

# Feasibility study of enhanced mineralization based on LCA/TEA platform



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University of Tsukuba  
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# Outline and Target

## Moonshot Goal 4 : Toward Carbon Neutral by 2050

Development of **LCA/TEA platform** to optimize the total system of **enhanced mineralization**: EM (Capture atmospheric CO<sub>2</sub> by enhanced mineralization of mafic rocks, etc., and accelerate the plant growth by soil application).

### Current recommendation of enhanced mineralization

- Accurate CO<sub>2</sub> reductions cannot be accounted, and effects are unknown.
- No empirical data on utilization of mafic, basaltic rocks or carbonate.
- Slow reaction, economically disadvantageous(≒\$218/t-CO<sub>2</sub> by Fuss, 2018).

### Outline of the project

- **Accurate accounting** of CO<sub>2</sub> reduction.
- Clarify the **optimal soil application method** of mafic rocks for plant growth.
- Development of **cost reducing technologies**.
- Development of **LCA/TEA platform**.



Mafic rocks

Worldwide abundant

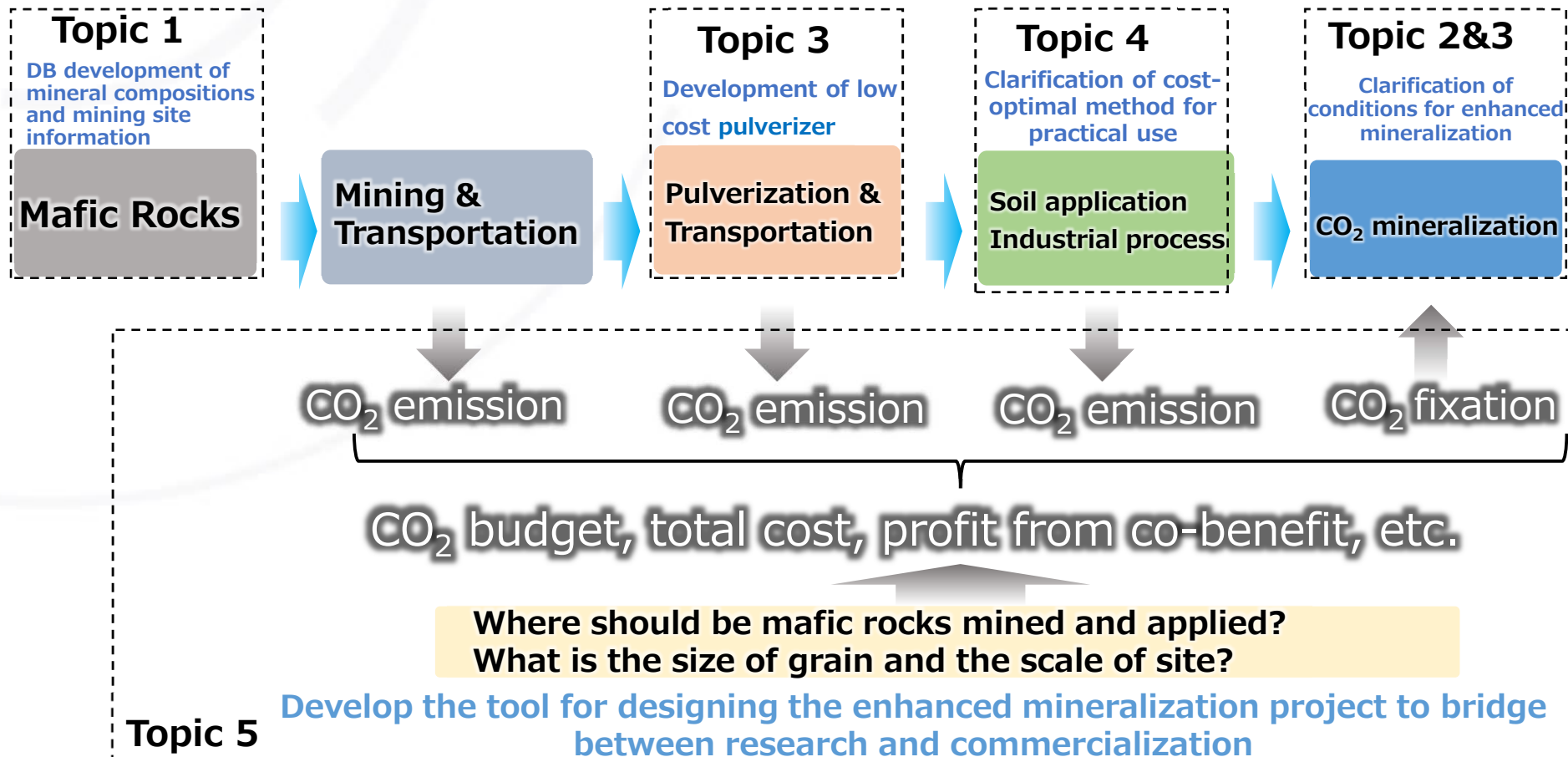


Accelerate plant growth

# Process and R&D of Enhanced Mineralization

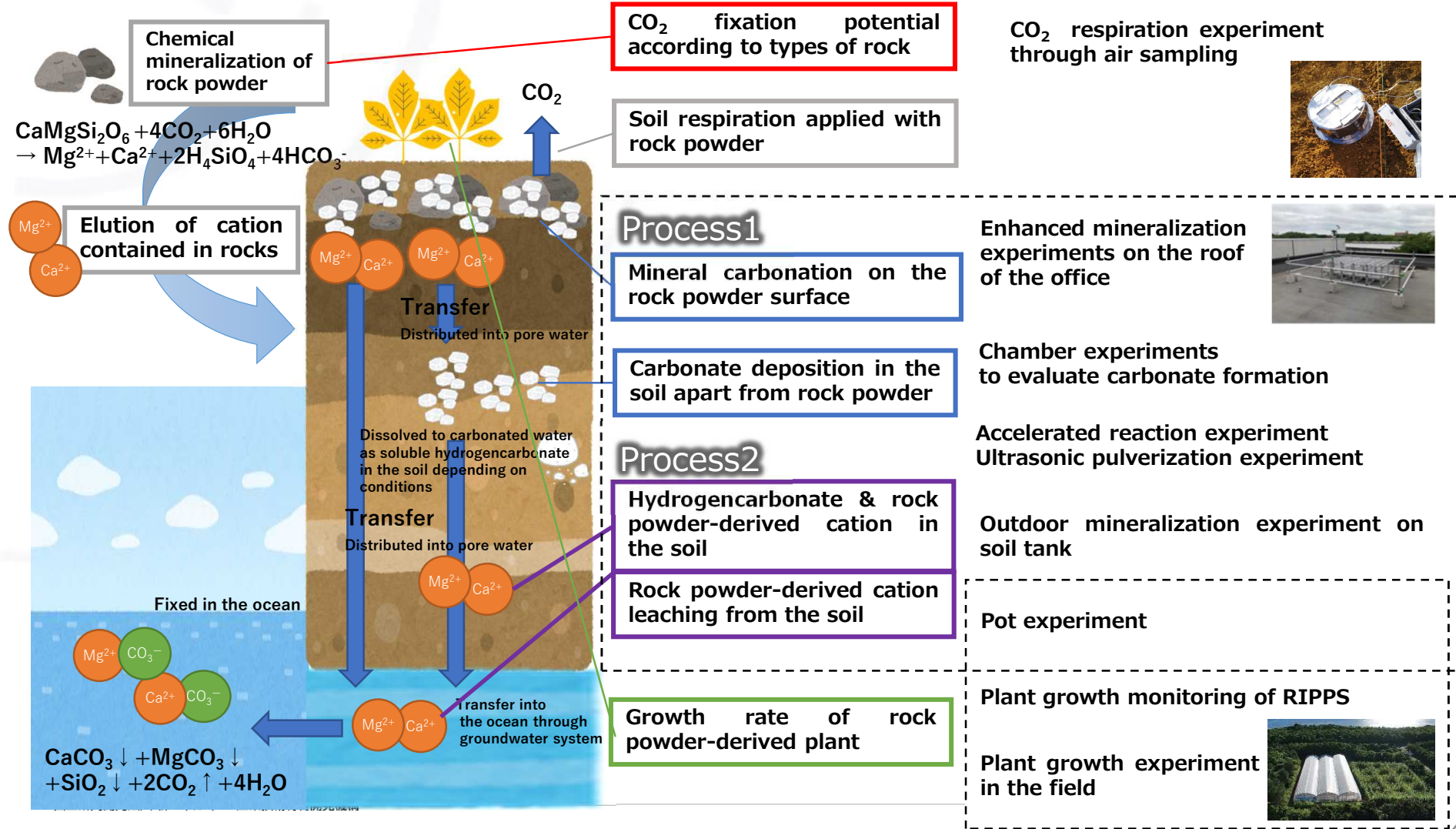
Commercializing the technology of Enhanced Mineralization needs:

- ① Accurate accounting of fixed CO<sub>2</sub> amount through enhanced mineralization.
- ② Development of cost-reducing technologies.
- ③ Development of tools for designing the commercialization.



