

A NEW ZEALAND AGRICULTURAL GHG INVENTORY METHODOLOGY FOR ENHANCED ROCK WEATHERING

Almond, P.¹ Heubeck, S.² and Eger, A.³

¹*Lincoln University Soil & Physical Sciences, Burns Building, PO Box 85084, Lincoln 7647*

²*BPO Environmental Consulting, 89 Colombo Street, PO Box 5067, Hamilton 3204*

³*Manaaki Whenua - Landcare Research Lincoln, PO Box 69040, Lincoln 7640*

Abstract:

Recent IPCC reports have suggested that meeting the Paris goals (<1.5/2.0°C warming) will most likely require a certain amount of active withdrawal of previously emitted GHG from the atmosphere through negative emission technologies. Similarly in New Zealand, the goals aspired to by the Climate Change Response (Carbon Zero) Amendment Act 2019 for 2050 will require GHG sequestration to off-set residual gross GHG emission.

Enhanced rock weathering (ERW) of silicate rock has previously been projected as a technique with the theoretical potential to sequester a large fraction of GHG emitted from anthropogenic sources. At the most basic level, ERW is a dramatic acceleration of the natural rock weathering cycle, using quarry technology and productive agricultural soils to liberate silicate bound cations from rocks, such as basalt, to absorb atmospheric CO₂, and permanently sequestering it as bicarbonate in the hydrosphere. At the applied level, ERW in New Zealand could be established as an alternative liming technique, where processed silicate rocks, rather than limestone, are land applied for liming, fertilization and GHG sequestration in an agricultural context.

We report key outcomes of a recently completed study, funded through the MPI Greenhouse Gas Inventory Research Fund, which reviewed fundamental mechanisms of ERW and experimental evidence of the efficacy of the technology as a negative emissions technology, spatially analysed the availability of suitable rock resources in NZ, identified knowledge gaps and future research needs around the technique, and proposed an initial draft NZ agricultural GHG inventory methodology for ERW on agricultural land.

While some detailed technology, agronomy and economic questions remain unanswered, the study highlights the basic working principles and applicability of ERW as a GHG emission management tool for NZ in the agricultural sector. Suitable rock materials for ERW are available in most key agricultural regions in NZ. The preliminary inclusion of a basic inventory methodology for ERW into the agricultural NZ GHG emission inventory therefore appears warranted. Short-term ERW has the potential to minimize NZ GHG emissions by ~1.6 million tCO₂/year, with the longer-term potential being as high as a 10% reduction of total agricultural GHG emissions.

Introduction:

Recent assessment reports and special reports by the IPCC have suggested that limiting global warming to either 1.5°C or 2.0°C above pre-industrial levels by the middle of this century (Paris goals) will most likely require carbon capture and storage of CO₂ from the atmosphere (IPCC 2023). Estimates range from 0 to 1,218 Gt CO₂ out to 2100, depending on the aggressiveness of GHG emissions reductions and the level of overshoot of 1.5 °C of warming (Masson-Delmotte et al., 2018). Aotearoa/New Zealand (AoNZ) has goals for climate change mitigation including the Climate Change Response (Carbon Zero) Amendment Act 2019 and the GHG reduction path to net zero emissions by 2050 outlined by the Climate Change Commission and agreed to by Cabinet. These goals, which require a 38% and 63% reduction of long-lived gases (net based on 2019) by 2030 and 2035, respectively, will require GHG sequestration to off-set residual gross emission.

Among a list of other negative emission technologies discussed within expert circles, is the technology of enhanced rock weathering (ERW) of silicate rock. Over the last decade, overseas studies have projected that ERW has the theoretical potential to sequester and off-set a large fraction of the GHG emitted from anthropogenic sources throughout this century. When silicate rocks and their minerals weather, cations released by chemical weathering processes combine with bicarbonate ions formed by dissolution of CO₂ in soil solution. Cation and bicarbonate ion pairs leached to the oceans eventually combine to form dissolved inorganic carbonate or, in suitable ocean conditions, biogenic CaCO₃. The latter eventually contributes to sediment that may produce carbonate rocks such as limestone. This process underpins the largest carbon (C) pool on the planet (the ocean C stock – 38,000 Pg C, Renforth & Henderson, 2017) and is a crucial component of how climate on Earth has been regulated over geological timescales. For comparison, the land carbon stock is only around 4,500 Pg C, including soils, vegetation, wetlands and permafrost (Ciais et al., 2013). Purposefully using this natural process and enhancing bicarbonate and cation fluxes to the ocean by widely amending agricultural soils with reactive silicate minerals has the potential to become a viable negative emission technology. However, as with any modification of our environment, the beneficial effects for our climate and the environment need to be weighed against the potential downsides. In addition, national and international frameworks need to be established that regulate ERW application and set inventory methodologies for ERW within national GHG accounting.

