Supplemental information for Soil minerals mediate climatic control of soil C cycling on annual to centennial timescales

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S1 Soil carbon

We did not observe clear trends in soil carbon concentration over time for the majority of sites, making us confident that most sites are at steady-state with regards to carbon stock changes (**Fig. S1**). Although we did observe substantial variation in some sites, this is likely due to spatial heterogeneity in soil C concentration that cannot be avoided when destructively resampling the same sites over time (**Fig. S1**). However, we did observe significant trends in soil C concentration with time for a a few of the sites when considered by specific depth increments. However, a caveat is that we did not account for potential differences in the mass of soil sampled over time, as we only considered depth-based increments. We observed significant changes at two sites for the surface layer (0-0.1 m), and at two additional sites in the intermediate depth layer (0.1-0.2 m), but C concentration changes were only significant at a single site showed changes for the deepest depth layer (0.2-0.3 m) (**Table S1**). The soil at the cold climate andesite site was an outlier in that the soil C concentration showed a consistently significant increase in the two deeper depth layers over the study period, while the other soils with significant changes showed decreases in C concentrations (**Table S1**).

Table S1

Changes in soil C concentration (%), 2001-2019. (Only signficant trends shown).

Depth	Site	Trend	*SE*	df	95% CI *lower*	95% CI *upper*
0-10cm	andesite (warm)	-0.20	0.09	62	-0.38	-0.02
	andesite (cold)	0.20	0.10	62	0.01	0.40
	basalt (cold)	-0.27	0.09	62	-0.45	-0.09
10-20cm	andesite (cold)	0.23	0.06	62	0.12	0.35
	granite (warm)	0.16	0.05	62	0.05	0.26

Table S1

Changes in soil C concentration (%), 2001-2019. (Only signficant trends shown). (continued)

					95% CI	
Depth	Site	Trend	*SE*	df	*lower*	*upper*
20-30cm	andesite (cold)	0.21	0.04	62	0.13	0.29

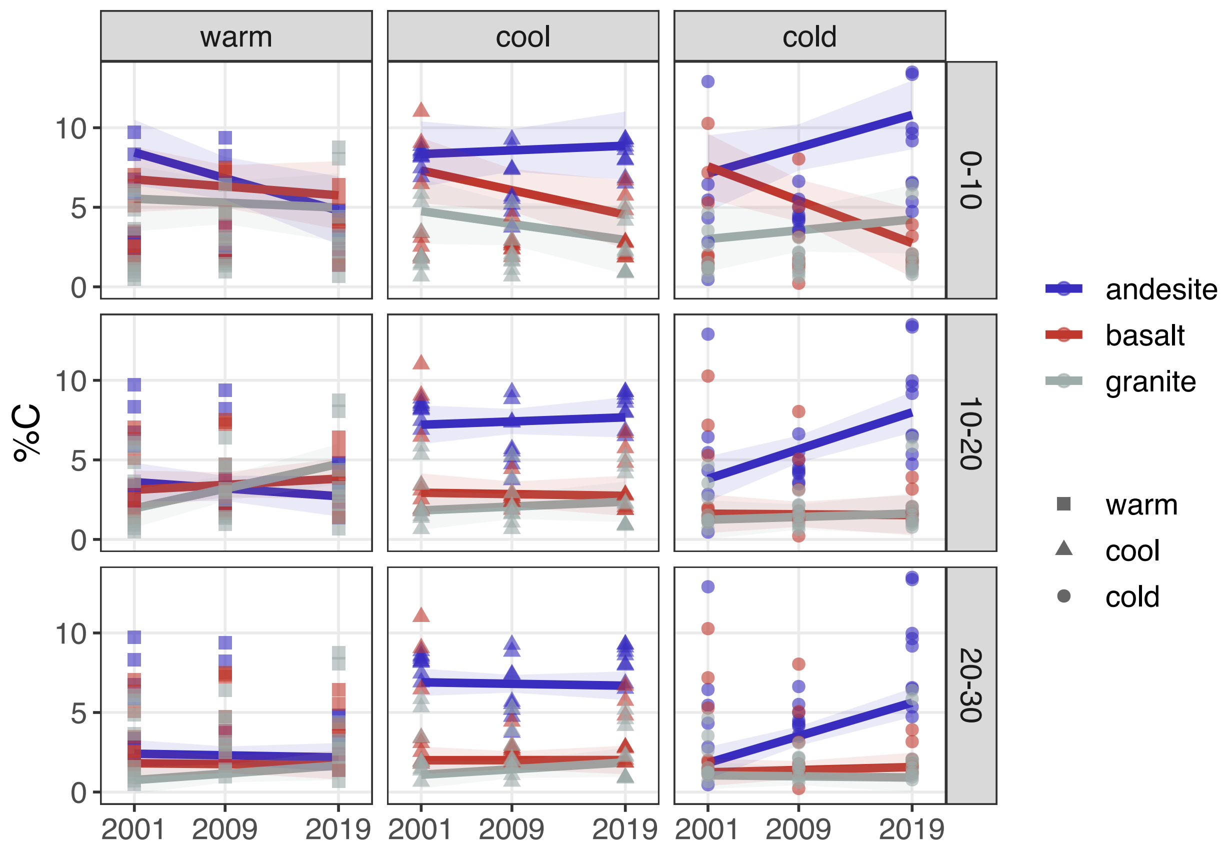

Figure S1. Changes in soil C concentration, 2001-2019. Points show replicate profiles (n = 3); lines show marginal mean estimates of linear trends in soil C concentration with time; ribbons show 95% CIs around trend estimates.