# Accurate Accounting through Various Types of Experiments

## Obtain parameter for tools through various types of experiments

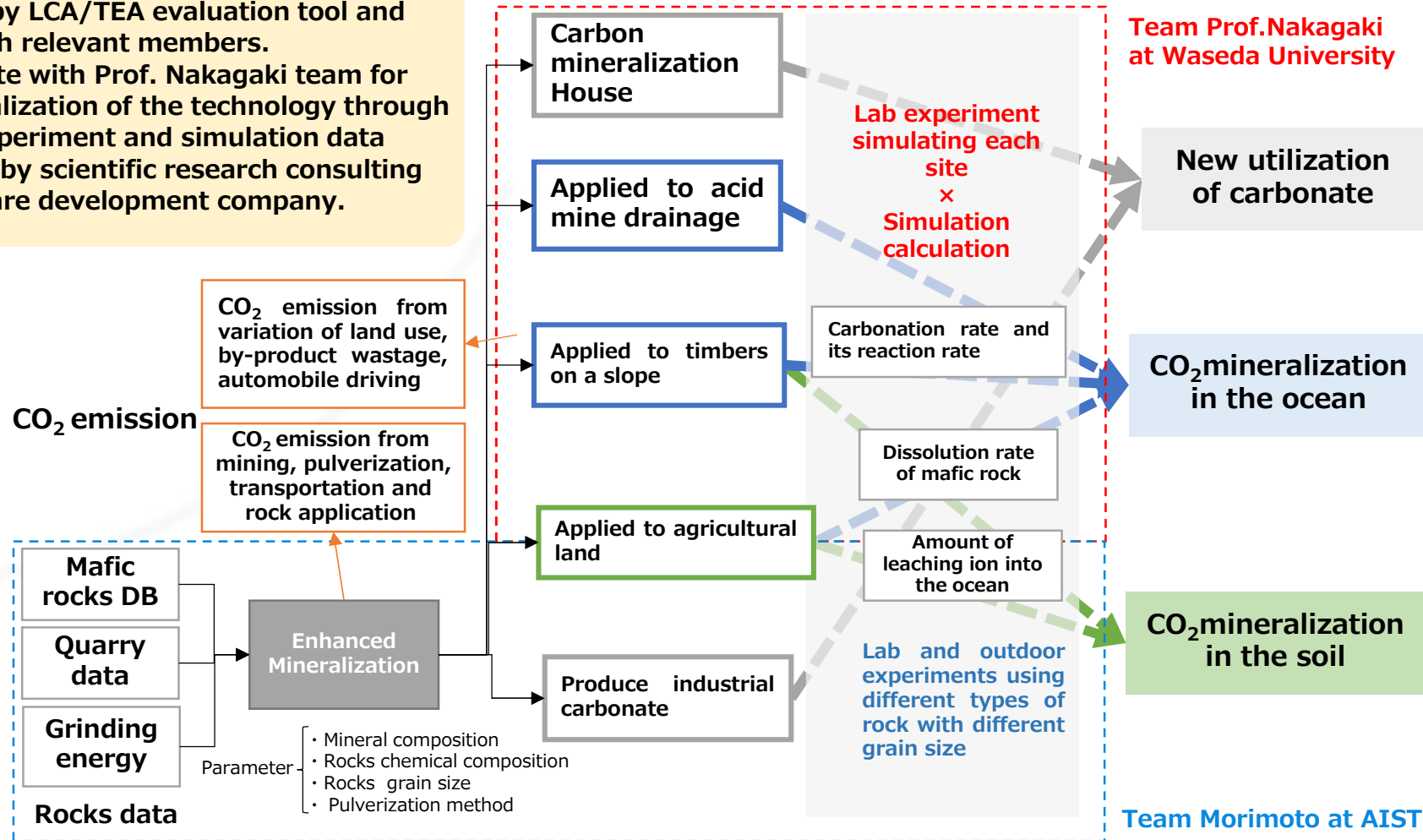


# Data Management / Collaboration with Prof. Nakagaki Team

- Experiment and analysis data are centrally managed by LCA/TEA evaluation tool and shared with relevant members.
- Collaborate with Prof. Nakagaki team for commercialization of the technology through sharing experiment and simulation data supported by scientific research consulting and software development company.

## Method and Output of Mineral Carbonation

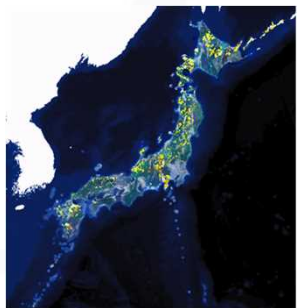
\*demonstration experiment is scheduled to be held





# Scenario for Social Implementation of Enhanced Mineralization

## Select Mining Site



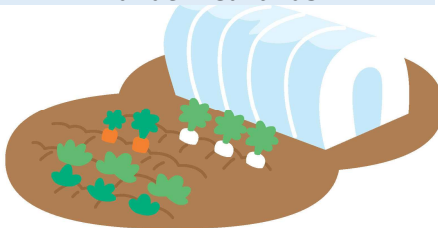
Mining at appropriate sites with the regional development effect including job creation, etc.



Mining and pulverization from existing quarries

