**Parent material and climate interact to control soil C cycling on timescales of years to centuries**

*Alternate titles:*

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

“Poorly crystalline mineral content is more important than parent material or

climate for explaining soil C dynamics”

**Key messages:**

* Climate effect explains more variance in surface ∆14C, but parent material explains more at depth
* Poorly crystalline mineral content is more important than parent material or climate alone for protecting soil C from decomposition

**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
  + Soil C heterogeneity and bulk vs. respired 14C
  + Respired 14C gives relative contribution of faster or more slowly cycling soil C
  + Difference between two is evidence for protection of soil C
* 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 and respired C
  + Show how poorly crystalline minerals implicated in soil C protection

**Methods**

*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 are a perfect setting for this study as they make up a natural gradient 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.

*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.

*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).

*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.

*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.

*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 δ13C to a common δ13C value of 25 per mil (Stuiver & Polach, 1977).

*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 bulk soil 14C and respired 14C-CO2. For each model we considered the two-way interaction between parent material and climate as well as the three-way interaction with time. 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 bulk 14C and respired 14C-CO2 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.

We assessed the relative importance of poorly crystalline versus crystalline iron minerals in protecting soil C from microbial decomposition by regressing the difference between bulk soil 14C and respired 14C-CO2 against the concentrations of ammonium-oxalate extractable iron, ammonium-oxalate extractable aluminum, pyrophosphate extractable aluminum, and dithionite-citrate extractable iron. We did not observe a significant relationship between the bulk and respired 14C difference and time, so we used 14C data from both 2001 and 2019 in the model. Selective dissolution was performed on splits of the soils collected in 2001. Extracted mineral concentrations did not change substantially by horizon, so in order to simplify data interpretation we conducted regressions for the entire 0-30 cm depth. We computed carbon mass-weighted means for bulk soil 14C data and flux-weighted means for the respired 14C-CO2 data.

**Results**

*Bulk soil radiocarbon: Parent material and climate effects*

Both parent material and climate had strong effects on the distribution of bulk soil 14C, but climate explained more of the variance for the uppermost soil layer (0-10cm) whereas parent material explained more in the bottom two layers (10-20cm, 20-30cm). Focusing on the overall climate effects, soils at the cool climate sites tended to be more depleted in 14C than soils at the cold climate sites, while soils at warmest sites tended to be the most enriched in 14C. Comparing parent materials within climate zones, andesite soils tended to be the most depleted in 14C, while the granites tended to be the most enriched.

∆14C declined with depth for all sites, regardless of parent material or climate. However, linear models for bulk soil ∆14C revealed significant two-way interactions between parent material and climate at all depths. Accordingly, differences in bulk ∆14C among parent materials were greatest at the warm and cool sites. In contrast, bulk ∆14C at the coldest sites was similar across the three parent materials.

*Bulk soil radiocarbon: Temporal trends*

As with the trends in bulk soil ∆14C within years, parent material and climate interacted to control the change in ∆14C observed over time. However, we observed the greatest change in the warm climate sites, while bulk soil ∆14C at the cold climate sites remained relatively unchanged over time. Temporal trends in bulk soil ∆14C were greater in magnitude at the surface than in the deeper soil layers. For the uppermost soil layer we observed significant changes in both warm and cool climate granitic soils, as well as in the warm climate andesitic soils. In the deeper soil layers (10-20 cm and 20-30 cm) the only significant change over time was observed in the cool climate basalt and granite soils. Bulk soil ∆14C of the cool climate andesitic soils remained essentially unchanged between 2001 and 2019. Additionally, bulk soil ∆14C at this site was the most depleted relative to the atmosphere in 2001, 2009, and 2019.

In 2001, the warm climate sites were the only sites where the basaltic and andesitic soils were enriched relative to the atmosphere, and even then only in the A horizon. Granitic soil A horizons were enriched relative to the atmosphere at both the cool and warm sites in 2001, while the bulk 14C of all three lithologies were depleted relative to atmospheric 14C for both A and B horizons at the cold climate sites. For the 2019 samples, surface soil 14C (0-10 cm) was enriched relative to the atmosphere at all sites except for the cool climate andesite soils. At two of the sites bulk soil 14C remained enriched relative to the atmosphere down to 30cm in 2019: the warm climate granite soil and cold climate basalt soil.

