Evaluating Long Term Soil Organic Matter Dynamics on Cocoa Farms in Indonesia

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Cocoa yields are suboptimal

One cause: **progressive soil fertility decline**

**Soil organic matter** (SOM) is a cornerstone of tropical soil fertility

Characterizing **SOM dynamics** is a critical step to:
- Determine **soil fertility trends** in cocoa farms
- Meet the **climate mitigation goals** of the cocoa industry
Research aims and objectives

Individual objectives:

1. Assess temporal variations of C storage in cocoa systems by analyzing available data.
2. Compare the effects of soil inputs on soil and cocoa.
3. Characterize SOM dynamics on a chronosequence.
4. Describe and predict SOM dynamics by using a modeling approach.
5. Propose a SOM management recommendation.
Methodological approach

**STUDY #1**
Meta-analysis: C storage in cocoa farms
- 37 references
- Analysis of temporal variations of C stocks

**STUDY #2**
Fertilizer and amendments field experiment
- Comparison of 8 treatments:
  - Mineral fertilizer
  - Compost
  - Dolomite
  - And their combinations

**STUDY #3**
SOM, C and N Chronosequence
- Set of 13 farms in Sulawesi
- Soil sampling & analysis (0-100 cm)
- Measurement of cocoa trunk sizes

**STUDY #4**
Modelling SOM long-term dynamics
- Adapt/develop a cocoa-soil model
- Backward/Forward modelling to forecast SOM variations
- “How much OM to offset SOM losses?”
Key findings to date

STUDY #1 Meta-analysis: C storage in cocoa farms

37 references

Farm plots distribution:
- 25 plots in Africa
- 189 in Asia/Oceania
- 243 in America

Mondelez dataset
Somarriba dataset
Cumulated mean C stocks

- 1. Aboveground shade
- 2. Aboveground cocoa
- 3. Litter
- 4. Roots
- 5. Soil

Key findings to date

STUDY #1 Meta-analysis: C storage in cocoa farms

Error bars represent standard errors
Key findings to date

STUDY #3 Chronosequence

SOM stock (adjusted LOI)

Soil organic matter stock (Mg ha⁻¹; 0-20 cm)

Location
- Mambu
- Pussu
- Pussui (forest)
- Tarengge

Age of the cocoa trees (years)

2022 International Symposium on Cocoa Research (ISCR), Montpellier, France
Key findings to date

STUDY #4 Modelling SOM long-term dynamics

Simulation of an “average cocoa farm”

Averages of the chronosequence dataset
Reverse modelling

Main missing information… the initial SOM content: Obtained by optimisation

2 different farms in Sulawesi
Key findings to date

Simulation using exogenous organic matter inputs (EOM)

Rate of input calculated to completely offset SOM losses

$k_1 =$ fraction of EOM remaining as SOM after one year (the rest is “respired”).

### EOM | Approximate $k_1$ | Reference
--- | --- | ---
Rice straw | 0.10 | Chabalier et al., 2006
Cattle manure | 0.30 | Chabalier et al., 2006
Goat manure | 0.50 | Montaigne et al., 2019
Ramial chipped wood | 0.70 | Montaigne et al., 2019
Biochar | 1.00 | Montaigne et al., 2019
Conclusions and Recommendations

Main findings
- Importance of SOM to support cocoa production
- Large variability in plant and soil C stocks
- Shade tree C = approx. 4x cocoa C
- High risk of SOM losses during early years after planting
- First stepping-stone to model SOM dynamics in cocoa systems

Main limitations
- Meta-analysis: lack of large dataset for Africa, methodological inconsistencies between studies
- Chronosequence: comparing different farms
- Modelling: validation dataset

Recommendations
- Target the first 3-5 years with high rates of organic inputs
- Take advantage of fast-growth shade trees and cover crops to generate SOM inputs
- Start a long-term experiment to calibrate and improve plant/soil models

Potential impact
- Development of decision-support tools and roadmaps to maintain and improve soil fertility and assess C sequestration in cocoa farms
- Reward farmers who contribute to carbon sequestration?
Thank you for your attention.
Key findings to date

