil C, but contribute less to respired C fluxes
  + 14C of heterotrophically respired CO2 (14Crespired) gives relative contribution of faster or more slowly cycling soil C to flux
  + 14Crespired emphasizes contributions from smaller, fast cycling pools
  + Therefore difference between two provides a measure of the degree of protection of soil C (or presence of C pools that are persistent over centuries-millennnia because of strong mineral protection)
* Introduce sites
  + …
* Expectations for effects of parent material and climate effects
  + Linear models (?)
  + Teaser of findings, importance of weathering for mineral assemblage;
  + Interaction of parent material and climate key for understanding the variance in 14C of both bulk soil and respired CO2
  + Show how poorly crystalline minerals implicated in soil C protection

# 3 Methods

## 3.1 Site descriptions

We collected samples from 9 sites across a combined gradient of parent material and climate in the Sierra Nevada Mountains of California (Table 1). These mountains provide natural independent gradients of parent material and mean annual temperature (MAT). Moving from north to south along the cordillera the parent material changes from basalt to andesite to granite, while the change in elevation headed eastward from the Central Valley leads to a decrease in MAT that is consistent for each parent material.

Total mean annual precipitation is relatively constant with elevation, but falls mainly as rain at lower elevations, and mainly as snow at higher elevations. There is a slight precipitation gradient running north to south, with MAP of xxx mm yr-1 averaged across the basalt sites in the north, xxx mm yr-1 for the andesitic sites, and xxx mm yr-1 for the granodiorite sites in the south.

Vegetation at the study sites is typical of the Sierra Mixed Conifer habitat (Parker, I., and W. J. Matyas. 1981. CALVEG: a classification of Californian vegetation. U.S. Dep. Agric., For. Serv., Reg. Ecol. Group, San Francisco.). All of the sites are forested and dominated by conifers, although the species composition changes along with climate. Tree species at the lowest elevation, “warm”, sites are predominantly Pinus ponderosa mixed with lesser amounts of Quercus spp. The canopy species at the mid-elevation cool sites is comprised primarily of Abies concolor and Pinus lambertiana, while Abies magnifica is the dominant species at the highest elevation “cold” sites. Species present at all sites include Calocedrus decurrens in the canopy, the shrubs Arctostaphylos spp., Chamaebatia foliolosa, and Ceanothus spp. to varying degrees, and ground cover of grasses and forbs.

## 3.2 Sample collection

Site locations were initially established in 2001 by C. Rasmussen (Rasmussen et al., 2006), and resampled in 2009 (Rasmussen et al., 2018). We returned in late September of 2019 to collect samples for this study. Sites were located using GPS and geospatial coordinates recorded during site establishment. At each site we dug three replicate pits down to a depth of 0.3m. Prior to sample collection we compared the soil profiles to the pedon descriptions from the previous sampling campaigns. After confirming profiles were comparable we collected samples from the pit sidewalls in 0.1m increments for each of the three pits. We also measured the depth of the litter layer and collected representative litter samples from each site.

## 3.3 Spline fitting

Soils collected in 2001 and 2009 were sampled by horizon, while soils collected in 2019 were sampled by depth. We were motivated to use consistent depth increments across sites because of the strong correlation between depth and 14C In order to make the horizon and depth-based measurements comparable, we fit a mass-preserving quadratic spline to the 2001 and 2009 profiles in order to convert soil property data to the equivalent depth increments sampled in 2019 (Bishop et al., 2001). We used the mpspline function of the GSIF package in R, with a lamba value of 0.1 (Hengl 2019).

## 3.4 Incubations

Laboratory soil incubations were performed on composite samples from the three replicate pedons sampled at each site. We composited and incubated each depth increment (0-10cm, 10-20cm, 20-30cm) separately in 1 L glass mason jars fitted with sampling ports in the lids. Incubations were performed in duplicate. Prior to the start of incubations we adjusted the soil moisture content to 60% of water holding capacity (WHC). We defined WHC as the gravimetric water content of water-saturated soil placed in mesh-covered (50µm) tubes (50ml) weighed after draining for 30 minutes on a bed of fine sand. Following rewetting we allowed the soils to respire for one week before closing the jars. Incubations proceeded until CO2 concentrations in the jar headspace reached approximately 10,000 ppm, at which point we collected a 400ml gas subsample for radicocarbon analysis. Gas samples were collected with pre-evacuated stainless-steel (Restec) vacuum canisters. All incubations were performed in the dark at 20°C.

