KAS Farm Soil Lab: Scalable On-Farm Monitoring with AI and Olivine Weathering

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Abstract

The KAS Farm Soil Lab represents a decentralized approach to agricultural monitoring, integrating olivine-enhanced weathering with AI-driven diagnostics for scalable carbon removal and soil regeneration. Designed as a modular, farmer-operated platform, the system enables direct measurement of key parameters such as soil pH, magnesium ion concentration, and CO_2 efflux using open-source sensors and low-power microcontrollers. AI models embedded within the system analyze time-series data to optimize amendment scheduling, application rates, and carbon yield projections based on climatic and crop-specific inputs. Olivine, a magnesium-rich silicate, is utilized for its dual role as a pH buffer and a permanent CO_2 sink through geochemical carbonation. The platform supports integration with existing farm infrastructure and enhances farmer autonomy by eliminating dependency on centralized soil testing labs. Its compatibility with voluntary carbon market verification frameworks further positions the KAS Lab as a practical solution for climate-smart agriculture. By coupling accessible hardware, mineral amendments, and real-time analytics, the system provides a reproducible pathway toward negative-emissions farming and resilient soil stewardship.

1 Introduction

The convergence of soil degradation, rising greenhouse gas concentrations, and escalating agricultural input costs has intensified the demand for regenerative, cost-effective, and scalable climate mitigation tools [1, 2]. Among the emerging solutions, enhanced weathering using silicate minerals—specifically olivine—has garnered increasing attention for its dual capacity to sequester atmospheric carbon dioxide (CO_2) and improve soil health [3, 4].

Olivine (Mg_2SiO_4), a naturally abundant magnesium-iron silicate, weathers in the presence of moisture and carbon dioxide to form stable bicarbonates and release beneficial ions such as Mg^{2+} and H_4SiO_4, enhancing plant nutrient availability and pH buffering [5, 2]. This geochemical transformation offers a permanent carbon sink while simultaneously rehabilitating degraded soils.

Building upon these properties, the KAS Farm Soil Lab introduces a decentralized, farmer-operated platform that integrates olivine application with real-time soil diagnostics and AI-based decision support. Unlike centralized laboratory franchises, the KAS model enables smallholder and industrial-scale farmers alike to directly monitor key soil parameters—such as pH, magnesium concentration, and CO_2 efflux—using portable lab kits and open-source software [6].

Recent field trials and carbon market methodologies suggest that olivine-enhanced weathering can remove approximately 0.8–1.0 t CO_2 per ton applied, with agronomic co-benefits that include increased cation exchange capacity (CEC), improved soil structure, and measurable yield gains [7, 8]. However, realizing these benefits requires not only material deployment but robust measurement, reporting, and verification (MRV) protocols [9, 10].

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This research outlines the foundational components of the KAS Lab system—hardware, software, agronomic protocols, and carbon accounting pathways—within a replicable framework aimed at bridging scientific rigor with on-farm practicality. By situating olivine weathering within an AI-enhanced soil health monitoring infrastructure, the KAS Farm Soil Lab contributes to a growing movement that prioritizes farmer autonomy, environmental resilience, and climate accountability.

2 Why Olivine?

Olivine (Mg_2SiO_4) is a naturally abundant magnesium-iron silicate mineral with unique geochemical properties that make it highly suitable for large-scale agricultural and environmental applications. When olivine particles are exposed to soil moisture and atmospheric carbon dioxide, they undergo a gradual but effective weathering process:

$$\mathrm{Mg_2SiO_4\,(s) + 4\,CO_2\,(g) + 4\,H_2O\,(l) \longrightarrow 2\,Mg^{2+}\,(aq) + 4\,HCO_3{}^{-}\,(aq) + H_4SiO_4\,(aq)} \tag{1}$$

This reaction converts gaseous CO_2 into stable bicarbonate ions ($HCO_3{}^-$) and silicic acid (H_4SiO_4), which either remain in soil water or are transported to oceans, contributing to long-term carbon storage [1, 2]. Unlike biological carbon sinks, which are vulnerable to disturbance or decomposition, olivine weathering ensures geological permanence of carbon sequestration.