Examples of methodological inconsistencies between the references

<table>
<thead>
<tr>
<th>Reference</th>
<th>refer to</th>
<th>C content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Owosu et al</td>
<td>C of tree parts including cocoa</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Leaves</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>Stem wood and branches</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>Coarse roots</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>Fine roots</td>
<td>0.44</td>
</tr>
<tr>
<td>Leuschner et al (2013)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stem wood and branches</td>
<td>0.47</td>
</tr>
<tr>
<td>Rajab et al (2016)</td>
<td>Stem wood and branches</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>Coarse roots</td>
<td>0.44</td>
</tr>
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<td></td>
<td>Litter</td>
<td>0.45</td>
</tr>
<tr>
<td>Santhyami et al (2018)</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Smiley &amp; Kroschel (2008)</td>
<td>Aboveground and belowground biomass to carbon</td>
<td>0.45</td>
</tr>
<tr>
<td>Somarriba et al. (2013)</td>
<td>Aboveground and belowground biomass to carbon</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Various allometric equations to calculate C stocks

Various plant C contents

Missing bulk densities
### Table 2.3: Examples of allometric equations used in the references to estimate cocoa and shade tree biomass

<table>
<thead>
<tr>
<th>Targeted stock</th>
<th>Equation number</th>
<th>Allometric equation</th>
<th>Variables</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aboveground cocoa biomass</strong></td>
<td>Equation 2.3</td>
<td>$AB = WD \times CSA \times (L + 2.32PB)$</td>
<td>WD: average wood density (0.34 Mg m$^{-2}$). CSA: mean cross-sectional surface area of the trunk (in m$^2$). L: trunk length (in m). PB: number of primary branches.</td>
<td>Boyer (1973)</td>
</tr>
<tr>
<td></td>
<td>Equation 2.4</td>
<td>$AB = -0.0376 + (0.133 \times BA)$</td>
<td>BA: stem basal area at breast height (in cm$^2$).</td>
<td>Beer et al. (1990)</td>
</tr>
<tr>
<td><strong>Shade tree biomass</strong></td>
<td>Equation 2.5</td>
<td>$AB = e^{-2.334 + 1.83 \ln(D_{DBH})}$</td>
<td>DBH: diameter at breast height (in cm).</td>
<td>Brown, (1967)</td>
</tr>
<tr>
<td></td>
<td>Equation 2.6</td>
<td>$AB = e^{-2.557 + 0.946 \ln(D_{DBH})}$</td>
<td>$\rho$: wood specific gravity (in g cm$^{-3}$). D: stem diameter at breast height (in cm). H: total tree height (in m).</td>
<td>Leuschner et al. (2013)</td>
</tr>
<tr>
<td><strong>Aboveground Gliricidia biomass</strong></td>
<td>Equation 2.7</td>
<td>$AB = 0.1185 \times D^2$</td>
<td>D: stem diameter measured at breast height (in cm).</td>
<td>Foroughbakhch et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>Equation 2.8</td>
<td>$BB = 0.142 \times D^{2.064}$</td>
<td>D: stem diameter.</td>
<td>Smiley &amp; Kroschel (2008)</td>
</tr>
<tr>
<td><strong>Belowground biomass</strong></td>
<td>Equation 2.9</td>
<td>$BB = e^{-1.0007 + 0.6976 \ln(AB)}$</td>
<td>AB: aboveground biomass, dry (kg per tree).</td>
<td>Cairns et al. (1997)</td>
</tr>
</tbody>
</table>
Table 3.1: Breakdown of the treatments applied between 2012 and 2018 (adapted from Mullia et al., 2019)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>C</th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
<th>S</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>120.5</td>
<td>24.5</td>
<td>46.6</td>
<td>0</td>
<td>0</td>
<td>Trace</td>
</tr>
<tr>
<td>C</td>
<td>930</td>
<td>130</td>
<td>37</td>
<td>45</td>
<td>551</td>
<td>15</td>
<td>18</td>
</tr>
<tr>
<td>D</td>
<td>850</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1100</td>
<td>850</td>
<td>0</td>
</tr>
<tr>
<td>E</td>
<td>930</td>
<td>250.5</td>
<td>61.5</td>
<td>91.6</td>
<td>551</td>
<td>15</td>
<td>18</td>
</tr>
<tr>
<td>F</td>
<td>850</td>
<td>120.5</td>
<td>24.5</td>
<td>46.6</td>
<td>1100</td>
<td>850</td>
<td>Trace</td>
</tr>
<tr>
<td>G</td>
<td>1580</td>
<td>130</td>
<td>37</td>
<td>45</td>
<td>1651</td>
<td>855</td>
<td>18</td>
</tr>
<tr>
<td>H</td>
<td>1580</td>
<td>250.5</td>
<td>61.5</td>
<td>91.6</td>
<td>1651</td>
<td>855</td>
<td>18</td>
</tr>
</tbody>
</table>