## 3.5 Soil Physical Analyses and Mineral Characterization

Data on soil particle size distributions, bulk density, and mineral characterization were obtained from previously published analyses of samples collected at the study sites in 2001 and 2009 (Rasmussen et al. 2006, Rasmussen et al., 2018). Both qualitative and quantitative approaches were used to characterize soil mineral assemblages, including X-ray diffraction (XRD) for the clay (<2µm) fraction, atomic absorption spectroscopy, and non-sequential selective dissolution. Details on these analyses are provided by Rasmussen et al. (20XX). In this study we use the amount of iron selectively dissolved from bulk soils by acid ammonium-oxalate and citrate dithionite as proxies for the quantity of poorly crystalline and crystalline minerals, respectively.

## 3.6 Carbon, Nitrogen, and Radiocarbon Analysis

Total carbon and nitrogen content was determined by dry combustion (Vario Max, Elementar Analysensysteme GmbH) on finely ground soils (Retch MM400). For radiocarbon analysis, we first purified CO2 from incubation flask samples and combusted soil samples on a vacuum line using liquid N2. Following purification, samples were graphitized with an iron catalyst under an H2 enriched atmosphere at 550°C. Radiocarbon content was then measured by accelerator mass spectrometry (Micadas, Ionplus, Switzerland) at the Max Planck Institute for Biogeochemisty (Steinhof, 2017).

We report radiocarbon values using units of 14C, defined as the deviation in parts per thousand of the ratio of 14C–12C from that of the oxalic acid standard measured in 1950. This unit also contains a correction for the potential effect of mass-dependent fractionation by normalizing sample 13C to a common 13C value of 25 per mil (Stuiver & Polach, 1977). Values with 14C >0 indicate the presence of ‘bomb’ C produced by atmospheric weapons testing in the early 1960s. Values with 14C < 0 indicate the influence of radioactive decay of 14C, which has a half-life 5730 years.

## 3.7 Statistical analysis

We used a linear modeling approach to assess the relative explanatory power of climate versus parent material on the observed variation in 14C, as well as potential interactions between these two factors. We constructed separate models for 14C*bulk* and 14C*respired* but with the same righthand side of the equation (**Eq. 1**). For each model we considered the two-way interaction between parent material and climate as well as the three-way interaction with time (**Eq. 1**). For ease of interpretation, we considered the effect of depth by modeling each depth layer separately (0-10 cm, 10-20 cm, 20-30 cm). We also made pairwise comparisons of 14C*bulk* and 14C*respired* across sites and within years, as well as comparisons of individual sites across years. We assessed the significance of the temporal trend for pairwise combinations of parent material and climate using the emmtrends function of the emmeans package (Lenth, 2021). We corrected for multiple comparisons using Tukey’s honestly significant mean difference.

**Eq. 1**

The relationship between 14C of bulk soil and respired CO2 provides insight into soil C dynamics and potential retention mechanisms (Sierra et al. 2018). We modeled the effects of parent material (**Eq. 2**) and climate (**Eq. 3**) on this relationship separately, as we did not have an adequate number of observations to consider the interaction between these two explanatory variables. We used 14C measurements made on samples collected in 2001 and 2019, and data from all depths. The three-way interactions of 14C*bulk* and the explanatory variables were not significant with either depth or time for either **Eq. 3** or **Eq. 4**, so we did not include those variables in the models.

