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玄武岩施用が農地土壌の土壌物理性および CO_2 動態に及ぼす影響

Effects of basalt application on soil physical properties and CO_2 dynamics in agricultural soils

Introduction:

Soils represent the largest terrestrial reservoir of organic carbon and play an essential role in regulating atmospheric CO_2 concentrations and global climate. Soil carbon dynamics are governed by the balance between carbon inputs from plant residues and roots and carbon losses through microbial respiration, gas transport, and dissolved carbon leaching. These processes are strongly influenced by soil physical properties, hydrological conditions, and biological activity, which together control the production, storage, and movement of CO_2 within the soil profile.

Enhanced rock weathering (ERW) has recently been proposed as a promising land-based carbon dioxide removal strategy. In this approach, finely ground silicate minerals such as basalt are applied to soils to accelerate natural weathering reactions that consume atmospheric CO_2 and produce dissolved inorganic carbon. Basalt is considered a suitable material for ERW because it is widely available, contains reactive Ca–Mg silicate minerals, and may also provide agronomic benefits such as increasing soil pH and supplying plant nutrients.

However, most previous ERW studies have focused primarily on geochemical processes such as mineral dissolution and alkalinity generation. Comparatively little attention has been given to how basalt amendments influence soil physical properties, water–gas transport processes, and short-term soil CO_2 dynamics. In reality, silicate weathering occurs within complex soil systems where biological activity, soil structure, hydrological conditions, and gas transport interact. Basalt incorporation may modify soil porosity, bulk density, and water retention, which in turn can influence microbial respiration and the movement of CO_2 through the soil profile.

Furthermore, results from laboratory incubation studies cannot always be directly applied to field conditions because soil CO_2 behavior in situ reflects both production and transport processes under variable environmental conditions. Similarly, many existing reactive transport models have been developed primarily to estimate mineral weathering and alkalinity export, but they often simplify soil hydrological variability and biological CO_2 production.

To address these limitations, this study investigated how basalt application influences soil CO_2 dynamics in agricultural soils through a combination of laboratory incubation experiments, field monitoring, and reactive transport modeling. The specific objectives of this thesis were to:

1) quantify short-term responses of dissolved organic carbon (DOC) and soil CO_2 respiration to basalt amendment,

2) evaluate how basalt application modifies soil physical properties, water–gas transport, and CO_2 dynamics

3) develop a reactive transport modeling framework to distinguish the relative contributions of physical transport processes and geochemical weathering reactions to soil CO_2 behavior.

Summary of experimental approaches and major findings:

Incubation experiment:

A controlled laboratory incubation experiments were conducted to examine the short-term effects of basalt addition on soil chemical properties, dissolved organic carbon (DOC), and soil CO_2 production in two contrasting agricultural soils. The soils consisted of a Gray-lowland soil collected from Hokkaido University and a Red-yellow soil collected from Ishigaki Island, which differ in mineralogy, organic carbon content, and buffering capacity. Finely ground basalt powder was applied at 10 wt% and mixed with soils prior to incubation.

Soils were incubated for 90 days under controlled temperature and moisture conditions, with soil moisture maintained at 70% of water-holding capacity. Soil CO_2 flux was measured repeatedly using a closed-chamber headspace method followed by gas chromatographic analysis. In addition, two operationally defined dissolved organic carbon fractions were analyzed, including water-extractable DOC (DOC-H_2O) and K_2SO_4-extractable DOC (DOC-K_2SO_4). Soil pH and exchangeable cations were also measured to evaluate chemical changes associated with basalt dissolution.

Basalt application increased soil pH and altered the distribution of dissolved organic carbon fractions. DOC-H_2O increased while DOC-K_2SO_4 decreased under basalt addition, indicating a redistribution of organic carbon from exchangeable pools toward freely soluble fractions. DOC-H_2O increased by up to 2.5-fold, accompanied by 147–293% higher CO_2 flux immediately after mixing with basalt (Day 0–4). However, no sustained enhancement of CO_2 production was observed during the later stages of incubation despite persistently elevated soil pH. These results indicate that basalt applications primarily affected short-term carbon dynamics by mobilizing a labile DOC pool under altered soil chemical conditions, leading to a brief stimulation of microbial respiration.

Field monitoring experiment:

To evaluate basalt effects under realistic agricultural conditions, a field monitoring experiment was conducted at the experimental farm of Hokkaido University in Sapporo, Japan, using a Gray-lowland soil under crop cultivation. Basalt powder was incorporated into the surface soil at 10 wt% (≈150 t ha^{-1}) and mixed into the upper 0–15 cm of the soil profile. Soybean was cultivated during the 2023 growing season, followed by maize during 2024.

