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

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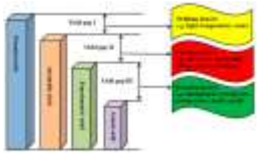
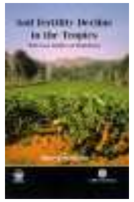
Context



- Cocoa yields are suboptimal

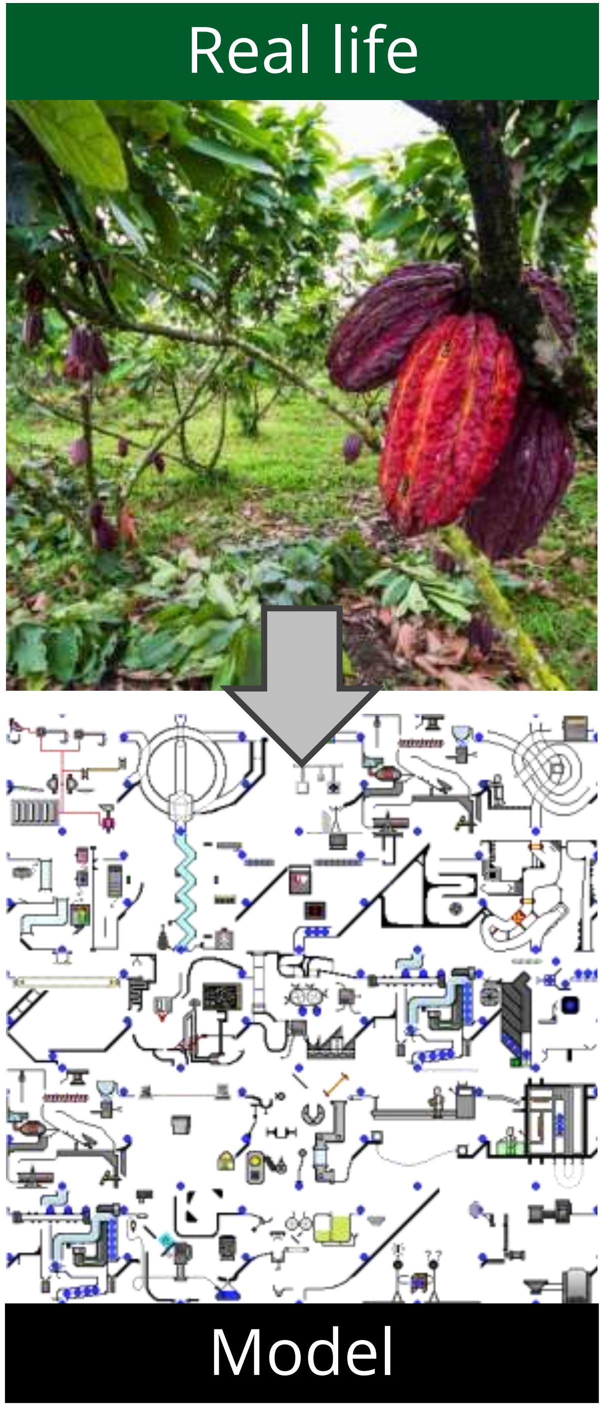


- One cause: **progressive soil fertility decline**

- **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:

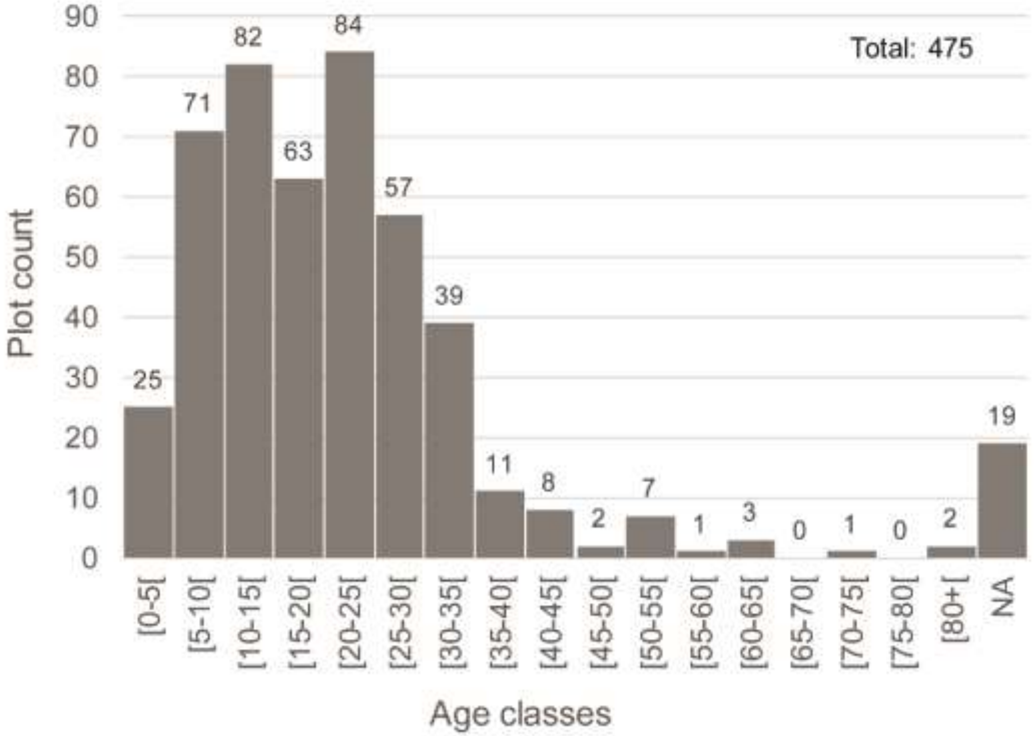
1. Assess temporal variations of C storage in cocoa systems by analyzing available data.
2. Compare the effects of soil inputs on soil and cocoa.
3. Characterize SOM dynamics on a chronosequence.
4. Describe and predict SOM dynamics by using a modeling approach.
5. Propose a SOM management recommendation.