**Eq. 2**

**Eq. 3**

We assessed the relative importance of poorly crystalline versus crystalline iron minerals in protecting soil C from microbial decomposition by regressing 14C against the concentrations of ammonium-oxalate extractable iron, ammonium-oxalate extractable aluminum, pyrophosphate extractable aluminum, and dithionite-citrate extractable iron (**Eq. 4**). We fit the model for 14C*bulk*, 14C*respired*, and the difference between 14C*respired* and 14C*bulk* (14C*bulk-respired*). We used 14C data from 2001 and 2019. Selective dissolution was only performed for the soils collected in 2001, as these data reflect weathering processes that operate timescales beyond the 18 year duration of this study. Extracted metal concentrations did not change substantially by horizon; therefore we conducted regressions for the entire 0-30 cm depth in order to control for the depth dependence of 14C and simplify interpretation of the data. We computed carbon mass-weighted means for 14C*bulk* data and flux-weighted means for 14C*respired* data prior to calculating 14C*bulk-respired*.

**Eq. 4**

# 4 Results

## 4.1 Soil carbon concentration depth profiles

We observed both parent material and climate effects on soil C concentration. Carbon concentrations were similar among parent materials for the warm climate sites (**Fig. 1, a**), while at the cool and cold climate sites (**Fig. 1, b, c**) the andesitic soils had higher C concentrations than either the basaltic or granitic soils. The basaltic and granitic soils had similar C concentrations across climate zones, while the cool and cold climate andesitic soils were enriched in C relative to the warm climate soils. Soils showed a similar decrease in C concentration with depth across all sites (**Fig. 1**).

We did not observe significant changes in soil C concentration over time at the majority of sites. However, there were a few exceptions. Most notably, we saw significant increases in soil C concentration for the cold climate andesitic soils at all depths (lower and upper 95% confidence limits given in brackets), with increases of: 0.20 [0.01, 0.40], 0.23 [0.12, 0.35], 0.21 [0.13, 0.29] percent C yr-1, for the 0-10, 10-20, and 20-30 cm depth increments, respectively. We also saw a significant increase in percent C over time for the 10-20cm layer at the warm climate granitic site (0.16 [0.05, 0.26] percent C yr-1), and significant decreases for the 0-10cm layer at the warm climate andesitic and basaltic sites (-0.19 [-0.37, -0.01], 0.04 [-0.07, 0.14] percent C yr-1).

Figure 1.   Profiles of soil C concentration. Points show means of 2001, 2009, and 2019 data; error bars show ±2SE.

*Figure* *1.*  Profiles of soil C concentration. Points show means of 2001, 2009, and 2019 data; error bars show ±2SE.

## 4.2 Radiocarbon depth profiles

### 4.2.1 Bulk soil.

The distribution of 14C*bulk* showed both parent material and climate controls, as with soil C concentration. However, contrary to what would be expected from the decomposition-temperature relationship, 14C*bulk* of soils at the cool climate sites was equally or more depleted than what we observed at the cold climate sites (**Fig. 2, b, c**), although we observed the most enriched 14C*bulk* at the warm climate sites (**Fig. 2, a**). When comparing 14C*bulk* from different parent materials within a given climate zone, 14C*bulk* of andesitic soils tended to be the most depleted, while the granitic soils tended to be the most enriched (**Fig. 2**).

Analysis of variance for 14C*bulk* revealed significant two-way interactions between parent material and climate at all depths (**Table 1**). This interaction was evident in the differences in 14C*bulk* that we observed among parent materials within a given climate zone. We observed the greatest differences in 14C*bulk* among parent materials at the warm and cool sites (**Fig. 2, a, b**), while 14C*bulk* was similar among parent materials at the coldest sites (**Fig. 2, c**). We also found depth to be an important factor influencing the relative importance of climate versus parent material effects on 14C*bulk*. Although 14C*bulk* declined with depth for all sites, climate explained more of the variance in 14C*bulk* in the uppermost soil layer (0-10 cm) whereas parent material explained more in the bottom two layers (10-20 cm, 20-30 cm) (**Table 1**).

### 4.2.2 Heterotrophically respired CO2.

The patterns we observed in 14C*respired* were similar to those we observed in 14C*bulk* (**Fig. 2**). We found climate to be the most significant factor for explaining the variance observed in 14C*respired* for the uppermost soil layer, and parent material to be more important than climate for explaining in 14C*respired* variance at the deepest depth, as with 14Cbulk. However, unlike 14C*bulk*, parent material was not significant for explaining the variance in 14C*respired* in the uppermost soil layer (**Table 1**). Overall, the two-way interaction between parent material and climate explained more of the variance in 14C*respired* data than in the 14C*bulk* data (**Table 1, values**).

