SUMMER SCHOLARSHIP REPORT

1.	**Project Title**	:	
	Drought resilience potential in cropping soils using naturally occurring rocks and minerals		
2.	**Proposed Start Date**	:	1 December 2018
	Proposed Cease Date	:	15 April 2019
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Drought resilience potential in cropping soils using naturally occurring rocks and minerals

1. Executive Summary:

Climate change means that future projections of extreme weather events are set to escalate in frequency and intensity. Drought is one of these natural weather phenomena set to accelerate that causes massive losses to agricultural crops, increase land degradation, reduce clean water supplies and thereby inducing malnutrition and starvation, and jeopardise global food security. One potential mitigation is the development of drought resilience in typical cropping soils by using a form of Negative Emissions Technology (NET) called Enhanced Weathering (EW), which is the application of silicate rockdust to soil and/or water. This paper will investigate the ability of rockdust to increase the water holding capacity of two typical Queensland cropping soils and also examine the silicon release from each type of rockdust, as silicon is an important plant element in drought resistance. Four types of geomaterials will be used for rockdust: vesicular basalt; bentonite clay; pumice and zeolite. Using six application rates control (0t/ha), 5 t/ha, 10 t/ha, 20 t/ha, 40 t/ha and 100 t/ha and overnight oven temperatures of 30°C, 35°C, 40°C, 45°C, 50°C, 55°C and 60°C, each treatment started at field capacity. Total water loss was calculated inclusive of soil moisture, geomaterial moisture and water added for field capacity. Initially, there were no clear results indicating that the geomaterials reduced water loss. The bentonite treatments developed cracking at higher temperatures and condensation was evident on the inside of the all of the containers. It was noted that the weights of each treatment were continually decreasing on the scales hinting that water loss had not reached its equilibrium. Further experimentation revealed that the treatments required 6-8 days in the oven to reach this equilibrium, which would be more reflective of drought conditions. However, a final experiment that focused on the sandier soil with bentonite applied at higher rates did conclude with a definite reduction of water loss at 40°C. Nutrient testing on the soils showed that zeolite released the highest amounts of silicon in leached Quilpie soil, however, silicon was not released in the soil water of the Mungindi soil. It is recommended that further studies would investigate different application rates and methods amongst different soil types and climates in combination to specific plant species requirements.

2. Background:

This paper investigates the potential of Enhanced Weathering (EW), a form of Negative Emissions Technology (NET) to increase the soil moisture holding capacity of two types of Australian cropping soil by application of specific silicate rocks (geomaterials) in rockdust form. The geomaterials of focus are vesicular basalt, bentonite clay, pumice and zeolite.

The application of rock dust to agricultural soils is one recommended mitigation for climate change that captures and stories carbon dioxide (CO_2) from the atmosphere, reduces ocean acidification and increases soil fertility and plant growth (Beerling, Leake, Long, & al, 2018; Goreau, et al., 2011). It involves the application of finely ground, highly reactive silicate rocks to soil (and/or water). The rockdust reacts with water while drawing in CO_2 from the atmosphere into the resultant solution, which will end up as runoff with the captured carbon stored carbonates on the ocean floor (Parlimentary Office of Science and Technology, 2013; Hartmann, et al., 2013; Taylor, et al., 2016). Although the implementation of NETs like enhanced weathering may become vital in tackling climate change, there are challenges including: addressing potential social, environmental and economic side effects; lack of public knowledge and understanding of NETs; financial and carbon costings and efficacy predictions and the lack of an international regulatory framework to oversee operations (Parlimentary Office of Science and Technology, 2013). Another problem is that EW will work better in some regions rather than others. Warm, wet (humid tropic) climates allow for more rapid weathering of rockdust (Edwards, et al., 2016; Hartmann, et al., 2013; Strefler, Amann, Bauer, Kriegler, & Hartman, 2018) and some regions have a suitable and readily available mineral supply while others don't (Hartmann, et al., 2013; Edwards, et al., 2016; Goreau, et al., 2011). Applications of rockdust would have to be catered for individual regions in regard to factors like the climate, weather patterns, soil types and rock supply. Negative impacts of EW include deforestation due to mining, the carbon cost of mining, processing and transporting, the potential inorganic turbidity and sedimentation in waterways of unweathered rockdust and other unknown impacts on biodiversity (Edwards, et al., 2016; Taylor, et al., 2016).

