What drives geochemical variability in soils? Applicability to the fossil record.

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Abstract

Soil geochemistry can act as a fingerprint of parent material, climate, soil biota, and age of exposure of soil and weathering regimes. Currently, there are soil metal oxide geochemical indices for climate and chemical weathering such as PWI and CIA-K. In this work, I attempted to go back to the drawing board by compiling ~1000 modern soil, irrespective of soil type, in an attempt to understand the underlying factors driving variability in soils geochemistry. I utilize soil metal oxide geochemistry data and associated climate data for soils in the United States, and try to constrain what drives variability in soil geochemistry using Principle Component Analysis (PCA). I found that PC2, which explains ~17.8% of the variability is linearly proportional to the Paleosol Weathering Index (PWI) and inversely proportional to the Chemical Index of Alteration minus Potassium (CIA-K) index. However, I was unable to find any relationship between climatic variables and PC2, PWI & CIA-K index. This suggests that PWI/CIA is being driven by a physical control that scales with mean annual temperature and precipitation but is not necessarily directly related to mean annual temperature and precipitation. Using variability in PC1 and PC2, I developed a new index- Smart Geochemical Index (SCI) that appears to scale with soil weathering. It is thus a promising tool in the development of a terrestrial chemical weathering proxy.

Introduction

Soils represent subaerial exposure of sediment. Soils are thus a function of chemical, physical, and biological alteration and the time for which they were exposed to these processes (Jenny, 1941; Retallack, 2001). Soils can be divided into different classes based on these characteristics. Soils are preserved in the sedimentary record in meandering river and lacustrine deposits. Such fossil soils have been identified as far back as the Devonian, and possibly even into the Archean (Retallack, 2001). They are therefore an important archive in our understanding of the Earth's deep past.

Chemical weathering of terrestrial silicate rocks is one of the most important controls on the carbon cycle by acting as a sink of atmospheric carbon dioxide (pCO_2)

on geological timescales (Hartmann, 2009). This reaction results in the formation of clay minerals in soils. Clay minerals make up the bulk of the B horizon of soils and their mineral geochemistry can thus be used to reconstruct weathering. Different metals leech out of soils at different kinetic rates. Thus, using the bulk geochemistry of soils should logically reflect the extent of chemical weathering.

Fossilized soils (Paleosols) have long been used as indicators of terrestrial climate, biology, and weathering regimes. The Paleosol Weathering Index (PWI) (Gallagher & Sheldon, 2013) and Chemical Index of Alteration minus Potassium (CIA-K) (Sheldon et al., 2002) were developed as a climate proxies representative of soil chemical weathering- with PWI being an indicator of mean annual temperature and CIA-K an index of precipitation regimes. As shown in this work, these indices do not always reconstruct their climate proxies.

Soil color is often used as an indicator of weathering. However, the color of paleosols is often affected by diagenesis. This can often lead to incorrect conclusions about weathering (Retallack et al., 2001). The development of a robust chemical proxy as a tracer for chemical weathering is thus of paramount importance.

Methods

- Data was compiled from previously published soil geochemistry data set including, Gallagher & Sheldon, 2013; Stinchcomb et. al 2016; Rasmussen and Tabor, 2007; Nordt and Driese, 2010; Marbut, 1935. Allied climate data including Mean Annual Temperature (MAT), Mean Annual Precipitation (MAP), Growing Season Temperature (GST), and Growing Season Precipitation (GSP), land use data, elevation data, among other physical data was also included.
- Excluded soils disturbed by human activity.
- Excluded soils that had incomplete geochemical or soil type information.
- PCA analysis was performed on soil geochemistry.
- PC axis was compared to PWI and CIA-K.
- Using the element ratios that very most linearly with PC1 and PC2 weights were computed using the following formulae-

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Element_Matrix1 = [Ti Fe Al]; %Elements varying most with PC1
Element_Matrix2 = [Ca Na Mg];%Elements varying most with PC2
Weight_Matrix1 = PC1 \ Element_Matrix1;
Weight_Matrix2 = PC2 \ Element_Matrix2;
SCI = Weight_of_Ti*Ti + Weight_of_Fe*Fe + Weight_of_Al*Al +
Weight_of_Ca*Ca + Weight_of_Na*Na + Weight_of_Mg*Mg
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SCI = -0.18*Ti - 1.18*Fe - 0.83*Al + 1.94*Ca + 0.18*Na + 0.47*Mg

- SCI, PWI, and CIA-K were then compared against climatic proxy data (MAT, MAP, GST, GSP) to evaluate any relationships.