S2 Respiration fluxes

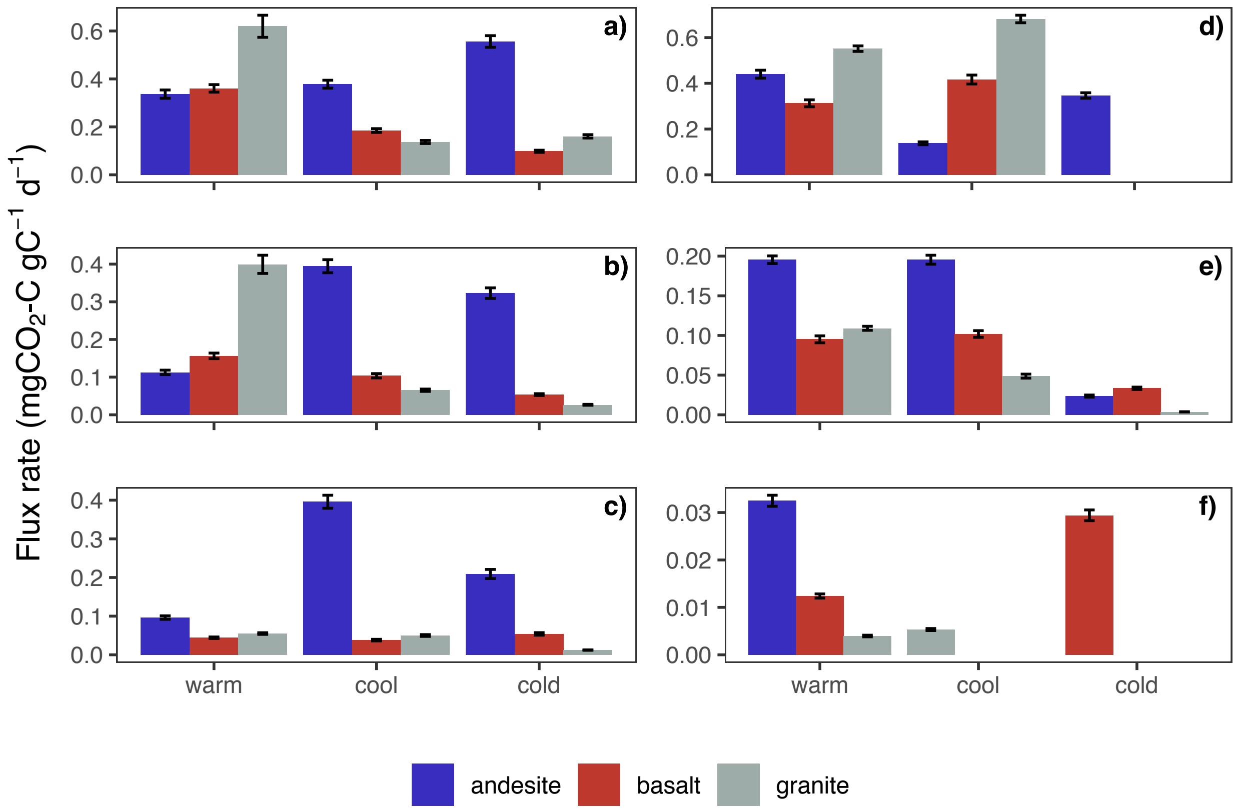

Figure S2. Heterotrophic respiration rates from incubations of 2019 and 2001 samples. Panels a-c show 2019 data, and panels d-f show 2001 data. Panels in the top row (a, d) show the first depth increment for each year, middle row shows the second depth increment (b, e), and the bottom row shows the third depth increment (c, f). Bars show means for laboratory duplicates averaged over the whole incubation period; error bars ± 1 standard error of the mean. NB: Total CO_2 respired was controlled to be within 10,000 ppm (±1,000 ppm) for all samples; incubation duration varied between 4 and 40 days.

S3 Radiocarbon depth profiles: 2001 data

Depth profiles of $\Delta^{14}C_{bulk}$ were similar in 2001 (**Fig. S3**) as to what we observed in 2019. We observed the most depleted ^{14}C overall in the cool climate sites, where we also observed the clearest differences among parent materials. Parent material differences were least apparent for the cold climate sites, as we also observed in 2019. Within climate zones andesitic soils tended be most depleted and the granitic soils most enriched, with the basaltic parent material intermediate between the other two.

