Opportunity for increasing the soil quality of non-arable and depleted soils in South Africa: A review

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Abstract

The improvement of food security strategies on highly degraded soils has become a major challenge for South Africa, as the need to secure food sources for the growing population under harsher climatic conditions. South Africa is one of the many water scarce countries and is label 30th driest country in the world. The ability of a soil to serve as a growth medium for plants is directly influenced by the chemical, physical, and biological parameters but most importantly the fertility of the soil, which is a prominent part of soil quality. Numerous methods exist to enhance and maintain soil quality including the application of fertilizers and the other includes the application of geological materials to the soil. Basalt (commonly referred to as rock dust) application as a soil amendment has been the focus of numerous long-term studies on soil fertility. The results of long-term application of rock dust have indicated a reduction in continuously applying additional amendment, resulting in more sustainable farming operations. When considering South Africa's relative scarcity of available agricultural land and harsh climatic conditions against the increasing demand placed on food production by a growing population combined with water scarcity, it becomes evident that it is necessary to search for new innovative methods to improve soil quality, which is deemed non-arable and/or depleted. The potential for basalt in re-mineralisation and application on non-arable soil in South Africa hold enormous benefits for the economy.

1. Introduction

South Africa is but only one of the countries worldwide challenged by improving food production and sustaining food security on highly degraded land (Sithole, Magwaza, Samukelo & Mafongoya 2016). South Africa needs to develop new innovative methods to ensure food security for the increasing population under changing climatic conditions, which are predicted to worsen in the future (Sithole et al. 2016). It is predicted that climate change will have adverse impacts on southern Africa due to more recurrent and protracted droughts with higher temperatures (Stats SA 2010; Sithole et al. 2016). These predictions place more pressure on South Africa’s already restricted arable land (Figure 1) and available water required for food production and food security, on both a household and national level (Sithole et al. 2016). The usage of rock dust in areas already being cultivated for food production has shown considerable positive contributions to soil health as it increases essential nutrient re-mineralisation and trace element addition where regular fertilizers are lacking. The lack of localised studies on the usage of rock dust in the improvement of non-arable and poor quality soils on crops grown and climatic conditions in South Africa have created gaps in sustainable agricultural practices and food production currently implemented in South Africa. Contextualising South Africa's relative scarcity of available agricultural land against the increasing demand placed on food production, it is crucial to search for new innovative methods to improve the quality of soils, which is deemed non-arable. The focus of this review paper is to determine the utility of augmentation with rock dust, in terms of benefits to soil properties (soil quality and function). Within this review paper a background will be discussed on the current situation in South Africa followed by the properties of rock dust as an amendment and what properties of rock dust contribute to the improvement of soil properties with further literature sited relating to soil quality and sustainability, and includes an overview of rock dust usage in the agricultural sector as well as the benefits of this product. This article will also discuss the weathering of the rock dust and secondary products including their chemical makeup.

2. Review Questions

This review paper pursues to establish, through the available literature, on the soil improvement abilities of rock dust amendment. The specific review questions to be addressed are:

What is the influence on the soil quality and properties when non-arable and depleted soils are amended by rock dust?
What specifically are the weathering products of rock dust which contribute to soil quality?

3. Review Methodology

3.1 Literature Search and Database

This review paper aim to identify the potential of the amendment rock dust for soil property improvement in South Africa. In order to retrieve information on existing studies, data was retrieved from Google, Google Scholar, Science Direct and EBSCO through the North West University database by making use of the review questions. The search strategy was developed using key words such as rock dust, crushed basalt, basalt as a nutrient, organic soil fertilizers, soil quality improvement, soil fertility, soil improvement with rock dust, rock dust fertilizer, and basalt as a fertilizer.

The search sensitivity was increased; additional records were identified by hand searching and review of the referenced list of retrieved and screened papers. Data was eliminated based on product marketing and purchase products. Abstract and keywords were used to identify relevant studies regarding the improvement capabilities of rock dust around the world. The data and material were screened carefully based on duplication, relevance, importance and references. The remaining material were reviewed and selected for further study. Geology, Soil Science and Environmental books were examined for relevant information and sited accordingly.

3.2 Schematic maps

The maps for this review article were created by making use of ArcGIS. The data for the shapefile was retrieved form the Council of Geoscience, Agricultural Research Council, Department of Environmental Affairs, Department of Agriculture Fisheries and Forestry and Soil Science Society of South Africa.