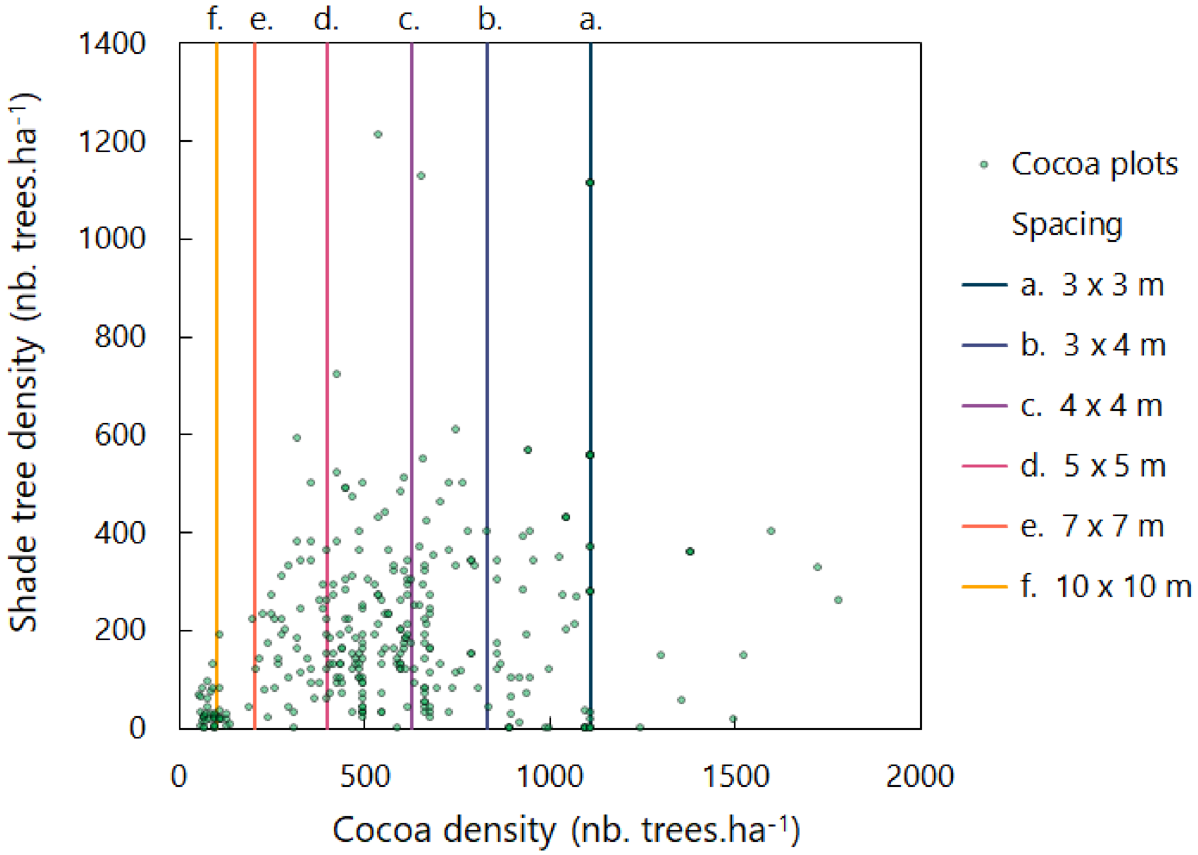
Methodological approach

STUDY #1	STUDY #2	STUDY #3	STUDY #4
Meta-analysis: C storage in cocoa farms	**Fertilizer and amendments field experiment**	**SOM, C and N Chronosequence**	**Modelling SOM long-term dynamics**
37 references Analysis of temporal variations of C stocks	Comparison of 8 treatments: • Mineral fertilizer • Compost • Dolomite • And their combinations	Set of 13 farms in Sulawesi Soil sampling & analysis (0-100 cm) Measurement of cocoa trunk sizes	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





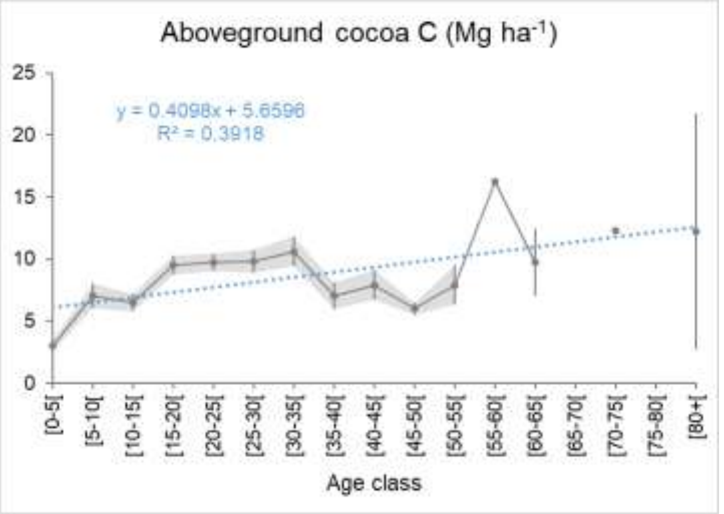
37 references

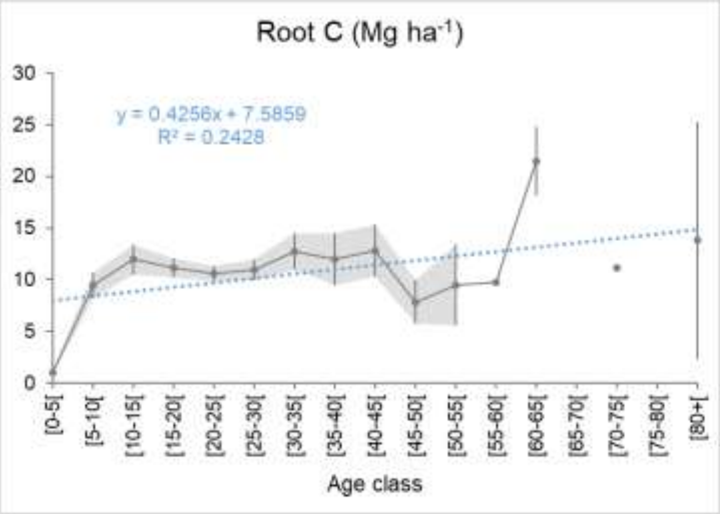
Farm plots distribution:

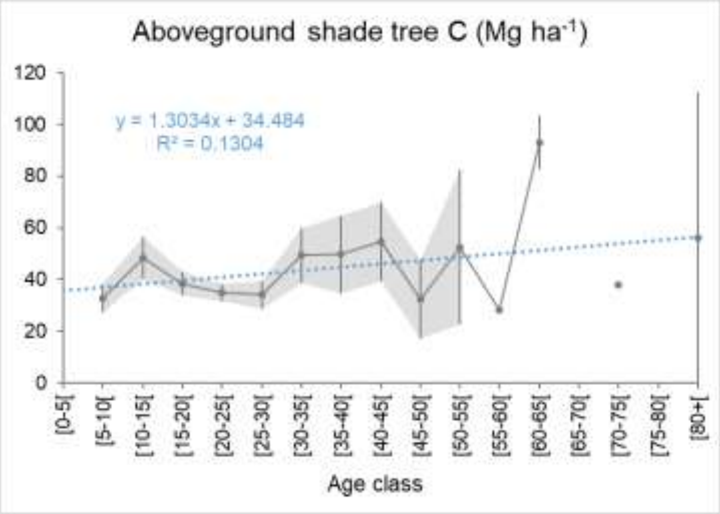
- 25 plots in Africa
- 189 in Asia/Oceania ⟵ Mondelez dataset
- 243 in America ⟵ Somarriba dataset