Soil amendments and fertilizers were applied twice per year and per tree to provide total quantities as follows: 374 g NPK (‘Phonska’) and 225 g urea (mineral fertilizer), 5 kg dolomite, and 10 kg compost. Combinations (treatments E–H) were additive. The columns on the right show the total quantity of elements (g) provided per tree each year in each treatment. Phonska is a subsidized compound fertilizer made from three raw materials: urea, DAP (diammonium phosphate), rock phosphate, MOP (potassium chloride), and ‘other macronutrients’ according to the manufacturer (https://www.pupukkalim.com/en/distribution-product-product-knowledge). At the time of planting, mineral fertilizer, 100 g NPK (Phonska) and 150 g triple superphosphate (35%), was added to each tree in equal amounts to provide adequate and uniform nutrient conditions for the establishment of all plants in the first few months after planting out (Mulla et al., 2019).
Key findings to date

**STUDY #2** Fertilizer and amendments field experiment

**Cumulated productivity**
(kg of dry beans ha\(^{-1}\); 2015-2018)

**Annual productivity**
(kg of dry beans ha\(^{-1}\); 2015-2018)

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Mineral Fertiliser</td>
<td>Compost</td>
<td>Dolomite</td>
<td>B+C</td>
<td>B+D</td>
<td>C+D</td>
<td>B+C+D</td>
</tr>
<tr>
<td>Fert. + Compost</td>
<td>Fert. + Dolomite</td>
<td>Compost + Dolomite</td>
<td>Full mix</td>
<td></td>
<td></td>
<td></td>
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</table>
### Key findings to date

**STUDY #2**  Fertilizer and amendments field experiment

<table>
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<tr>
<th>A</th>
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<td>C+D</td>
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<tr>
<td></td>
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<td>Compost + Dolomite</td>
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</tr>
</tbody>
</table>

#### Change in soil properties

(comparison with Mulia et al. 2019, about 4 years later)

- **pH**
- **Organic C (%)**
- **Total N (%)**
- **C/N**
- **CEC (coul mol kg⁻¹)**
- **B8 (%)**
- **Extractable P (ppm)**
- **Available P (ppm)**
Key findings to date

**STUDY #3** Chronosequence

**Conceptual / Hypothetical SOM dynamics in cocoa farms**

1. At planting, there is a fixed soil SOM stock.
2. When cocoa trees are young, residue deposition is small.
3. As a result, the SOM stock should decline.
4. When cocoa trees become larger, plant inputs can offset/exceed losses.
5. This balance can result in SOM gains.
6. Ultimately, a new equilibrium can be reached.

The long-term trend depends on the local context and farm management.
Key findings to date

STUDY #3  C and N chronosequence

• 3 locations in Sulawesi
• 13 cocoa farms + 1 adjacent forest
• Ranging from 0.5 to 31 years old
• Trunk measurements (16 cocoa trees)
• Soil samples at 5 depths (0-100 cm)

### Location

<table>
<thead>
<tr>
<th>Location</th>
<th>Farm code</th>
<th>Age (years)</th>
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</thead>
<tbody>
<tr>
<td>Tarengge</td>
<td>A</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>G</td>
<td>15</td>
</tr>
<tr>
<td>Mambu</td>
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<tr>
<td></td>
<td>I</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>J</td>
<td>31</td>
</tr>
<tr>
<td>Pussui</td>
<td>K</td>
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</tr>
<tr>
<td></td>
<td>L</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>Forest</td>
<td>-</td>
</tr>
</tbody>
</table>

Same ages
Key findings to date

STUDY #3 Chronosequence

**Cocoa tree biomass accumulation pattern**

Based on Smiley & Kroschel (2008) Temporal change in carbon stocks of cocoa-glicidic agroforests in Central Sulawesi, Indonesia

Allometric relationship
Key findings to date

STUDY #3  C and N chronosequence

CONTENTS (%)

5 depths
3-5 samples per farm X depth
Key findings to date

Results adjusted for clay content

5 depths

3-5 samples per farm X depth
The model:
• Adaptation of the AMG soil model

Procedure:
1. Determine the initial SOM stock
2. Estimate SOM inputs
3. Estimate SOM outputs
4. Calculate the balance: SOM stock + inputs - outputs
5. Repeat every year
Key findings to date

STUDY #4 Modelling SOM long-term dynamics

Soil organic matter dynamics in cocoa
Model v1.2

- ✔ environmental effects on soil processes
- ❌ no environmental effects on cocoa growth
- ❌ no shade trees