4. Situation In South Africa

When considering the critical nature of the agricultural industry, the centrifugal role it plays within South Africa, and the current pressures it faces, the development of more efficient, profound and cost reductive techniques of crop production become imperative. Food availability has become a growing concern for residents and policymakers alike within South Africa. Given the sustained population growth of 2% each year, it is expected that food production will need to double globally by 2050 (Hunter et al. 2017), and will need to double by 2035 for South Africa in order to sustain demand while leveraging potentially fewer resources available to producers today (Goldblatt 2010). Agriculture is one of the main driving forces of the South African economy. Therefore, agriculture and food production are integral to South Africa, its populace and its overall sustainability from both social and economic perspectives. When expressed in terms of export earnings, 2.59% of South Africa's Gross Domestic Product (GDP) is attributed to the contribution of agriculture, equal to around $ 4.89 billion towards the total economic value of South Africa in 2018 (Stats SA 2019).

However, of the 122.34 million ha of land, which makes up South Africa's surface area, around 12% is suitable for dryland and rainfed cropping, represented by Classes I-III [11 040 ha] (Figure 1, Table 1 and Figure 2) (Twomlow, Steyn & du Preez 2006; Goldblatt 2010; Pringle 2013; DAFF 2017). Of this a quarter, 2-3% (approximately 4 million ha) may be considered to be of high agricultural potential, fertile land (Figure 1, Table 1 and Figure 2) (Beukes, Bennie & Hensley 1998; Twomlow et al. 2006; Goldblattb 2010; Pringle 2013). The rest is either non-arable (grazing or wildlife as illustrated in Figure 1, Table 1, and Figure 2) or influenced by urbanisation. As shown in Table 1, 98% of South Africa land use is dominated by Classes III –VIII, which indicates severe limitations with respect to climate (rainfall), terrain, or soils. Class IV covers around 11% of South Africa. Because of the persistent drought and uncertain political and economic conditions facing South Africa, the total number of producing farms has been reduced by a third since the early nineties, while end-user demand has increased, leading to the amplified adoption of industrialised agricultural practices (Goldblatt 2010).

Table 1
Land capability classes in South Africa.

Class	†Land use option	Groups	Percentage land occupation (%)
I	W F LG MG IG LC MC IC VIC	Arable land	0.2
II	W F LG MG IG LC MC IC		1.8
III	W F LG MG IG LC MC		10.6
IV	W F LG MG IG LC	Poor adaptive cultivation	11.0
V	W F LG MG	Grazing	10.5
VI	W F LG MG		15.5
VII	W F LG		36.1
VIII	W	Wildlife	14.4
† W - Wildlife LC - Poorly adapted cultivation			
5. **F - Forestry MC - Moderately well adapted cultivation**			
LG - Light grazing IC - Intensive, well adapted cultivation			
MG - Moderate grazing VIC - Very intensive, well adapted cultivation			
IG - Intensive grazing			

Barnard & du Preez (2004) and Scotney & Dijkbuis (1990) highlighted numerous changes in soil fertility in South Africa. Soil acidification is considered as the single most important cause of declining soil fertility in South Africa (du Preez, Huyssteen & Mnkeni 2011). In high rainfall regions, soils with a low buffer capacity are naturally acidic (Bernard & du Preez 2004). The acidification problem is mostly anthropogenic, caused by extended cultivation on the same areas (Figure 3), as well as unnecessary large quantities of reduced nitrogen fertilizer (Mills & Fey 2004).

Misuse of land causes degradation, which poses (Figure 3) a threat to sustainable agriculture in South Africa (du Preez et al. 2011). Both the physical and chemical properties of soils have been adversely changed by land use practices in South Africa (Mills & Fey 2004). Large amounts of soils are degraded because of over utilisation (Figure 3) (van Straaten 2002; Goldblatt 2010). Unless these nutrients, removed from the landscape during crop production, are returned soil fertility will dwindling over time (Figure 3) (Mills & Fey 2004). It is evident that there is considerable acidification and nutrient depletion in South African soils as well as lack of soil structure due to degradation (Mills & Fey 2004). However, in the context of water scarcity, the most difficult facet is the ability of the soil to absorb and retain rainwater. The overall dependence and overuse of synthetic fertilisers, pesticides, and herbicides on arable farmlands further reduce long-term soil fertility leading to, soil erosion, water pollution, and poisoning of the ecosystem aid to climate change (Goldblatt 2010). Furthermore, crop farmers are faced with persistently increasing input costs due to a volatile domestic currency, contributing to overall reduction in profitability (Goldblatt 2010). Agricultural systems, which are productive and sustainable is vital to the general well-being of a nation as well as the foundation to the development thereof (van Straaten 2002). Therefore, soil is considered the basis of survival, food security, and employment in a country. To ensure sustainable agricultural, strategies, which ensure proper resource management of the land, needs to be adopted. Therefore, famers need to improve and/or maintain soil fertility (Goldblatt, 2010).

