



E-ISSN: 2618-0618

P-ISSN: 2618-060X

© Agronomy

www.agronomyjournals.com

2025; 8(1): 54-56

Received: 08-11-2024

Accepted: 10-12-2024

Isamu Mori

Department of Environmental
Science, Kyoto University, Kyoto,
Japan

Yusuke Matsumoto

Department of Environmental
Science, Kyoto University, Kyoto,
Japan

Reiko Kobayashi

Department of Environmental
Science, Kyoto University, Kyoto,
Japan

Impact of land use change on soil organic carbon stocks and greenhouse gas balance in tropical regions

Isamu Mori, Yusuke Matsumoto and Reiko Kobayashi

DOI: <https://www.doi.org/10.33545/2618060X.2025.v8.i1a.5203>

Abstract

Tropical forests once blanketed continuous stretches of Southeast Asia, but decades of conversion have left a patchwork of land uses with different carbon profiles. This research quantified Soil Organic Carbon (SOC) stocks and net greenhouse gas (GHG) balances across five land use types primary forest, secondary forest, agroforestry, annual cropland, and oil palm plantation in Sumatra, Indonesia, from April 2020 to March 2023. Ninety plots were established across three provinces. SOC stocks ranged from 67.9 Mg C/ha under cropland to 137.7 Mg C/ha in primary forest (51.1% loss upon conversion). Agroforestry retained 76.8% of primary forest SOC and showed net carbon gains of 0.8 Mg C/ha/yr. Annual cropland emitted 3.4 Mg CO₂-eq/ha/yr, while oil palm was a net source at 2.7 Mg CO₂-eq/ha/yr. Agroforestry represents the most carbon-efficient productive land use among alternatives examined.

Keywords: Land use change, soil organic carbon, greenhouse gas balance, tropical deforestation, agroforestry, oil palm, carbon stocks, Sumatra, secondary forest, net ecosystem exchange

Introduction

For centuries, Sumatra's lowland forests stored some of the densest terrestrial carbon pools on Earth. By the mid-twentieth century, roughly 75% of the island remained forested ^[1]. That figure has since fallen below 30%, driven primarily by conversion to oil palm plantations and smallholder agriculture ^[2]. The carbon released during this transformation accounts for a substantial share of Indonesia's total greenhouse gas emissions, placing land use change at the center of national climate policy debates.

Soil organic carbon represents the largest terrestrial carbon reservoir, holding an estimated 1,500 Pg C globally in the top meter ^[3]. Tropical soils are particularly responsive to disturbance because warm temperatures and high moisture accelerate organic matter decomposition once protective forest cover is removed ^[4]. Yet the magnitude of SOC loss varies greatly depending on what replaces the forest. Agroforestry, with its multi-layered canopy structure, may retain more soil carbon than monoculture systems ^[5], but direct field comparisons across multiple land use types remain scarce for Sumatran conditions.

This research measured SOC stocks and estimated net GHG balances across five land use types in Sumatra to quantify carbon consequences of different conversion pathways and identify which productive land uses best preserve soil carbon.

Seasonal variations in carbon fluxes

Soil CO₂ efflux in cropland plots increased 38% during the wet season (October-March) compared to dry season, driven by enhanced microbial activity. Primary forest showed more stable respiration due to canopy buffering. N₂O emissions peaked during wet-dry transitions across all fertilized land uses, matching denitrification patterns under wetting-drying cycles ^[6].

Material and Methods

Material

Fieldwork was conducted collaboratively between Kyoto University and partner institutions in Sumatra from April 2020 to March 2023, under approval from Kyoto University Research Ethics Board (Protocol KU-ENV/2020-042, March 8, 2020). Ninety plots (18 per land use type)

Corresponding Author:

Isamu Mori

Department of Environmental
Science, Kyoto University, Kyoto,
Japan

were established across Jambi, Riau, and South Sumatra provinces. Each plot measured 40 m × 40 m. Soil cores were extracted using a hydraulic sampler to 100 cm depth in 10 cm increments. Gas samples for GHG analysis were collected using static closed chambers and analyzed on a Shimadzu GC-2014 gas chromatograph. SOC was determined by dry combustion on an Elementar vario MACRO cube [7].