## Establish Exit Strategy with Private Sectors

Cooperate with local agricultural cooperatives and fertilizer manufacturers for using agricultural fields and unutilized lands



Time period to foster social receptivity  
Examine industrial production process

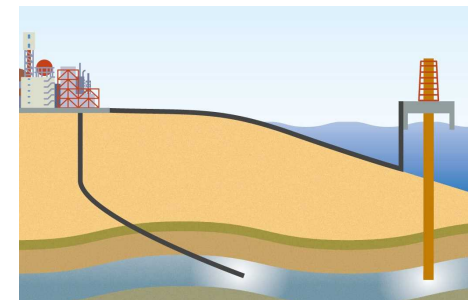


Produce carbonate industrially and examine exit strategy in cooperation with private sectors

Pilot-scale operation based on experiment data



World-class social implementation expanding to other countries

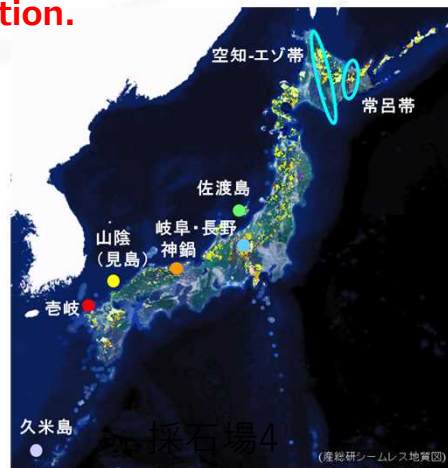


Examine disposal method taking social receptivity into consideration

accounting · low cost · utilization

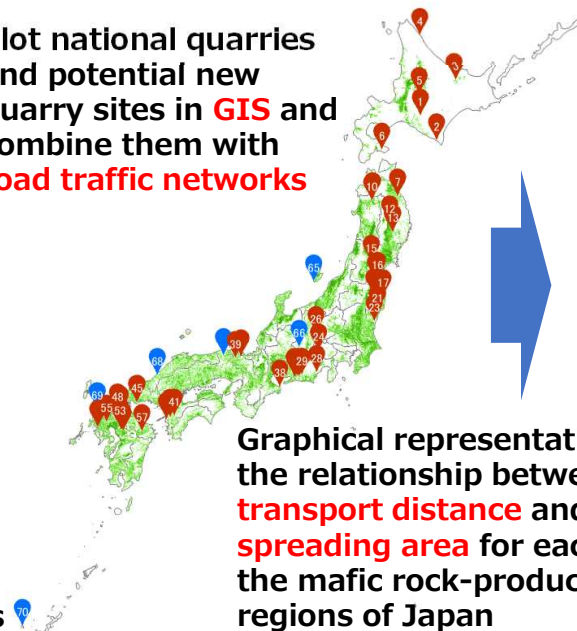
### Development of the domestic database on mineral composition, properties, and mining site information of mafic rocks

Construction of the database of mafic rocks for the selection of rocks for enhanced mineralization  
**A national database is required because chemical and mineral composition of mafic rocks affects CO<sub>2</sub> fixation.**

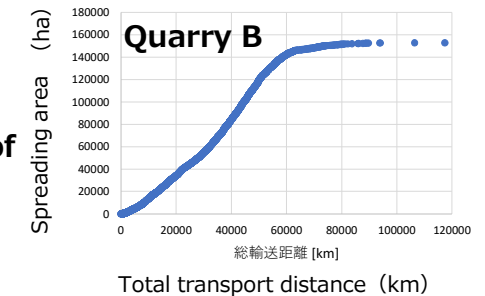
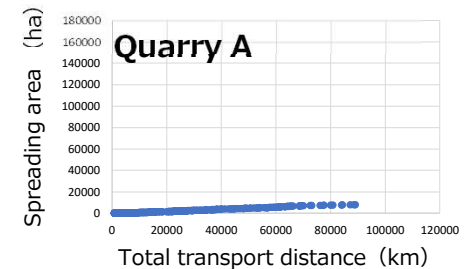