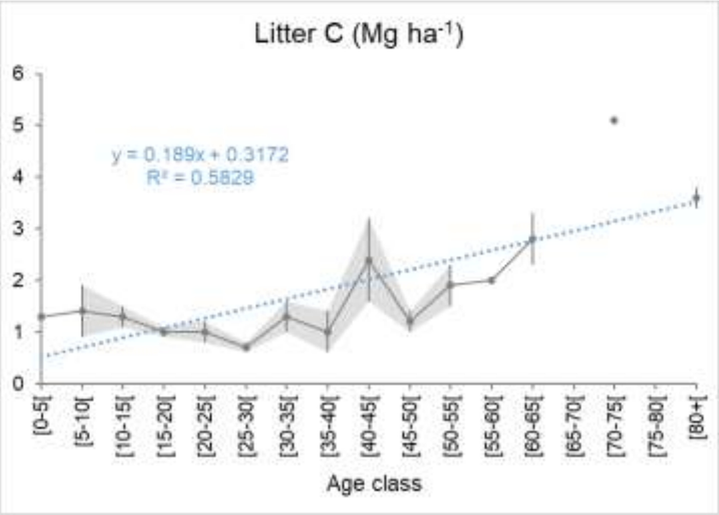
Key findings to date

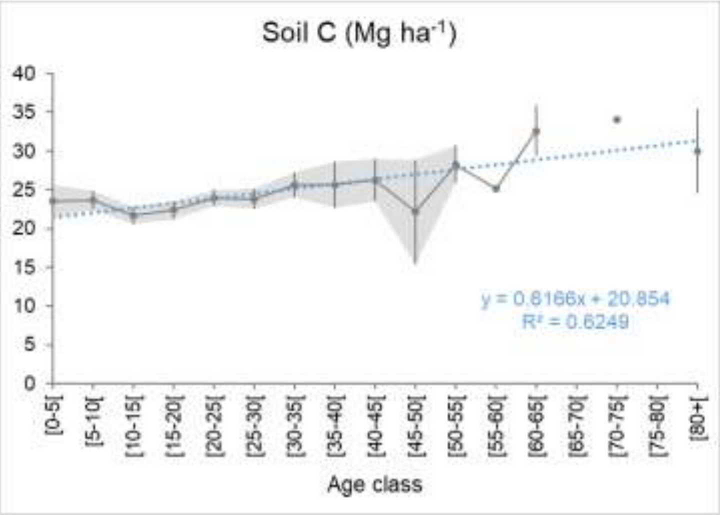
STUDY #1 Meta-analysis: C storage in cocoa farms