The Ministry for Primary Industries (MPI), through funding from the Greenhouse Gas Inventory Research Fund (Grant 406939), has supported us to compile a first assessment of the applicability of ERW within the context of AoNZ. The specific objectives of this project were to:

- Review and present the fundamental mechanisms underlying the application of ERW as negative emissions technology.
- Review and present experimental evidence of the efficacy of the technology for carbon dioxide sequestration.
- Conduct spatial, national-scale analysis of the available rock resources for ERW using existing geoscientific data sets.
- Define a draft ERW methodology for the Greenhouse Gas Inventory and discuss uncertainties and future research needs that specifically pertain to the methodology.
- Identify knowledge gaps and future research needs that arise if ERW is adopted more widely as negative emissions technology specifically in the agricultural sector (environmental/cultural/economic/social/legal).

Methods

The starting point for the project was a systematic literature review of silicate weathering in general, and its application as ERW specifically, involving review of 186 articles or reports, including various IPCC reports, assessments and data bases.

The key parameters for a draft New Zealand GHG inventory methodology for ERW were derived from evaluated published research articles, complemented with data from various chemical, geochemical and freshwater data bases, national production statistics and geochemical and freshwater models, and follows the fundamental format and layout recommended for all GHG inventory methodologies by the IPCC 2006 GHG Inventory guidelines (Eggleston et al. 2006). The assessment of New Zealand's total and available rock resources for ERW was based on the GNS data bases QMAP and PetLab, while the statistical package 'R' was used for the geospatial and geostatistical resource analysis. Additionally, the programme PHREEQC was used for the aqueous geochemical calculations of chemical speciation and saturation indices.

The gaps analysis addressed key open questions raised in the cited literature and was complemented with the authors experience in the fields of agronomy, geology and environmental technology.

Results and conclusions

- Silicate weathering by carbonic acid is a key component of the long-term global carbon cycle, namely the removal of CO₂ from the atmosphere (CDR) and long-term storage of carbon in inorganic form as solute or solid. Its natural rate depends on a range of environmental factors and feedbacks (e.g., climate, geomorphic processes). Through purposefully increasing the rate of this process at large scale, silicate weathering has been suggested as a negative emission technology to reduce anthropogenic CO₂ in the atmosphere at relevant timescales.
- The theoretical effectiveness of CDR by ERW is initially dictated by the quantity of major cations (Ca, Mg, K, Na) in silicate minerals, which differs across rock types. This is quantified by the RCO₂ (Rock Carbonation Potential) value which accounts for rock cation concentration and speciation of dissolved inorganic C (DIC) produced by silicate weathering in receiving waters (assumed often to be the ocean). Further constraints on the CDR efficiency are imposed by the reaction affinity and rate of different silicate minerals with carbonic acid (kinetics, thermodynamics). The latter are affected by mineral surface area, mineral type, climate and other environmental conditions, the fraction of silicate weathering by reactions other than those involving carbonic acid, and removal of weathering products in the soil solution (Renforth 2012, Lewis et al. 2021).
- Results from micro-/mesocosm (~1 m²-scale lysimeter and smaller) and field studies are currently limited, but the number is growing rapidly. Existing studies differ widely in their methodologies, and the measured or modelled CDR efficiencies. At present the longest-term experiment spans 15 years but it is an outlier; most are five years or less and the micro/mesocosm studies usually in the order of months. Reliably estimated efficiencies (relative to RCO₂) range from 0.01 to 35% for micro/mesocosm studies (i.e., 3 orders of magnitude), and from 0.15 to 82% for field and catchment studies. Field studies suggest CO₂ sequestration of 0.4-8.6 t ha⁻¹ are possible with application rates of 50 – 200 t ha⁻¹ with rock amendments with RCO₂ values ranging 0.21 – 0.64.