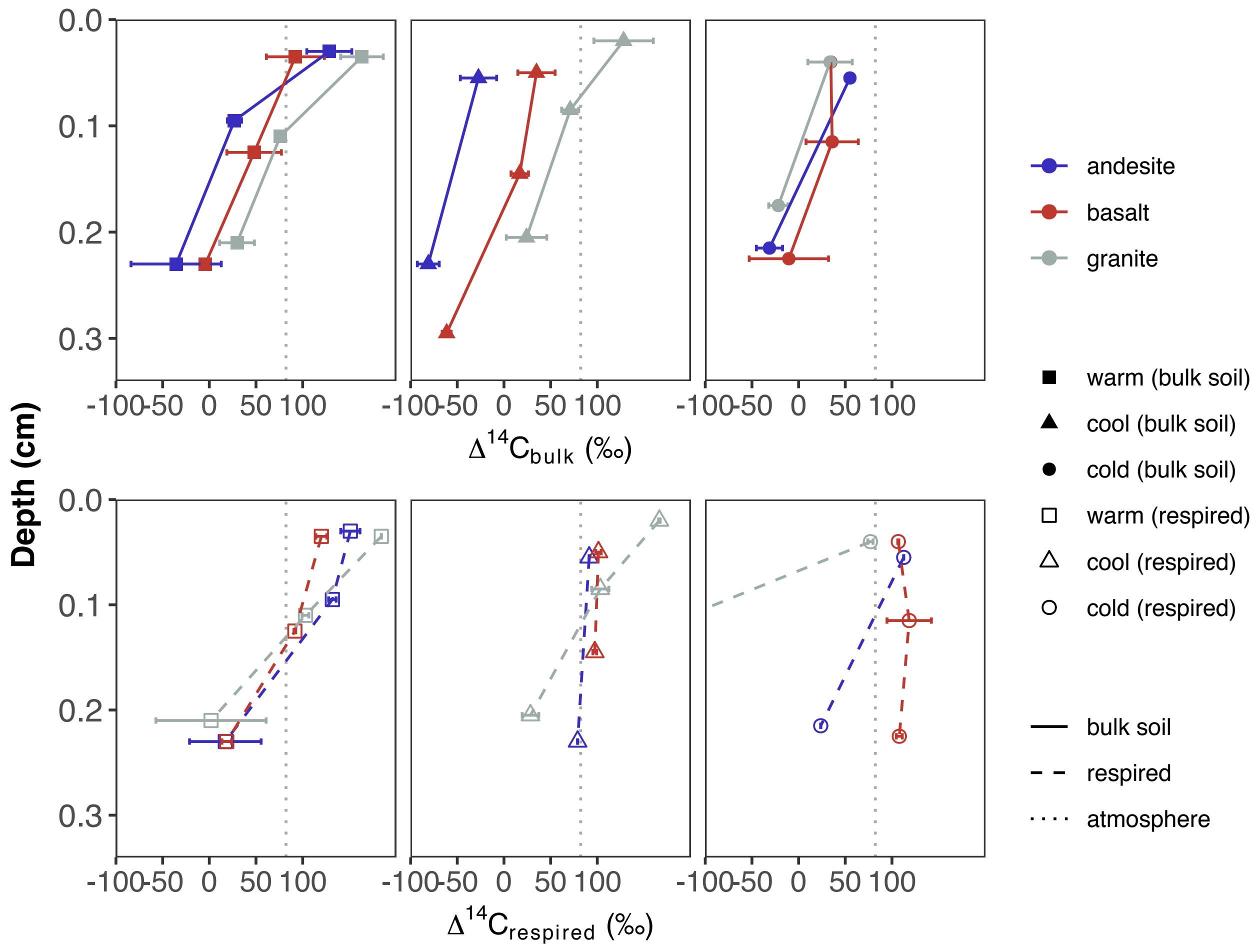

Figure S3. Depth profiles of $\Delta^{14}C_{bulk}$ and $\Delta^{14}C_{respired}$ for 2001 data. Top panels show bulk data, bottom panels respired data. Dotted vertical lines show $\Delta^{14}C$ of the atmosphere in the year of sampling. Points show the mean of three replicate profiles for bulk soil, and the mean of laboratory duplicates for respired CO_2. Error bars show ±1 SD for bulk soils and the minimum and maximum for respired CO_2. Respired CO_2 from the cold granite site (panel f) was extremely depleted in $\Delta^{14}C$ and thus is excluded for display purposes.

S4 Parent material and climate effects on bulk and respired ^{14}C

S4.1 Contrasts

Table S2

Contrasts of bulk and respired $\Delta^{14}C$ for parent material and climate factors, 0-0.1 m (all pairs). P value adjustment: Tukey method for comparing a family of 3 estimates.

			Bulk			Respired		
Year	Group	Contrast	Est.	*SE*	*p*	Est.	*SE*	*p*
2001	cool	andesite - basalt	-62.0	18.8	**0.011**			
		andesite - granite	-124.5	18.8	**$<$ .001**			
		basalt - granite	-62.4	18.8	**0.011**			
	cold	andesite - granite				84.0	22.1	**0.016**
		basalt - granite				82.1	18.1	**0.006**
	andesite	warm - cool	126.6	18.8	**$<$ .001**			
		cool - cold	-82.1	21.0	**0.003**			
	basalt	warm - cool	48.7	18.8	**0.048**			
		warm - cold	66.1	18.8	**0.007**			
	granite	warm - cold	107.3	18.8	**$<$ .001**	114.5	18.1	**$<$ .001**
		cool - cold	83.6	18.8	**$<$ .001**	104.1	18.1	**0.002**
2019	warm	andesite - basalt	-56.5	16.3	**0.007**			
		andesite - granite	-79.8	16.3	**$<$ .001**			
	cool	basalt - granite				-43.6	18.0	0.089
	andesite	cool - cold	-42.0	16.3	**0.047**			
	basalt	warm - cool	52.3	16.3	**0.013**			
	granite	warm - cool	65.0	16.3	**0.002**			
		warm - cold	58.5	16.3	**0.006**	47.1	18.0	0.066
		cool - cold				49.0	18.0	0.056

Table S3

Contrasts of bulk and respired $\Delta^{14}C$ for parent material and climate factors, 0.1-0.2 m (all pairs). P value adjustment: Tukey method for comparing a family of 3 estimates.