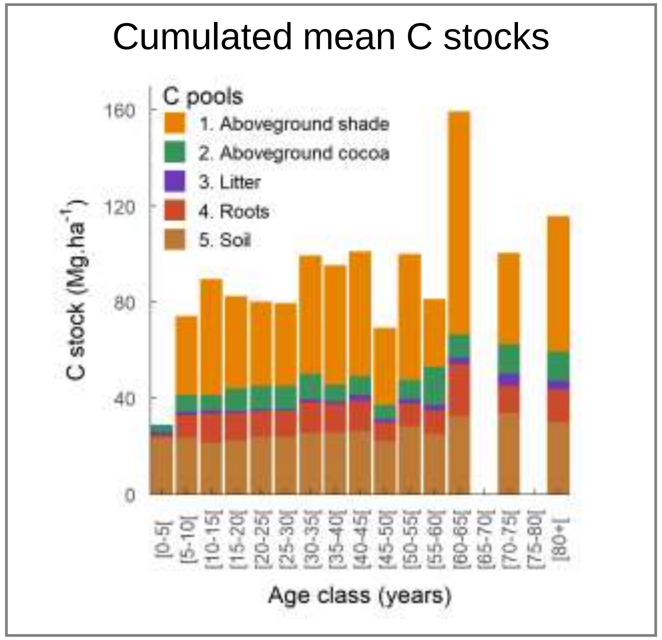








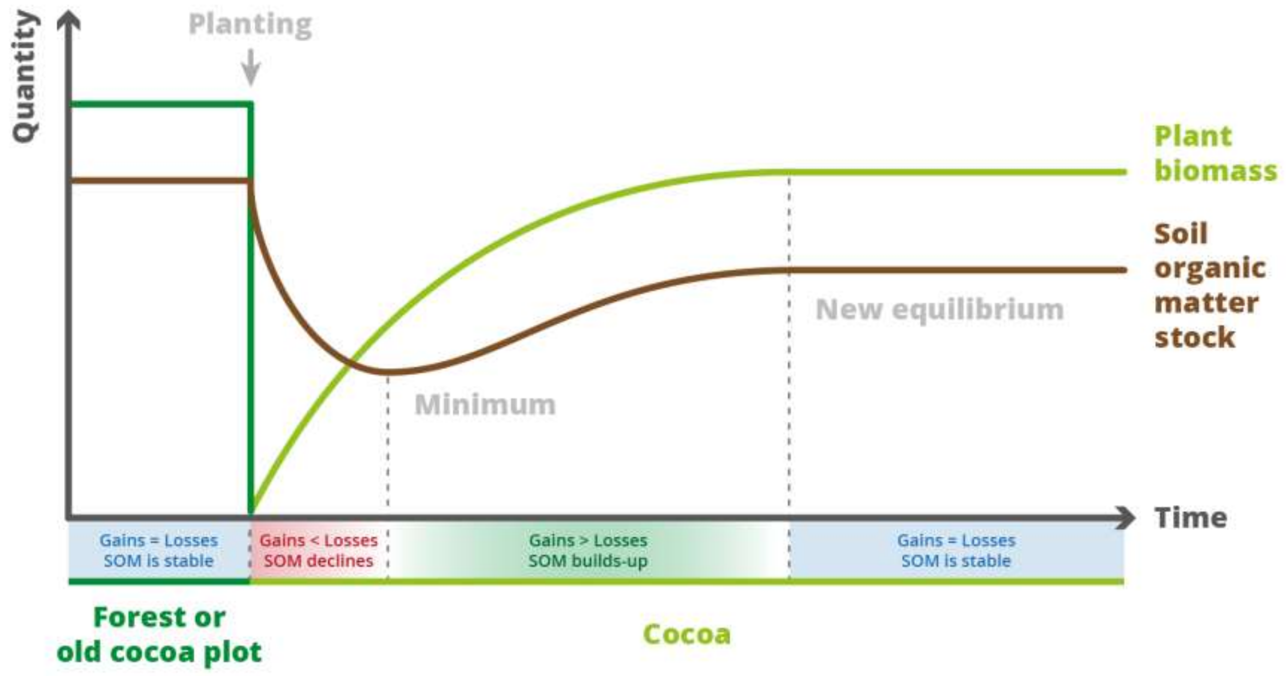




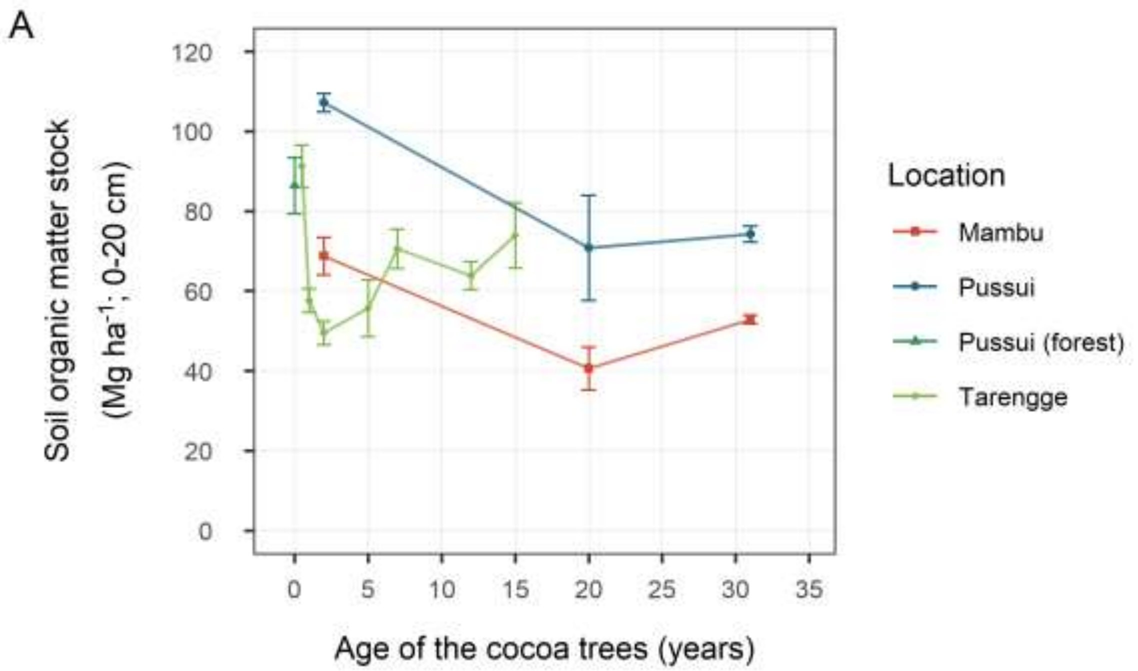
Error bars represent standard errors

Key findings to date

STUDY #3 Chronosequence



SOM stock
(adjusted LOI)

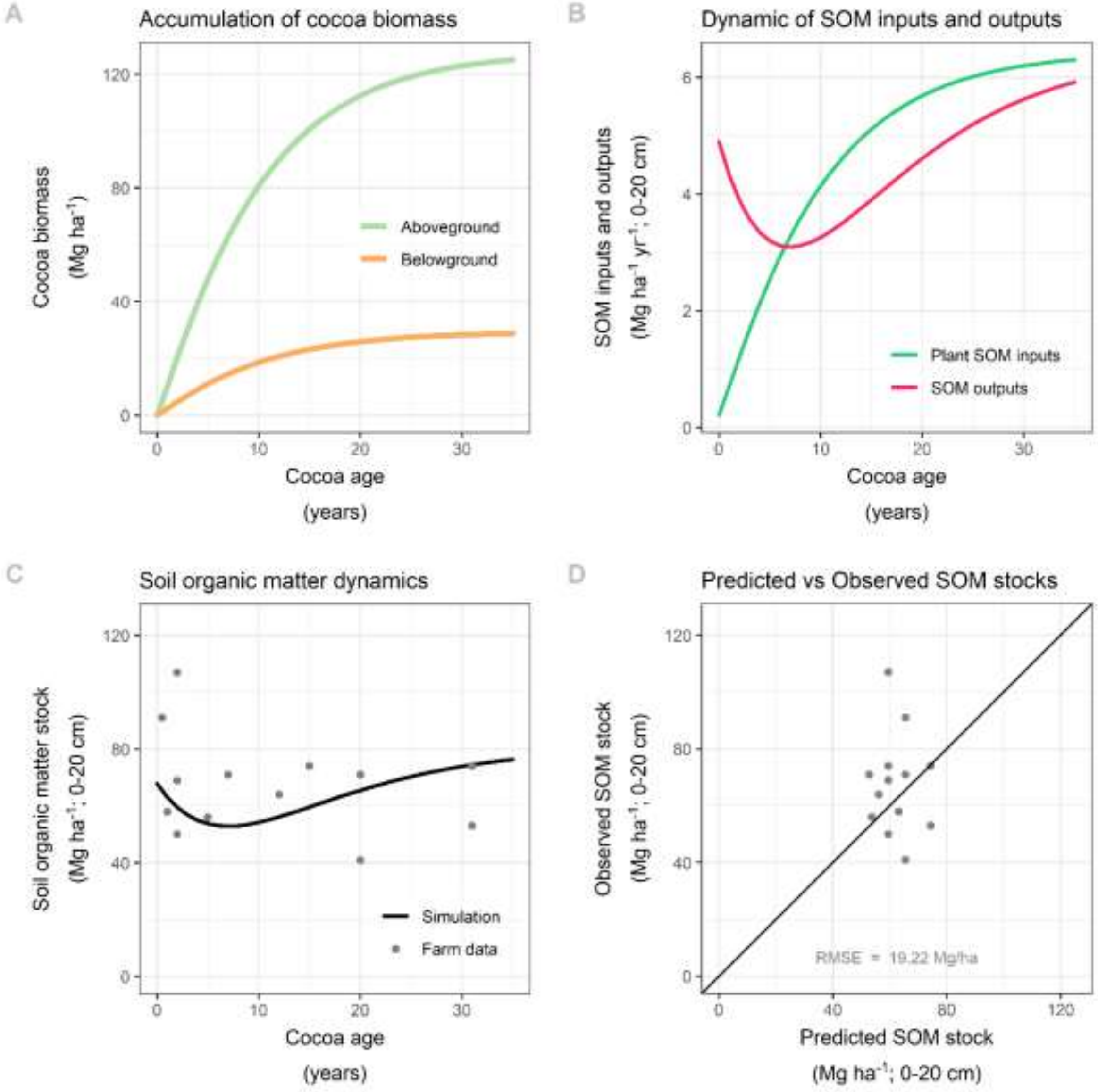


Key findings to date

STUDY #4 Modelling SOM long-term dynamics

Simulation of an “average cocoa farm”