*Heterotrophically respired radiocarbon: Parent material and climate effects*

The trends in respired 14C-CO2 were distinct from what we observed in the bulk soil. 14C-CO2 was enriched relative to the bulk soil at all sites, although bulk and respired 14C were not significantly different from one another for the majority of the granitic soils. While 14C-CO2 declined with depth at some of the sites, the decrease was always less than what we observed in the bulk soil. The andesitic soils did not show much of a decline in 14C-CO2 with respect to depth at all, whereas the granitic soils tended to follow the trend in bulk 14C closely.

The interaction between parent material and climate explained more of the variance in 14C-CO2 data than in the bulk 14C data. For the andesitic soils there were no significant differences between respired 14C-CO2 between the different climate zones at any depth. In contrast, 14C-CO2 respired by the basaltic and granitic soils diverged substantially between climate zones, particularly for the 10-20 cm and 20-30 cm depth layers. Overall, 14C-CO2 across sites was most similar at the soil surface, and most divergent at the intermediate depth (10-20 cm).

*Heterotrophically respired radiocarbon: Temporal trends*

We observed significant negative trends for respired ∆14C-CO2 over time in the 0-10 cm soil layer at the majority of our study sites. The two exceptions were the cool climate andesitic soils and the cold climate granite soils, which were not significantly different between 2001 and 2019. Overall, the change in ∆∆14C -CO2 over time in these surface soils was greater on average at the warm sites than at the cool sites, and greater at the cool sites than the cold sites. The importance of parent material became apparent below 10 cm. The basaltic soils showed significant changes over time in ∆14C -CO2 for the cool climate soils at all depths and the cold climate soil at the 10-20cm depth, while the granitic soil showed a significant negative trend at the cool site for the 10-20cm depth. For the warm climate zone, the only significant decline in ∆14C -CO2 over time we observed below 10 cm was for the andesitic soils in the 10-20 cm depth layer.

We observed extremely depleted ∆14C -CO2 in both 2001 and 2019 for two of the deeper soil layers at the cold climate granite site: -469.1 and -127.8 per mil for the 8-27 cm layer in 2001, and -396.7 and -23.5 per mil for the 10-20 cm layer in 2019. We do not believe this was due to laboratory error, given that it was consistent over time and restricted to the deeper soil layers from this one site. However, since it appears to be a unique response to these soils, we excluded these highly depleted samples from the analysis.

Respired ∆14C-CO2 was either enriched or indistinguishable from atmospheric ∆14C-CO2 for surface soil layers in both 2001 and 2019, and for nearly all of the deeper layers in 2019 as well. Changes in ∆14C -CO2 over time that we observed in this study were typically lower in magnitude than the change in atmospheric ∆14C over the same time period, with the exception of the cool climate basalt site. Similar to what we observed with the bulk soil ∆14C temporal trends, changes in ∆14C-CO2 over time tended to be lower in magnitude at the soil surface than in the deeper soil layers.

*Bulk and respired 14C differences*

Respired 14C-CO2 was enriched relative to bulk soil 14C for all sites with the exception of the soils at the cold granite site. When comparing differences between bulk and respired 14C across sites, the effect of parent material is immediately evident (table?). Depth profiles of bulk and respired 14C are very similar for the granitic soils, slightly offset for the basaltic soils, and most divergent for the andesitic soils. We also observed a clear climatic effect on the difference between bulk and respired 14C. When compared across parent materials, differences between bulk and respired 14C were smallest for the warm sites and typically greatest at the cool sites in both 2001 and 2019. However, we observed the greatest overall differences at the cool andesitic sites.

The difference between bulk and respired 14C did not change substantially with depth for the granitic or basaltic soils, although it was slightly greater at depth for the andesitic soils. Changes in the bulk and respired 14C difference between 2001 and 2019 were within a single standard deviation of the mean at all sites except for the cold climate basaltic soil, where the difference was 97.9 ± 13.3 per mil in 2001 and 26.2 ± 6.2 per mil in 2019.

*Mineral assemblages*

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 bulk soil ∆14C, respired ∆14C-CO2, and the difference between bulk soil and respired ∆14C. We observed a significant negative correlation between the concentration of oxalate extractable iron and bulk soil ∆14C. The relationship was also significant for oxalate extractable aluminum and pyrophosphate extractable aluminum (SI), but we focus on the oxalate extractable iron alone for simplicity as a proxy for poorly crystalline mineral abundance. In contrast, we did not find a significant relationship between the concentration of extractable iron from crystalline minerals (dithionite-citrate Fe - oxalate Fe) and bulk soil ∆14C.