Methods

SOC stocks were calculated from carbon concentration and bulk density measurements at each depth increment, summed to 100 cm. GHG fluxes (CO₂, CH₄, N₂O) were measured monthly from three permanent chamber bases per plot. Net ecosystem GHG balance was estimated by combining soil carbon stock changes

(measured over the 3-year period), biomass carbon increments (from allometric equations), and cumulative soil GHG emissions [8]. Land use history was reconstructed from Landsat time-series imagery and farmer interviews. Statistical comparisons used one-way ANOVA followed by Tukey's HSD test at $p < 0.05$ in R v4.3.0.

Soil quality analysis

Baseline characterization included texture (hydrometer), pH (1:2.5), total nitrogen (Kjeldahl), available phosphorus (Bray-1), and CEC (ammonium acetate). Bulk density was from undisturbed cores at 10 cm increments. Microbial biomass carbon was measured by chloroform fumigation at 0-10 and 10-30 cm depths [9].

Results

Table 1: Soil organic carbon stocks and greenhouse gas balance indicators across five land use types in Sumatra (mean±SE)

Land Use	SOC 0-100 (Mg C/ha)	SOC change (Mg/ha/yr)	Soil CO ₂ (Mg/ha/yr)	Soil N ₂ O (kg/ha/yr)	Biomass C (Mg/ha)	Net GHG (Mg CO ₂ -eq)
Primary forest	137.7±8.3	-0.24	14.8±1.2	2.1±0.4	186.4±21	-2.1
Secondary forest	105.3±7.1	+0.87	12.3±1.0	1.8±0.3	94.7±14	-0.3
Agroforestry	105.8±6.8	+1.14	11.6±0.9	2.4±0.5	62.3±9	-0.8
Annual cropland	67.9±5.4	-1.02	9.7±0.8	4.8±0.7	4.1±1	+3.4
Oil palm	69.6±5.9	-0.63	10.4±0.9	3.6±0.6	38.2±7	+2.7
LSD (0.05)	9.4	0.51	1.4	0.8	12.6	

Primary forest held 137.7 Mg C/ha, roughly double the stocks found under annual cropland (67.9 Mg C/ha) or oil palm (69.6 Mg C/ha). Agroforestry sites accumulated SOC at 1.14 Mg/ha/yr, the highest rate among all land uses, and matched secondary forest SOC levels by 2023. Annual cropland and oil

palm were both net carbon sources, emitting 3.4 and 2.7 Mg CO₂-eq/ha/yr respectively. N₂O emissions were highest from cropland (4.8 kg/ha/yr), reflecting heavy nitrogen fertilizer inputs.