Although a number of studies have investigated the ability of geomaterials to increase the water holding capacity of soil, few in conjunction with the nutrient release in different soil textures. Cousin, et al (2003) highlight the importance of hydraulic properties of the rock fragments in soil which can positively impact the overall the available water holding content (AWC) of the soil. Malekian et al (2012) demonstrated pumice application to soil substantially increased the moisture retention and with increasing application rates, significantly increased the growth characteristics of maize (vegetative growth and yield). The application of bentonite to soil was found by Mi, et al (2017) to increase soil moisture, soil water storage and saturated hydraulic conductivity in the 0-60 cm layer, and increased above-ground biomass, grain yield and water use efficiency in millet crops in a semi-arid region over 5 years. As a soil amendment, bentonite has long lasting effects with increased water content in microplots applied with bentonite that were used in a trial and left abandoned for nearly thirty years (Czaban, Czyz, Siebielec, & Niedzwiecki, 2014). A study by Xiubin &

Zhanbin (2001) found that zeolite application in fine-grained calcareous loess soil could increase water infiltration and soil moisture of 0.4-1.8% in extreme droughts and 5-15% in general condition.

There has been a growing awareness about the benefits of silicon application to plant development. Silicon is the second most abundant element on Earth but is only bio-available to plants once it has reacted with water and forms Monosilicic acid (H_4SiO_4) and this is influenced by factors like soil pH, the amounts of clay, minerals, organic matter and Fe/Al oxides/hydroxides (Tubaña & Heckman, 2015). Silicon is only bioavailable when it reacts with water to form Monosilicic acid (H_4SiO_4) and this is influenced by soil pH, clay percentage, other minerals, organic matter and Fe/Al oxides/hydroxides (Tubaña & Heckman, 2015). Silicon has numerous attributes as an inorganic fertiliser including increasing plants tolerance to numerous biotic and abiotic stresses (Anwaar, et al., 2015; Ahmed, Hassan, & Asif, 2014; Sonobe, et al., 2010; Ma J., 2004). It can provide protection from insect and non-insect pests (Savant, Snyder, & Datnoff, 1997), fungal infections (Menzies, Bowen, & Ehret, 1992), bacterial infections (Chang, Tzeng, & Li, 2002) and reduce nutrient toxicity stress (Anwaar, et al., 2015). As an inorganic fertiliser, silicon releases higher Si:P and Si:N ratios than that of chemical fertilisers and this reduces the possibility of eutrophication in waterways while increasing the amount of diatoms in water that are responsible for removing excess nutrients and provide the food base of aquatic environments (Edwards, et al., 2016). Silicon can reduce water stress in plants by reducing transpiration through the stomata increasing water use efficiency in plants (Gao, Zou, Wang, & Zhang, 2006; Gao, Zou, Wang, & Zhang, 2005) and by forming a silicon-cuticle double layer under the cuticle of leaves (Ma J., 2004). Osmotic adjustment can occur in the root systems, increasing root water uptake and reducing dry weight when silicon is applied on drought stressed sorghum plants (Sonobe, et al., 2010). Silicon can also increase photosynthesis and water-holding capacity of drought-stressed cucumber plants (Ma, Li, Gao, & Xin, 2004), alleviate salt-stress by increasing antioxidant enzymes activity (Zhujun, Wei, Li, Qian, & Yu, 2004; Zhang, et al., 2017; Zhang, et al., 2018) and promote the growth and root yield (Zhujun, Wei, Li, Qian, & Yu, 2004).