6. Rock Dust Properties And Benifits

Soil health and quality can be improved and maintained through various ways including the application of fertilizers and the application of geological materials to improve and increase the productivity of the soil (van Straaten 2002; van Straaten 2006). The fertilizer sector almost only focusses on the manufacture of synthetically concentrated products, which are soluble and contain macronutrients (nitrogen (N), phosphorous (P) and potassium (K)) with limited secondary and microelements.

With the exception of nitrogen, 18 of the elements essential for plant health are derived from rocks (Weil & Brady 2017). The rate of release and solubility of nutrients derived from rocks and minerals are mostly low (Atputhan 2018; van Straaten 2002; van Staaten 2006). Chemical, physical, and biological modifying processes accelerate the rate at which nutrients are discharged. Rock dust application as a soil amendment has been the focus of numerous long-term studies on soil fertility (Gervais & Herbert 2014). The application of rock dust over long periods has reduces the need to apply additional amendments constantly, resulting in more sustainable farming operations. Gervais & Herbert (2014) showed that rock dust, as a sustainable soil amendment, has the ability to enhance the overall quality of the soil, stabilise the pH, increase cation exchange capacity (CEC), increase nutrient storage and reduce leaching while offering better protection against contamination and degradation, improving soil texture and water retention and holding capacity. Van Straaten (2006) listed six subdivisions of natural mineral and rock-based fertilizers to increase soil fertility on smallholder farms:

- Multi-Nutrient Silicate Rock Fertilizers, e.g., fine-grained volcanic rocks,
- Single-Nutrient Rock Fertilizers,
- Rock Fertilizers from rock and mineral waste.
- Translocated Rock Fertilizers such as alluvial/ sediment and volcanic ash
- Specific Nutrient Rock Fertilizers and
- Biofertilizers, organic forms of nutrients extractance

Von Fragstein, Pertl & Vogtmann (1988) found that high silicate rocks, such as granite, release a lower number of cations compared to volcanic rocks such as rock dust due to fast weathering rates and release rates of macro- and micronutrients of rock dust. Basalt, often referred to as rock dust, contains 72 macro-, micronutrients, and trace elements resulting in rock dust amendment being able to provide a more comprehensive variety of plant nutrients for more healthy plant growth and development with higher quality production and more nutritious food (Gervais & Herbert 2014).

Fyfe, Kronberg, Leonardos & Olorufemi (1983) stated that young volcanic areas where weathered lavas and ashes are commonly present are often the most fertile areas. A healthy soil is the result of a sequence of complex interactions between geology and biology; as rock weathers, it reacts with soil microorganisms resulting in the release of essential minerals and plant nutrients such as Ca, Mg and iron (Fe) to increase crop yields and assist with plant growth and development (Affeldt 2015, 2016 and Earle 2015). In the past people instinctively settled near active volcanoes and volcanic islands due to the rich and extremely fertile soil found near volcanoes (Affeldt 2015, 2016; Brady 2018).

When Mount St. Helens erupted in 1980 clouds of volcanic ash was sent into the atmosphere and resulted in the landscape surrounding being covered the with dark grey ash layer. Soon afterwards nature's regenerative abilities took over leading to long-term beneficial effects of the basaltic volcanic ash that was deposited on the soil in agricultural land downwind of the eruption (Affeldt 2015, 2016).

Farmers have long before relied on powdered basalt to serve as a natural way to improve soils root system development, increase crop yields and aid in plant health and conditions (Affeldt 2015, 2016; Tanveer et al. 2017). By amending soil with crushed volcanic basalt, the biological process of healthy soils required for optimum and sustainable plant growth is mimicked (van Straaten 2002; Affeldt 2015, 2016).

However, now that the global issue of soil degradation and food scarcity are in the forefront of research initiatives, the benefits of making use of rock dust in the restoration of soil health and sustainable crop production are regaining attention (Affeldt 2015, 2016; Tanveer et al. 2017). Basalts are generally used as rock dust in organic fertiliser since they have the highest supply of nutrients and micronutrients for soil remineralisation (Ramos, de Mello & Kautzmann 2014; Earle 2015; Garner n.d). According to Affeldt (2015, 2016) and Gillman, Burkett and Coventry (2002) the earliest and most complete studies done on the benefits of rock dust primarily in the agricultural sector was that by D' Hotman de Vulliers (1947, 1961) on sugarcane on the volcanic island of Mauritius.