- Theoretically, rock resources suitable for ERW occur throughout AoNZ; only Hawkes Bay and the Lower North Island lack large suitable deposits. After imposing additional constraints on this selection (land use, protection status) the by-area largest ERW rock resources in AoNZ are basalt or andesite-type rocks, occupying ~3700 km² with an average RCO₂ of 0.26, and ~1600 km² with an average RCO₂ of 0.13, respectively. Our data indicate that the supply of rock amendments for ERW in AoNZ would be likely met by a multitude of smaller rock deposits instead of coming from few and large sourcing operations.
- The draft ERW inventory methodology we propose is based on the stoichiometric Mg, Ca, Na and K cation content of the applied rock material, as represented by the RCO₂ value, which quantifies potential CDR over long timescales under idealised weathering conditions. The RCO₂ value is then corrected for:
 - A kinetic effect, modulated by environmental factors and ERW amendment properties (e.g. grain size, specific surface area), relevant to a nominated inventory timescale (we recommend 30 years) - correcting for incomplete weathering over relevant time scales.
 - A cation retention effect, which adjusts for cations released by weathering but not leached to ground or surface waters and eventually to the ocean.
 - An alternate acid effect, which adjusts for non-carbonic acid weathering of silicate minerals.
- A variety of gaps exist in our knowledge of ERW with respect to CDR efficiency and the extent of positive and negative side effects. These include the fate of the weathering products within the relevant timescales, particularly that of the cations; effects on biological, chemical and physical soil quality (e.g., potential to reduce soil acidity, potential sources of contamination, potentially improving mineral soil fertility and modifying the nitrogen, and phosphorus nutrient cycles, modifying soil organic matter cycling, modifying hydraulic soil properties, and soil biological communities); effects on other parts of the environment like water quality (e.g., increase of solute load and pH, effects on nutrient availability in aquatic habitats) and air quality; perception and reception of ERW by the public considering the bicultural context of AoNZ and logistical, economical, legal considerations.
- While the fundamentals of silicate weathering and associated CDR are sound (Renforth 2012, Lewis et al. 2021), the many uncertainties about the efficacy of ERW in different environments and its side-effects remain a key barrier to its adoption. Scientific enquiry must take place in parallel with efforts to establish the legal and administrative mechanisms by which any CDR can be quantified, implemented and regulated.
- New data sets that we generated by synthesising existing data are:
 - 1) Resource maps of rock types in AoNZ that have high suitability for CO₂ sequestration by ERW based on their concentrations of Ca, Mg, K and Na in silicate minerals (mafic and intermediate lithologies, expressed as RCO₂); the maps also consider some limitations in the availability of these resources for application in ERW (land use/protection status, transport distances).
 - 2) Speciation data and saturation indices with a focus on Ca and Mg cations, including susceptibility for calcite and dolomite precipitation, for various rivers of AoNZ.

Recommendations

We propose that New Zealand could adopt an Enhanced Rock Weathering GHG inventory methodology as a sister methodology to that for agricultural liming emissions (CRF 3.G), within the Agriculture, Forestry and Other Land Use (AFOLU) category, subcategory Agriculture (MfE 2023).

A recommendation is made for an inventory methodology, following the general format recommended in the 2006 IPCC Guidelines (Eggleston et al. 2006), as:

$$CDR_{ERW} = M_{ERW\text{silicate rock}} \times ERW_{CO_2,30}$$

where:

CDR_{ERW} = annual removal of CO₂ by ERW, tonnes C y⁻¹

$M_{ERW\text{silicate rock}}$ = annual amount of silicate rock applied for ERW, tonnes y⁻¹

and:

$$ERW_{CO_2,30} = \underbrace{AA_{corr,30}}_{\text{alternate acid effect}} \times \underbrace{(1 - C_{ret,30})}_{\text{cation retention effect}} \times \underbrace{E_{w,30}}_{\text{time limitation on weathering effect}} \times R_{CO_2}$$

with:

$ERW_{CO_2,30}$ = total (negative) CO₂ emissions from ERW rock material application (sequestration) accumulated over 30 years in t CO₂ per t of silicate rock material.

$AA_{corr,30}$ = alternate acid correction factor.

$C_{ret,30}$ = retention of alkali metal cations in terrestrial pools over a 30-year time period thereby preventing them from being leached to the ocean.

$E_{w,30}$ = weathering kinetic limitation factor, which involves rock reactivity, climatic, management and grain size (surface area) effects.

R_{CO_2} = theoretically possible CO₂ draw-down from silicate rock weathering, based on total weatherable alkali metal cation content.