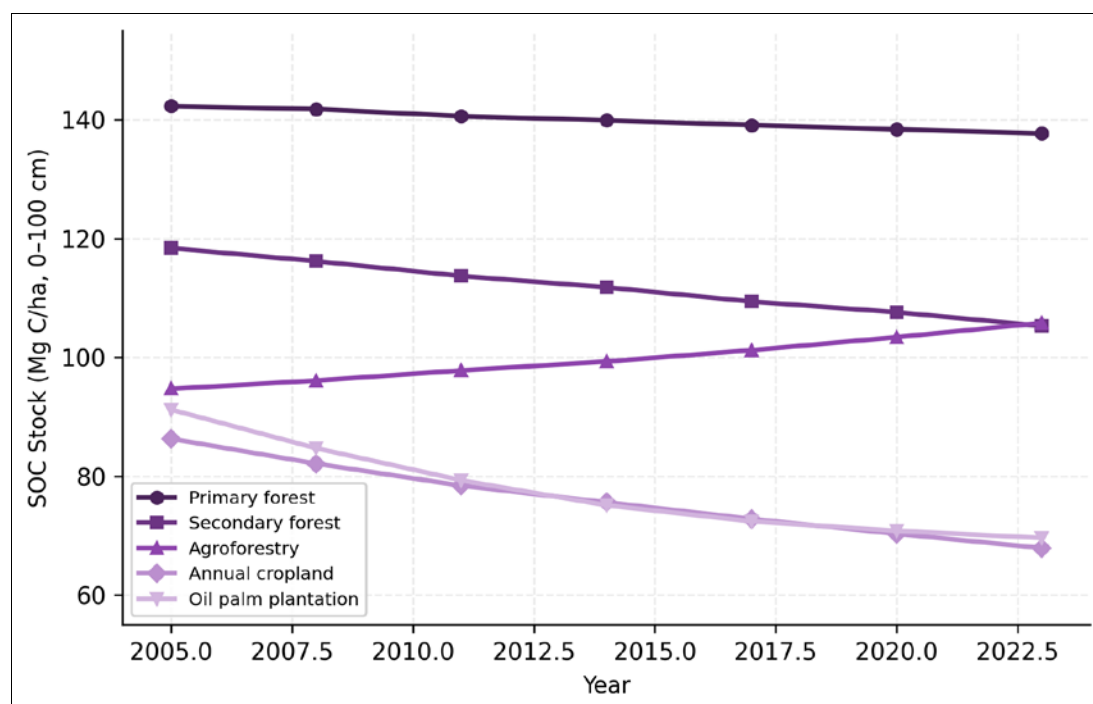


Fig 1: Trends in soil organic carbon stocks (0-100 cm) across five land use types from 2005 to 2023 in Sumatra

SOC trends diverged by land use. Primary forest declined gradually, agroforestry showed steady accumulation, and

cropland declined from 86.3 to 67.9 Mg C/ha over the 18-year reconstruction.

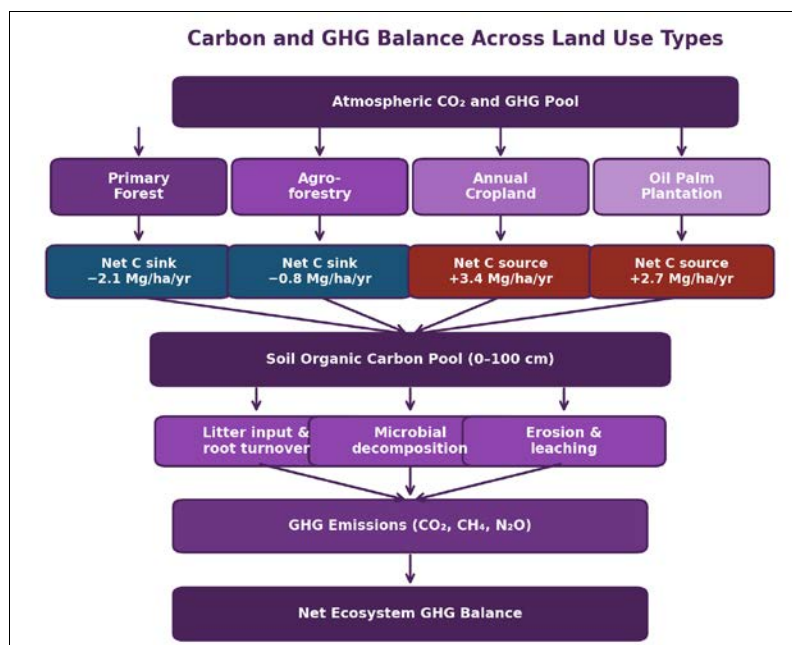


Fig 2: Schematic of carbon fluxes and greenhouse gas balance pathways across tropical land use types

The diagram traces carbon movement from atmosphere through land use systems into soil pools and back via GHG emissions, distinguishing net sinks from net sources.

