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Revisiting the Factors Responsible for Mineral Nutrient Production in Zamfara State

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ABSTRACT

The Earth's critical zone (CZ) has been constantly evolving and changing over geological timescales, historically driven by tectonic and climatic forcings. Recently CZ changes have also been driven by anthropogenic factors occasioned by increases in population, which has increased demand for resources and expansion of agriculture, leading to unsustainable land use practices. As a result, about one-third of global arable lands have been eroded and degraded and they are continually being lost at a rate of about 0.5% a year. Soils are especially vulnerable to loss and degradation in different environments where lithology, climate and landscape may contribute to leaching out of mineral nutrient elements in the soils. In this paper we explored the factors that control mineral nutrient production in Zamfara state with a view to developing this area of research in the state.

Keywords: Critical zone, weathering, lithology, climate, vegetation.

1.0 INTRODUCTION

It has been projected, according to the Millennium Assessment Board (2005) that human population globally will reach about 9 billion by the year 2050. This increase in population – both human and livestock – has increased competition for resources, mostly food and fibre. Competition for food resources has resulted in the transformation of vegetation and, by extension, climate leading to a pressure exerted on the thin veneer on the Earth's surface known as the Critical Zone. The Critical Zone has been described by Brantley *et al.* (2007) as the outer skin of the Earth encompassing lower atmosphere, most of the biosphere, hydrosphere and upper lithosphere from the top of the vegetation canopy to the bottom of the groundwater zone.

In the Critical Zone, an interplay of complex processes that involve interactions between water, microorganisms and minerals from soils and rocks (Brantley *et al.*, 2007). These interactions sustain life forms by providing energy and nutrients. Some of these interactions are driven by (coupled) processes such as weathering and erosion. These processes are usually integrated over spatial and temporal scales to help study the evolution of the CZ and its response to (human) perturbations (Anderson *et al.*, 2007; Brantley *et al.*, 2007). As a critical

part of the Critical Zone, soil, which is easily impacted by human activities has been identified as the major link through which energy and nutrients are exchanged between different Earth systems.

Therefore, coupled processes such as weathering and erosion are intensively studied to understand both the function and evolution of the CZ over long and short timescales (Anderson *et al.*, 2007; Brantley *et al.*, 2007). Weathering has been identified as the primary process that shapes landscapes, regulates climate and drives the formation of mineral nutrient elements. Soil formation as well as the release of mineral nutrient elements through weathering reactions are seen as the most important processes that created and sustained the CZ. However, the weathering processes as well as the production of mineral nutrient elements (such as Ca, K, P, Fe) depend on the environment, climate and vegetation. In this paper, we intend to review weathering processes in the contexts of vegetation and climate in Zamfara state North-western Nigeria.

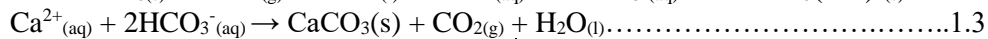
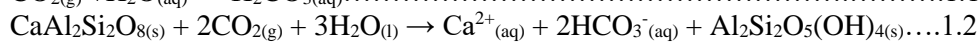
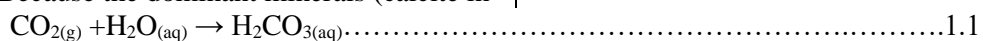
2.0 WEATHERING CONTROLS

2.1 Lithology

Although weathering is the key process through which soils are formed, different factors (such as climate, vegetation, land use and lithology) can

affect the rate of soil formation and production, mobilisation, and distribution of mineral nutrients (Frings and Buss, 2019; Riebe *et al.*, 2017). In terms of lithology, different rock types (such as silicate and carbonate rocks) have different weathering rates as well as mineral composition. Silicate rocks which constitute about 90% of rocks on the global surface (Chapela Lara *et al.*, 2018 Oeser *et al.*, 2022; Pastore *et al.*, 2022) weather slower than other rocks such as carbonates and/or evaporites (Jin *et al.*, 2010). Lithology also strongly influences weathering rates by influencing the availability of fresh minerals of varying reactivity for weathering reactions. For example, in silicate weathering, mafic (basaltic) lithologies are generally more reactive than felsic (granitic) lithologies and have a wider proportion of minerals containing Ca and Mg (such as apatite, feldspars and amphiboles) to drive carbonate formation in marine sediments (Chapela Lara *et al.*, 2018; Hahm *et al.*, 2014).