Several default factors for silicate (basaltic) ERW material cation content (R_{CO_2}), weathering kinetic limitation factor, cation retention factor and alternative acid correction factor were discussed and justified. Based on these default factors a simplified initial GHG inventory methodology equation for NZ could be derived, as:

$$CDR_{ERW} = M_{ERW\text{silicate rock}} \times R_{CO_2} \times 0.61$$

with:

CDR_{ERW} = the total (annual) amount of negative emissions for AoNZ from ERW activity,

$M_{ERW\text{silicate rock}}$ \equiv activity data = total amount of ERW rock material applied to agricultural land in AoNZ during the reference time period (reporting year).

RCO_2 = theoretically possible CO_2 draw-down from silicate rock weathering, based on total weatherable alkali metal cation content.

If a similar rock type were used across AoNZ, this could be simplified further by using the rock type's RCO_2 value, otherwise total AoNZ CDR by ERW would have to be aggregated over regions using homogeneous rock type.

Recommendations to address current uncertainties and knowledge gaps can be summarised as follows:

- 1) Support for targeted scientific studies preferably at field/catchment scale to better constrain parameters of CDR and the side-effects of ERW within the specific environmental variability of AoNZ. Those studies should include measurement of leached cations and anions to avoid the necessity for assumptions of cation fate when only soil properties are measured.
- 2) Support research on social and cultural acceptance, economic and logistical, and legal consideration of ERW in AoNZ.
- 3) Evaluate undesired effects of ERW against the consequences of a further deteriorating climate situation due to lack of mitigation of greenhouse gas emissions. We recommend also considering mitigation efforts that are in place to minimise currently existing negative side-effects of agricultural production, like eutrophication, erosion, and heavy metal contamination, as precedent. Most negative side-effects of ERW application are similar to existing challenges in sustainable agricultural management.
- 4) Given increasing discussion of ERW, including in recent IPCC reports, communicate with the functional equivalents of the MPI GHG inventory team in other countries about ERW to get a better understanding of their national perspectives on the role of ERW within a greenhouse gas inventory framework.

Outlook

Overall, it is concluded that ERW holds great potential as a fundamentally practical and technologically feasible options for the New Zealand agricultural sector to reduce net emissions of long-lived Greenhouse Gases. The technique appears applicable to current NZ agricultural production system, utilizing only currently existing technologies and practices. Furthermore, AoNZ has sufficiently large ERW rock deposits of adequate quality, strategically located in close proximity to most key agricultural regions, to support the broad uptake of ERW as a negative agricultural GHG emission technique.

Short-term, ERW rock application to AoNZ farmland has the potential to replace currently applied amounts of agricultural lime as a soil pH neutralisation agent, thereby substituting current liming GHG emissions of 0.5 million tCO_2 /year, and simultaneously sequestering CO_2 via silicate weathering CO_2 draw-down, for a combined GHG emission reduction of ~ 1.6 million tCO_2 /year, equivalent to $\sim 4\%$ of current AoNZ agricultural GHG emissions (MfE 2023). With adequate support mechanisms the scope for ERW in New Zealand may eventually be expanded, potentially as far as up to a 10% reduction of total agricultural GHG emissions.

References

- Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., et al. (2013). Carbon and Other Biogeochemical Cycles. In S. T.F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*: Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., & Tanabe, K. (Eds.). (2006). *2006 IPCC guidelines for national greenhouse gas inventories (Vol. 4)*. Japan: IGES.
- IPCC. (2023). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva: IPCC.
- Lewis, A. L., Sarkar, B., Wade, P., Kemp, S. J., Hodson, M. E., Taylor, L. L., et al. (2021). Effects of mineralogy, chemistry and physical properties of basalts on carbon capture potential and plant-nutrient element release via enhanced weathering. *Applied Geochemistry*, 132, 105023.
- Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., et al. (2018). Summary for Policymakers. In *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (pp. 3-24)*: Cambridge University Press, Cambridge, UK and New York, NY, USA.
- Ministry for the Environment. (2023). *New Zealand's Greenhouse Gas Inventory 1990–2021*. Wellington: (MfE) Ministry for the Environment.
- Renforth, P. (2012). The potential of enhanced weathering in the UK. *International Journal of Greenhouse Gas Control*, 10, 229-243.
- Renforth, P., & Henderson, G. (2017). Assessing ocean alkalinity for carbon sequestration. *Reviews of Geophysics*, 55(3), 636-674.