3. Aims and Objectives:

The aim of this study is twofold, firstly to investigate the potential for specific types of naturally-occurring rocks and minerals (vesicular basalt, pumice, bentonite, zeolite) to improve soil moisture-holding capacity of common Australian cropping soils. Secondly, to analyse the nutrient release of the geomaterial in leached soil with particular focus on silicon.

4. Materials and Methods:

Materials:
Two samples of soils were collected from cotton farms for other research projects being conducted simultaneously at Griffith University which were shared for the purpose of this study. Both of the cotton farms are located in south-western Queensland, one in the Quilpie region with more sandy based soil and the other in the Mungindi region with more clayish based soil. The geo materials were chosen for their potential to enhance the water holding capacity in soil. The basalt, bentonite and zeolite were sourced within Australia but the pumice was sourced from New Zealand. The vesicular olivine basalt is an igneous rock from the Baramba, a locality of Gympie, Queensland and sourced from Rockhoundz, an online store supplying rocks, minerals, metals and fossils (Rockhoundz, 2019). The specimen was approximately 15 cm long and was put in a large metal tray then covered in a sheet of black plastic and hit with a mallet into it was broken down into smaller fragments of various sizes and dust. A bag of SAN-I-PET ® Clumping Cat Litter, consists of 100% natural bentonite clay and easily accessible from a local Aldi store. As a geomaterial it is often used as a sealant due to its high swelling rate, high surface area and high cation exchange rate. Pumice is a light, porous igneous rock formed during explosive volcanic eruptions. This pumice was sourced from a bag of pumice produced by Auspearl, a commercial pumice supplier in New Zealand and mined from a land resource within 50kms of Lake Taupo in the North Island of New Zealand. This company washes the pumice to remove any salt within it and screens it for separation into different grain sizes. The zeolite was sourced from Castle Mountain Zeolites in Quirindi, New South Wales. There are 42 types of naturally formed zeolites and this zeolite is a natural mixture of 85% clinoptilolite and 15% mordenite (What is Zeolite, 2019). Formed millions of years ago when volcanic ashes fell into semi-saline lakes, this zeolite is a hydrated crystalline aluminosilicate with a high internal surface area loaded with negative charge sites and high ion exchange capacity (What is Zeolite, 2019).

Methods:
Soil with Applied Rock Dust Cooking:
The soil with applied rockdust cooking consisted of Quilpie and Mungindi soils each having a prescribed quantity of rockdust applied to each container. These application rates of each independently applied geomaterial consisted of a Control (0 t/ha), 5 t/ha, 10 t/ha, 20 t/ha, 40 t/ha and 100 t/ha were placed in the oven overnight (generally 21 hours) at field capacity at 30°C, 35°C, 40°C, 45°C, 50°C, 55°C and 60°C on consecutive days. The amount of water loss (%) were calculated on the total amount of water loss including that of the soil, geomaterial and the water added. The R^2 recorded the percentage of variation within the response, ideally a high R^2 means that the data and model fit but even with a high percentage R^2 it is important to check the plots against the model assumptions.
Rate of Water Loss at 45°C
The Rate of Water Loss at 45°C Overnight were tested for the Quilpie and Mungindi soils, each with geomaterials applied at the highest application rate of 100 t/ha. The first sample was placed in the oven at 4pm and the first measurement at 10.20am the following day, then the following three measurements on the hour afterwards (11.20am, 12.20am and 1.20pm).

Follow up experiment: Quilpie Soil with Bentonite at 40°C
A follow up experiment was conducted using Quilpie Soil with Bentonite at 40°C with higher application rates then previous experiments.

Nutrient testing
The samples were saturated with de-ionised water at 150% volume with leached water collected for laboratory analysis for silicon, sodium, magnesium, calcium, phosphorus, potassium, aluminium, nickel, chromium and manganese.