			Bulk			Respired		
Year	Group	Contrast	Est.	SE	p	Est.	SE	p
2001	warm	andesite - granite	-47.8	20.1	0.072			
	cool	andesite - basalt	-72.2	20.1	**0.006**			
		andesite - granite	-99.5	20.1	**$<$ .001**			
	cold	andesite - granite				162.8	31.4	**0.005**
		basalt - granite				227.2	27.2	**$<$ .001**
	andesite	warm - cool	65.0	20.1	**0.013**			
		cool - cold	-57.2	22.5	0.052			
	granite	warm - cold	70.4	20.1	**0.007**	165.1	27.2	**0.002**
		cool - cold	57.2	20.1	**0.029**	163.9	27.2	**0.002**
2019	warm	andesite - basalt	-62.6	20.1	**0.016**			
		andesite - granite	-124.9	20.1	**$<$ .001**	-52.4	13.7	**0.013**
		basalt - granite	-62.3	20.1	**0.016**	-35.2	13.7	0.078
	cool	andesite - basalt				74.2	13.7	**0.002**
		andesite - granite				87.3	13.7	**$<$ .001**
	cold	andesite - granite				62.2	16.8	**0.015**
		basalt - granite				70.8	16.8	**0.007**
	basalt	warm - cool	74.8	20.1	**0.004**	63.0	13.7	**0.004**
		cool - cold	-63.5	20.1	**0.014**	-54.2	13.7	**0.011**
	granite	warm - cool	118.2	20.1	**$<$ .001**	111.3	13.7	**$<$ .001**
		warm - cold	105.3	20.1	**$<$ .001**	114.7	16.8	**$<$ .001**

Table S4

Contrasts of bulk and respired $\Delta^{14}C$ for parent material and climate factors, 0.2-0.3 m (all pairs). P value adjustment: Tukey method for comparing a family of 3 estimates.

			Bulk			Respired		

Year	Group	Contrast	Est.	*SE*	*p*	Est.	*SE*	*p*
2001	warm	andesite - granite	-70.2	21.0	**0.01**			
	cool	andesite - granite	-106.5	21.0	**< .001**			
		basalt - granite	-62.9	21.0	**0.021**			
	granite	warm - cold	51.8	21.0	0.061			
2019	warm	andesite - granite	-51.9	19.6	**0.042**			
		basalt - granite	-51.3	19.6	**0.044**			
	cool	andesite - basalt				93.9	20.6	**0.005**
		basalt - granite	-53.5	19.6	**0.035**	-61.0	20.6	**0.043**
	cold	andesite - basalt	-46.3	19.6	0.073			
	andesite	warm - cool	57.6	19.6	**0.023**			
	basalt	warm - cool	75.7	19.6	**0.003**	64.7	20.6	**0.033**
		cool - cold	-106.5	19.6	**< .001**	-86.8	25.3	**0.022**
	granite	warm - cool	73.5	19.6	**0.004**			
		warm - cold	51.5	19.6	**0.043**	57.8	20.6	0.054

S4.2 Temporal trends & contrasts

Please see the main text for discussion of the temporal trends in both $\Delta^{14}C_{bulk}$ and $\Delta^{14}C_{bulk}$. See SI tables **S5** and **S6** for statistics.

Table S5

Change in $\Delta^{14}C_{\text{bulk}}$, 2001-2019. Degrees of freedom = 44; confidence level used = 0.95.

		0-10cm		10-20cm		20-30cm	
Climate	Parent material	Trend	*SE*	Trend	*SE*	Trend	*SE*
warm	andesite	**-5.8**	1.0	-1.9	1.3	1.1	1.3
	basalt	-1.8	1.0	-0.1	1.3	-1.1	1.3
	granite	**-2.5**	1.0	2.4	1.3	0.2	1.3
cool	andesite	0.1	1.0	0.4	1.3	0.3	1.3
	basalt	-2.1	1.0	**-3.2**	1.3	**-3.3**	1.3
	granite	**-4.9**	1.0	**-3.5**	1.3	**-3.6**	1.3
cold	andesite	-2.2	1.1	-0.9	1.4	0.4	1.5
	basalt	0.9	1.0	0	1.3	1.4	1.3
	granite	0.1	1.0	0.3	1.3	0.1	1.3

Table S6

Change in $\Delta^{14}C_{\text{respired}}$, 2001-2019. Degrees of freedom = 44; confidence level used = 0.95.

		0-10cm		10-20cm		20-30cm	
Climate	Parent material	Trend	*SE*	Trend	*SE*	Trend	*SE*
warm	andesite	**-6.2**	1.0	-2.1	1.0	1.4	2.0
	basalt	**-2.3**	1.0	-0.9	1.0	0.4	2.0
	granite	**-3.7**	1.0	2	1.0	3.2	2.0
cool	andesite	-1.4	1.2	-1	1.2	-1.5	2.5
	basalt	**-3.7**	1.0	**-5.9**	1.0	NA	
	granite	**-3**	1.0	**-4.1**	1.0	0	2.0

Table S6

Change in $\Delta^{14}C_{\text{respired}}$, 2001-2019. Degrees of freedom = 44; confidence level used = 0.95. (continued)

		0-10cm		10-20cm		20-30cm	
Climate	Parent material	Trend	*SE*	Trend	*SE*	Trend	*SE*
cold	andesite	**-2.9**	1.2	-0.8	1.2	1.4	2.5
	basalt	**-3.9**	1.0	**-3.9**	1.0	-3.5	2.5
	granite	0.1	1.0	**4.8**	1.4	NA	

We saw more significant contrasts in the change over time in $\Delta^{14}C_{respired}$ than we did for $\Delta^{14}C_{bulk}$ (**Table S7**). When considered within climate zones, trends for the basaltic and granitic soils were more similar to one another overall than were either to the andesitic soils. We observed parent material trend contrasts more commonly in the cool and cold climate sites than in the warm sites; however we only observed significant trend contrasts for the cold climate sites in the $\Delta^{14}C_{respired}$ data, and not for $\Delta^{14}C_{bulk}$. When considered within parent materials, we saw more siginificant trend contrasts for the granitic and basaltic soils than for the andesitic soils (**Table S7**).

Table S7

Contrasts for bulk and respired $\Delta^{14}C$ by year and depth. P value adjustment: Tukey method for comparing a family of 3 estimates.