Results & Discussion

Percentage of Varience on PC axis (Increasing PC axis starting at PC1) (%):

30.4124
17.7805
14.1218
7.6559
7.0611
6.6039
6.0673
5.0467
2.8012
1.4318
1.0173

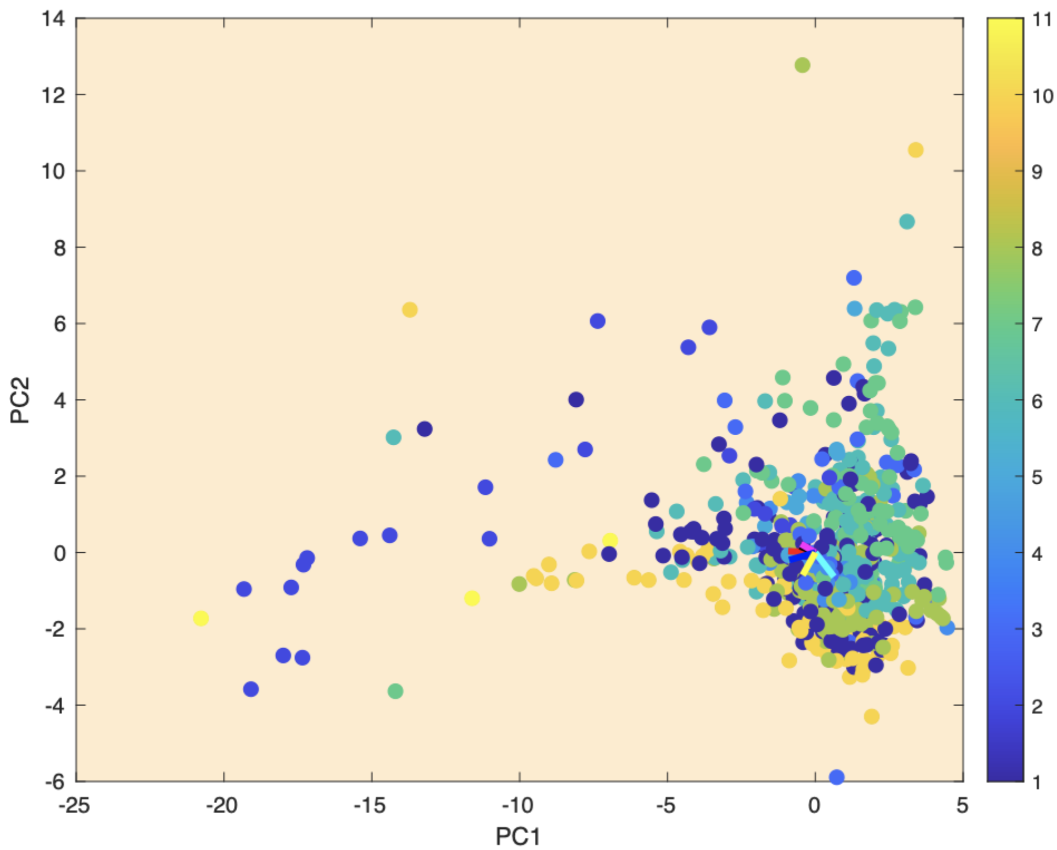
Relative abundance of minerals i.e. eigenvalues -

3.3454
1.9559
1.5534
0.8421
0.7767
0.7264
0.6674
0.5551
0.3081
0.1575
0.1119

Communalities: How much of the original varience was contained in variable using 3.000000 PC axis

0.8453
0.3814
0.3508
0.8449

0.8308
0.5411
0.6014
0.7334
0.6624
0.4020
0.6610



11-> Oxisols, 10-> Ultisol, 9-> Histosols, 8-> Alfisol, 7-> Aridisol, 6-> Mollisol, 5->Vertisol, 4-> Spodosols, 3-> Entisol2-> Andisols, 1-> Inceptisols

Fig 1: Different soil orders appear to diverge in the PC1 vs PC2 plot. With 'older' soils plotting lower on the PC2 axis, 'middle-aged soils' alfisols/mollisols plot higher, and younger entisols and entisols plot throughout the figure.

