Enhanced Rock Weathering in Acid Mine Drainage and Sandy Soil Systems: Assessments of CO_2 Removal Potential and Co-benefits

(酸性鉱山廃水および砂質土壌における岩石風化促進: CO_2 除去ポテンシャルとコベフィットの 評価)

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SUMMARY

Enhanced Rock Weathering (ERW) has emerged as a promising negative emissions technology capable of both capturing atmospheric CO_2 and delivering valuable environmental co-benefits. This dissertation extends ERW research beyond the traditional focus on croplands by systematically exploring its mechanistic, modelled, and field-based performance in two geochemically distinct and underutilized environments: acid mine drainage (AMD) channels and degraded sandy soils. Both settings present unique challenges and opportunities—AMD systems offer highly acidic, mineral-reactive waters ideal for rapid dissolution, while sandy soils provide a medium for nutrient replenishment and long-term carbon stabilization in agriculturally marginal lands.

The research framework integrates geochemical modelling, laboratory dissolution studies, and real-world field trials, underpinned by rigorous thermodynamic calibration and mineralogical characterization. Using one-dimensional reactive transport modelling (1-D RTM), the study quantifies mineral dissolution rates and CO_2 sequestration potentials under site-specific conditions. Modelling results reveal that in AMD channels with pH 2–4 and adequate flow rates, fine basalt particles (10 µm) can achieve sequestration rates up to 3,660 tCO_2 per year per channel—among the highest recorded in ERW scenarios. Sandy soil models predict more modest but still meaningful CDR rates (~8 tCO_2 ha^{-1} yr^{-1}), with co-benefits maximized under slightly acidic pH and optimal porosity ranges.

Field trials bridge the gap between theoretical prediction and operational feasibility. In AMD channels at an abandoned mine in Hakodate, Japan, crushed basalt ($D_{50} \approx 1.5$ mm) achieved 40–80% dissolution over 358 days, with water pH increases of 0.5–1.7 units and arsenic removal efficiencies of 25–30%. The absence of passivation layers, aided by textural detachment and schwertmannite precipitation, suggests sustained dissolution capacity in acidic waters. In the sandy soils of Central Myanmar, basalt application raised soil pH by ~1.5–2 units,

increased calcium and magnesium availability, and improved cation exchange capacity—enhancing fertility and supporting long-term carbon storage through bicarbonate retention and potential secondary carbonate precipitation.

Synthesis of results underscores that ERW performance is strongly context-dependent, governed by environmental controls such as pH, mineralogy, hydrological conditions, and particle size. Technical limitations—such as risks of over-application, influence of vegetation, and scaling logistics—are critically assessed. Importantly, the research assesses the readiness of Monitoring, Reporting, and Verification (MRV) frameworks for sandy soil ERW and outlines an imminent path toward MRV readiness for AMD applications, enabling integration into carbon credit schemes in near future.

Subsequently, the study also clarifies the near-term deployment pathways for ERW in both environments. For AMD systems, the transition toward full MRV readiness appears imminent, aided by the inherent monitoring advantages of river-based systems. For sandy soils, immediate scalability is supported by the maturity of MRV protocols for soil-based applications. Strategically, this research expands ERW beyond cropland to address two contrasting but complementary contexts—achieving both carbon sequestration and contaminant remediation in AMD, and land rehabilitation with enhanced agricultural productivity in sandy soils. The close alignment between 1-D RTM simulations and field results validates the predictive framework and highlights the importance of tailoring ERW design to local geochemical and physical conditions. Demonstrating sustained basalt dissolution, long-term CO_2 uptake, and passive contaminant removal in AMD further supports its integration into mine remediation programs, while the sandy soil results strengthen its role in sustainable agriculture. Collectively, these insights establish technical foundations, policy relevance, and practical guidelines for scaling ERW as a combined climate mitigation and environmental restoration strategy.

This work contributes novel scientific insights by demonstrating that ERW can be effectively adapted to non-traditional systems, achieving substantial CDR potential in AMD channels and significant agricultural co-benefits in sandy soils. It also offers a validated methodological blueprint—combining predictive modelling, empirical validation, and MRV compatibility—that supports scalable deployment. Policy implications are equally significant, as diversified ERW applications open new opportunities for climate finance and ecosystem rehabilitation, particularly in post-mining landscapes and nutrient-poor agricultural zones.

By uniting mechanistic understanding, quantitative modelling, and field-based evidence, this dissertation moves ERW from conceptual potential toward operational reality in geochemically diverse settings. It establishes a foundation for future upscaling efforts and positions ERW as both a climate mitigation tool and a vehicle for sustainable land and water management on a global scale.

The key highlights of findings from this dissertation are as follows:

- Pioneered ERW application in Acid Mine Drainage (AMD) and sandy soil systems
- Combined validated modelling with real-site experiments
- Demonstrated large-scale Carbon Dioxide Removal (CDR) potential
- Key findings:
  – Textural detachment in AMD–ERW
  – Nutrient enhancement in sandy soils-ERW
- Identified environmental controls (pH) & technical limits (overdose, plant influence)
- Policy impact: New opportunities for carbon credit markets
- Achieved all objectives: CDR potential, geochemical insights, co-benefits
- MRV ready for sandy soils; AMD MRV in near future
- Takeaway: ERW can be effectively extended to AMD and sandy soil systems