Collecting data on **chemical and mineral compositions** of mafic rocks through **field surveys** and **rock sampling** in representative mafic rock-producing areas

Plot national quarries and potential new quarry sites in **GIS** and combine them with **road traffic networks**



Graphical representation of the relationship between **transport distance** and **spreading area** for each of the mafic rock-producing regions of Japan



**Achievements:** Data collection of mafic rocks in 7 regions. Estimation of transport distance and area of spreading in potential quarry sites across the country  
 FY2023: Selection of candidate quarry sites suitable for enhanced mineralization and construction of **a prototype mafic rock database.**  
 FY2024: Completing a database covering mafic rocks in dozens of locations across the country.

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- Measurement of CO<sub>2</sub> absorption at the micro level under various environments, such as in the controlled sample room, long-term outdoor exposure conditions, and in the soil.

Development of technology for evaluating the CO<sub>2</sub> carbonation rate

Confirmation of the carbonation (process 1) and dissolution (process 2) of mafic rocks, and measurement of enhanced mineralization conditions

Evaluation of carbonation rate under outdoor conditions



Demonstration of increased pH of rainwater depending on rock types and carbonation in some MgO

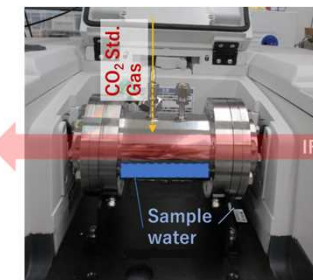
Field observations to evaluate weathering of mafic rock



Net CO<sub>2</sub> flux due to weathering of mafic rock was examined based on soil chamber experiments at Miyakojima.



Monitoring of weathering of mafic rock using large vessels at Tsukuba



Development of a gas cell for measuring carbonation rate.

Achievements: Confirmation of carbonation of some samples and rock type-dependent leaching behavior. Preparation of field experiment systems to monitor of mafic rock. Development of a device to evaluate carbonation rate.

FY2023: Development of a method for measuring CO<sub>2</sub> carbonation rate and CO<sub>2</sub> concentration decrease.

FY2024: Evaluation of effects of rock type, temperature, humidity, and inhibitor on CO<sub>2</sub> carbonation. Soil chamber experiments in the field.



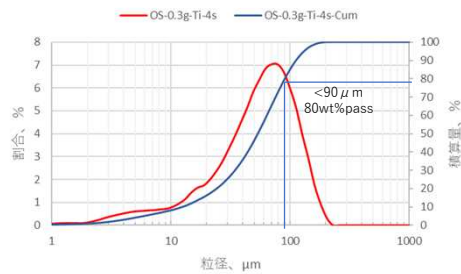
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➤ Reducing the cost of CO<sub>2</sub> fixation by half of current cost using ultrasonic pulverization

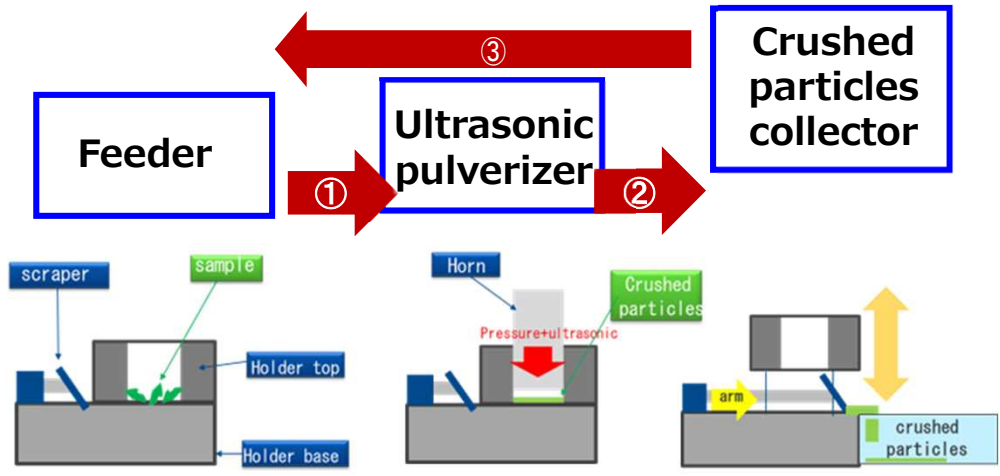
**High-efficiency ultrasonic pulverization technology for enhanced mineralization**

**Reduction of pulverization energy cost that accounts for more than 70% of total energy cost of CO<sub>2</sub> fixation by enhanced mineralization, will make enhanced mineralization low-cost technology**

Fine particle size is an effective mean to promote EW. Therefore, efficient pulverization technology is an important issue.



Schematic design of continuous ultrasonic pulverization system



	Ref. (1)	Ref. (2)	This study
Crushing	Ball mill	Ball mill	Ultrasonic
efficiency	80wt% pass <38 μm	80wt% pass <106 μm	80wt% pass <90 μm
Crushing energy kWh/t	83	38	<25~50% of Ref. (1)&(2)

**Achievements:** Ultrasonic pulverization of olivine sand yields >80%, <100μm particles, and the energy was 25~50% lower than the conventional ball mill method. Continuous system is under development.  
**FY2023:** Obtain conditions for 50% energy reduction, with yields of >40%, <100μm.  
**FY2024:** Development and construction of continuous ultrasonic pulverization system.

# Topic ③-2 : Development of Technology for Accelerated Enhanced Mineralization

Account · cost reduction · Application

Investigation of effect humidity, temperature, CO<sub>2</sub> concentration, pH, etc. have on the reaction rate.