PC2 versus PWI and CIA-K

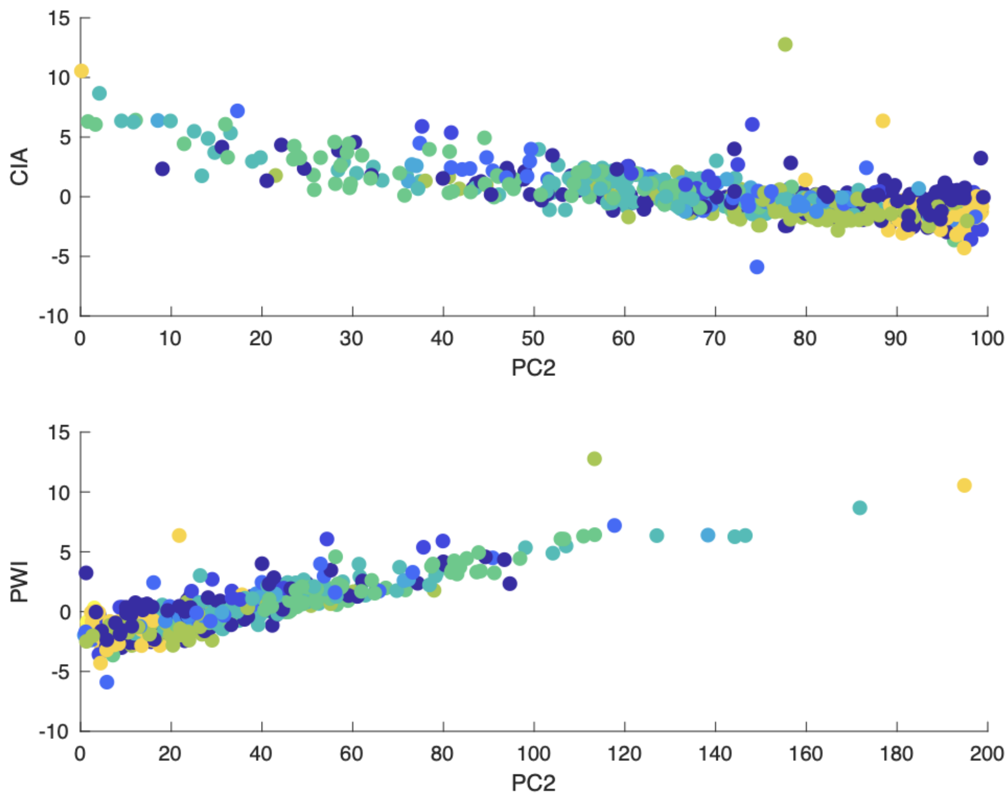


Fig 2: PWI and CIA-K appear to explain variability on PC2.

PWI/CIA a reliable temperature proxy?

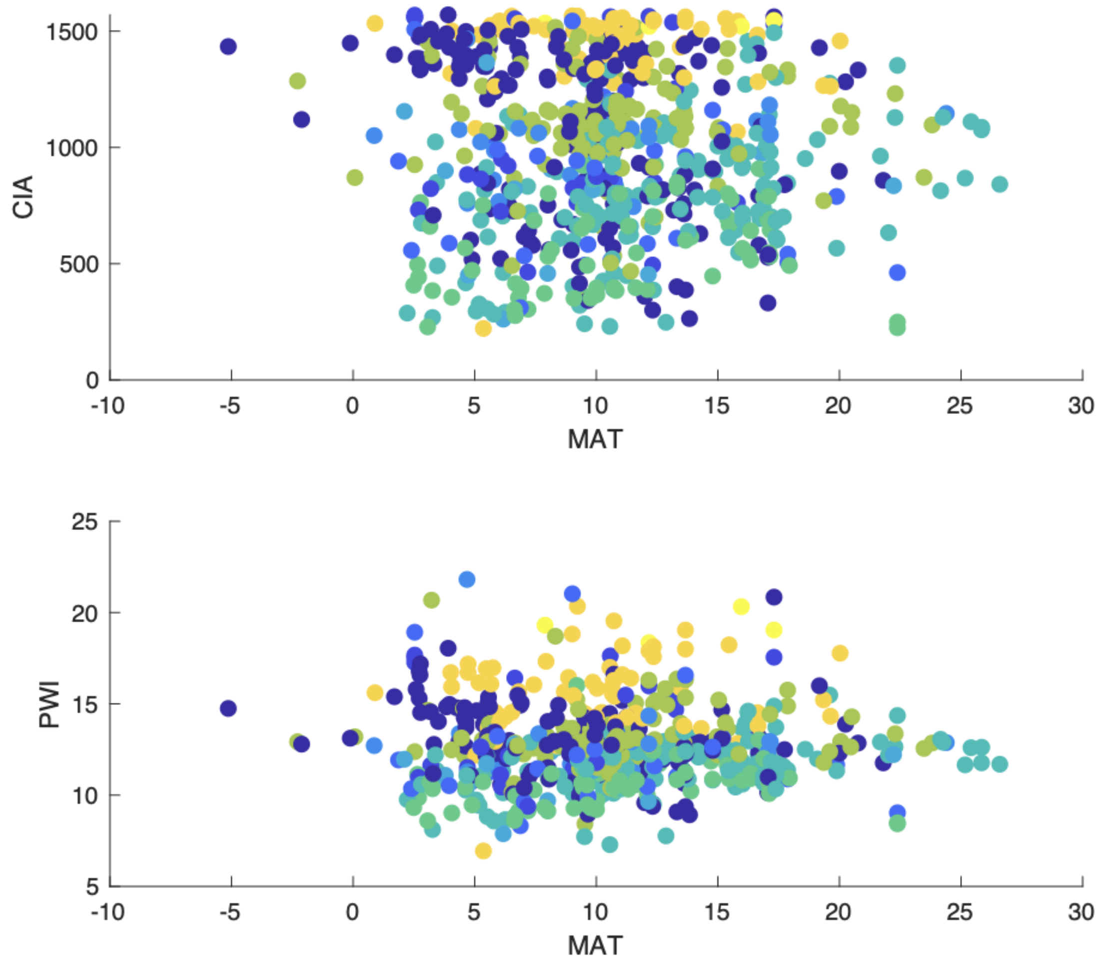


Fig 3: No apparent relationship between temperature and CIA or PWI

PWI/CIA a reliable temperature proxy?

