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How trees shape soil carbon stabilisation in smallholder silvopastoral systems in Colombia

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Abstract

Colombia is promoting silvopastoral systems (SPS) as part of its climate mitigation and land restoration agenda, yet the belowground outcomes of smallholder SPS—where tree cover and management vary widely—remain poorly quantified, especially in the first decade after establishment. We studied 10 smallholder SPS (5–12 years old) in the Colombian Amazon to assess where soil carbon accumulates and whether tree-derived inputs are entering more persistent soil pools. Soils were sampled at two depths (0–10 and 10–30 cm) along transects extending from trees into pasture (1–25 m). We combined aggregate fractionation and natural-abundance ¹³C to trace C3-derived carbon across aggregate fractions, used mixed-effects models to test spatial and farm-level influences, and drew on semi-structured interviews to contextualize management and implementation challenges. Bulk SOC stocks showed only modest spatial variation with distance from trees. In contrast, partitioning SOC into aggregate fractions revealed a clear tree signal: the C3-derived fraction declined non-linearly with distance from trees, with the steepest change occurring close to trees. C3-derived carbon was relatively enriched in finer fractions (silt-clay and, in subsoil, microaggregates), suggesting early movement of tree-derived inputs into more physically protected pools. Aggregate fraction strongly structured SOC stocks across depths, with most aggregate-associated SOC held in macro- and mesoaggregates. Variation among farms in C3-derived outcomes was partly associated with greater tree abundance and larger crown radius. Interviews identified high tree mortality as a major implementation bottleneck, highlighting the need for continued support to improve tree establishment and retention. Together, these results show that even within the first decade, smallholder SPS can generate detectable, spatially patterned shifts in SOC origin and stabilisation pathways, but realising durable soil carbon gains will depend on management and support that maintain tree cover over time.

Keywords: Aggregate fractionation, Amazon, C3-derived carbon, carbon isotopes, carbon stabilisation, Colombia, livestock systems, silvopastoral systems, smallholder systems, soil organic carbon, tree management, tropics