In addition to its carbon removal function, olivine provides essential agronomic benefits. The dissolution of olivine releases bioavailable magnesium (Mg^{2+}), a critical nutrient for chlorophyll production and enzymatic activity in plants [5, 3]. Silicic acid, another weathering product, enhances plant resilience by strengthening cell walls and improving resistance to drought and disease.

Another key benefit of olivine is its ability to neutralize soil acidity. In acidic soils, hydrogen and aluminum ions dominate the cation exchange complex, limiting nutrient uptake and microbial activity. The weathering of olivine supplies divalent magnesium ions that displace toxic cations, thereby raising the pH and enhancing the soil's buffering capacity [7]. This buffering process can reduce the need for traditional liming materials such as agricultural lime ($CaCO_3$), leading to significant cost savings and fewer machinery passes across fields [11].

Olivine has been shown in pot trials and field studies to increase biomass yield, improve nutrient uptake, and contribute to soil structural improvements when applied at rates between 1 to 5 tons per hectare [5]. These findings support the role of olivine not just as a carbon drawdown tool, but as a multifunctional input that supports regenerative soil management practices.

Its natural abundance, compatibility with conventional farm equipment, and dual benefit profile make olivine a practical and scientifically validated amendment for use in climate-resilient agriculture.

3 Kit Architecture

Each KAS Soil Lab kit includes:

- pH, EC, and CO_2 probes
- Olivine spreader integration sensors
- ESP32 microcontroller
- LoRa/Cellular uplink module
- Mobile dashboard interface (Streamlit)

4 AI Dashboard and MRV Data Models

The KAS Farm Soil Lab connects each decentralized farmer-operated unit to a centralized AI-driven dashboard system, enabling real-time monitoring, modeling, and verification of both soil health and carbon sequestration performance.

KAS Data Interface and Field Analytics

The KAS Data Interface is a proprietary, modular visualization system developed to support real-time decision-making at the farm level. Each KAS Lab workstation securely transmits field data—including pH, magnesium, and CO_2 efflux—via StarLink satellite connectivity to the KAS platform for analysis and guidance.

The interface provides:

- Real-time CO_2 efflux and bicarbonate generation visualization,
- Per-site olivine demand forecasts calibrated by pH and cation exchange capacity (CEC),
- Crop-specific yield prediction based on historical climate-soil-crop interaction datasets,
- Geo-tagged sampling logs with soil mineral trends and treatment overlays.

KAS Field Analytics is designed for ease of use by trained farmers and cooperatives, offering intuitive insights and decision tools without exposing raw model architecture. All underlying frameworks remain proprietary to the Kapodistrian Academy of Science.

KAS MRV Tools for Carbon Verification

The KAS Measurement, Reporting, and Verification (MRV) Toolkit enables secure, field-validated carbon accounting aligned with international standards for carbon dioxide removal (CDR). Each KAS Farm Soil Lab workstation collects and encrypts observational data using onboard AI modules, transmitting results over StarLink to a centralized KAS validation node.

Core MRV functionalities include:

- Time-stamped CO_2 flux tracking calibrated with local weather data,
- pH-buffering and silicate dissolution monitoring for olivine activity confirmation,
- Automated calculation of bicarbonate yield and projected carbon permanence,
- Secure farmer ID tagging to support pooled carbon credit eligibility.

All data is processed using KAS-owned verification algorithms that translate field measurements into carbon credit forecasts. These forecasts are formatted for compatibility with major carbon markets, while retaining internal audit trails and reproducibility logs.

The MRV system is integrated with the KAS Dashboard Suite and functions autonomously in remote environments with no external dependencies.