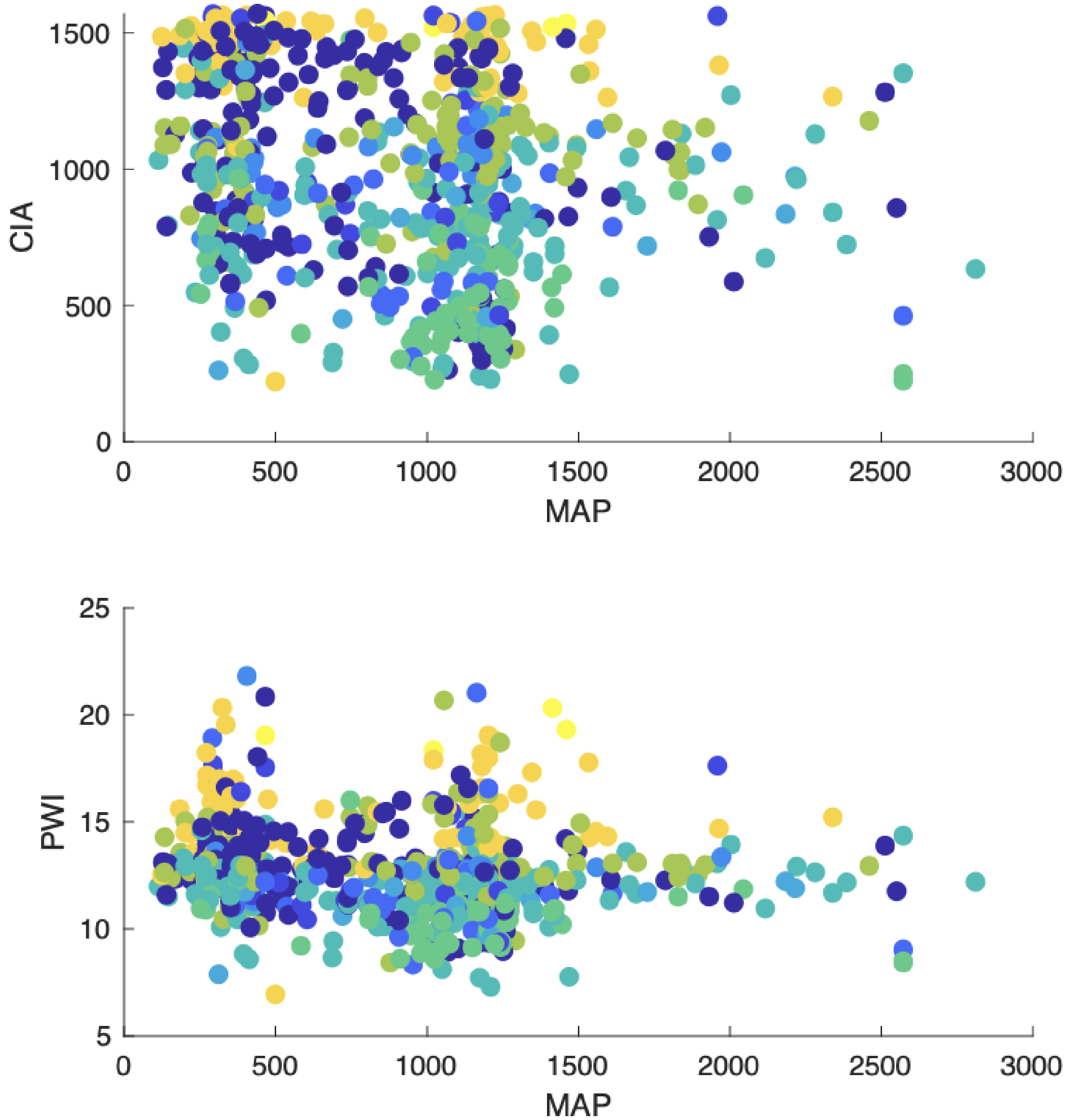


Fig 4: No apparent relationship between temperature and CIA or PWI

Which metal oxides contribute most to PC1?