The scientist at the Sustainable Ecological Earth Regeneration (SEER) Centre in Scotland noted that the benefits of rock dust amendment include the increases in water retention, enhancement of the CEC and improvement of the soil structure and drainage abilities of the soil (Campe 2010; Garner n.d; Geater 2012). The Jatropha costaricensis trees in Costa Rica have illustrated an increase in yield and vigour with the application of rock dust (Campe 2010). In Tasmania, an increase in organic matter, available P and pH values found in soils formed on basalts (Sparrow et al. 2013). Scientist from southern Philippines incubated soil that had extreme fertility problems with amongst others, ground pyroclastic basalt to study soil chemical property changes (Biniao et al. 2002). This study found that nutrient uptake increased with the applied amendments and that the comparative plant heights and weights of maize had a linear correlation with Mg concentration in the soil (Biniao et al. 2002). In tropical regions such as Brazil, the addition of basaltic rock dust to acid soils with low productivity resulted in correcting the pH in nutrient supply and has a long residual effect with the presence of micronutrients such as Zn, B, Cu, Fe, and Mn (Ramos et al. 2014). In the USA, soils amended with gravel dust produced double the volume of maize when compared chemically fertilised soils, the maize was higher in protein, Ca, P, Mg, and K compared to conventionally grown maize (Campe 2010). Rock dust was also found to reduce crop damage by acting as long-term pest control through destroying and disabling insects and thereby limit their population (Campe 2010).

7. Rock Dust Weathering

Rock weathering is shown to be controlled by a very complex relationship between climate, biota, topography, parent rock composition, and time and is a function of various processes. Weathering of silicate minerals, especially mafic minerals, is often considered one of the most important mechanisms in the removal of CO_2 from the atmosphere and therefore regulation of global climatic changes (Dessert et al. 2003).

In basaltic rocks minerals susceptible to chemical weathering commonly follows the reverse of the Bowen reaction series glass ≈ olivine > plagioclase ≈ pyroxene > Fe–Ti oxide (Babechuk, Widdowson & Kamber 2014; Nesbitt & Wilson 1992). Chemical weathering of basalt is incongruent as some primary minerals do not dissolve and secondary minerals are formed. The generalised weathering sequence for primary minerals is illustrated in Figure 4 (Weil & Brady 2017). Babechuk et al. (2014); Prudêncio et al. (2002); Rasmussen, Dahlgren & Southard (2010) stated that the parent rock mineralogy, climate, biota, oxidation-reduction state, and drainage of the profile give rise to the pedogenetic mineralogy and order of mineral formation in the soil.

The general alteration products produced from the weathering of basalt are clay minerals such as Mg-Fe smectite, celadonite and saponite-celadonite-chlorite, calcite, silica such asopal, chalcedony, and quartz and zeolites such as mordenite and heulandite as well as Mn- and Fe –oxides/ oxyhydroxides (Abreu, Korchagin, Bergmann & Bortoluzzi 2014; Babechuk et al. 2014). During the initial too early stages of basalt weathering 2:1-layer phyllosilicates typically form, while substantial hydration takes places (Babechuk et al. 2014). End products such as 1:1-layer clay minerals (kaolinite or halloysite) are stable when weathering progresses from intermediate to advanced phases (Babechuke et al. 2014). The secondary products produced from weathering of primary minerals in basalt are presented in Table 2. Gislason, Arnorsson and Armannsson (1996) showed that the mobility of elements during the wreathing of basalt decrease as follows S>F>Na>K>>Ca>Si>Mg>P>Sr>>>Mn>Al>Ti>Fe. These workers also showed that close to 90% of Mg and Ca in the original rock is left behind at the weathering site of the original rock. An overall net loss of mobile elements including Mg, Ca, Na, ±K accompanies the mineralogical transformations in the early weathering stages of basalt while Al, Fe, and Si are mainly retained (Babechuk et al. 2014; Chesworth, Dejou & Larroque 1981; Kronberg & Nesbitt 1981; Nesbitt, Markovics & Price 1980; Nesbitt & Wilson 1992). The mineralogy of the parental basalt controls the bulk leaching rates of the major elements (Nesbitt & Wilson 1992). However, climate dramatically affects the rates of chemical and physical weathering (Nesbitt & Wilson 1992) and therefore has an important impact on the clay mineral suites observed in soils.

Table 2
Mineral composition and weathering products of basalt (Weil and Brady, 2017).