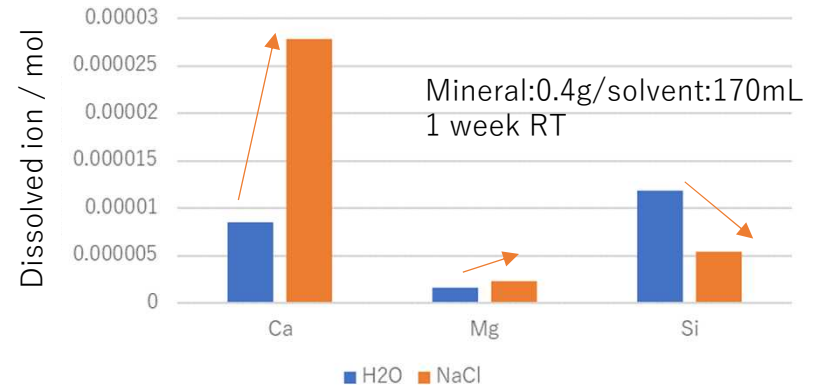
Rocks	Crushing	Dissolution & mineralization	
<ul style="list-style-type: none"> <li>• Composition</li> <li>• Mineral type</li> <li>• Impurities</li> <li>• Hazardous Elements</li> </ul>	<ul style="list-style-type: none"> <li>• Cost</li> <li>• Method</li> <li>• Size</li> <li>• Time</li> <li>• Energy</li> </ul>	<ul style="list-style-type: none"> <li>• Moisture</li> <li>• Temperature</li> <li>• pH</li> <li>• CO<sub>2</sub></li> <li>• Salt water</li> <li>• Additives</li> </ul>	<ul style="list-style-type: none"> <li>• Pore distribution</li> <li>• Crystallinity, strain</li> <li>• Coexisting ions</li> <li>• Redeposition</li> <li>• Coating</li> <li>• Soil effect</li> </ul>



• In the mixture of atmosphere, minerals, and pure water, HCO<sub>3</sub><sup>-</sup> was main anion form with cations. CaCO<sub>3</sub> and Na<sub>2</sub>CO<sub>3</sub> solid salts were extracted from mineral dissolution water.

• The dissolution promotion effect was confirmed by temperature, pH, and addition of organic acid and NaCl. →The results suggest the possibility of using dissolved water in high-temperature regions, acidic water, soil organic matter, and brine.

• Various particle size samples were prepared by milling and classification.



**Dissolution acceleration of basalt by NaCl (0.5M)**  
(it was effective for olivine and wollastonite)

**Achievements:** Many factors affecting the rate of dissolution and solid carbonate formation were clarified. Two patent applications are in preparation.

**FY2023:** To present several new methods for dissolution and carbonate formation that are more advantageous than conventional methods for accounting and economics.

**FY2024:** To accumulate information from various experiments and prepare all data for outdoor demonstration of new methods with economic rationality.

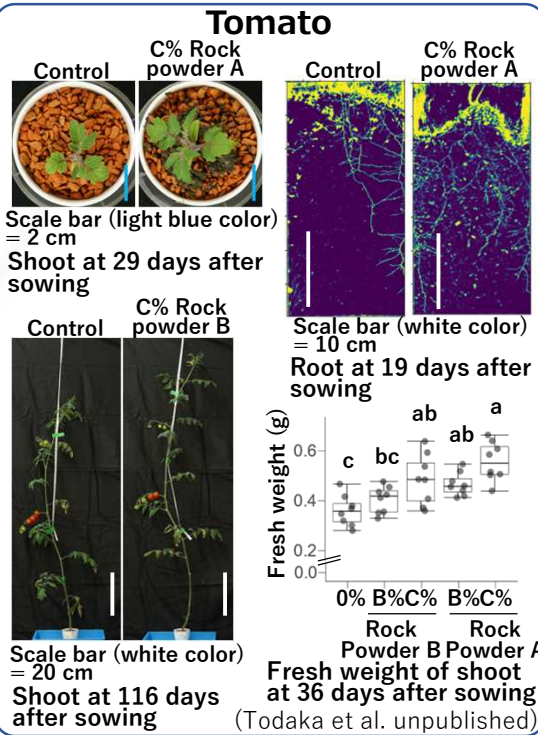
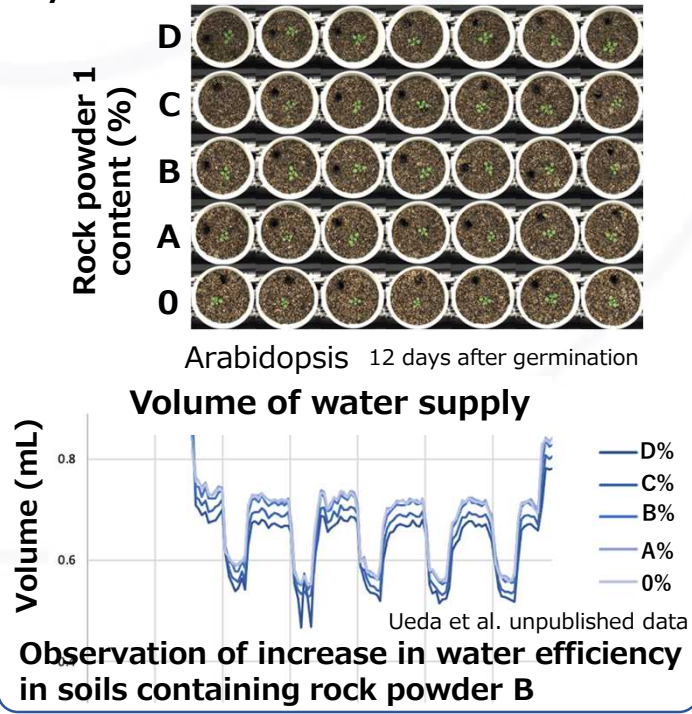
# Topic ④-1