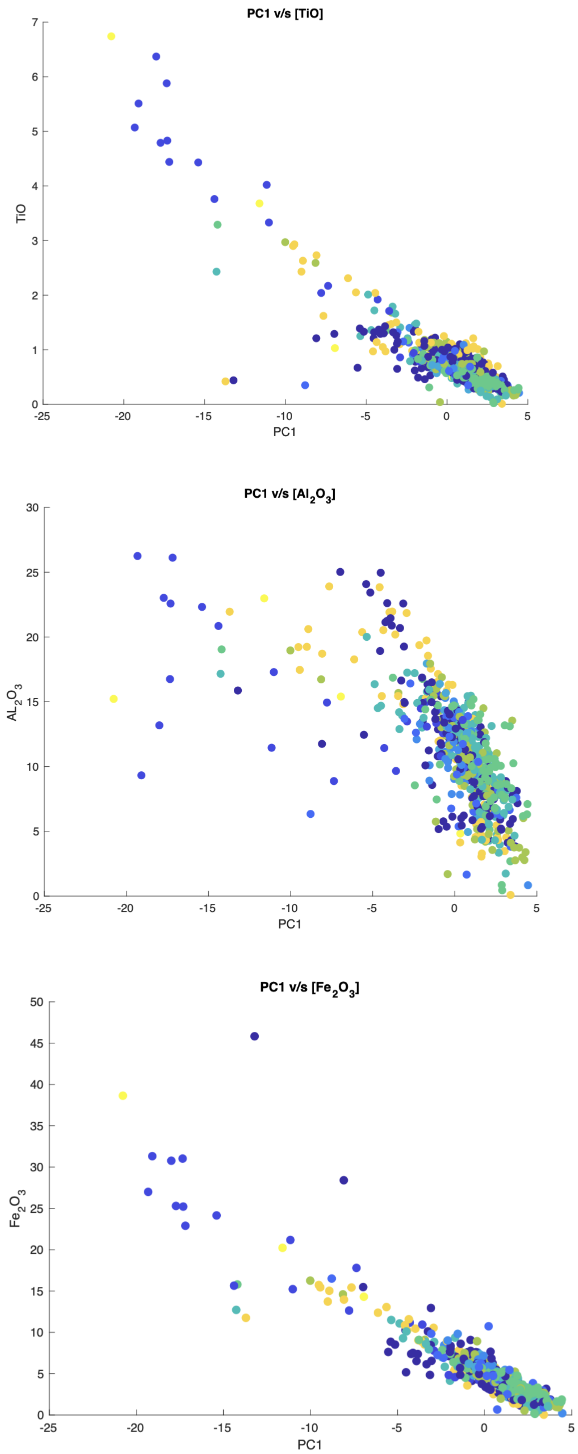


Fig 5: Iron, Aluminum and Titanium oxides vary linearly with changes to the PC1 axis.

Which metal oxides contribute the most to PC2?

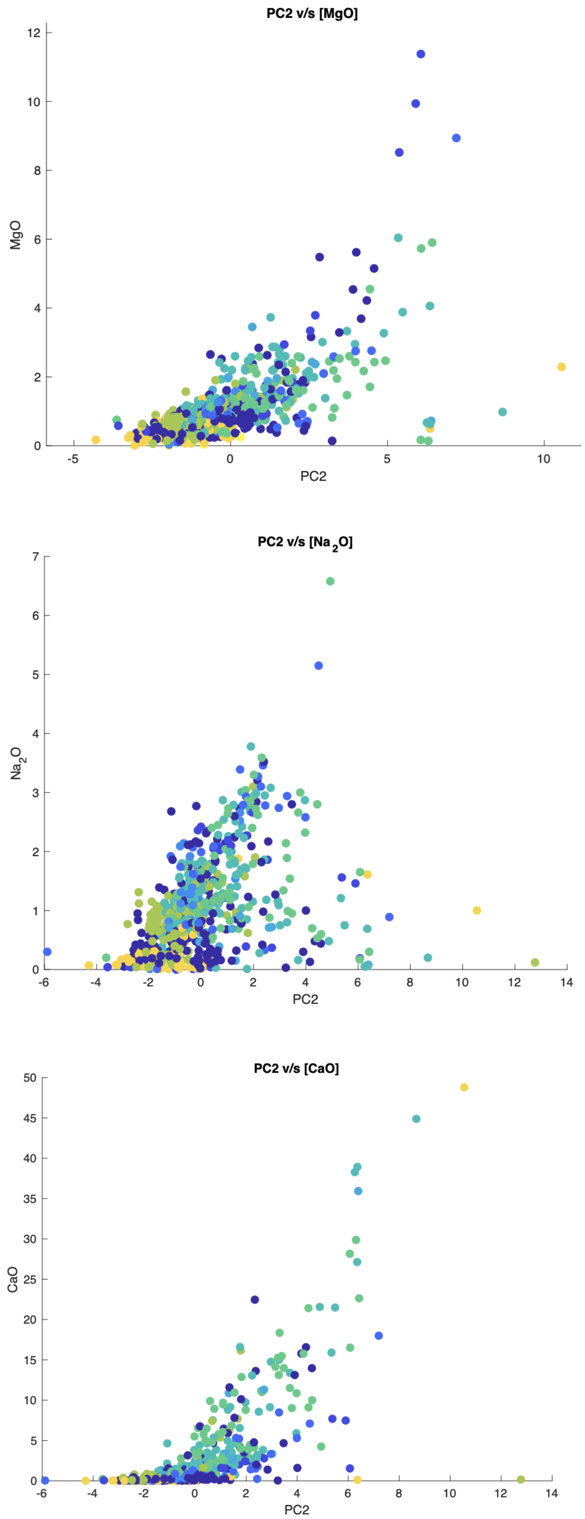


Fig 6: Magnesium, Sodium, and Calcium oxides vary linearly with changes to the PC2 axis.