5. Results:

Soil with Applied Rock Dust Cooking
In summary, the results for each of the soils/geomaterials combinations, the application rates (t/ha) were plotted against the water loss (%) see Appendix: The graphs showed small decreases of water loss (%) across the geomaterials at the higher temperatures but overall, little decrease. High R^2 were recorded in the results as plotted in the following figures, the trajectory of the plots was contrary the assumptions of the model that an increased application of geomaterials (depending on specific water holding ability of the geomaterials and the soils) should decrease the amount of water loss in the soils. Such would be displayed as a negatively sloping trendline.

Rate of Water Loss at 45°C
The rate of the water loss for both soils with respective applied geomaterials continued a decreasing linear slope with no treatments showing any signs of plateauing to indicate that water loss had reached an equilibrium. The Rate of Water Loss at 45°C over 8 days was conducted in the same manner but over a period of 8 days. The results were plotted with the trend lines indicating an equilibrium has been reached for water loss of all geomaterials in the Quilpie soil between the measurements on days 6 and 8. For Mungindi soils, the basalt appears to be the closest to plateauing by Day 8 with the possibility of further small amounts of water loss for the other geomaterials.

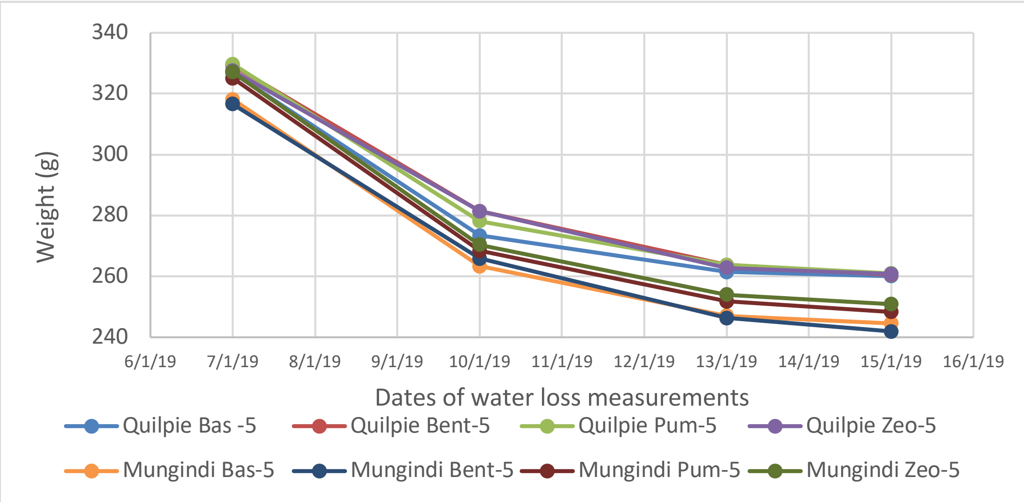

Figure 1 Rate of Water Loss at 45°C over 8 days.

Follow up experiment: Quilpie Soil with Bentonite at 40°C
The result was a strong negative sloping trendline showing a distinct decrease in water loss as confirmed with R^2 = 0.9778. This indicates that at 40°C with an increasing rate of application, Bentonite is successful at retaining water within the soil – up to 30% at the highest application rate.

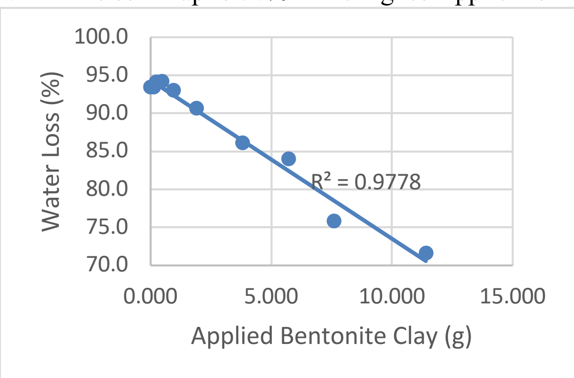

Figure 2 Follow up experiment at 40°C using 20g of Quilpie soil with higher application rates of Bentonite Clay.