## Analysis for the Effect of Applying Rock Powder to Soil on Plant Growth and Microbiome Diversity

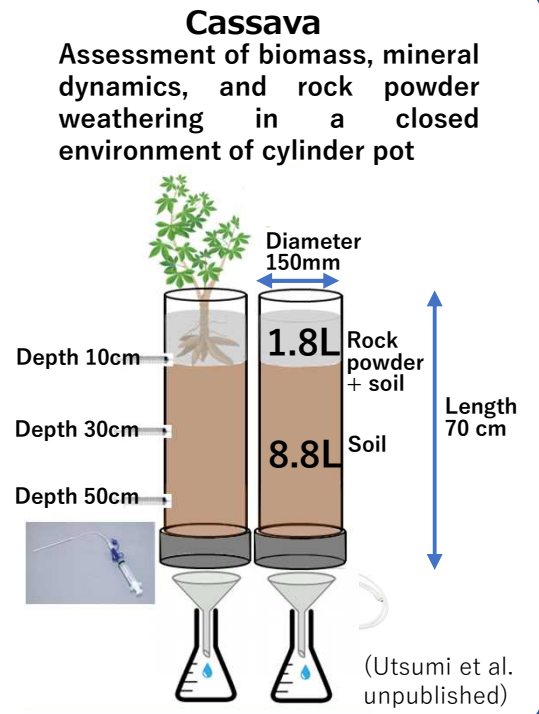
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- Measurement of photosynthetic activity, growth, and CO<sub>2</sub> fixation rate of plants grown in soils containing different types and particle sizes of rocks which affect mineral content and pH

### Measurement of water content in the soil by RIPPS



### Evaluation of plant growth and CO<sub>2</sub> fixation effect by pot test (with AIST)



Contact : Motoaki Seki (RIKEN CSRS, email:motoaki.seki@riken.jp)

**Achievements :** Increase in plant biomass by rock-powder treatments in a pot and green house  
**FY2023 :** Confirmation of increase in growth rate and water use efficiency by real-time observation of RIPPS  
**FY2024 :** Multi-omics and physiological analyses to reveal mechanism underlying increased plant biomass by rock-powder treatment

# Topic ④-2

## Analysis for the Effect of Applying Rock Powder to Soil on Plant Growth and Microbiome Diversity



- Validation of the effect on plant growth in soils containing different types and particle sizes which affect mineral content and pH.
- Evaluation of the effect of rock powder on the soil including rock weathering and microbial flora under field condition.



### ① Pot trials (Soil type:2, Rock:A,B)

- Yam (in progress)
- Cassava (B rock powder enhanced growth of top and root.)  
(A rock powder enhanced growth of top)
- Upland rice (mafic rock powder enhanced the growth of top and did not inhibit germination of rice seed.)
- Coffee (in progress)

### ② Evaluation on field level (Soil type:1, Rock:A,B)

- Yam (Enhanced growth of top on going)
- Cassava (in progress)

### ③ Evaluation of microbiome

(DNA%, metagenomic analysis, in progress)

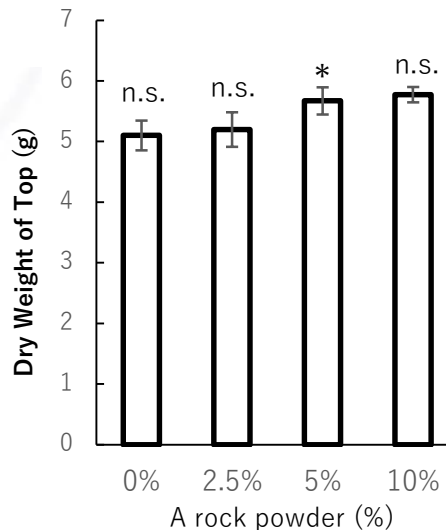
### ④ Water retentivity/permeability of soil

(in progress)

### ⑤ Effect of rock weathering (by AIST in progress)

Contact: Hidehiko KIKUNO  
Tokyo University of Agriculture (Kikuno et al, unpublished)  
Miyako Subtropical Farm,  
e-mail:h3kikuno@nodai.ac.jp

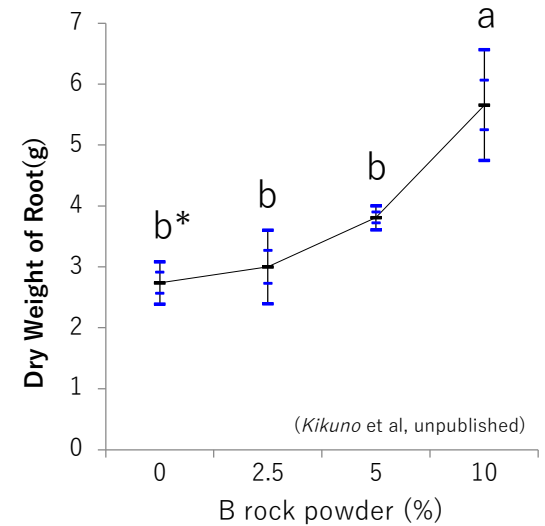
Mafic rock application on soil enhanced growth of upland rice at early stage (Pot trial without fertilizer application)



\*Values followed by different letter is significantly different at P < 0.05 by Tukey-Kramer test .

Some results of upland rice presented by oral at JSTA 134<sup>th</sup> conference at Kinki University, Nara Japan 2023 Oct. 14

Mafic rock application on soil enhanced growth of roots of cassava (Pot trial without fertilizer application)



\*Values followed by different letter is significantly different at P < 0.01 by Tukey-Kramer test .