We did not observe any significant relationship between respired ∆14C-CO2 and any of the extracted metals. However, the concentration of oxalate extractable iron explained more of the variance in the difference between bulk soil and respired ∆14C than it did for bulk soil ∆14C alone. As with bulk soil ∆14C, there was no relationship between crystalline mineral abundance and the difference between bulk soil and respired ∆14C

**Discussion**

In this study we considered the relative effects of parent material and climate on the distribution of radiocarbon in bulk soils and heterotrophically respired CO2 in order to determine how these factors control the cycling of soil C across timescales of years to centuries. Climate has been found to be the most important variable aside from depth for explaining the distribution of ages of soil carbon at a global scale. Yet our current understanding of soil organic matter decomposition underscores the importance of the physical mechanisms that attenuate the climate response. Among the most salient of these mechanisms is the association of soil organic matter with minerals.

The relevance of soil minerals for mediating soil organic matter protection appears to be a function of the specific minerals present, rather than simply due to total mineral surface area or the amount of clay (cite). Soil mineral assemblages are the result of the weathering of primary minerals to form secondary minerals, and the preferential loss or stabilization of those secondary minerals over time. Differences in climate can therefore lead to different soil mineral assemblages when starting from the same parent materials, or to similar mineral assemblages despite starting from disparate parent materials.

The soils we studied comprise a parent material by climate gradient, but also a weathering gradient. For soils developed on granitic, andesitic, and basaltic parent materials we compared high elevation, cold climate soils that were poorly developed to cool climate soils in intermediate stages of weathering with high concentrations of secondary minerals, to highly weathered soils in a still warmer climate. Previous research characterizing the mineral assemblages at these sites using XRD and selective dissolution found that the dominant mineral species in the soils of the most weathered “warm” climate zone are 1:1 clays with large accumulations of crystalline iron oxides. Parent material differences are most evident in the cool climate sites, with high contents of allophane in the andesitic soils, minor amounts of both 2:1 and 1:1 clays in the basaltic soils, and hydroxy-interlayered vermiculite in the granitic soils. The basaltic and andesitic soils found in the cold climate sites both had substantial amounts of SRO minerals, although with a greater concentration of 1:1 clay in the basaltic soils. In contrast, the cold climate soils developed on granite showed a mixture of HIV and kaolinite, but also a substantial accumulation of gibbsite.

**Conclusion**

[change to focus on timescales rather than ∆14C trends?]

Our study shows clearly that parent material and climate interact to control soil C dynamics. This interaction was the key to explaining trends in both bulk soil ∆14C, which is a proxy for the mean age of soil C, and respired ∆14C-CO2, which reveals the relative contributions of faster or more slowly cycling soil C to respiration. We observed that the trends in both bulk and respired ∆14C at the soil surface were best explained by climate, but best explained by parent material in deeper soil layers. This importance of climate was reflected in the changes in ∆14C we observed over time, which were greater for surface soils than deeper soils, and greater for the highly weathered soils at the warm sites than the poorly developed soils at the cold sites. Yet contrary to expectations, we saw the most depleted bulk soil ∆14C in the cool climate andesitic soil, which is also where we saw the least change over time at all depths.

The interaction between parent material and climate can be characterized by the effects of weathering on the development of the soil mineral assemblage through formation and subsequent loss of secondary minerals. We confirm the findings of other studies that specific mineral assemblages are highly correlated with the age of soil C, as measured by proxy with bulk soil ∆14C. We extend this finding to show that it is specifically the poorly crystalline mineral content that is correlated with bulk soil ∆14C, while crystalline mineral content is not. Finally, we provide mechanistic evidence for the protective effect of mineral-association on decomposition of soil organic matter by demonstrating that the difference between bulk soil ∆14C and respired ∆14C-CO2 is even more strongly correlated with poorly crystalline mineral content than bulk ∆14C alone.

In future work we intend to quantify the timescales of soil carbon cycling in mineral and non-mineral associated pools with a compartmental modeling approach, using the radiocarbon time series presented here in addition to radiocarbon measurements of soil density and thermal fractions as constraints.