Nutrient testing
Results clearly indicated that with the addition of geomaterials to the Quilpie soil, nutrients were readily released into the soil water with Zeolite releasing the highest amounts of silicon. However, the opposite trend occurred with Mungindi soil which nutrient release appeared to be not only blocked the nutrients but seemingly sorbed them out of the potential release into the soil water.

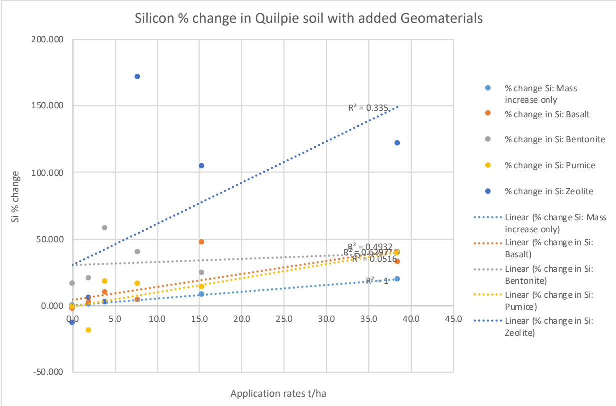

Figure 3 Silicon % change in Quilpie soil with added Geomaterials

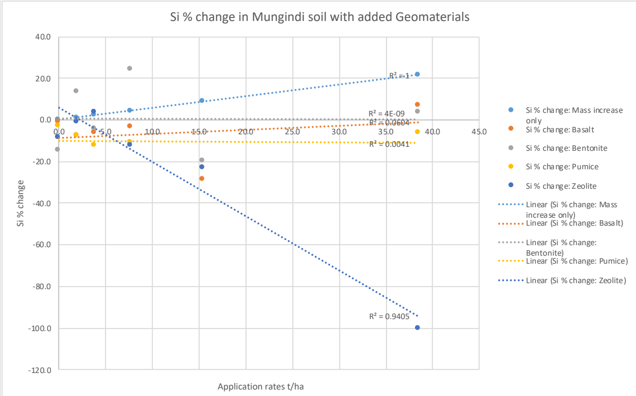

Figure 4 Silicon % change on Mungindi soil with added Geomaterials.

6. Discussion and Conclusions:

The overriding goal of this study was to determine if the application of silicate rocks and minerals like basalt, bentonite, pumice and/or zeolite would increase the water holding capacity of two common Australian cropping soils. This was investigated using agricultural soil from south western Queensland and running basic soil tests, moisture factor and percentage tests then testing the water loss (%) via rockdust/soil cooking at various temperatures and prescribed application rates. Basic soil tests reveal that Quilpie soil has a lower Ratio of Water/Soil content (1.36) and Field Capacity (36.5 %) and a higher amount of Dry Soil (96.3 %) than the Mungindi indicating it has a sandier composition and is more likely to be susceptible to the influence of geomaterials with higher water factors and so should increase its water holding capacity. The water factor of the Bentonite and Zeolite was more than that of Quilpie and Mungindi soils. Hypothetically, this indicates that the Bentonite and Zeolite have greater potential to retain water in their structures in comparison to these soils. This means that it is possible with the application of these geomaterials, the water holding capacity of both soils should increase yet most clearly so with the Quilpie due to its lower moisture factor. However, in the rockdust/soil cooking, the results were inconsistent and do not support this hypothesis. The figures showed no clear decrease of water loss (%) across the application rates of any of the geomaterials at higher temperatures.