			Bulk			Respired		
Depth	Group	Contrast	Est.	*SE*	*p*	Est.	*SE*	*p*
0-10cm	warm	andesite - basalt	-4.0	1.4	**0.021**	-3.9	1.4	**0.036**
	warm	andesite - granite	-3.3	1.4	0.068			
	cool	andesite - granite	5.0	1.4	**0.004**			
	cold	basalt - granite				-4.0	1.4	**0.031**
	andesite	warm - cool	-5.9	1.4	**$<$ .001**	-4.8	1.6	**0.021**
	andesite	warm - cold	-3.6	1.5	0.06			
	granite	warm - cold				-3.7	1.4	**0.045**
	granite	cool - cold	-5.0	1.4	**0.004**			
10-20cm	warm	andesite - granite	-4.3	1.8	0.051	-4.1	1.4	**0.03**
	cool	andesite - basalt				4.9	1.6	**0.019**
	cool	andesite - granite	4.0	1.8	0.08			
	cold	andesite - granite				-5.6	1.9	**0.024**
	cold	basalt - granite				-8.7	1.7	**$<$ .001**
	basalt	warm - cool				5.0	1.4	**0.008**
	granite	warm - cool	5.9	1.8	**0.005**	6.1	1.4	**0.002**
	granite	cool - cold	-3.8	1.8	0.094	-8.9	1.7	**$<$ .001**
20-30cm	basalt	cool - cold	-4.7	1.9	**0.04**			

S5 Mineral assemblages

We simplified the data in the main text to consider the relationship between $\Delta^{14}C$ and either poorly crystalline metal oxides or crystalline metal oxides. We present here the individual regression plots for $\Delta^{14}C_{bulk}$ (**Fig. S7**) and $\Delta^{14}C_{respired}$ (**Fig. S8**).

We also present here the results of the individual regression analyses for $\Delta^{14}C_{bulk}$ (**Fig. S5**), $\Delta^{14}C_{respired}$ (**Fig. S6**), and $\Delta^{14}C_{respired\text{-}bulk}$ vs. Al selectively dissolved with ammonium oxalate (Al_o) or sodium pyrophosphate (Al_p), and Fe selectively dissolved with ammonium oxalate (Fe_o), or dithionite citrate (Fe_d) **Fig. S4**. The relationships between Al_o, Al_p, and Fe_o and $\Delta^{14}C_{respired\text{-}bulk}$ in the models derived from Eq. (4) (main text) were all highly significant ($p < 0.001$). P-values for the metal oxide concentration coefficients in the $\Delta^{14}C_{respired\text{-}bulk}$ and $\Delta^{14}C_{bulk}$ models were highly significant (< 0.001 at $\alpha = 0.1$) for Al_o, Al_p, and Fe_o. The coefficient for Al_o in $\Delta^{14}C_{respired}$ model also had a p-value of < 0.001, but while still significant, p-values were larger for Al_p and Fe_o in the $\Delta^{14}C_{respired}$ models: 0.028, 0.086, respectively. In contrast, the concentration of Fe_d was not significant in any of the models.

