Developing low-cost soil health and carbon indicators in West African cocoa plantations

Third Year Student Progress Report

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By

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Background and rational

Cocoa, a vital commodity and cash crop, supports the livelihoods of 5–6 million smallholder farmers across tropical countries such as Ghana and Côte d'Ivoire. It is a key driver of economic growth in many rural regions, particularly in West Africa. However, cocoa production faces numerous challenges that threaten the sustainability of its value chain. These challenges include climate change, soil erosion, declining soil health, and significant greenhouse gas emissions from agrochemical inputs, all contributing to environmental degradation at both field and catchment scales. Declining soil productivity often drives agricultural expansion into forested areas, leading to substantial carbon losses and catchment-wide pollution. Addressing these issues requires not only halting further degradation but also urgently measuring and enhancing carbon storage and soil health in already converted areas.

Effective soil health indices must correlate with specific soil functions, respond to management practices, be accessible and interpretable by users, cost-effective, applicable across diverse management systems, and scalable from field to national levels to align with climate change mitigation and adaptation goals.

While soil health indices have been developed for various agricultural systems, particularly annual temperate crops, there is limited work on perennial ecosystems like cocoa. This gap highlights the need to integrate low-cost measurement approaches, such as near-infrared reflectance spectroscopy (NIRS) and semi-quantitative test strips, with conventional methods. These approaches require minimal soil preparation, use little to no chemicals, and offer significant advantages in supporting timely and spatially informed soil health management decisions, thereby promoting sustainable cocoa production.

Enhancing carbon storage in cocoa systems is also critical for improving the sustainability of cocoa farming and contributing to climate change mitigation. Over the years, various interventions such as adopting agroforestry systems and regenerative agricultural practices (e.g., reduced agrochemical use, organic management, and shade control) have been proposed to enhance carbon storage in cocoa systems. However, questions remain about how management practices, including shaded and unshaded cocoa systems, as well as plantation age, influence carbon flows and soil health in cocoa systems.

Despite growing recognition of the importance of carbon dynamics in cocoa systems, there is limited understanding of how shading systems and plantation age regulate carbon inputs and losses. While some studies have examined carbon sequestration in cocoa agroforestry, comprehensive research evaluating the interaction between shading practices, plantation age, and carbon flux pathways is still lacking. This study aims to fill this knowledge gap by assessing how different shading systems (e.g., monoculture vs. shaded cocoa) and plantation age influence carbon input and loss pathways. It also seeks to develop simple carbon budgets to determine the overall carbon balance of cocoa plantations and explore the potential of cocoa agroforestry systems to mitigate climate change through enhanced carbon sequestration. By investigating the relationships between shading, plantation age, and carbon flows, this research will provide valuable insights for improving cocoa production practices, supporting sustainable land-use management, and contributing to global climate change mitigation efforts through enhanced carbon management in agricultural systems.

The objectives of the research are to;

1. Identify and develop low-cost indicators for monitoring carbon and soil health in cocoa farms.
2. Assess the role of time under management in accounting for the spatial and temporal heterogeneity of carbon flows and soil health.
3. Use the DNDC (DeNitrification-DeComposition) model to assess the resilience of carbon storage and upscale.

Progress made in the second year.

Objective 1.

In the first year, soil samples were collected from 72 cocoa farms in 6 cocoa districts spanning four administrative regions of Ghana. To guide the selection of farms for the collection of soil samples for the development of the soil health index (SHI), three factors were considered. These factors were agroecological zones, management practices, and the age of cocoa farms. Management practices comprising shaded and unshaded cocoa systems and ages of cocoa farms made up 0-5, 6-10, 11-20, and 20 years and above were considered.

In the second year, soil samples were collected in Côte d'Ivoire from cocoa plantations in three key cocoa-producing regions: the eastern, central, and western parts of the country. Samples were collected from both shaded and unshaded cocoa farms of varying ages (1-5, 6-10, 11-20, and 20+ years).

In the third year of the project, I completed the analysis and spectral readings of all soil samples. Following this, the data was subjected to chemometric analysis where raw soil reflectance spectra were pre-processed to remove baseline shifts, scattering effects and high-frequency noise before calibration of model. I then used partial least squares regression (PLSR) to link the pre-processed spectral data to the measured soil properties following protocols for multivariate calibration in soil spectroscopy to develop models for predicting soil parameters. To ensure reliable predictions, standard statistical methods were used to evaluate model performance. Only models that met widely accepted performance criteria were selected for predicting soil parameters. Following the predictions, a standard approach was used to identify a smaller set of soil health indicators that captured most of the important information from the full dataset. Indicators that were closely related were carefully reviewed, and only the most representative ones were retained. The selected indicators were then converted to scores on a common scale using established rules. These scores were then combined to develop the final soil health index.