Although felsic lithologies have similar minerals, albeit in lower proportions compared with mafic silicates, it could be said that mafic lithologies exhibit greater control on silicate weathering rates, long-term climate regulation and faster soil forming processes and mineral production rates (Brantley *et al.*, 2013). In carbonate weathering on the other hand, the rocks are usually dominated either by limestone or dolomite with small quantities of other minerals often regarded as 'impurities' (Jiang *et al.*, 2014; Moraetis *et al.*, 2011). Because the dominant minerals (calcite in



High atmospheric CO₂ concentrations block the outflux of radiation from Earth into space by acting as a greenhouse and warms the atmosphere thereby increasing the rate of evaporation and acid precipitation which, in turn, increases silicate dissolution and CO₂ removal from the atmosphere. On the other hand, low atmospheric CO₂ concentrations cool down the atmosphere and reduce the evaporation and, by extension, precipitation rates which, in turn, slow down silicate dissolution (Jin *et al.*, 2010). However, weathering of carbonate rocks does not affect atmospheric CO₂ concentrations over geological timescales due to the release of CO₂ during the

limestone and dolomite in dolostone) are highly soluble (Dere *et al.*, 2016), carbonate rocks are reported to drive regional weathering. For example, in the mountainous Himalayas in Pakistan, Brimhall *et al.*, (1987) established that weathering is driven by carbonate minerals even though they consist of only 1% of the area. Also in the carbonate landscapes in Mallorca, Spain, Muhs *et al.* (2010) established that carbonate minerals, calcite and dolomite, dissolve faster thereby leaving the soils enriched with silicate mineral residues such as quartz, feldspar and kaolinite. In Zamfara, there are no known studies that explored the lithological composition of the soils as well as its influence on weathering, soil formation and distribution of mineral nutrient elements.

2.2 Climate

Weathering of silicate rocks has also been credited with the regulation of long-term climate through the drawdown of atmospheric CO₂ over geological timescale. Dissolution of silicate minerals such as plagioclase through acidic precipitation sequesters CO₂ from the atmosphere through carbonate-silicate cycle and produces metal ions such as Ca²⁺ and bicarbonate ions HCO₃⁻ which are then transported through rivers to the ocean (Amundson *et al.*, 2007; Bernhard *et al.*, 2018; Starke *et al.*, 2017). Equations 1.1 – 1.3 explained the process of plagioclase weathering by acidified rainwater and the subsequent deposition of calcite in the oceans:

formation of marine sediments (Brantley *et al.*, 2013).

Several studies have examined different components of climate such as temperature, precipitation and run-off to unravel the effect of climate on weathering rates (e.g., Egli *et al.*, 2008). For example, Egli *et al.* (2008) reported that increase in temperature and run-off increased weathering rates in Iceland over 40 years. Also, White *et al.*, (2005) in a study of 68 small watersheds established that temperature and precipitation are the major drivers of weathering rates. White *et al.* (2005) also reported that temperature and run-off control weathering rates

in granitic rocks. In alpine regions, precipitation was found (Egli *et al.*, 2008) to have greater influence of weathering rates than temperature and vegetation. Similarly, White *et al.* (2005) postulated that although warmer environments should have higher weathering rates, some warm environments have low cation weathering rates and water fluxes strongly influence weathering rates in such environments. Hayes *et al.* (2020) also established that precipitation has greater control on weathering rates in temperate forests than temperature and erosion.

Vegetation has also been reported to impact weathering rates. While the low pH in the root zone from microbial respiration and vegetation degradation increases the dissolution of minerals and weathering rates, vegetation also reduces erosion rates, encouraging formation of thick soils which block the bedrock from interaction with water, thereby reducing weathering rates at depth. In a study of African rivers, Jin *et al.* (2010) established that thick soils resulting from dense vegetation are responsible for slow weathering in the Congo region in central Africa. Edmond *et al.* (1995) reported similar findings in the Amazonian forests of Venezuela and Brazil. In addition, mineral nutrient elements in acidic soils are more significantly weathered around the root zone than deeper in the soil and more nutrient elements are depleted around the root zone. However, nutrient mobilisation and distribution in the soil is essential in providing the nutrient needs of the vegetation. As such, root exudates contribute in restructuring the microbial activity and distribution and enhance the dissolution of minerals (Calvaruso *et al.*, 2010; Napieralski *et al.*, 2019). Mycorrhizal fungi associated with plant roots develop symbiotic relationships with some microbial species, mostly bacteria, that are more efficient in mineral weathering and ensure faster mineral dissolution especially in forest ecosystems (Zhu *et al.*, 2020). Marzioli *et al.*, (2010) also established that microbes in the rhizosphere enhance the dissolution of Ca-bearing minerals such as apatite in nutrient deficient soils.

2.3 Vegetation

In addition to the chemical and microbial activities that hasten mineral dissolution in the rhizosphere, plant roots also contribute to the weathering rates by physically breaking up rocks

and soil aggregates, thereby increasing access of fresh minerals to water which increases weathering rates (Bernhard *et al.*, 2022; Jobbagy and Jackson, 2004) or by directly absorbing nutrients such as P from the rocks.