KAS MRV Data Architecture for Field Analytics

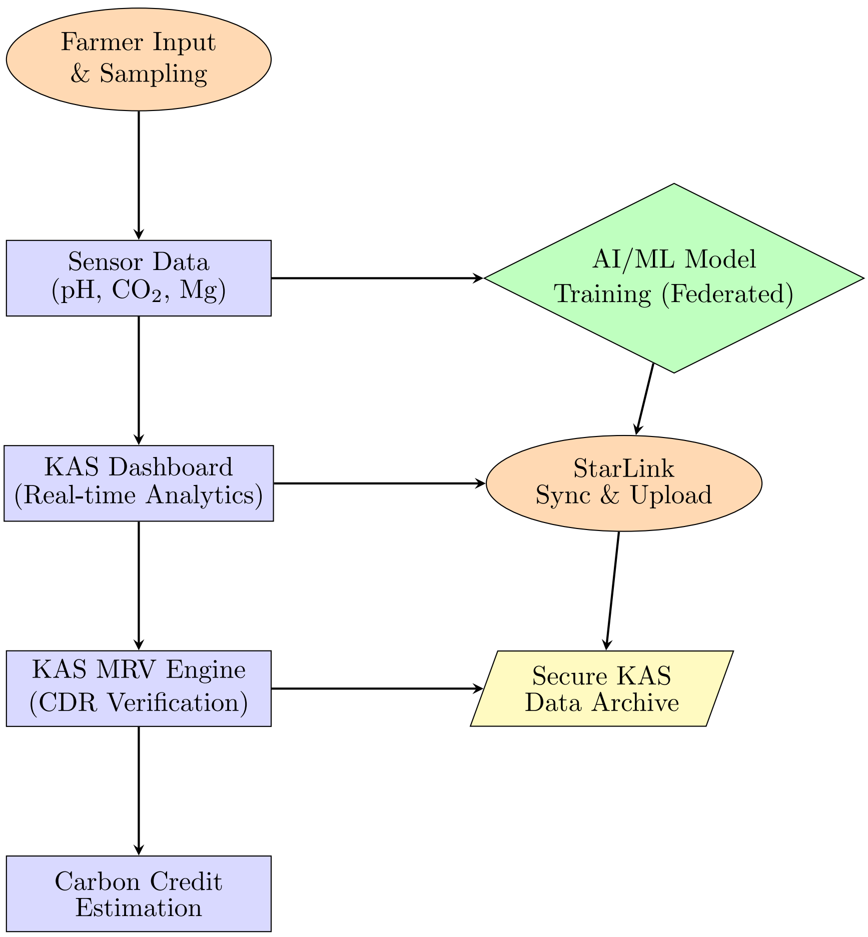

Figure 1: KAS MRV Data Architecture for Field Analytics. Each decentralized KAS workstation gathers soil and atmospheric data, transmits via satellite uplink, and processes results with onboard AI and a centralized verification engine. The system supports federated learning and secure, standards-aligned carbon estimation. Adapted from internal MRV schema [12].

The KAS Farm Soil Lab integrates a modular architecture that combines decentralized sensor inputs, onboard machine learning, satellite uplink, and a centralized carbon verification engine. Each unit continuously streams field data—such as pH, magnesium, and CO_2 flux—to the real-time dashboard via StarLink, ensuring rural coverage.

AI models are trained locally on rainfall trends, bicarbonate production, and crop yield, then aggregated via federated learning to improve predictive accuracy while preserving privacy. The MRV engine transforms raw input into verified carbon metrics aligned with global registries. Outputs are archived, forecasted, and visualized live in the dashboard for farm decisions and market interfacing.

MRV Compliance Tools

The dashboard architecture is aligned with emerging MRV standards from Verra, Puro.Earth, and the UNFCCC SBSTA. It includes:

- Automated MRV protocol calculators for enhanced weathering (e.g., net carbon removed per hectare),
- Exportable reports with time-stamped soil metadata,
- Isotopic proxy integration (e.g., δ^{13}C tracking),
- APIs for registry upload or voluntary carbon platform integration.

By offering these tools at the point of production, the KAS system eliminates the need for external verification consultants in most low-risk scenarios, drastically reducing the overhead for small and medium farms.

Summary

The AI-powered dashboard is not just a visualization tool, but a strategic interface enabling smallholder participation in carbon markets, agronomic decision-making, and self-guided sustainability. With decentralized NVIDIA AI hardware and global connectivity via StarLink, the system ensures robust monitoring, reporting, and verification—anywhere on Earth.

5 Farmer Training and Certification Program

The KAS Farm Soil Lab includes a modular training and certification program designed to equip farmers and local operators with the skills needed to measure soil parameters, apply olivine effectively, and interpret AI-based agronomic recommendations. The program is structured over a period of **two weeks**, combining theoretical modules with practical fieldwork.