Mineral name	Composition	Weathering products
Labradorite	$(Na,Ca)_{1-2}Si_{3-2}O_8$	Allophone and smectite (Winegardner, 1995)
Calcic plagioclase	Ranges from $NaAlSi_3O_8$ (Albite) to $CaAl_2Si_2O_8$ (Anorthite)	Allophone and smectite (Winegardner, 1995)
Augite	$(Ca,Na)(Mg,Fe,Al)(Si, Al)_2O_6$	Chlorite (Bell, 2007), smectites (Winegardner, 1995)
Pigeonite	$(Ca,Mg;Fe)(Mg,Fe)Si_2O_6$	Chlorite (Bell, 2007), smectites (Winegardner, 1995)
Olivine	$(Mg,Fe)_2SiO_4$	Serpentine, Talc, carbonate, smectite and oxidized iron (Fe) (Bell, 2007; Winegardner, 1995)
Hornblend	$(Ca,Na)_{2-3}(Mg,Fe,Al)_5Si_6(Al,Si)_2O_{22}(OH)_2$	Chlorite (Bell, 2007) smectites (Winegardner, 1995)
Biotite	$K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$	Vermiculite, montmorillinite (Shroeder, 1984) and goethite (Winegardner, 1995)
Volcanic glass	-	Chlorite and epidote (Tuğrul, 1997)

Several factors can contribute to the rapid and/or enhance weathering of basalts such as deuteric alteration of primary minerals, swelling and shrinking of smectite clays (an alteration product of either volcanic glass or primary silicates such as olivine, pyroxene, and plagioclase) and zeolites as well as extensive microfracturing (Bell 2007). Mechanical disruption of small rocks close to an exposed surface is the result of recurring hydration and dehydration (Bell 2007). This process of swelling and shrinking leads to flaking and surface cracking which allows the access of water causing the degree and rate of weathering of these rocks to increase (Bell 2007). Once exposed to the atmosphere, some basalt is susceptible to rapid weathering referred to as slaking (Bell 2007).

8. Conclusion

Contextualising South Africa's relative scarcity of available agricultural land (Figure 1 and Table 1) and harsh climatic conditions against the increasing demand placed on food production by a growing population combined with water scarcity, it is necessary to search for new innovative methods to improve soil quality, which is deemed non-arable and/or depleted. Because of the increase population, the demand for food and land space also increases dramatically. This place considerable amount of strain on arable soil resources for food production as the food produced on the same soil needs to increase exponentially unless non-arable, poor soil quality areas can be improved to contribute to food production.

As an ameliorant, basalt rock dust has been implicated in directly influencing soil quality and function, by increasing fertility, the proportion of soil organic carbon, and enhancing moisture retention. Augmenting poor quality soils, caused by repeated cycles of growing crops on the land and removal of the crops, with basalt rock dust has proven successful elsewhere in the world. Amendment of croplands with rock dust has the potential to modify sandy soils as basalt, produce soils with higher clay content. Basalt rock dust also has the potential to increase the pH and the CEC and cation concentrations in the soils. Research should be conducted on the use of local basalt units as a source of rock dust for soil and plant health under local conditions on local soils to validate previous positive results from around the world. The potential for basalt rock dust in re-mineralisation and application on non-arable soil in South Africa hold enormous benefits for the economy.