**Achievements : Rock powder enhanced growth of plants verified. (Presented at JSTA conference), Field trial on going.**  
**FY2023 : Analysis of effects of rocks on the growth of plants and microbiome under pots and field condition, identifying effective concentration of rock powder application.**  
**FY2024 : Exhibit integrated effects of rock powder application on the growth of plants and microbiome under different soil and fertilization conditions.**



# Topic5 Development of LCA/TEA Platform of Enhanced Mineralization



**Input Data**  
(= experiment conditions of each test )

- Rock Information
- Application Conditions
- Soil Conditions
- Climate Conditions

**Tool Element**

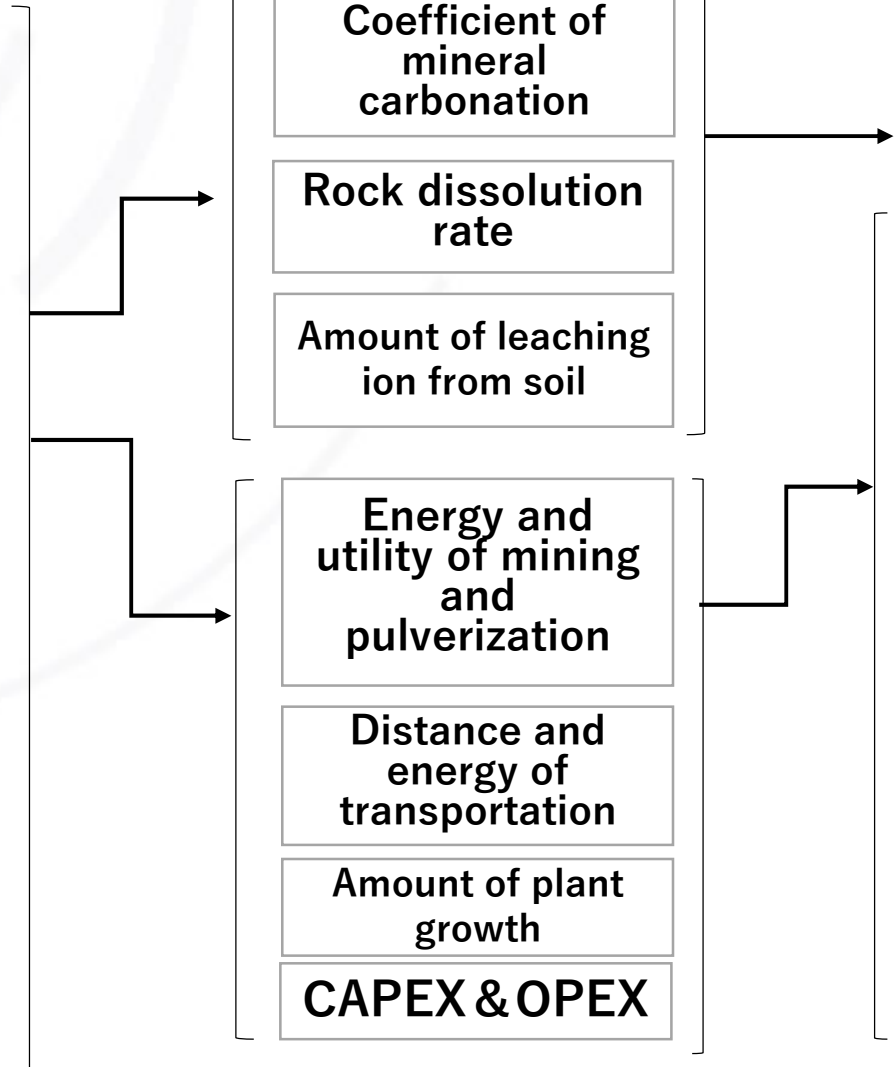
- Coefficient of mineral carbonation
- Rock dissolution rate
- Amount of leaching ion from soil
- Energy and utility of mining and pulverization
- Distance and energy of transportation
- Amount of plant growth
- CAPEX & OPEX

**Output Data**

(= accumulated calculation of CO<sub>2</sub> fixation and emission)

- CO<sub>2</sub> fixation potential Process 1&2
- CO<sub>2</sub> emission from soil
- CO<sub>2</sub> emission in the whole process
- Total cost in the whole process
- Profit through enhancing plant growth

CO<sub>2</sub> fixation



# Topic⑤

## Development of LCA/TEA Platform for Enhanced Mineralization

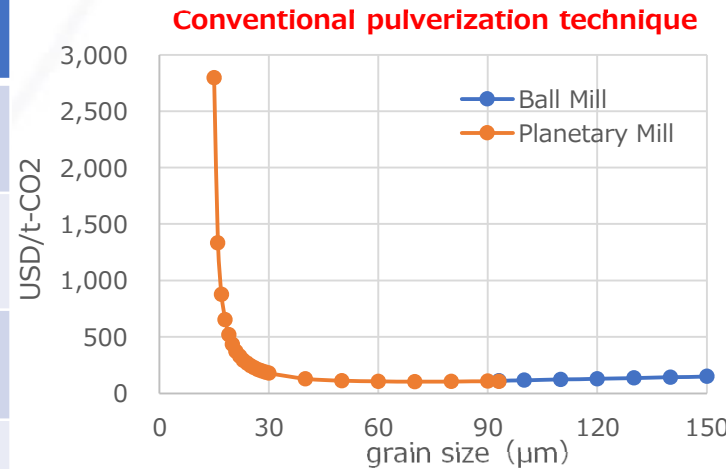
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- Development of LCA/TEA platform based on a future scenario considering time series of CO<sub>2</sub> absorption.
- Designing of total system that can optimize the cost of mineralization.

### Development of LCA/TEA platform for designing system of enhanced mineralization

- Create a base of assessment tool and collect Japan's original inventory data.
- Create future scenario and background data. Examine the energy consumption for mining based on mining simulation.