Averages of the chronosequence dataset



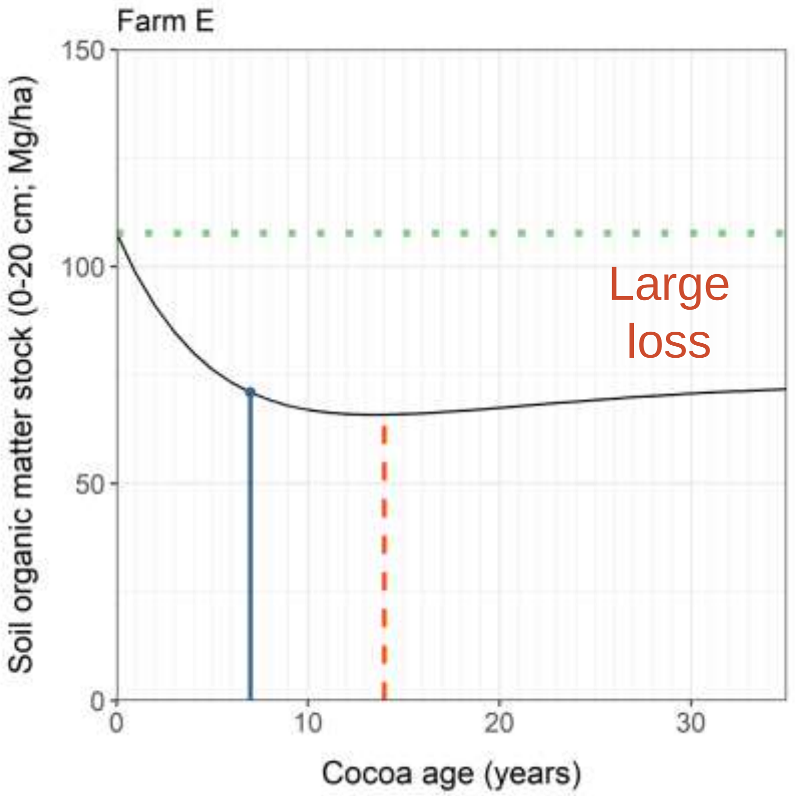
Key findings to date

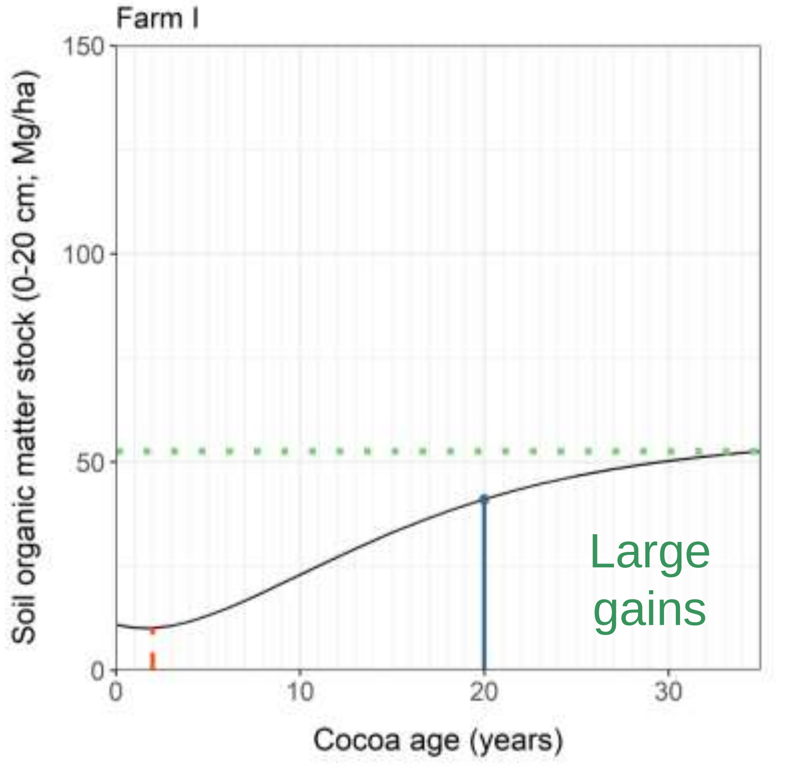
STUDY #4 Modelling SOM long-term dynamics

Reverse modelling

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

2 different farms in Sulawesi



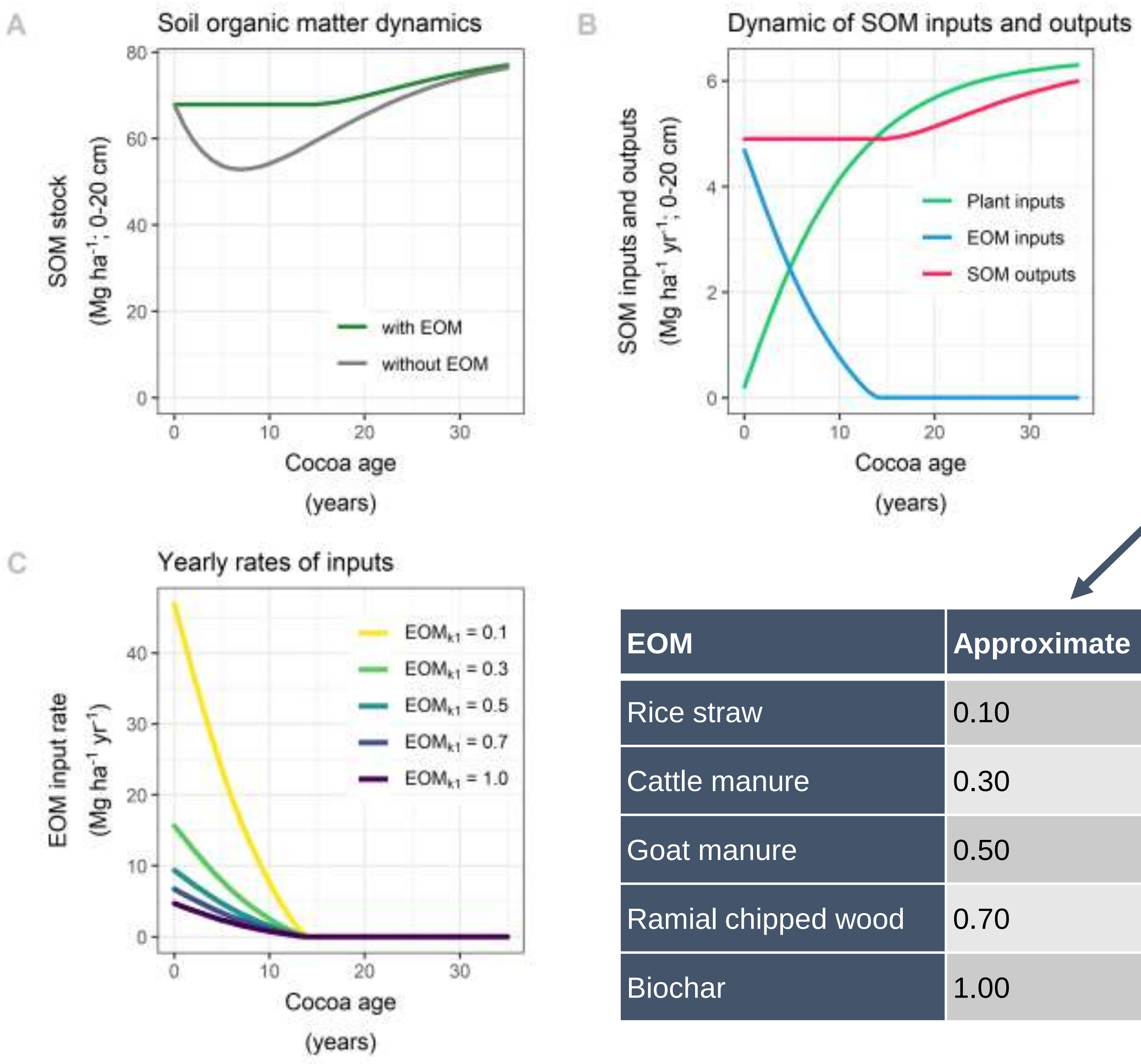


Key findings to date

STUDY #4 Evaluation of SOM inputs

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.