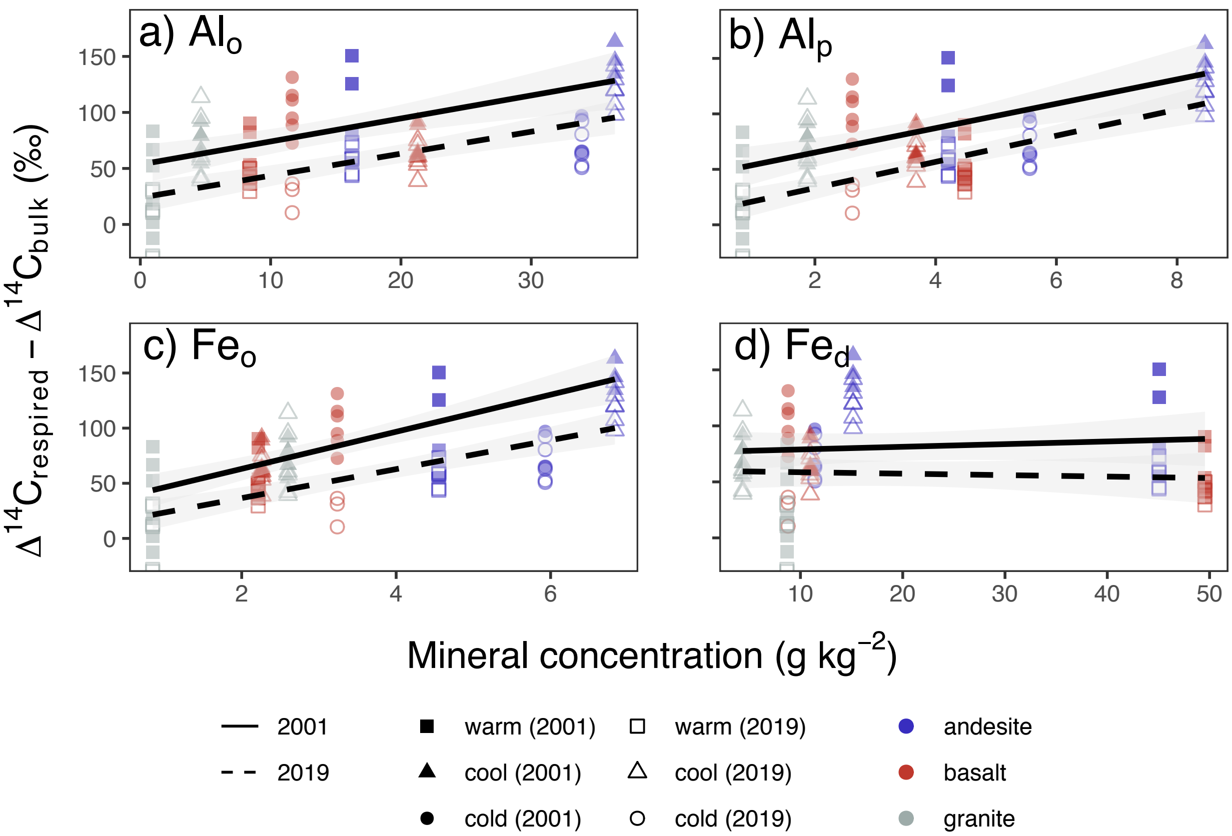

Figure S4. Relationship of selectively dissolved iron and alumnimum to the difference between $\Delta^{14}C_{respired}$ and $\Delta^{14}C_{bulk}$ ($\Delta^{14}C_{respired\text{-}bulk}$). (a) Oxalate-extractable aluminum (Al_o), (b) Pyrophosphate-extractable aluminum (Al_p), (c) Oxalate-extractable iron (Fe_o), (d) Dithionite extractable iron (Fe_d). Points show mass-weighted mineral concentrations and carbon-weighted values of $\Delta^{14}C_{respired\text{-}bulk}$ for 0-30cm profiles. Lines show linear model fits from Eq. (5) (main text).

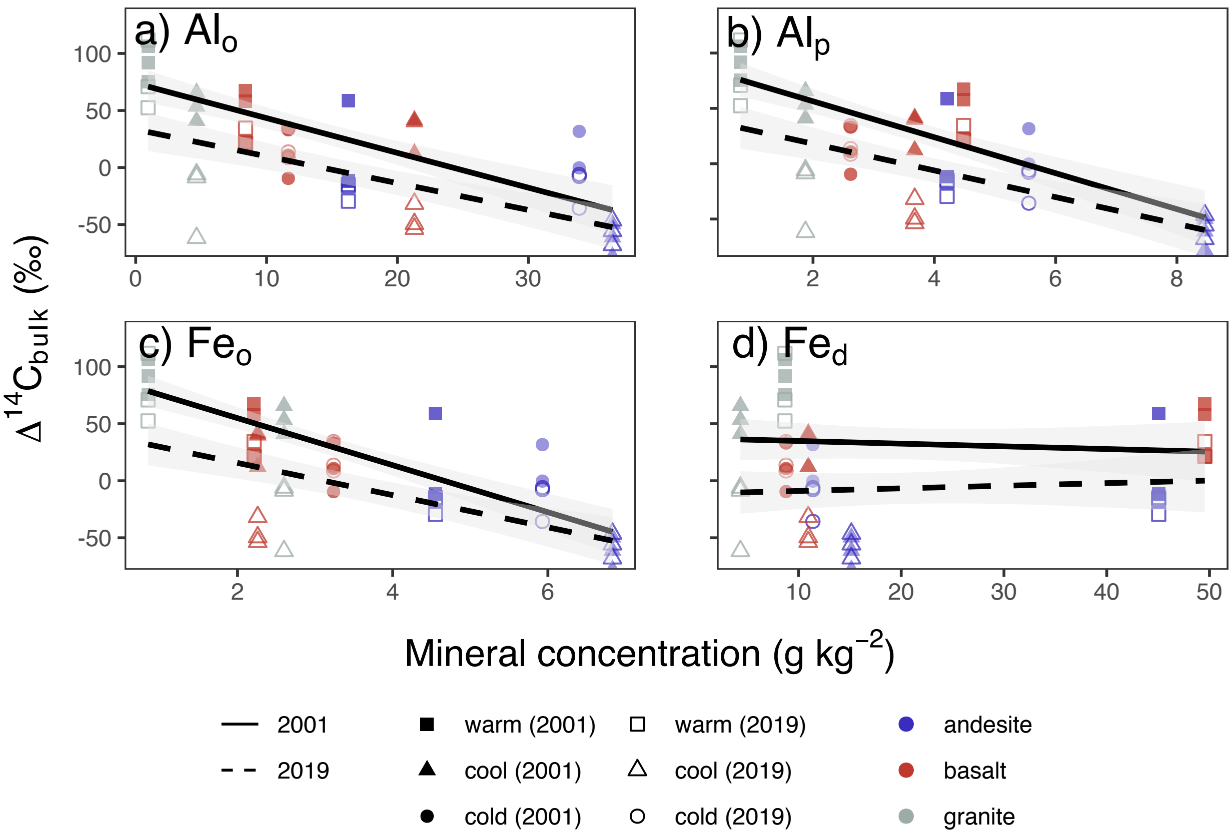

Figure S5. Relationship of selectively dissolved iron and alumnimum to $\Delta^{14}C_{bulk}$. (a) Oxalate-extractable aluminum (Al_o), (b) Pyrophosphate-extractable aluminum (Al_p), (c) Oxalate-extractable iron (Fe_o), (d) Dithionite extractable iron (Fe_d). Points show mass-weighted mineral concentrations and carbon-weighted values of $\Delta^{14}C_{bulk}$ for 0-30cm profiles. Lines show linear model fits from Eq. (5) (main text).