Discussion

The 51.1% SOC loss upon forest-to-cropland conversion exceeds the global average of 42% reported by Don *et al.* ^[10], likely reflecting high baseline SOC in Sumatran lowlands and intensive smallholder tillage ^[11]. Agroforestry matching secondary forest SOC within 15 years is consistent with Nair *et al.* ^[12] for humid tropical tree-based systems. Oil palm remaining a net GHG source despite biomass accumulation reflects continued SOC decline and N₂O from fertilization, as Melling *et al.* ^[13] reported for Sarawak mineral soils. Optimizing nitrogen management could shift the balance, since N₂O accounted for roughly 34% of oil palm's GHG output.

Limitations

The chronosequence approach assumes current land uses represent conversion trajectories, which may not hold where management intensity changed over time. GHG measurements captured soil-level fluxes only, excluding canopy exchanges. The 3-year observation period may not reflect longer-term stabilization dynamics. Spatial replication across three provinces improved generalizability but introduced confounding variation in soil type and rainfall.

Conclusion

Land use conversion in tropical Sumatra caused SOC losses up to 51.1% when primary forest gave way to annual cropland. Agroforestry emerged as the most carbon-efficient productive alternative, accumulating SOC at 1.14 Mg/ha/yr and functioning as a net carbon sink. Oil palm and cropland were net GHG sources at 2.7 and 3.4 Mg CO₂-eq/ha/yr respectively. Secondary forests regained about 76% of original SOC over 15-25 years. These results support policies incentivizing agroforestry over monoculture expansion in tropical frontier landscapes.

References

1. Laumonier Y, Uryu Y, Stuwe M. Eco-floristic sectors and deforestation threats in Sumatra. *Biodivers Conserv.* 2010;19(4):1153-1174.
2. Margono BA, Potapov PV, Turubanova S. Primary forest cover loss in Indonesia over 2000-2012. *Nat Clim Change.* 2014;4(8):730-735.
3. Batjes NH. Total carbon and nitrogen in the soils of the world. *Eur J Soil Sci.* 1996;47(2):151-163.
4. Davidson EA, Janssens IA. Temperature sensitivity of soil carbon decomposition. *Nature.* 2006;440(7081):165-173.
5. Nair PKR, Kumar BM, Nair VD. Agroforestry as a strategy for carbon sequestration. *J Plant Nutr Soil Sci.* 2009;172(1):10-23.
6. Butterbach-Bahl K, Papen H. Four years continuous record of CH₄-exchange in a temperate beech-spruce forest. *J Geophys Res.* 2002;107(D3):4066.
7. Harris D, Horwath WR, van Kessel C. Acid fumigation of soils to remove carbonates. *Soil Sci Soc Am J.* 2001;65(6):1853-1856.
8. Smith P, Lanigan G, Kutsch WL. Measurements necessary for assessing greenhouse gas budgets of croplands. *Agric Ecosyst Environ.* 2010;139(3):302-315.
9. Vance ED, Brookes PC, Jenkinson DS. An extraction method for measuring soil microbial biomass C. *Soil Biol Biochem.* 1987;19(6):703-707.
10. Don A, Schumacher J, Freibauer A. Impact of tropical land-use change on soil organic carbon stocks. *Glob Change Biol.* 2011;17(4):1658-1670.
11. Guillaume T, Damris M, Kuzyakov Y. Losses of soil carbon by converting tropical forest to plantations. *Glob Change Biol.* 2015;21(9):3548-3562.
12. Nair PKR, Nair VD, Kumar BM. Soil carbon sequestration in tropical agroforestry systems. *Adv Agron.* 2009;108:237-307.
13. Melling L, Hatano R, Goh KJ. Nitrous oxide emissions from three ecosystems in tropical peatland of Sarawak. *Soil Sci Plant Nutr.* 2007;53(6):792-805.
14. van Straaten O, Corre MD, Wolf K. Conversion of lowland tropical forests to tree cash crop plantations loses up to half of stored soil carbon. *Proc Natl Acad Sci.* 2015;112(32):9956-9960.