	Literature	MS LCA/TEA
CAPEX (\$/ton-year)	Medium: 2.8 Minimum: 0.03 Maximum: 13.5	1.91~ 10.01
Mining & Pulverization (\$/t)	Medium: 9.9 Minimum: 3.13 Maximum: 58.6	3.43
Transport (\$/t.km)	0.05	0.06
Spreading (\$/t)	Medium: 10.7 Maximum: 17.8	8.05



Optimal grain size for minimum CO<sub>2</sub> reduction cost

**Challenges**

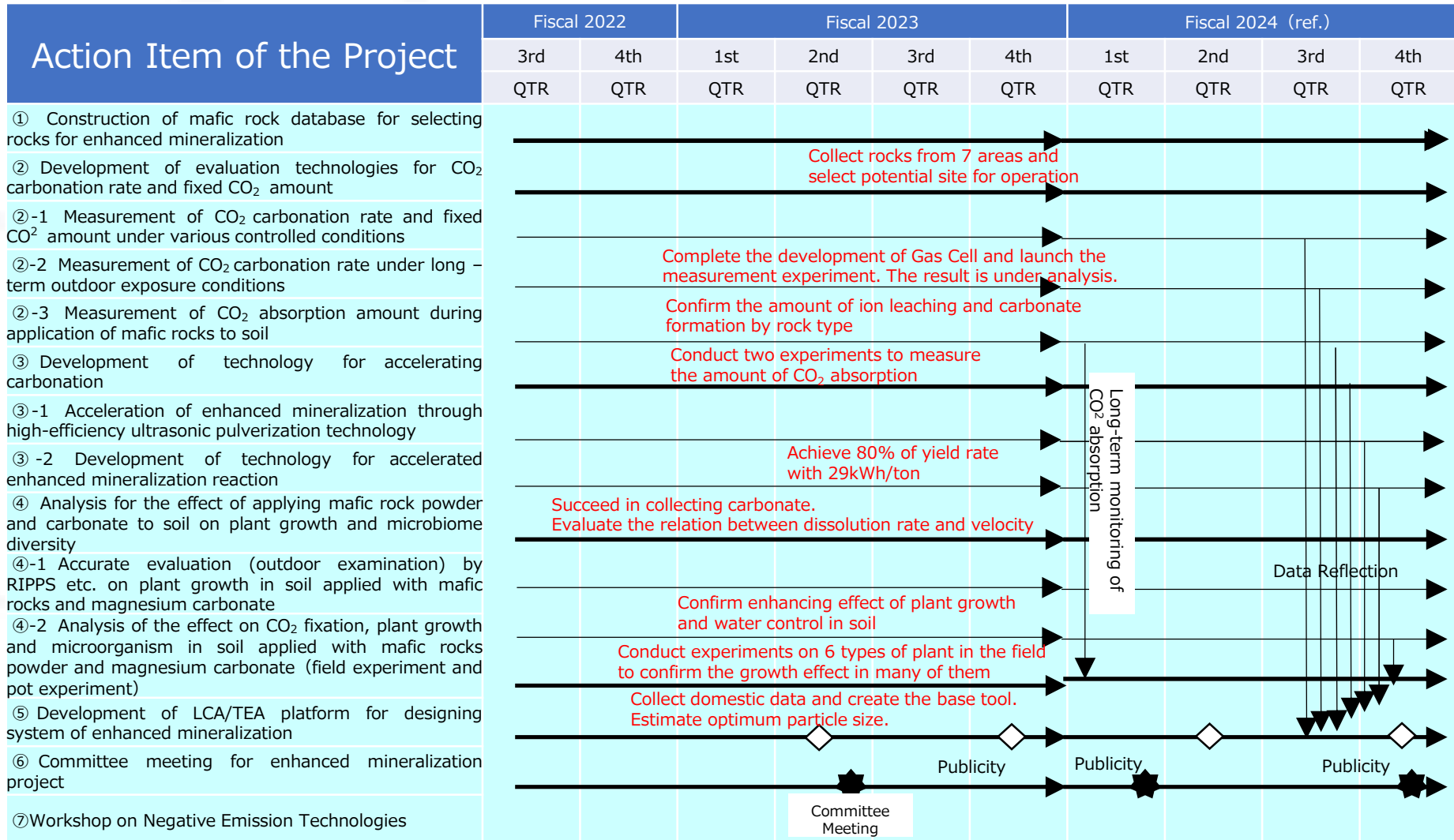
- Examination of transportation and soil application by GIS
- Reflect the result of CO<sub>2</sub> fixation simulation.
- Reflect the data of ultrasonic pulverization of rock (Two presentations in conference are scheduled)

**Achievements :** Create a base of Japanese assessment tool for enhanced mineralization. Estimate the optimal grain size of rock by simplified tool.

**FY2023 :** Collect inventory data of enhanced mineralization system and construct a basic framework of assessment tool.

**FY2024 :** Design the system that can reduce CO<sub>2</sub> cost of 200~250USD/t-CO<sub>2</sub> or less through our developed assessment tool.

# Progress of the Project (2023)



# Dissemination of Research Results through Corporate and International Collaboration



## AIST Moonshot R&D Project

Discussing for collaboration with 4 companies (fertilizer application, industrial enhanced mineralization, fix CO<sub>2</sub> from gas emission, disposal method of carbonate).

**Prof. Nakagaki**  
Exchange information for social implementation of EM through AIST tool.

United States Department of Energy (ARPA-E)

### U.S. Collaboration

**Mission Innovation**

Collaborate with Cote d'Ivoire and Kenya for the study on fertilizer application.

**University and National Laboratory**  
Enhanced mineralization is under way utilizing ores at mines.  
Collaborative development of LCA method especially for dynamic LCA.

**DOE related laboratory**  
Development of LCA method for CO<sub>2</sub> removal technology  
**Canada**  
Creating LCA methodology for EM  
**Australia, Saudi Arabia, UK**  
Create database for world's enhanced mineralization project and organize the previous LCA method for EM. Draft of the guideline is in preparation.



# Workshop and Committee Meeting



## The First Workshop on Moonshot R&D Project

Date and Time)13:00-17:30 on Mon.Oct.30,2023

Place)UDX AKIHABARA SPACE – UDX GALLERY

Details) · The first major workshop in Japan on Enhanced Mineralization.

- Joint workshop with the Project Manager, Prof. Nakagaki at Waseda University.
- Introducing video message from ARPA-E in the program.
- The number of online registration: 528
- The total number of participants :407 (101 on-site participants and 306 online participants)

## Committee for Enhanced Mineralization Project

The First committee meeting was held on Jul.14 (2023) after completion of appointment procedure.

### ELSI Management

- Confirm and examine the law of health damage prevention.
- Interview the related organizations in collaboration with the research team of Waseda University.