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Figures

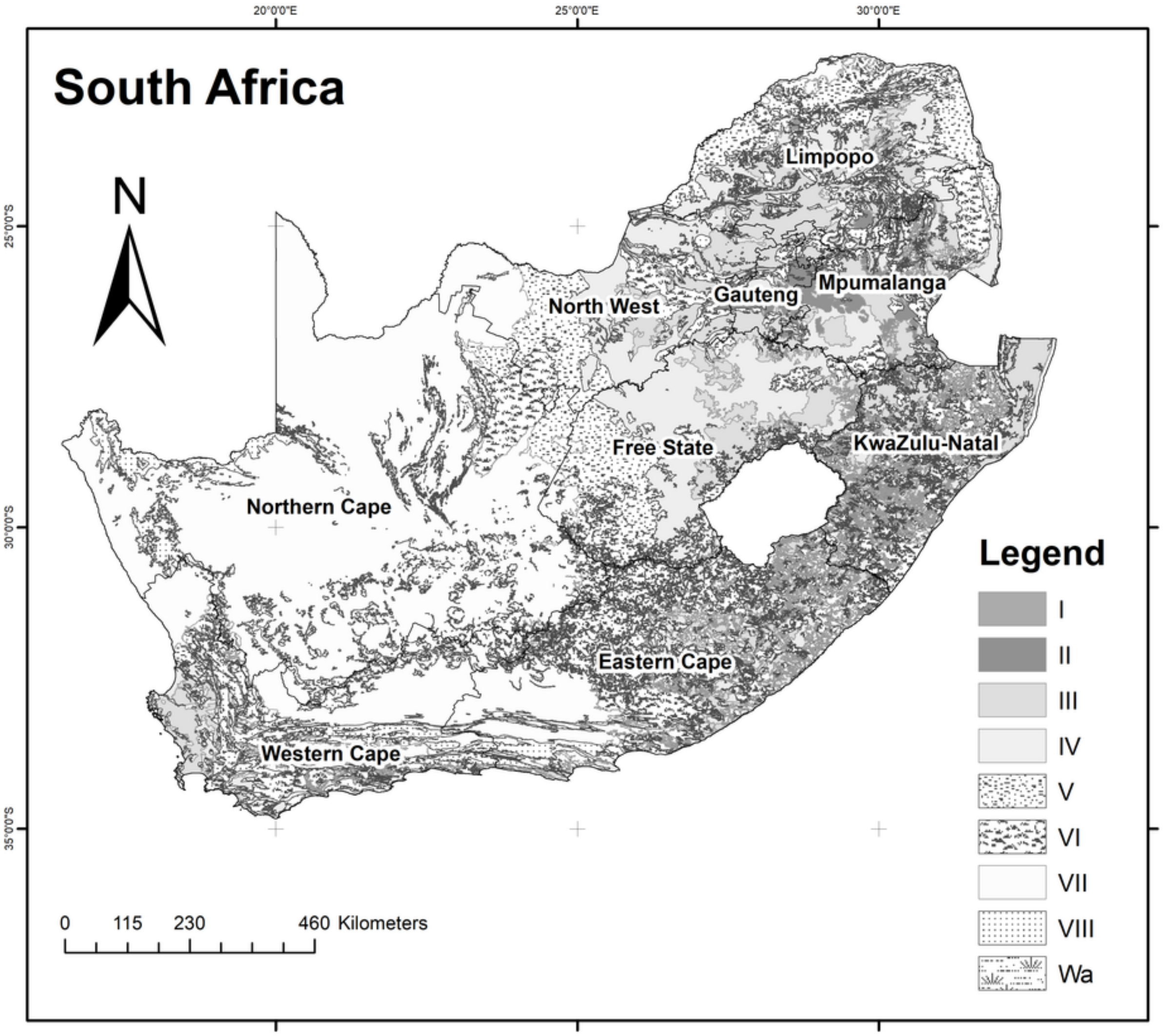

Figure 1