In general, the effect of climate on 14Crespired appeared to be moderated by the effect of parent material. For example, we did not observe significant differences in 14C*respired* among the andesitic soils when compared across climate zones at any depth (SI Table X Tukey results for emm?). In contrast, 14C*respired* for the basaltic and granitic soils diverged substantially between climate zones, particularly for the 10-20 cm and 20-30 cm depth layers (**Fig. 2**). Overall, 14C*respired* across sites was most similar at the soil surface, and most divergent at the intermediate depth (10-20 cm) (**Fig. 2**).

Figure 2.   Depth profiles of \Delta14Cbulk and \Delta14Crespired. Top panels show bulk data from 2001, bottom panels show respired data. Panels (a) and (d) show data from the warm climate sites, (b) and (e) from the cool climate sites, and (c) and (f) from the cold climate sites. Black vertical lines show \Delta14C of the atmosphere in the year of sampling. Points show the mean of three replicate profiles for bulk soil, and the mean of laboratory duplicates for respired CO2. Error bars show ±1 SD for bulk soils and the minimum and maximum for respired CO2.

*Figure* *2.*  Depth profiles of 14C*bulk* and 14C*respired*. Top panels show bulk data from 2001, bottom panels show respired data. Panels (a) and (d) show data from the warm climate sites, (b) and (e) from the cool climate sites, and (c) and (f) from the cold climate sites. Black vertical lines show 14C of the atmosphere in the year of sampling. Points show the mean of three replicate profiles for bulk soil, and the mean of laboratory duplicates for respired CO2. Error bars show ±1 SD for bulk soils and the minimum and maximum for respired CO2.

## 4.3 Radiocarbon timeseries

Figure 3.   Temporal trends in \Delta14C for 0-10 cm and 10-20 cm depth layers. Panels a-f show \Delta14Cbulk data; from left, the first column (panels a, c, and e) show 0-10 cm data, and the second column (panels b, d, and f) shows 10-20 cm data. Panels g-l show \Delta14Crespired data; the third column from left (panels g, i, k) shows 0-10 cm data, and the rightmost column (panels h, j, and l) shows 10-20 cm data. Points show observed data; lines show linear trend estimates for marginal means; ribbons show 95% confidence intervals for trends. Dotted line shows atmospheric \Delta14C.

*Figure* *3.*  Temporal trends in 14C for 0-10 cm and 10-20 cm depth layers. Panels a-f show 14C*bulk* data; from left, the first column (panels a, c, and e) show 0-10 cm data, and the second column (panels b, d, and f) shows 10-20 cm data. Panels g-l show 14C*respired* data; the third column from left (panels g, i, k) shows 0-10 cm data, and the rightmost column (panels h, j, and l) shows 10-20 cm data. Points show observed data; lines show linear trend estimates for marginal means; ribbons show 95% confidence intervals for trends. Dotted line shows atmospheric 14C.

### 4.3.1 Bulk soil.

We observed a significant three-way interaction between parent material, climate, and time at all three depths in the linear models (**Eq. 1**) for 14C*bulk* (**Table 1**). The change over time in 14C*bulk* was also affected by depth, with greater differences between 2001 and 2019 seen in the uppermost soil layer than in the deeper layers (**Fig. 3**). We observed a significant decrease in 14C*bulk* in both warm and cool climate granitic soils for the uppermost soil layer, and additionally for the warm climate andesitic soils (**Fig. 3, a**). In the deeper soil layers (10-20 cm and 20-30 cm), we only observed a significant change over time in 14C*bulk* in the cool climate basalt and granite soils (**Fig. 3, b, c**). 14C*bulk* of the cool climate andesitic soils remained essentially unchanged between 2001 and 2019 for all depths (**Fig. 3, a, b, c**), underscoring the importance of the interaction between parent material and climate for explaining temporal trends in 14C*bulk* as well as variance in a given year.