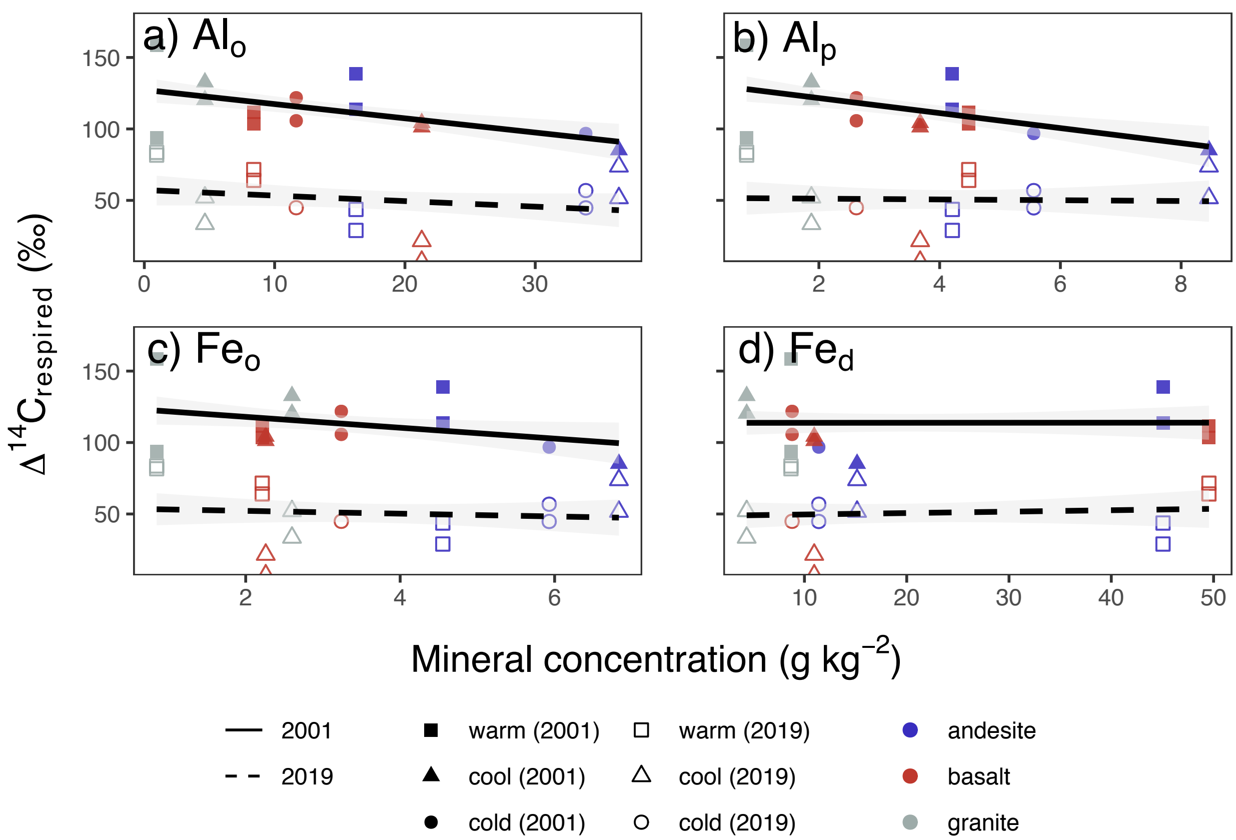

Figure S6. Relationship of selectively dissolved iron and alumnimum to $\Delta^{14}C_{respired}$. (a) Oxalate-extractable aluminum (Al_o), (b) Pyrophosphate-extractable aluminum (Al_p), (c) Oxalate-extractable iron (Fe_o), (d) Dithionite extractable iron (Fe_d). Points show mass-weighted mineral concentrations and carbon-weighted values of $\Delta^{14}C_{respired}$ for 0-30cm profiles. Lines show linear model fits from Eq. (5) (main text).