Week 1: Theoretical Foundation and Instrument Training

- **Day 1: Introduction to Soil Health**
  - Soil pH, nutrient cycling, organic matter.
  - Soil degradation and carbon farming principles.
- **Day 2: Olivine Mineralogy and Carbon Sequestration**
  - Mg_2SiO_4 weathering chemistry.
  - Benefits of olivine over lime.
  - Stoichiometry of CO_2 capture.
- **Day 3: Soil Sampling and Lab Calibration**
  - Use of portable probes: pH, EC, CO_2 sensors.
  - Proper sample collection, storage, and prep.
- **Day 4: Data Logging and Quality Control**
  - Daily variability handling.
  - Data cleaning and composite analysis.
- **Day 5: AI Dashboard Training**
  - Overview of the Streamlit dashboard.
  - Uploading field data and interpreting ROI outputs.
  - Exporting MRV-compliant reports.

Week 2: Field Application and Certification

- **Day 6: Olivine Application Strategies**
  - Calibration by soil texture, pH, and rainfall.
  - Integration with existing fertilizer and compost routines.
- **Day 7: Plot-Level Planning and Safety**
  - GIS-based zoning for acid-prone soils.
  - Personal protective equipment and field protocols.
- **Day 8: Practical Field Day**

  - Applying olivine with spreaders.
  - Using probes and logging environmental metrics.
- **Day 9: Farmer Outreach and Advisory**
  - Communicating soil health reports.
  - Advising on reapplication cycles and carbon market access.
- **Day 10: Certification and Assessment**
  - Knowledge and field test.
  - Upload credentials for MRV registry access.

Certified participants may connect their dashboard to the national carbon MRV platform and join the pooled soil-carbon credit system.

6 Scaling and Outreach

The KAS Farm Soil Lab is currently in the pre-deployment phase, with outreach and training infrastructure being designed to support rapid pilot activation across multiple continents. As the creator of the system, the lead author is coordinating with academic collaborators, agritech partners, and soil science networks to enable regional customization based on climate, soil chemistry, and logistical access to olivine resources.

Target Deployment Regions

- **Greece**: Southern and central Greek farmland exhibits moderate to high soil acidity, particularly in vineyard, olive grove, and cotton-producing regions. Preliminary planning is underway with agronomy cooperatives in Thessaly and the Peloponnese to support early-stage rollout.
- **Brazil**: Agricultural zones in Minas Gerais and Pará have been identified as viable candidates due to their proximity to ultramafic formations and ongoing interest in enhanced weathering by climate research groups. Potential integration with Brazil's ABC+ program (Low Carbon Agriculture Plan) is under review.
- **Kenya**: Pilot discussions are being scoped with soil and agroforestry NGOs operating in acidic, rain-fed croplands in central Kenya. The goal is to integrate KAS Lab training with climate-smart agriculture programs backed by international donors such as the IFAD and GCF.
- **United States**: The U.S. offers an ideal landscape for KAS deployment, especially in the Midwest and Southeastern agricultural belts. These regions are affected by acidification due to heavy fertilizer use and host a large network of precision agriculture infrastructure. Initial outreach includes land-grant university extension programs and USDA-backed climate-smart grant initiatives. Additionally, dunite sources in North Carolina and olivine-related quarrying activity in the Pacific Northwest offer feasible local supply for soil amendment trials.

Localization and Customization

Each pilot zone will adapt the KAS system to its specific agronomic and environmental context:

- Rainfall patterns and seasonal variation guide the timing of olivine application and dashboard calibration intervals.
- Soil pH maps and legacy nutrient profiles inform AI model training and application dose optimization.
- Access to local olivine or dunite sources influences transport logistics and carbon breakeven thresholds.

Outreach Strategy

To support growth, KAS Lab is pursuing the following outreach structure:

- Collaboration with public agricultural extension agencies for farmer training and certification.
- Partnership with existing cooperatives for kit distribution and pooled carbon offset registration.
- Deployment of region-specific AI dashboards with localized default soil chemistry models and calibration datasets.
- Support for multi-lingual documentation and open licensing to ensure equitable access in under-resourced areas.

Summary

By leveraging decentralized deployment, local training, and cloud-based analytics, the KAS Farm Soil Lab is designed for adaptable scaling across both developed and developing agricultural economies. Its modular approach and science-grounded architecture enable it to meet regional needs while upholding rigorous standards for soil health monitoring and mineral carbon sequestration.

