The Effect of Nutrient Management on Organic Matter and Microorganisms in Soils of Tropical and Temperate Agroecosystems

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Introduction and context

Agricultural intensification over the past century, while boosting productivity, has resulted in significant environmental degradation including soil compaction, erosion, loss of organic matter, and reduced biodiversity. These "negative externalities" threaten food production systems worldwide, particularly in tropical regions where smallholder farmers face mounting challenges from climate change and soil degradation. Soil organic carbon (OC) serves as a fundamental indicator of agroecosystem stability, contributing to drought resilience, structural stability, and stable crop yields. While approximately 50% of global soil OC stocks are located below 30 cm depth, agricultural research has predominantly focused on surface soils (0-30 cm), leaving the subsoil critically understudied. This research gap is particularly problematic given that most plant roots extend below 30 cm depth and subsoil OC has residence times spanning decades to millennia, making it crucial for long-term OC sequestration and climate mitigation. Central to these soil processes is the soil microbiome, which encompasses microorganisms that drive virtually all biogeochemical processes in soil, including OC decomposition and nutrient cycling. Yet our understanding of how agricultural practices influence these microbial communities in deeper soil layers remains limited, especially in tropical smallholder farming contexts where livestock integration could provide essential manure inputs to build soil organic matter, improve soil structure and increase biodiversity. This knowledge gap hinders developing management strategies that optimize soil biology along the rooting zone to improve crop productivity and environmental sustainability. The results of this thesis, performed in collaboration with IITA (International Institute for Tropical Agriculture), Agroscope and FiBL, demonstrate that microbial communities are more sensitive indicators of management impacts than carbon stocks, reveal depth-stratified microbial life strategies, and show that surface practices- particularly livestock integration and manure application - significantly influence the subsoil environment. These findings challenge the surface-focused paradigm in soil science and reveal the untapped potential of subsoil management, especially through integrated crop-livestock systems.

Research objectives and questions

This PhD research aimed to understand how agricultural management practices, particularly nutrient management, affect soil OC stocks and the soil microbiome down to 70-90 cm depth in two long-term field trials across temperate and tropical environments. This research addressed three key questions: (1) To what depth do organic residue applications affect soil OC stocks? (2) How do different organic residues affect soil microbial community composition along the depth profile? And (3) How do organic and conventional cropping systems influence taxonomic composition and genetic potential of soil microbiomes across depth gradients?

Approach and methods

This research utilized soil samples from two long-term field trials in contrasting climatic regions. The first was the SOM trial in Kenya, a tropical maize monoculture with different organic (farmyard manure, *Tithonia diversifolia* residues, and maize stover residues) and inorganic fertilizer treatments. The second trial was the DOK trial in Switzerland, a temperate complex cropping system comparing organic and conventional farming practices. Soil samples were collected in 5 cm increments down to 70-90 cm depth, providing high-resolution detail on the depth-specific responses of soil organic matter and the soil microbiome to management practices. Analytical methods included soil OC quantification using dry combustion, and microbial community analysis via metabarcoding (16S rRNA for bacteria, ITS for fungi), and shotgun metagenomics to assess functional genetic potential.

Key results

Agricultural management influence on subsoil characteristics varied substantially between field trials, depending on soil physical barriers, the type of residue, and local environmental conditions. This highlights the importance of context-specific management approaches. Our findings demonstrated that management practices can significantly affect soil properties beyond the conventionally studied 0-30 cm depth, with livestock-derived manure emerging as the most influential amendment throughout the entire soil profile.

Depth-dependent soil OC responses: In the Kenyan field trial, the application of manure significantly increased soil OC stocks down to 60 cm depth, while plant residues (*Tithonia*, maize stover) only affected the top 20-40 cm. Manure application was the only treatment to significantly affect the subsoil (30-70 cm) OC stocks, demonstrating its superior capacity to influence deeper soil layers, compared to the other amendments.

Microbial community sensitivity: Microbial community composition proved more sensitive to management practices than OC stocks, with effects detectable throughout the entire 70 cm profile even when differences in OC stocks between treatments were not statistically significant. All organic residues significantly affected bacterial and fungal communities down to 70 cm depth in the Kenyan trial, while agricultural practices in the Swiss trial affected bacterial communities only in the topsoil but influenced fungal communities down to 70 cm. These findings suggest that microbial community composition may provide a more sensitive early warning system for detecting management impacts on soil health than traditionally measured carbon stocks.

Functional adaptation strategies: Metagenomic analysis revealed distinct microbial life strategies across the soil profile of the Swiss field trial. Topsoil microbial communities exhibited dual characteristics of both fast-growing copiotrophs and slow-growing oligotrophs with environmental response capabilities, while subsoil communities were dominated by specialized oligotrophs with enhanced nutrient recycling strategies adapted to resource scarcity. This vertical stratification of microbial life strategies suggests that different soil layers contribute distinct functional roles to overall ecosystem processes, with implications for understanding how management practices may differentially impact nutrient cycling at various depths.

Relevance for development and achievement of SDGs

By demonstrating that agricultural management effects extend deeper than conventionally studied, this research opens new possibilities for managing the soil as a complete ecosystem rather than just a surface phenomenon, ultimately contributing to more resilient and productive food systems worldwide by achieving multiple Sustainable Development Goals (SDGs), addressing food security, climate mitigation, and ecosystem health simultaneously.

SDG 2 (Zero Hunger): By demonstrating how different agricultural management practices affect soil OC and microbial diversity throughout the soil profile, this research revealed that subsoil environments are significantly influenced by surface management. This is a crucial step toward the development of sustainable intensification strategies, as it indicates that land management efforts such as applying manure extend their benefits to subsoil layers, where deep plant roots increase crop access to water and nutrients. This information becomes increasingly important as plant breeding programs worldwide are focusing on developing deeper root systems for enhanced drought resistance under climate change. Furthermore, the finding that manure application affects the subsoil is particularly relevant for smallholder farming systems in Sub-Saharan Africa, where integrated livestock management and manure recycling can simultaneously enhance soil fertility and food security.

SDG 13 (Climate Action): This research reveals which agricultural management practices are more likely to reduce OC losses in the form of CO_2 from tropical and temperate arable soils. Understanding these dynamics is crucial for developing climate change mitigation strategies through improved soil OC management.

SDG 15 (Life on Land): The detailed characterization of microbial life history strategies along the soil profile and the responses of the microbial community structure to agricultural management provides fundamental ecological knowledge essential for assessing and preventing soil ecosystem degradation and restoring degraded landscapes. For example, the characterization of microbial life history strategies along the soil profile can serve as reference points to assess the extent of microbial gene pool changes in degraded soils and guide targeted restoration efforts.