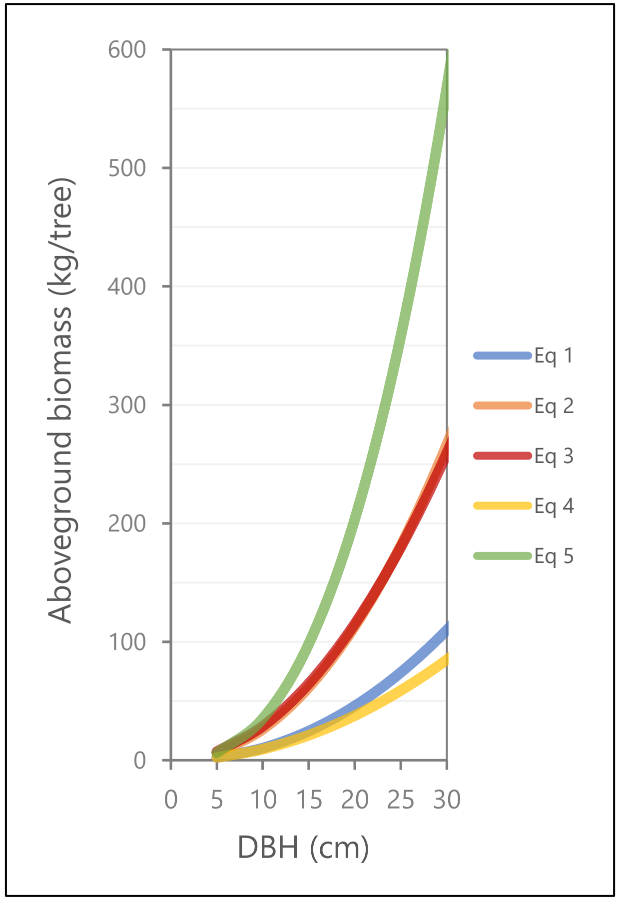
Key findings to date

PAPER 1 Meta-analysis

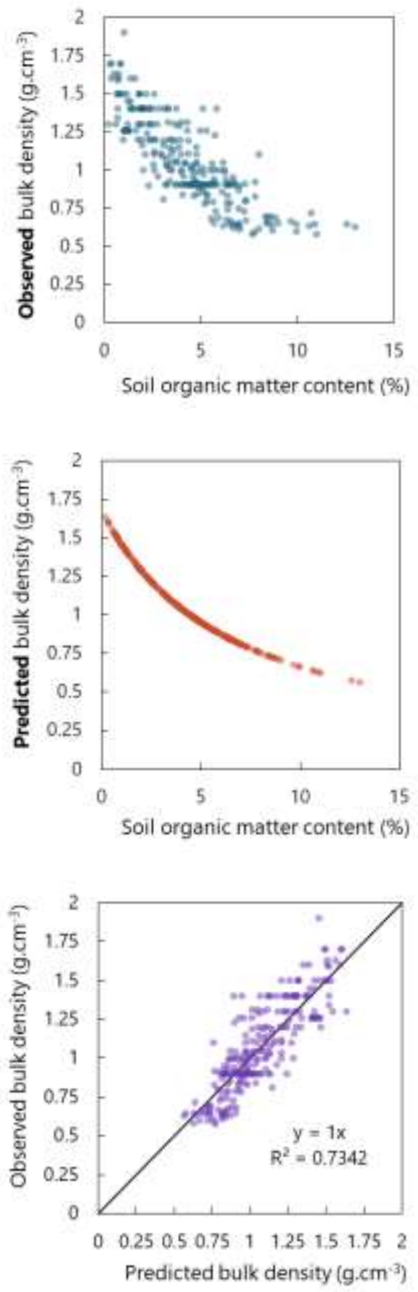
Examples of methodological inconsistencies between the references