SCI versus soil order as a proxy for weathering

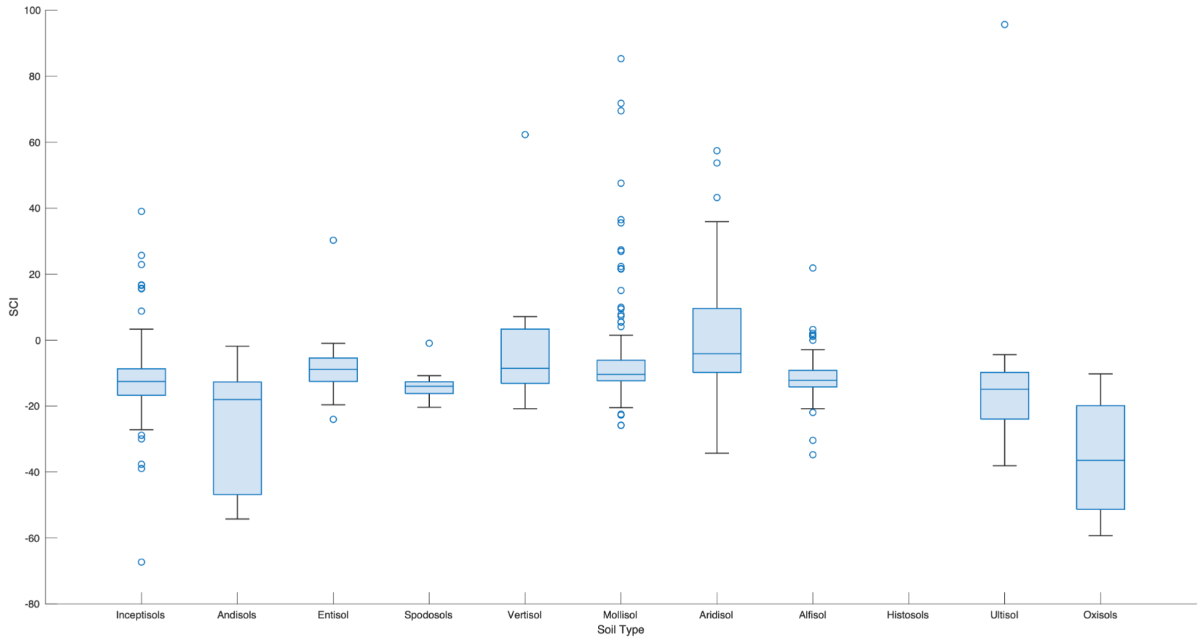


Fig 7: With the exception of Andisols, Inceptisols, and Aridisols, Ultisols and Oxisols appear to plot lower than other soil types in SCI space. Andisols are young volcanic soils and their mineralogy reflects their volcanic source, inceptisols are young soils and their mineralogy reflects their source rock and aridisols are soils forming in hot arid climates where chemical weathering is rate limited by water availability and so their weathering ratios might not reflect other soil types.

The SCI ratio of soils can thus be regarded as a proxy for weathering in regions that are not volcanic, tectonically young, and/or in regions of arid climates.