The relationship of 14C*bulk* to atmospheric 14C also depended on the combination of parent material and climate. In 2001, the warm climate sites were the only sites where the basaltic and andesitic soils were enriched relative to the atmosphere, and this enrichment was only observed for the uppermost soil layer (**Fig. 3)**). In contrast, granitic soils at both the warm and cool granitic sites were enriched relative to the atmosphere in 2001 (**Fig. 3**). For the cold climate sites, where 14C*bulk* was most similar, all three lithologies were depleted relative to atmospheric in both surface and subsoil layers (**Fig. 3**).

We observed that 14C*bulk* tended to decrease or remain unchanged between 2001 and 2019 across sites, but the rates of change in 14C*bulk* were typically smaller than the corresponding change in atmospheric 14C over the same period (-5.13 per mille yr-1). Accordingly, 14C*bulk* measured in 2019 tended to be enriched relative to the atmosphere at more sites, and also deeper into the soil than in 2001. We observed surface soil 14C*bulk* (0-10 cm) in 2019 to be enriched relative to the atmosphere at all sites except for the cool climate andesite soils (**Fig. 3; Fig. 2, d-f**). Furthermore, 14C*bulk* remained enriched relative to the atmosphere down to 30 cm at two of the sites in 2019: the warm climate granite soil (**Fig. 2, d**) and cold climate basalt soil (**Fig. 2, f**). 14C*bulk* at the cool andesite site was the most depleted relative to the atmosphere at all time points (**Fig. 3**).

### 4.3.2 Heterotrophically respired CO2.

Temporal trends in 14C*respired* were similar to what we observed for 14C*bulk*, but tended to be of greater magnitude (**Fig. 3, g-l**). Although greater than the change over time we observed in 14C*bulk*, changes in 14C*respired* between 2001 and 2019 still tended to be smaller in magnitude than the change observed in the atmosphere over this period (**Fig. 3, g-l**). In contrast to 14C*bulk*, 14C*respired* tended to be indistinguishable or enriched relative to the atmosphere in both 2001 and 2019; while the majority of samples were enriched relative to the atmosphere in 2019, even at depth (**Fig. 3, g-l**).

We saw significant decreases in surface soil 14C*respired* at seven of the nine sites, with the only exceptions being the cool andesitic and cold granitic sites (**Fig. 3, i, k**). In absolute terms, the changes in 14C*respired* over time in these uppermost soil layers were greatest at the warm sites (-4.43835320190356 per mil ±1.99225321446124 yr-1), while changes were similar for the cool and cold sites (-2.73813429537826 per mil ±1.20546613003229 yr-1, and -2.25428740225863 per mil ±2.07929272876693 yr-1, respectively). The magnitude of the change in 14C*respired* over time tended to decrease with depth. We observed significant negative trends over time for 14C*respired* at only four of the nine sites for the 10-20 cm layer (warm andesite, cool basalt, cool granite, and cold basalt) (**Fig. 3**), and only one site for the 20-30 cm layer (cold basalt) (SI). 14C*respired* at the cool andesitic soils remained unchanged at all depths over the study period.

We observed a significant increase in 14C*respired* from 2001 to 2019 at only one site: from the cold climate granitic soils (**Fig. 3**). These were also the only soils for which 14C*respired* was more depleted than 14C*bulk*. We observed this anomaly for the deeper soil layers in both 2001 and 2019. For the 8-27 cm layer in 2001, the range of 14C*respired* values was -469.10 and -127.80 per mil, compared to a range of 14C*bulk* values of -30.80 and -10.50; similarly, for the 10-20 cm layer in 2019 we observed a range of 14C*respired* values of -396.70 and -23.50 per mil compared to -18.10 and 0.40 for 14C*bulk* (SI Table X). We do not believe this was due to laboratory error in spite of the high variance we observed in the samples, as the pattern was restricted to the deeper soil layers from this one site and consistent over time. However, since it appears to be a unique response to these soils, we have excluded these highly depleted samples from the statistical analyses.