2.4 Land Use

Although anthropogenic activities such as land use change are expected to impact weathering and denudation rates, it was reported that no correlation between weathering rates and land usage in granitic environments. However, in carbonate environments, land use was reported to impact on the weathering rates by enhancing elemental denudation and rocky desertification (Brecheisen *et al.*, 2021; Foley *et al.*, 2005; Jiang *et al.*, 2020). Alekseev *et al.* (2018) reported that land use in different soil profiles around the Moscow region in Russia affects the weathering and the distribution of minerals and elements by affecting the distribution of chemical elements between different subfractions of clay and silt between 50 – 150 years.

3.0 MINERAL NUTRIENT CYCLING

Soils, formed during weathering reactions, contribute significantly to the global biogeochemical cycling of elements (Derry and Chadwick, 2007). Depending on the environment, the distribution of mineral elements (e.g. Ca, Fe, P, Mg, K) is usually dependent on processes such as weathering, atmospheric deposition, leaching and/or vegetation (plant) cycling (Brantley *et al.*, 2013; Dawson *et al.*, 2020; Porder *et al.*, 2007a; Porder *et al.*, 2007b; Uhlig *et al.*, 2017; Uhlig and Blanckenburg, 2020) acting together or in isolation (Porder *et al.*, 2007b). Weathering enriches the soil with nutrient elements derived from lithospheric sources such as rocks (Buss *et al.*, 2017; Buss *et al.*, 2010; Porder *et al.*, 2007) and controls the depth and distribution of nutrient inputs (Buss *et al.*, 2010; Dawson *et al.*, 2020; Moore *et al.*, 2017; Moore *et al.*, 2005; Porder *et al.*, 2007; Uhlig *et al.*, 2017).

In environments where the rate of removal of soil by erosion is faster than dissolution of minerals through weathering, the nutrient elements provided in the soil by weathering are removed, becoming unavailable for vegetation, The cycling of mineral nutrients is usually then controlled by other processes such as atmospheric deposition

and/or vegetation cycling (a process in which plants recycle mineral nutrients through litterfall and throughfall) (Dawson *et al.*, 2020; Derry and Chadwick, 2007; Jobbagy and Jackson, 2004). In addition to these processes, leaching removes the mineral nutrient elements released by weathering in environments where removal of nutrient elements through erosion is slower than mineral dissolution, also making the elements unavailable for vegetation (Dawson *et al.*, 2020; Porder *et al.*, 20107). In these weathering-limited environments, nutrient elements such as P, K and, in some cases, Ca (which becomes the limiting mineral nutrient element in soils where P and K are either too low or absent, Tanner *et al.*, 1998; Uhlig *et al.*, 2017; Uhliq and Blanckenburg, 2020) tend to be more concentrated near the surface than elements such as Mg and Na (Dawson *et al.*, 2020; Jobbagy and Jackson, 2001; Porder *et al.*, 2007) due to biolifting (a process in which plants scavenge for nutrients at depth and concentrate them on the surface) and/or vegetation cycling (Dawson *et al.*, 2020; Uhlig and von Blanckenburg, 2019). Although K and P are the major mineral nutrient elements, in soils where both are either too low or absent, Ca becomes the more widely distributed mineral nutrient element in the soil. Globally, according to Jobbagy and Jackson (2001) Ca is the most widely distributed mineral elements in soils that are deficient in K and P.

4.0 CONCLUSION

The paper has clearly demonstrated that several geological and geographical factors are responsible for the distribution and production of mineral nutrients. The degree of influence of each factor is also dependent on the lithology and evolutionary history of the affected area. To date, no substantial details have been published in relations to studies that are specific to Zamfara state.

To establish the mineral nutrient production processes as well as the factors that control the bioavailability in the Northwestern state of Zamfara, Nigeria, soils as well as the underlying bedrock in cultivated and formerly cultivated sites that have been abandoned for various lengths of time, representing gradients in recovery were studied to understand the following:

- i. Are long-term mineral nutrient release processes the in Zamfara terrains controlled by the distribution of silicate-rich rocks in the soil?
 - a. In answering this question, it was hypothesized that the abundance of silicate minerals in the bedrock, which are lower in abundance than the dominant carbonate minerals (calcite and dolomite), are primarily responsible for the production and distribution of mineral nutrient elements in these soils with climate, and/or atmospheric deposition as minor negligible factors.
- ii. Is the soil quality and nutrient bioavailability across the terrains dominantly controlled by land use, silicate mineral distribution, or climate seasonality? It was also hypothesized that the bioavailability of nutrient elements in these soils is controlled primarily by land use (extent of recovery) and bedrock lithology.

To address these questions, soils were studied in two agricultural sites bearing similar mean annual temperatures and precipitation but differ in lithology (this is an assumption because there are no established studies that documented the composition and mineralogy of soils in Zamfara but this study intends to be the first to embark on such studies). The results will be published in the subsequent papers on this grant.

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