Soil environmental conditions were monitored continuously during both growing seasons. Soil water content and soil temperature were measured using in-situ sensors, while soil CO_2 concentrations were monitored at 10 cm and 25 cm depth. Soil physical properties including bulk density, total porosity, soil water retention characteristics, saturated hydraulic conductivity, and gas diffusivity were measured from soil samples collected during the experiment. Surface CO_2 flux was calculated using the concentration-gradient method, which combined soil CO_2 concentration gradients with gas diffusivity estimates as a function of air content.

Basalt incorporation increased bulk density and reduced soil porosity in the surface soil layer, which enhanced water retention in the lower soil water suction range. These structural changes were clearly observed during the 2023 growing season, whereas treatment differences became smaller in 2024. Despite the changes in bulk density, the relationship between air content and gas diffusivity remained unaffected by basalt application, suggesting that basalt addition modified soil water storage without altering the dominant pore networks responsible for gas transport.

Basalt-treated soils exhibited higher CO_2 concentrations and higher CO_2 flux between 10 cm depth and the atmosphere, resulting in larger net CO_2 production at 10 cm depth. This increase likely reflects pH-driven microbial priming, while the smaller pH difference between treatments in 2024 corresponds to weaker differences in net CO_2 production. Rainfall-induced

CO_2 bursts were more pronounced in basalt-amended soils, indicating strong coupling between soil water dynamics and soil CO_2 responses. Soil temperature dynamics were largely unaffected by basalt amendment during the monitoring period.

Reactive transport modeling:

To distinguish the physical and geochemical controls on soil CO_2 dynamics under basalt application, a reactive transport modeling framework based on HYDRUS–PHREEQC (HP1) was developed. The model coupled transient water flow, heat transport, gas-phase CO_2 diffusion, aqueous solute transport, microbial CO_2 production, and silicate mineral dissolution reactions within a one-dimensional soil profile.

The simulated soil domain consisted of a 300 cm vertical soil profile, with basalt amendment applied to the upper 20 cm of soil (control, 5 wt%, 10 wt%). Soil hydraulic properties of 3 different textured soils (sandy loam, clay loam, clayey soils) were described using pedotransfer functions, and microbial CO_2 production was represented as a function of soil depth, soil moisture, and temperature. Silicate weathering reactions were simulated using olivine as a proxy mineral for the reactive silicate component of basalt, with dissolution kinetics described by a transition-state-theory-based rate law. Two simulation scenarios were designed to separate physical and geochemical effects. In the first scenario, only compaction-induced changes in hydraulic properties were considered, while mineral weathering reactions were excluded. In the second scenario, both compaction and mineral weathering reactions were included.

Model simulations showed that compaction reduced soil porosity and gas diffusivity, resulting in slightly higher soil $CO_2(g)$ concentrations under wet and poorly aerated conditions. However, cumulative CO_2 fluxes remained largely unchanged, indicating that physical changes mainly influenced the spatial distribution of CO_2 within the soil profile rather than the total amount emitted. When silicate weathering reactions were included, part of the gaseous CO_2 was dissolved during mineral dissolution, producing significantly higher dissolved inorganic carbon (DIC) concentrations and lower soil $CO_2(g)$ in the soil profile compared with the compaction-only scenario. Despite enhanced DIC formation, cumulative DIC flux remained small because downward water flux was limited in the simulated scenario, meaning that most newly formed DIC was retained within the soil profile. Across different soil textures, simulated weathering responses differed when expressed as a function of water content but converged when expressed as a function of air content. This result suggests that gas diffusion constraints associated with soil aeration play an important role in regulating silicate weathering reactions in soils.

General discussion and implications:

By integrating incubation experiments, field observations, and reactive transport modeling, this study provides a multi-scale evaluation of how basalt application influences soil CO_2 dynamics in agricultural soils. The results demonstrate that basalt amendments affect soil CO_2 behavior through both chemical and physical pathways.

Short-term increases in soil CO_2 flux observed in incubation experiments are primarily associated with DOC mobilization and transient stimulation of microbial respiration under elevated pH conditions. Under field conditions, however, soil CO_2 concentrations and fluxes are strongly influenced by hydrological variability, soil structure, and gas transport processes. Basalt incorporation can modify soil physical properties such as bulk density, porosity, and water retention, thereby influencing soil aeration and CO_2 diffusion induced by lowered air content.

Reactive transport modeling further demonstrates that soil aeration state plays a key role in regulating the balance between CO_2 accumulation, dissolution, and weathering reactions. Reduced gas diffusion promotes CO_2 retention within the soil profile and increases its availability for aqueous dissolution, linking soil physical conditions to geochemical weathering processes.

These findings highlight that field-based CO_2 measurements alone cannot be directly interpreted as indicators of enhanced rock weathering effectiveness. Reliable evaluation of ERW in agricultural systems requires integrated consideration of biological production, physical transport, and geochemical transformation of carbon under realistic environmental conditions.