Basalt soil capability

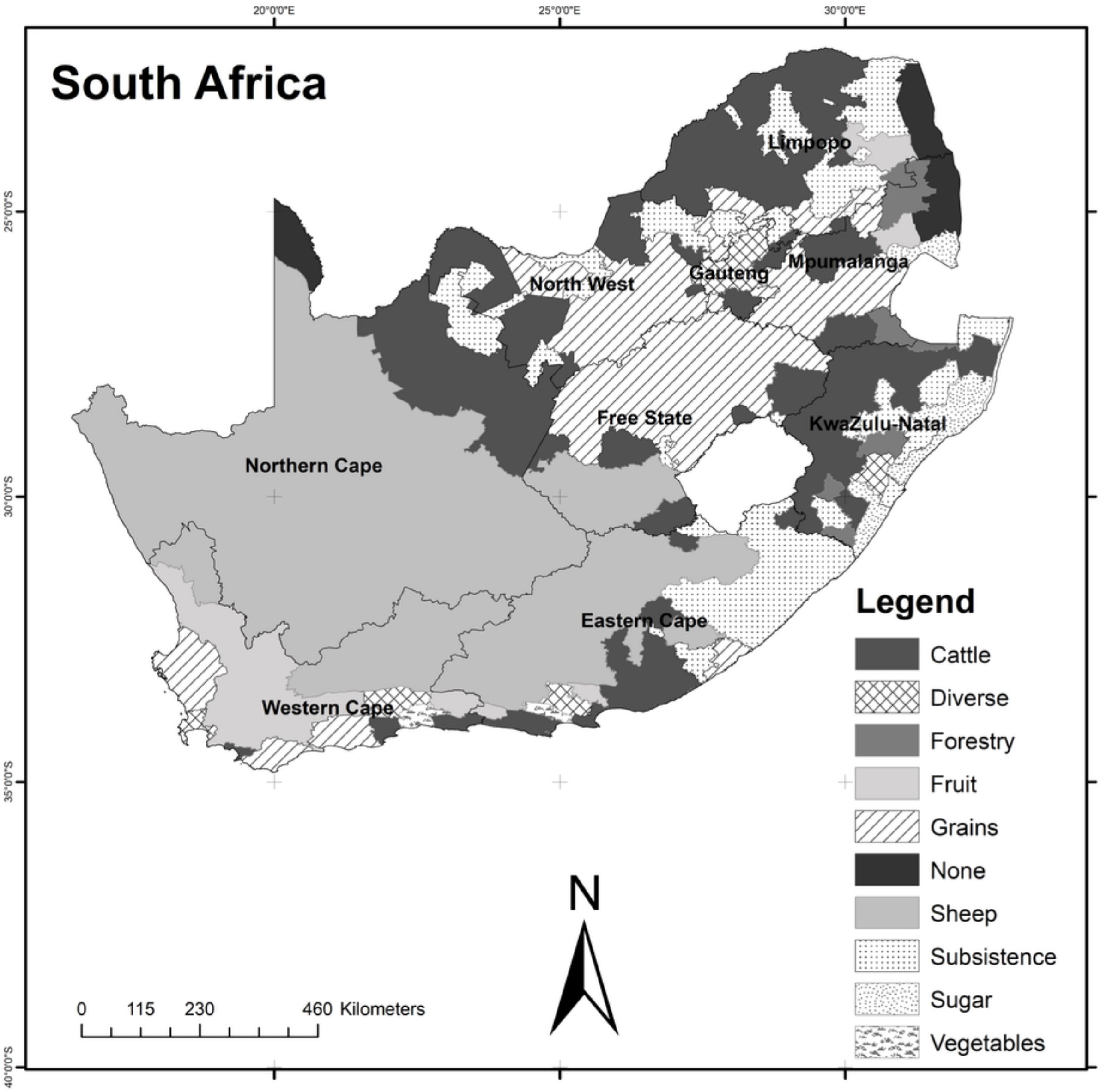

Figure 2

Map for land use

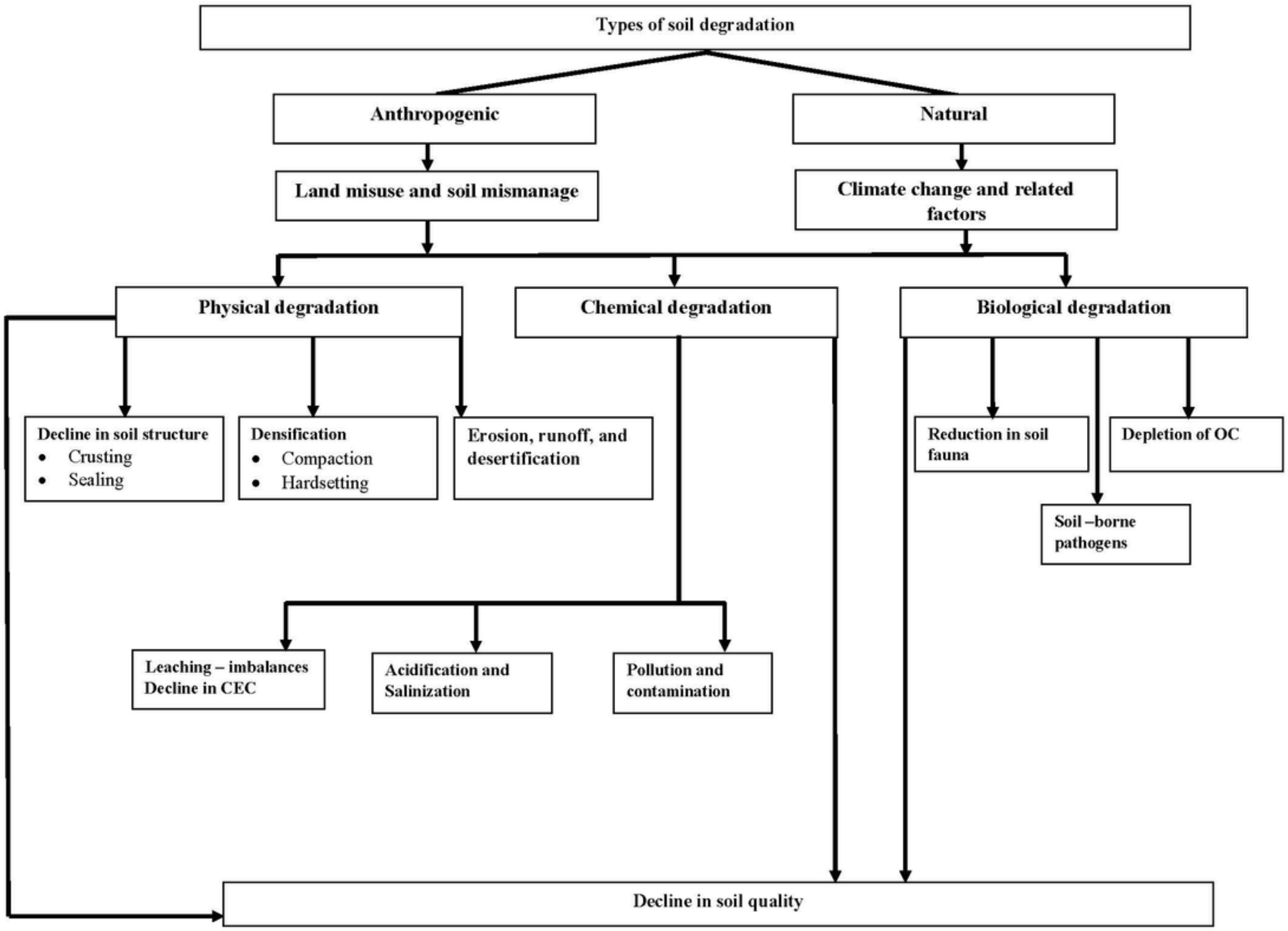