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

Various plant C contents



Various allometric equations to calculate C stocks



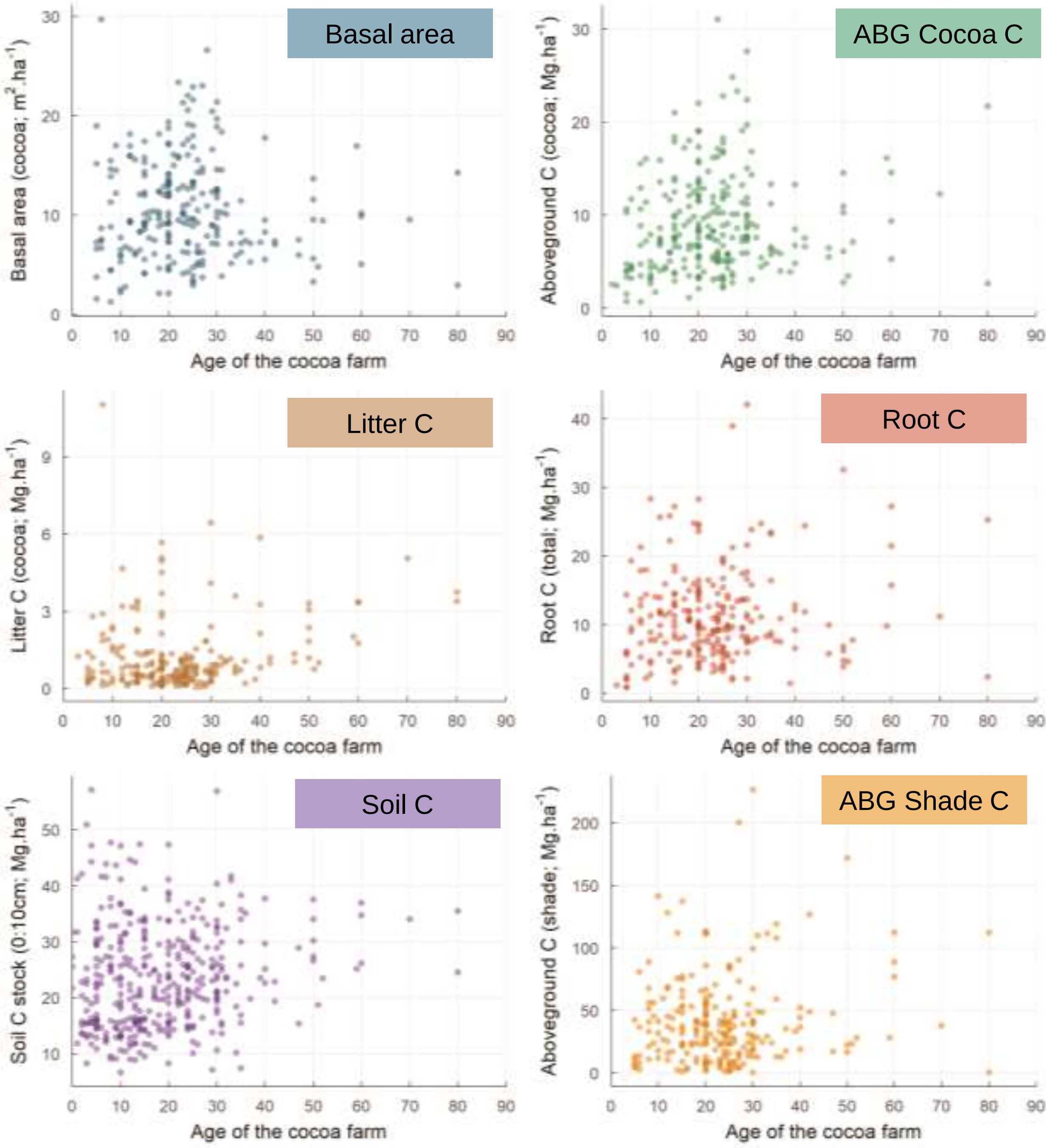
Missing bulk densities

Key findings to date

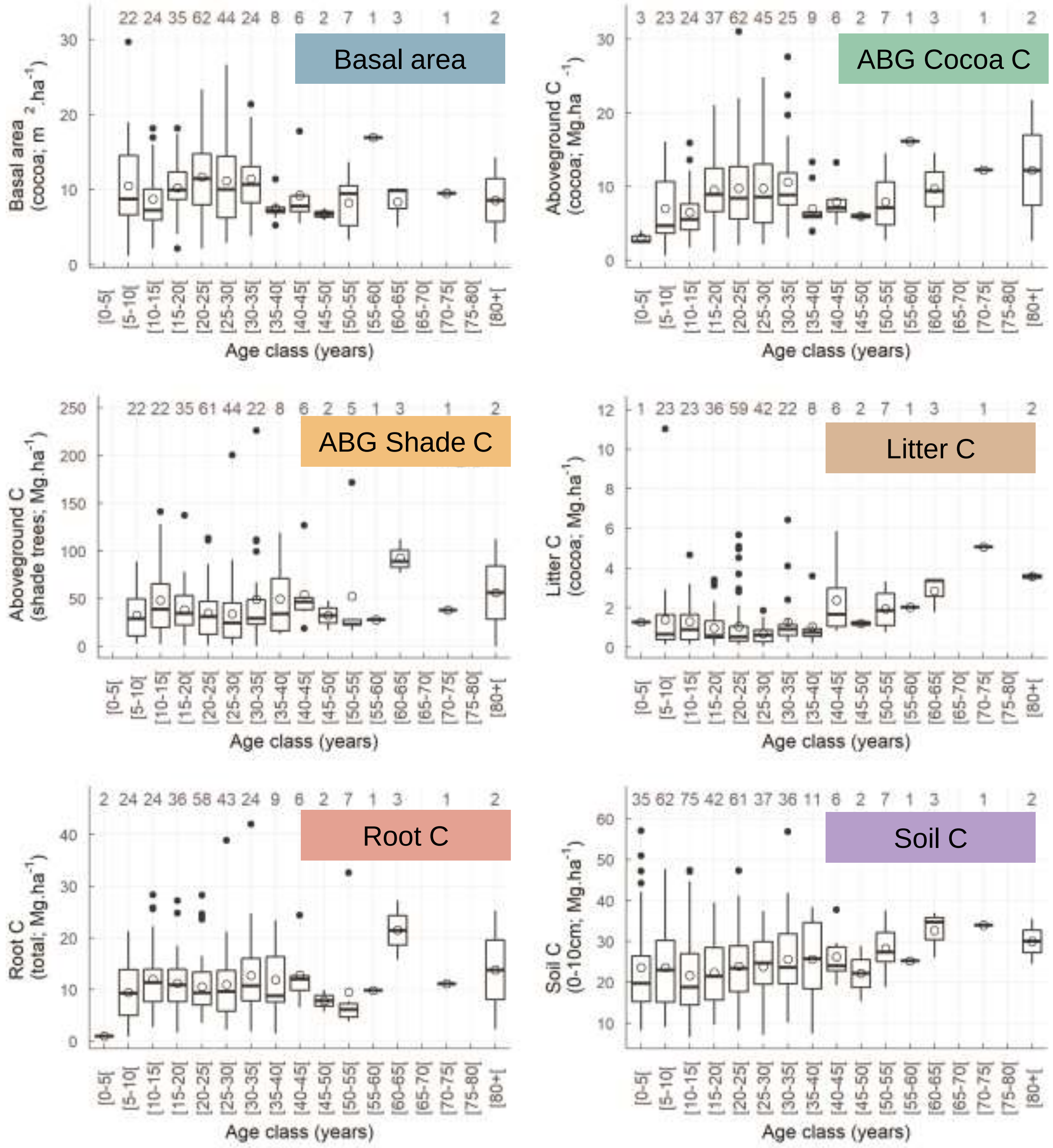
PAPER 1 Meta-analysis: C storage in cocoa farms

Table 2.3: Examples of allometric equations used in the references to estimate cocoa and shade trees biomass

Targeted stock	Equation number	Allometric equation	Variables	References
Aboveground cocoa biomass	Equation 2.1	$\log AB = (-1.684 + 2.158\ \log(D_{30}) + 0.892\ \log(TH)$	D30: diameter at 30 cm (in cm). TH: total height of the cocoa tree (in m).	Somarriba et al. (2013)
	Equation 2.2	$AB = 0.202 \times D^{2.112}$	D: stem diameter at breast height at 50 cm height (in cm)	Smiley & Kroschel (2008) Leuschner et al. (2013)
	Equation 2.3	$AB = WD \times CSA \times (L + 2.32PB)$	WD: average wood density (0.34 Mg m-3). CSA: mean cross-sectional surface area of the trunk (in m²). L: trunk length (in m) PB: number of primary branches.	Boyer (1973) Norgrove & Hauser (2013)
	Equation 2.4	$AB = -0.0376 + (0.133\ \mathrm{BA})$	BA: stem basal area at breast height (in cm²).	Beer et al. (1990) Rajab et al. (2016)
Aboveground cocoa and shade trees biomass	Equation 2.5	$AB = e^{-2.134 + 2.53\ ln(DBH)}$	DHB: diameter at breast height (in cm).	Brown, (1997) Dawoe (2009)
Shade tree biomass	Equation 2.6	$AB = e^{(-2.557+0.940\ln(\rho D^2 H))}$	ρ: wood specific gravity (in g cm-3). D: stem diameter at breast height (in cm). H: total tree height (in m).	Leuschner et al. (2013) Chave et al. (2005)
Aboveground Gliricidia biomass	Equation 2.7	$AB = 0.1185 \times D^2$	D: stem diameter measured at breast height (in cm).	Foroughbakhch et al. (2006) Leuschner et al. (2013)
Belowground biomass	Equation 2.8	$BB = 0.142 \times D^{2.064}$	D: stem diameter.	Smiley & Kroschel (2008)
	Equation 2.9	$BB = e^{(-1.0587 + 0.8836\ \ln(AB))}$	AB: aboveground biomass, dry (kg per tree).	Cairns et al. (1997) Somarriba et al. (2013) Rajab et al. (2016)