Of notice, at every weigh in at each temperature for all rockdust/soil combinations, the weights of the containers were continually decreasing on the scales. Possible reasons for this could be the air-conditioning of the lab evaporating the samples, though this is unlikely as the lids were removed only for the briefest period of time for weighing. If the containers were left sitting on the bench with no lids on for the total period of weighing all containers, which could take on average nearly two hours, then this might be a factor to consider. However, that is not the case there. Another reason could be that moisture, which was visible on the inside of the containers, particularly at higher temperatures which begs the question, have the samples been kept in the oven for long enough? This question was the basis for two further experiments measuring the Water Loss at 45°C overnight and over the period of eight days. Which did in fact conclude that overnight time in the oven was insufficient time for an equilibrium to be reached for water loss. Another interesting observation that may have influenced results is the cracking of surface soils with applied Bentonite at higher temperatures. Although hypothetically the Bentonite has the greater potential to decrease water loss due to its high swelling ability, high surface area, high cation exchange rate and a high Water Ratio, the cracking of surface soils could be counter-productive with heat able to enter and dry the soil from the inside out. It was theorised that with a different application method, surface cracking could be minimised, and water retained in the subsurface, but the question would be if it is a viable and practical method for farmers to adapt? However, this is a possible factor to consider in future testing and leads to further discussion as to what sort of equipment are farmers and land managers using and what would they be open to using if they were to apply rockdust as a fertiliser and/or water retaining material? How can rockdust be applied in a way that is financially acceptable, environmentally and carbon cost friendly and minimises land degradation? (Strefler, Amann, Bauer, Kriegler, & Hartman, 2018) On reflection of the potential difficulties with bentonite, zeolite with its high water factor and potential for water holding capacity might a more promising mineral to apply. It is a hard mineral and not prone to cracking soils like bentonite does. The different grain sizes, application rates and methods of zeolite should be considered for further research as it has already been shown to enhance water retention in soils under drought conditions (Xiubin, 2001)

Figure 4 Example of moisture retention on internal surface of all treatments.

Figure 3 Cracked surface of Quilpie/Bentonite treatment.

Due to the inconsistent results in the Rockdust/soil cooking due to possible lack of time in the oven, further studies were done with Water Loss at 40°C for both soils at 100 t/ha for each geomaterial. This was firstly tested over a period of one day with multiple weigh-ins, each an hour apart. Once the data was formatted into a graph, a levelling out in the trendline would indicate that an equilibrium has been reached between the pull of the surface charges of the rockdust/geo materials and the energy of the temperature. However, the trendline did not levelled out indicating a continual loss of water, concluding that an equilibrium had not been attained between the surface attraction of the geomaterials to the water and the heat of the oven. Overnight was therefore not long enough, the experiment was repeated over eight days. This time there was a clear levelling out of the trendline with equilibrium reached for both soils between days 6 and 8 as seen in Figure 1. This confirms this concept that the rockdust/soil cooking was not conducted over a long enough period of time to get clear results and should be repeated with oven time of at least eight days. Another method which could also attain results, is under air drying conditions in an enclosed glasshouse during summer. Both of these options would also be more reflective of drought conditions. To check that the theory that geomaterials can decrease water loss in soils, a follow up experiment was conducted using higher rates of Bentonite on the Quilpie soil at 40°C which were applied under the surface. As seen in Figure 2 there is a distinct decrease of water loss in relation to the increased application of Bentonite. Further experimentation of a wider range of application rates and methods is recommended. The area size of the containers might also need revising in further studies, 100ml plastic containers were used with a diameter of 7cm and soil added to a height of approximately 5cm. Larger area size of the containers (or pots) or experimentation on a larger scale using an urban plot or farmers properties would be more reflective of the area size for practical rockdust application which should accelerate the natural rates of EW (Hartmann, et al., 2013).