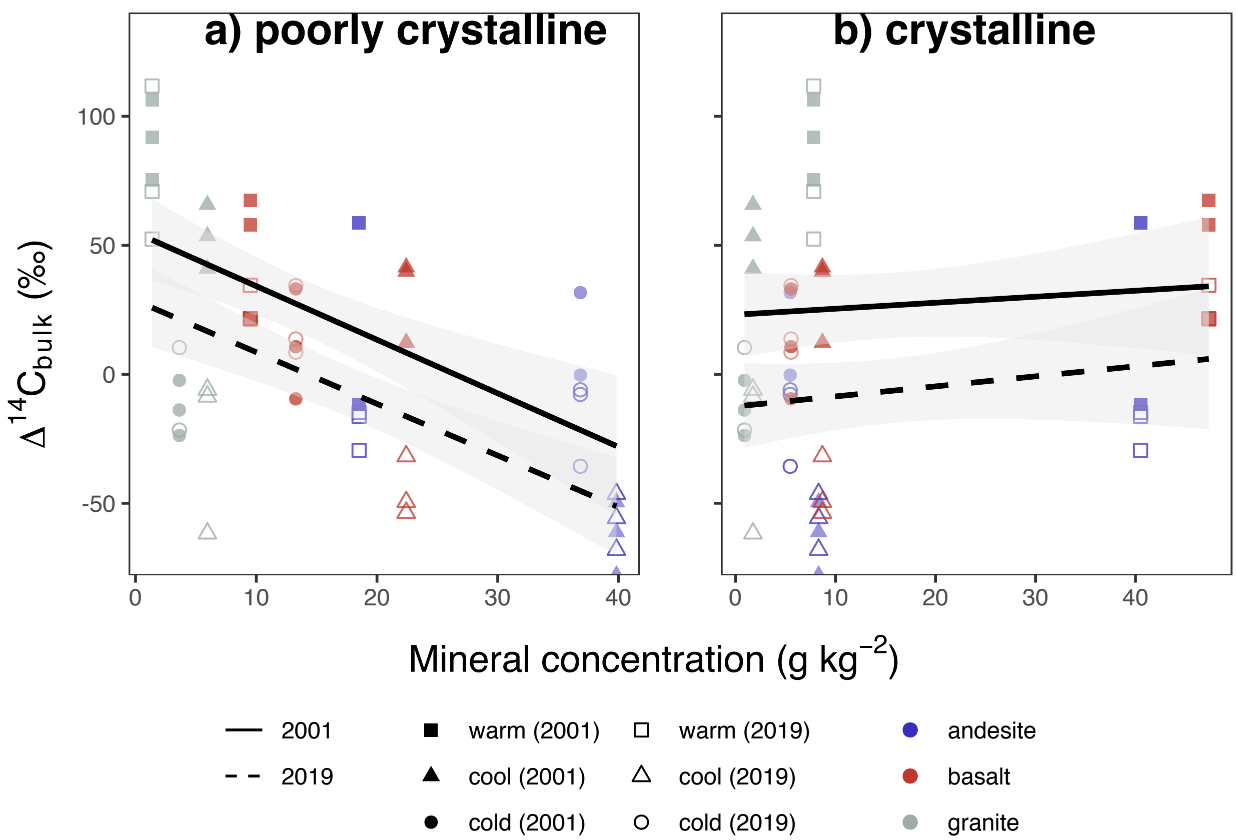

Figure S7. Relationship of poorly crystalline and crystalline minerals to $\Delta^{14}C_{bulk}$. (a) Poorly crystalline mineral content (oxalate-extractable aluminum + 1/2 oxalate-extractable iron), (b) Crystalline mineral content (dithionite-extractable iron - oxalate-extractable iron). Points show mass-weighted mineral concentrations and carbon-weighted values of $\Delta^{14}C_{bulk}$ for 0-30cm profiles. Lines show linear model fits from Eq. (5) (main text).

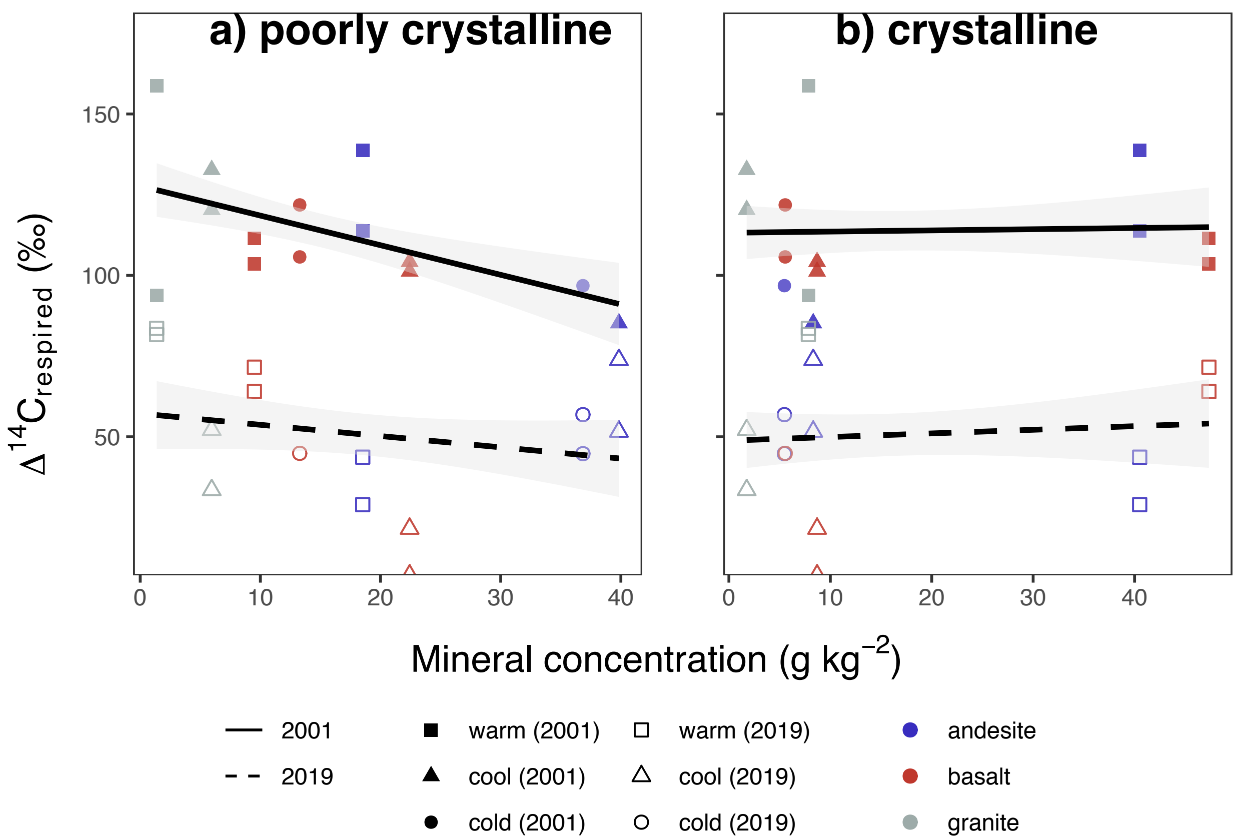

Figure S8. Relationship of poorly crystalline and crystalline minerals to $\Delta^{14}C_{respired}$. (a) Poorly crystalline mineral content (oxalate-extractable aluminum + 1/2 oxalate-extractable iron), (b) Crystalline mineral content (dithionite-extractable iron - oxalate-extractable iron). Points show mass-weighted mineral concentrations and carbon-weighted values of $\Delta^{14}C_{respired}$ for 0-30cm profiles. Lines show linear model fits from Eq. (5) (main text).