7 Conclusion

The KAS Farm Soil Lab represents a paradigm shift in how climate-smart agriculture can be implemented directly at the farm level. It offers a decentralized, scientifically grounded system that empowers farmers to monitor, manage, and improve their soil while simultaneously contributing to verified carbon dioxide (CO_2) removal through enhanced mineral weathering.

Olivine (Mg_2SiO_4) serves as the central geochemical agent in this system. Its weathering not only reduces soil acidity and supplies essential nutrients like magnesium and silica, but also captures atmospheric CO_2 in a stable, long-lived bicarbonate form. This positions olivine as a uniquely effective dual-purpose input—supporting both agronomic productivity and climate mitigation.

When paired with AI-powered analytics and real-time data collection via portable lab kits, the system enables granular insight into soil health parameters such as pH, Mg^{2+} levels, and CO_2 efflux. These tools allow for precision decision-making, optimized input application, and evidence-based reapplication cycles. Furthermore, they support compliance with emerging MRV (Measurement, Reporting, and Verification) frameworks, which are essential for participation in carbon offset markets.

Economically, the KAS Farm Soil Lab reduces farmers' dependence on costly synthetic inputs by enabling better soil stewardship and unlocking new revenue streams through carbon finance. Socially, it reinforces farmer autonomy by equipping them with open-source diagnostics and training resources, making climate farming both accessible and equitable.

Strategically, the lab aligns with major policy goals in regenerative agriculture, decentralized innovation, and just transitions for rural communities. Its modular architecture allows it to scale across diverse ecosystems, from Mediterranean vineyards to Midwestern row crops to tropical smallholder plots—each adapting to local constraints while sharing a common foundation of science, sustainability, and sovereignty.

In summary, the KAS Farm Soil Lab is not just a tool, but an integrated platform for grassroots climate action. By merging the durability of mineral-based carbon removal with the intelligence of AI diagnostics and the agency of farmer-led implementation, it offers a replicable model for building climate resilience from the ground up.

References

[1] Jens Hartmann, AJ West, Phil Renforth, Peter Köhler, Christina L De La Rocha, Dieter A Wolf-Gladrow, Hans H Dürr, and Jürgen Scheffran. Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Nature Climate Change*, 3(1):45–49, 2013.

[2] M. E. Kelland et al. Enhanced weathering of olivine as a carbon dioxide removal strategy. *Nature Communications*, 11(1):1–10, 2020.

[3] LL Taylor, J Quirk, RM Thorley, P Kharecha, J Hansen, and DJ Beerling. Mineral weathering and its potential role in carbon sequestration and ecosystem services. *Environmental Science & Technology*, 50(10):5606–5615, 2016.

[4] Jens Hartmann et al. Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Reviews of Geophysics*, 51(2):113–149, 2013.

[5] H. F. ten Berge, H. G. van der Meer, J. W. Steenhuizen, P. W. Goedhart, P. Knops, and J. Verhagen. Olivine weathering in soil, and its effects on growth and nutrient uptake in ryegrass (*Lolium perenne* l.): a pot experiment. *PLOS ONE*, 7(8):e42098, 2012.

[6] Independent Agricultural Advisors. Portable soil lab kits for farmer-owned monitoring, 2023. Available in: oviline and Farmland.rtf.

[7] S. Boogaard. Co2 sequestration by olivine for different applications in knowledge mile park. *University of Amsterdam*, 2021.

[8] Puro.earth. Enhanced rock weathering cdr methodology. *Puro.earth Blog*, 2023.

[9] Verra. Enhanced rock weathering: Draft methodology for cdr verification. `https://verra.org/methodologies`, 2023. Accessed via Verra methodology documentation.

[10] Ioannis P. Adamopoulos, Antonios Valamontes, John T. Karantonis, Nikoleta F. Syrou, Ioanna Damikouka, and George Dounias. The impact of pfas on the public health and safety of future food supply in europe: Challenges and ai technologies solutions of environmental sustainability. *European Journal of Sustainable Development Research*, 9(2):em0288, 2025.

[11] Eion. There's no carbon farming without the farmer. *Eion Carbon*, 2025.

[12] Antonios Valamontes. Kas farm soil lab mrv design architecture. Internal technical architecture notes, Kapodistrian Academy of Science, 2025. Used with permission in official documentation.

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