PWI versus soil order as a proxy for weathering

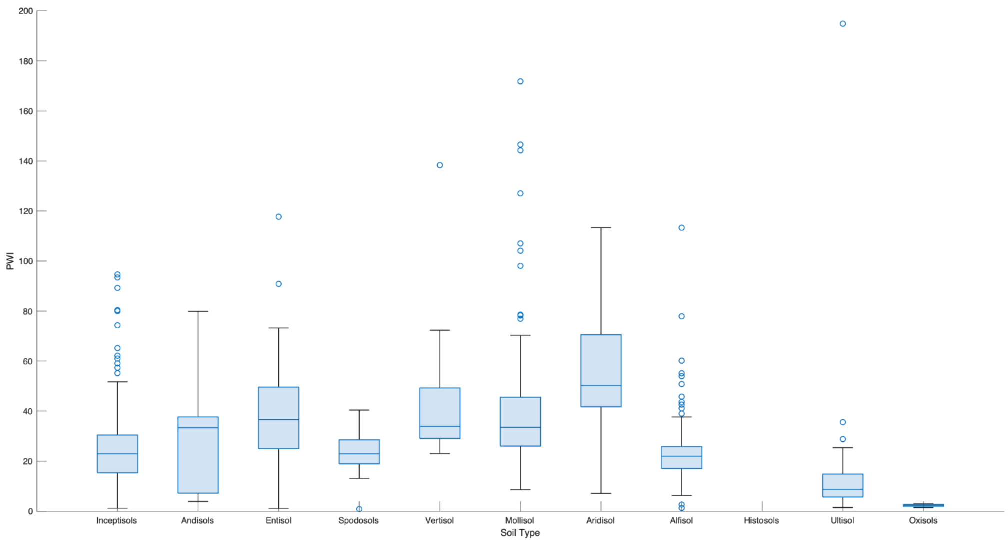


Fig 8: No obvious relation between soil order and PWI proxy

CIA-K versus soil order as a proxy for weathering

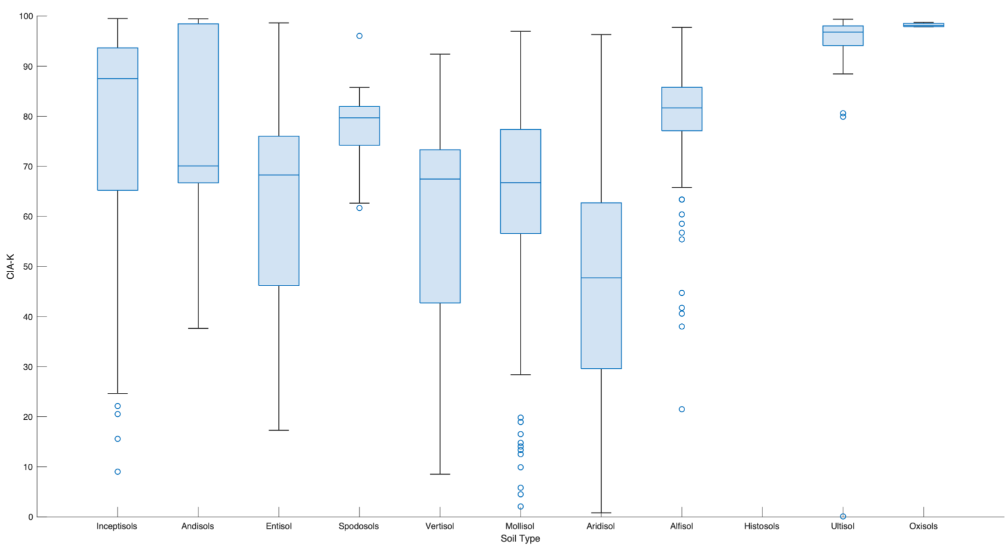


Fig 9: No obvious relation between soil order and CIA-K proxy

SCI versus Temperature

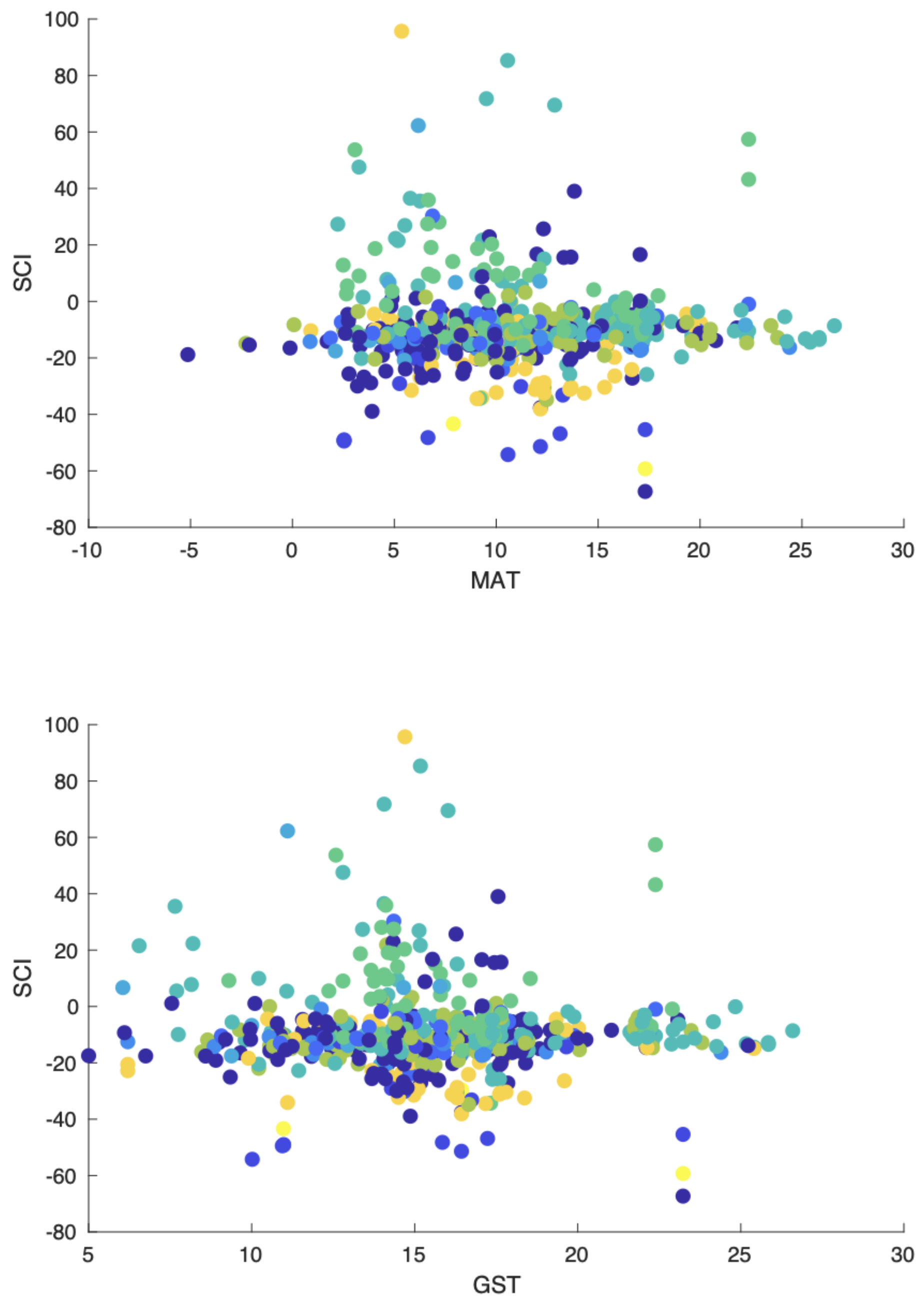
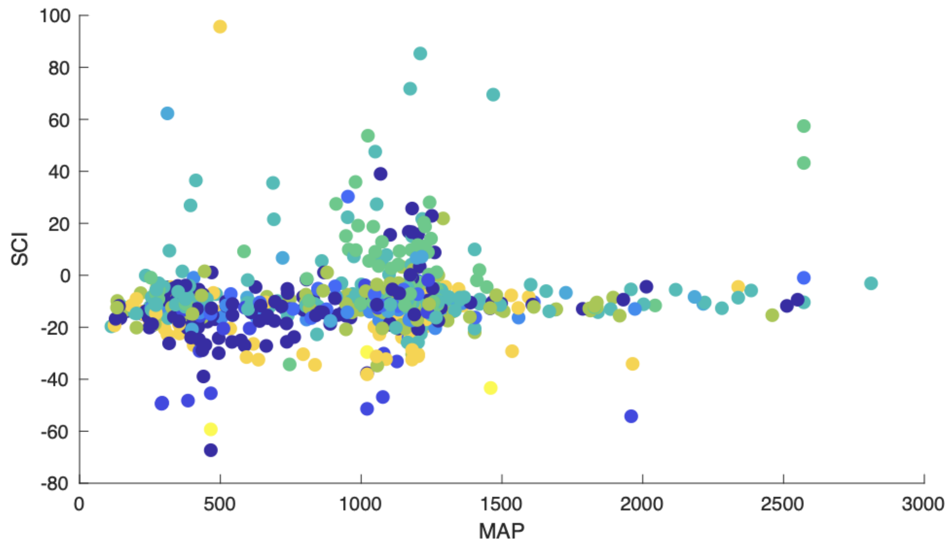