Objective 2.

In the first year, I established the monitoring plots in 8 cocoa plantations made up of 2 management practices (Shaded and Unshaded) and 4 ages of 5, 10, 15 and 20 year old cocoa plantations. In each cocoa farm, a triplicate of 20 x 20 m plots was established for monitoring the carbon flows. To assess carbon inputs, litter traps, and root in-growth were installed in the plots to collect litter falls and root productivity respectively. The above-ground biomass of the farms would be assessed by scanning the farms using a laser scanner. For carbon losses, tree, autotrophic, and heterotrophic respirations were measured using the EGM-5 infra-red gas analyser. Open and closed mesocosms were used to assess autotrophic and heterotrophic respiration respectively. Field measurements and sample collection were taken every 3 months for 18 months.

For year 2 and 3, field measurements and sample collections were undertaken in February, May, August, December 2024 and June 2025. At each field visit, total and autotrophic soil respiration were measured using an EGM-5 infrared gas analyzer from the open and closed mesocosms installed in the first year. Also, all litter within the litter traps was collected and placed in appropriately labelled bags (indicating site, plot, date, and measurement point number) and transported to the laboratory. Fine root biomass was also recovered from the installed root in-growth cores, washed to remove soil particles and gravel, and placed in labelled paper envelopes. These samples were oven-dried at 60°C for 48 hours until a constant mass was achieved. The dried samples were then weighed to determine litterfall and fine root biomass production rates. These samples were further analysed for carbon and nitrogen content to quantify carbon and nitrogen inputs into the cocoa system. During the June 2025 field visit, Ian Truckell, an expert from Cranfield University helped in scanning the various cocoa farms used for the study using terrestrial laser scanner (TLS) for estimating the above ground biomass of the plantations. Below are some photos documenting the implementation of Objective 2.



Objective 3.

For objective 3, I am using the data collected from the objective 2 to parameterise the DNDC model to simulate CO_2 fluxes as well as cocoa productivity. The input data for the model will include the climatic data, soil parameters as well as biomass productions for grain, leaf, stem and root for the study locations. I will then compare the simulated and measured parameters and will use metrics such as coefficient of determination (R^2), root mean square error (RMSE) and Nash efficiency (NSE) to evaluate the performance of the model.

Potential impact of the project

Soil Health Assessment: The study demonstrates that Near-Infrared (NIR) spectroscopy can accurately predict key soil indicators to develop Soil Health Index (SHI) that provides a holistic measure of soil condition. These tools enable rapid, cost-effective, and scalable soil monitoring, supporting data-driven management decisions and region-specific interventions in cocoa agroecosystems. This results when transferred, will enable farmers to evaluate soil health and fertility using low-cost measurement approaches to make informed investments for the necessary inputs to maintain and enhance soil health, ultimately increasing cocoa yields and improving their income and livelihoods.

Carbon Sequestration and Climate Change Mitigation: The study corroborates the role of shaded cocoa systems in carbon sequestration, making it a viable strategy for mitigating climate change. Policymakers and climate initiatives can use this evidence to promote agroforestry as part of carbon offset programs and sustainable land-use planning.

Sustainable Agriculture and Land Management: The trade-off between higher cocoa yield in unshaded systems and better carbon balance in shaded systems informs strategies for balancing productivity and sustainability. Farmers may adopt mixed approaches, integrating shade trees to enhance soil health and long-term carbon storage while optimizing yield.

Soil Conservation and Ecosystem Resilience: The findings of higher litter fall and fine root biomass in shaded systems suggest improved soil organic matter and nutrient cycling. This could enhance soil fertility, reducing dependency on chemical fertilizers and improving long-term land productivity.

Economic and Policy Implications: Governments and NGOs can develop incentive programs such as carbon credits and subsidies to encourage shaded agroforestry adoption for cocoa production. Additionally, certification schemes like Rainforest Alliance and Fair Trade can integrate these findings to promote climate-smart cocoa farming.

Capacity Building: The project will enhance my expertise in cocoa production systems, soil health indices development, carbon flows in cocoa systems, and modelling. With this enhanced capacity, I am better equipped to contribute to sustainable cocoa production.