Regarding silicon availability, easily released cations in silicon can react with water to provide bio-available, plant beneficial silicic acid. Follow up nutrient retention testing determined the amount of silicon and other nutrients that became available in leached soil water. It is possible that some geomaterials are more reactive with water than others and would therefore release more nutrients. In the Quilpie soil, all the geomaterials released silicon into the soil water, with Zeolite releasing a much higher amount in comparison to the others. However, it was very interesting to note for the Mungindi soil, that not only did all of the geomaterials not release silicon into the soil water, all the results were lower that the baseline indicating that the nutrients were actually not only blocked from release but possibly sorbed into either the soil or geomaterial. The silicon percentage change from zeolite in Mungindi soil was by far the most negative which may be attributed to the high clay content of the soil reacting with the chemical structure of the zeolite and is recommended for further research. As the application to zeolite (and other geomaterials) to certain soil types but be costly and counter-productive. This opens questions about other possible factors that can increase the reactions. Biological factors including micro-organisms, fungi and bacteria may influence nutrient release into soil water and environmental factors like solar radiation, wind flow and humidity (or lack of).

The mineral composition would also differ within a geomaterial type depending on its source and so would offer different degrees of suitability. For this reason, mineralogy reporting may also be of comparable notice when choosing between sources as such would result in different qualities minerals. Different particle sizes and weathering rates of geomaterials are crucial parameters (Strefler, Amann, Bauer, Kriegler, & Hartman, 2018) may influence water holding capacity as smaller particles sizes are indictive of larger surface area. This needs to be considered and experimented with from a practical view as smaller dust size particles are more likely to be subjective to wind and water erosion particularly on unstable soil or regions with volatile weather patterns. There is further research needed to optimise the use of various rockdust with plant species, soil types, climate regimes and management practices (Goreau, et al., 2011). The influence of organic matter on testing also needs to be accounted as it can interact with the elements and alter results and as Goreau et al (2011) found that the addition of biochar can greatly enhance the effects of basalt as a rockdust.

By applying minerals to soils, it increases their health and fertility, leading to increased crop health that in turn contributes to global food security all while sequestrating carbon dioxide and reducing ocean acidification and the use of pesticides, fungicides and fertilisers. With droughts increasing in severity and longevity and its disastrous effects on the ecosystem, the application of rockdust also has potential to increase the water holding capacity of soils, which could alleviate drought stress on cropping plants. However, would farmers and land managers embrace such novel new methods of agriculture and land management? Currently the use of rockdust is not a mainstream and accepted method of land management and would require education for farmers and land managers to adopt a new way of managing the land. The cost of water and carbon from a financial and ecological viewpoint would need to be calculated and possibly government incentives offered to help with the transition for practicalities like the adaption of equipment to meet the requirements of applying the rockdust to the land. However, these financial costs will need to be put into the context of the financial, human and ecological costs of doing nothing to mitigate climate change and increasing drought resilience and health in soil.

7. Highlights:

- Observed increase of water retention using geomaterials with key factors being time and application rate.
- Observed release of free silicon from geomaterials into soil water but key factor being soil texture.

8. Future Research:

Further research still required and questions to answer: Would we run out of suitable rock and would there be enough rock to last without having detrimental effects on the ecosystem? As a fertiliser, over what period of time does it release nutrients, it is a process that can be sped up or increase in longevity and does this affect the amount of time that it can have maximum water holding capacity? If it is a slow releasing material, is there a way to supercharge the rockdust to maximise its water holding capacity and nutrient release? What role does soil texture have on the chemical structure of the geomaterial, in particular the zeolite and how does this affect water holding capacity and nutrient release? The investigation in geomaterials has potential to factor in other elements like the effects of microbial activity, different mineral combinations and organic matter to 'supercharge' rockdust. It is recommended that further studies factor in the different soil textures, climatic conditions, practicalities, potential downfalls like increased turbidity in waterways as well as plant specific requirements.

9. Presentations and Public Relations:

Presentation at Griffith University as part of course assessment.

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11. Appendix:

Graphs for Water Loss (%) for Quilpie and Mungindi soils with Basalt, Bentonite, Pumice and Zeolite.