Fig 10: No apparent relationship between temperature and SCI proxy.

SCI versus Precipitation



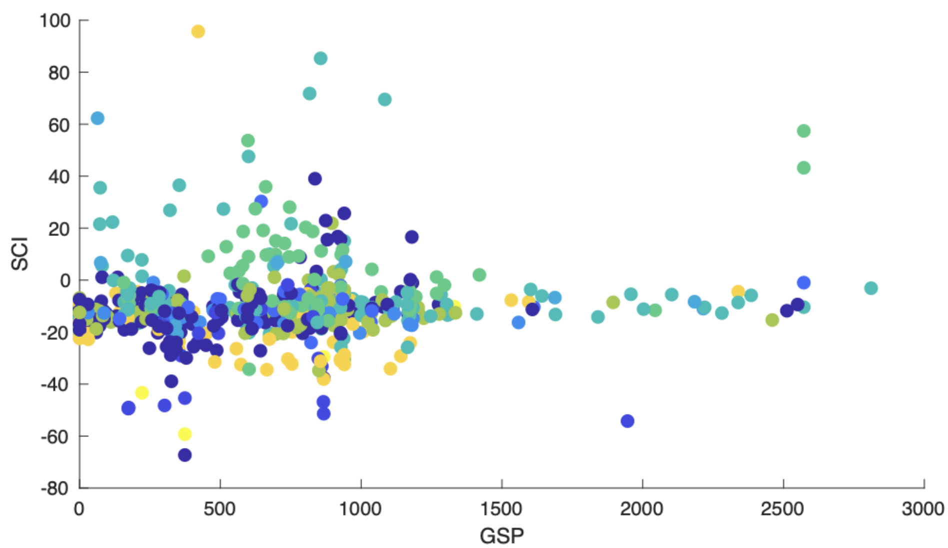


Fig 11: No apparent relationship between precipitation and SCI proxy.

Conclusions

I find that PWI and CIA-K, two proxies that have long been used in the literature, are not robust climate proxies. I find that they explain variability in soil geochemistry (PC2, 17.78% of total variability), but their variability does not always scale with climate. It would suggest that some other physical factor (not MAT, GST, MAP, GSP) is driving PWI and CIA-K which is not necessarily always (although sometimes is) dependent on these climatic parameters. The SCI index developed in this work appears to explain chemical weathering in soils and is thus an exciting tool in the reconstruction of past weathering regimes.

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