## 4.4 Relationship of bulk soil and respired CO2 14C

We also assessed whether interaction effects of parent material or climate with 14C*bulk* led to deviations from a 1:1 relationship with 14C*respired* (**Fig. 4**). We found that changes in 14C*bulk* led to correspondingly smaller changes in 14C*respired* for andesitic soils in the parent material only model (**Eq. 2**) (slope = 0.51, 95% CI = [0.22, 0.80]) (**Fig. 4, a**), and for cool climate soils in the climate only model (**Eq. 3**) (slope = 0.61, 95% CI = [0.30, 0.91]) (**Fig. 4, b**). While we could not directly test the interaction of parent material and climate factors in these models owing to the limited number of observations, mean differences in 14C*bulk* and 14C*respired* were substantially greater for the cool climate soils developed on andesitic parent material than for the other sites (Table? Numbers?).

Figure 4.   Parent material and climate effects on the relationship of \Delta14Cbulk and \Delta14Crespired. a) Parent material model (Eq. 3) and b) Climate model (Eq. 4). Dotted line shows 1:1 relationship. Points show the mean of three replicate profiles for bulk soil, and the mean of laboratory duplicates for respired CO2. Error bars show ±1 SD for bulk soils and the minimum and maximum for respired CO2. Respired CO2 from the cold granite site in 2001 was extremely depleted in \Delta14C and thus is excluded for display purposes.

*Figure* *4.*  Parent material and climate effects on the relationship of 14C*bulk* and 14C*respired*. a) Parent material model **(Eq. 3)** and b) Climate model **(Eq. 4)**. Dotted line shows 1:1 relationship. Points show the mean of three replicate profiles for bulk soil, and the mean of laboratory duplicates for respired CO2. Error bars show ±1 SD for bulk soils and the minimum and maximum for respired CO2. Respired CO2 from the cold granite site in 2001 was extremely depleted in 14C and thus is excluded for display purposes.

## 4.5 Mineral assemblages and radiocarbon

Mineral assemblage data is reported fully in Rasmussen et al. (2018). Here we focus on the selective dissolution data with respect to the trends we observed in 14C*bulk*, 14C*respired*, and 14C*respired-bulk*. We observed a significant negative correlation between 14C*bulk* and the concentration of oxalate extractable iron, oxalate extractable aluminum, and pyrophosphate extractable aluminum (SI). For simplicity, we focus here on the sum of oxalate extractable aluminum and half of the oxalate extractable iron as a proxy for poorly crystalline mineral abundance, and the difference of dithionite-citrate extractable iron and ammonium-oxalate extractable iron as a proxy for crystalline mineral abundance. The relationship between non-crystalline mineral abundance and 14C*bulk* was highly significant (*p* <0.001), with the model explaining 59 percent of the observed variation. In contrast, we did not find a significant relationship between crystalline mineral abundance and 14C*bulk*.

We also observed a significant (*p* = 0.02) negative relationship between 14C*respired* and non-crystalline mineral abundance, although it was not as strong as the 14C*bulk* relationship. However, we observed a stronger relationship between poorly crystalline mineral abundance and 14C*respired-bulk* (**Fig. 5, a**) than for either 14C*bulk* or 14C*respired*. As with 14C*bulk*, there was no relationship with crystalline mineral abundance for either 14C*bulk* or 14C*respired-bulk* (**Fig. 5, b**).

Figure 5.   Relationship of poorly crystalline and crystalline minerals to the difference of \Delta14Crespired and \Delta14Cbulk (\Delta14Crespired-bulk). a) Poorly crystalline mineral content (oxalate-extractable aluminum + 1/2 oxalate-extractable iron), b) Crystalline mineral content (dithionite-extractable iron - oxalate-extractable iron). Points show mass-weighted mineral concentrations and carbon-weighted values of \Delta14Crespired-bulk for 0-30cm profiles. Lines show linear model fits from Eq. 5.

*Figure* *5.*  Relationship of poorly crystalline and crystalline minerals to the difference of 14C*respired* and 14C*bulk* (14C*respired-bulk*). a) Poorly crystalline mineral content (oxalate-extractable aluminum + 1/2 oxalate-extractable iron), b) Crystalline mineral content (dithionite-extractable iron - oxalate-extractable iron). Points show mass-weighted mineral concentrations and carbon-weighted values of 14C*respired-bulk* for 0-30cm profiles. Lines show linear model fits from **Eq. 5**.

**Discussion**