Figure 3

Degradation Diagram

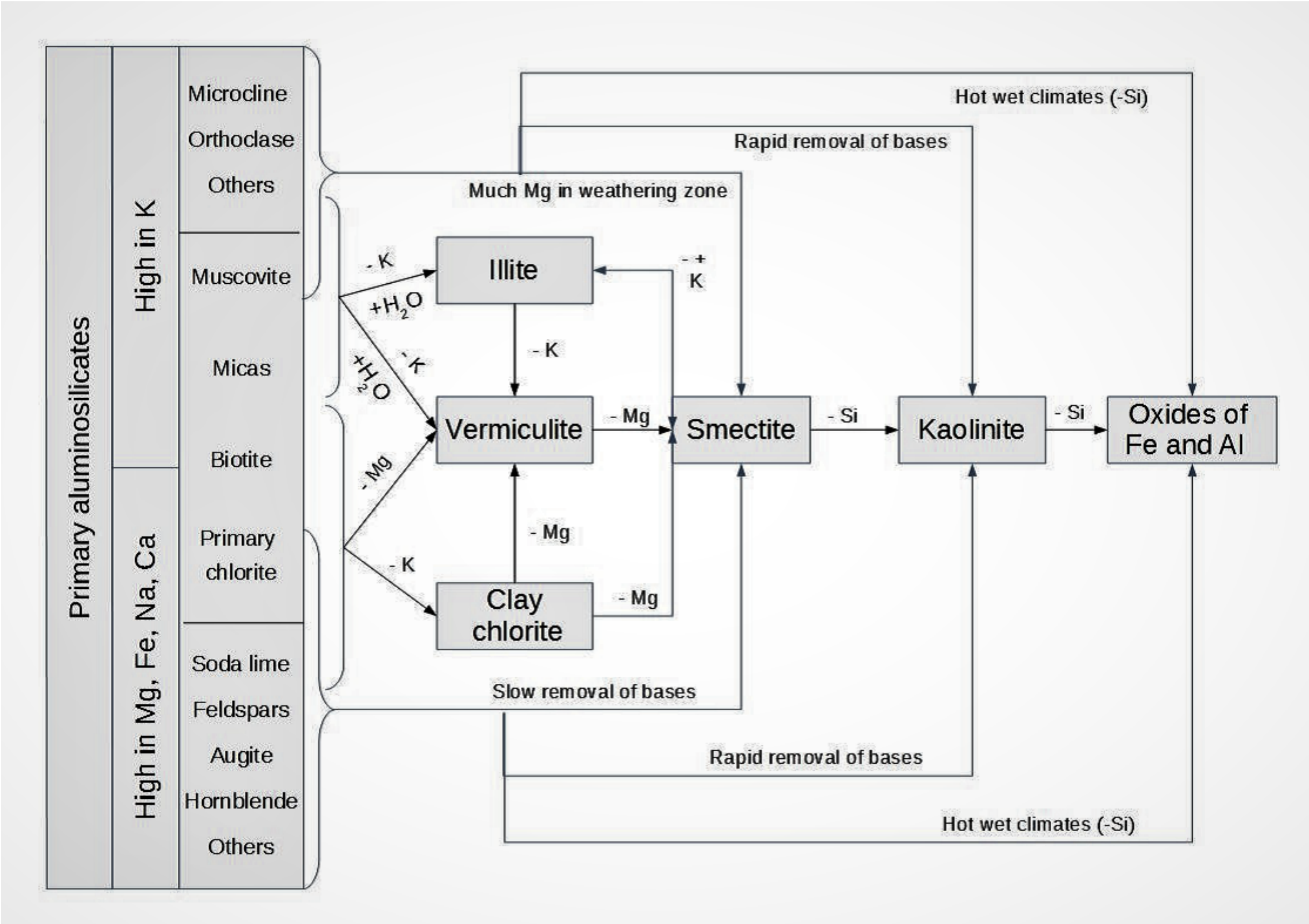

Figure 4

Weathering diagram