Basal area
Basal area (cocoa; m2.ha-1)
Age of the cocoa farm
ABG Cocoa C
Aboveground C (cocoa; Mg.ha-1)
Age of the cocoa farm
Litter C
Litter C (cocoa; Mg.ha-1)
Age of the cocoa farm
Root C
Root C (total; Mg.ha-1)
Age of the cocoa farm
Soil C
Soil C stock (0-10cm; Mg.ha-1)
Age of the cocoa farm
ABG Shade C
Aboveground C (shade; Mg.ha-1)
Age of the cocoa farm



Basal area
Basal area (cocoa; m2.ha-1)
Age class (years)
ABG Cocoa C
Aboveground C (cocoa; Mg.ha-1)
Age class (years)
ABG Shade C
Aboveground C (shade trees; Mg.ha-1)
Age class (years)
Litter C
Litter C (cocoa; Mg.ha-1)
Age class (years)
Root C
Root C (total; Mg.ha-1)
Age class (years)
Soil C
Soil C (0-10cm; Mg.ha-1)
Age class (years)

Key findings to date

STUDY #2 Fertilizer and amendments field experiment

Table 3.1: Breakdown of the treatments applied between 2012 and 2018 (adapted from Mulia et al., 2019)

Rates in g tree^{-1} year^{-1}, equivalent to kg ha^{-1} year^{-1} (considering a density of 1000 cocoa trees per hectare)								
Treatment		C	N	P	K	Ca	Mg	S
A	No amendment	0	0	0	0	0	0	0
B	Mineral fertilizer	0	120.5	24.5	46.6	0	0	Trace
C	Compost (10 kg)	930	130	37	45	551	15	18
D	Dolomite (5 kg)	650	0	0	0	1100	650	0
E	B + C	930	250.5	61.5	91.6	551	15	18
F	B + D	650	120.5	24.5	46.6	1100	650	Trace
G	C + D	1580	130	37	45	1651	665	18
H	B + C + D	1580	250.5	61.5	91.6	1651	665	18

Soil amendments and fertilizers were applied twice per year and per tree to provide total quantities as follows: 374 g NPK ("Phonska") and 250 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 quantities 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.pupukkaltim.com/en/distribution-product-product-knowledge). At the time of planting, mineral fertilizer, 100 g NPK (Phonska) and 150 g triple superphosphate (36%), 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 (Mulia et al., 2019).

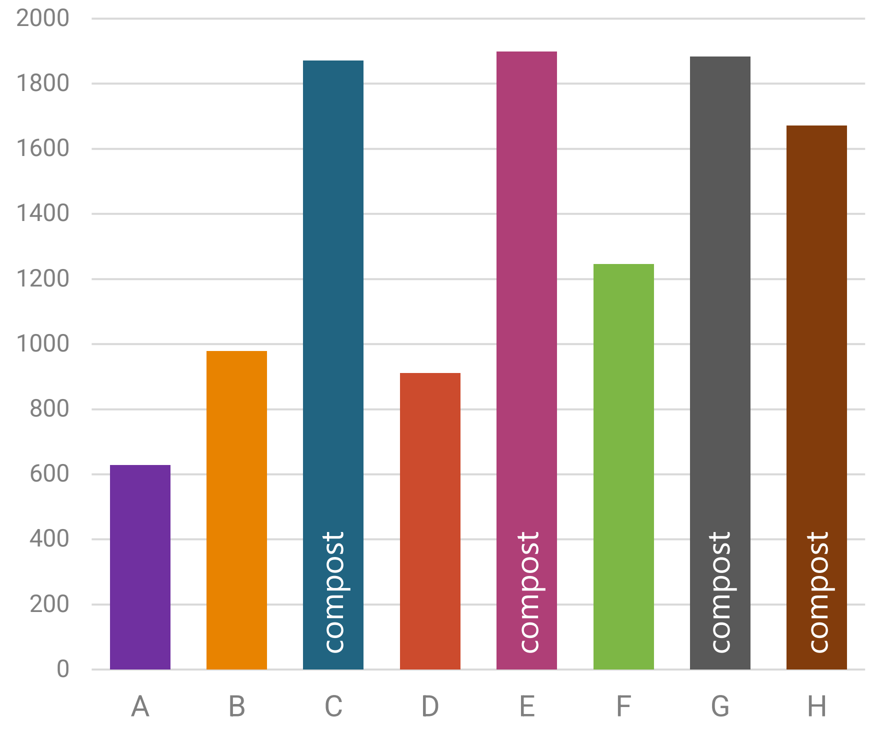
Treatments

A	B	C	D	E	F	G	H
Control	Mineral Fertiliser	Compost	Dolomite	B+C	B+D	C+D	B+C+D
				Fert. + Compost	Fert. + Dolomite	Compost + Dolomite	Full mix

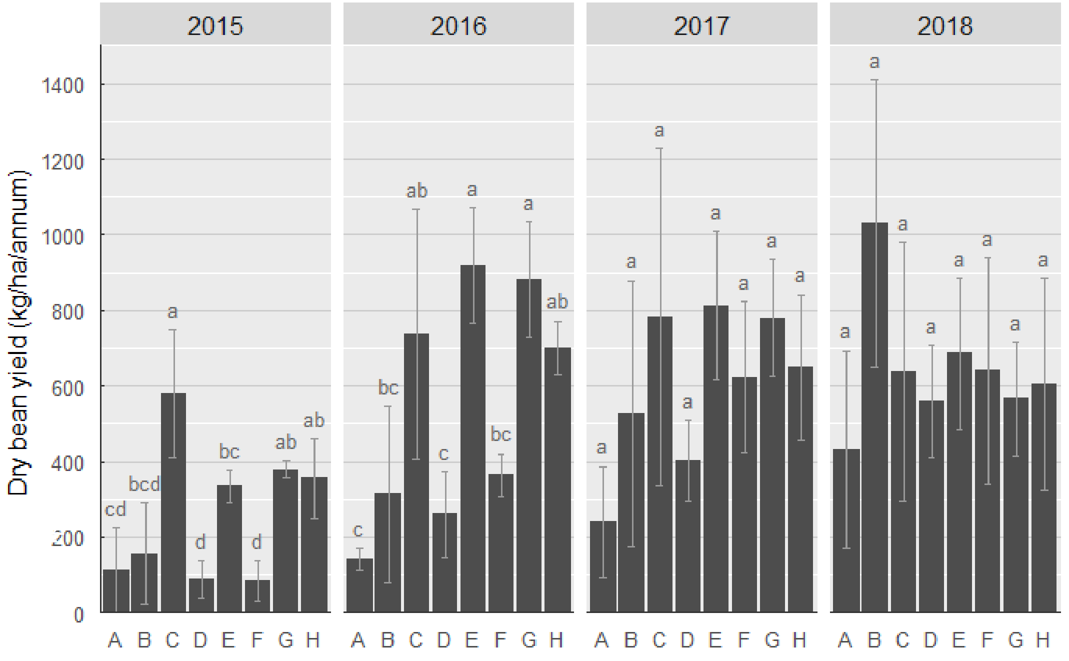
Key findings to date

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)



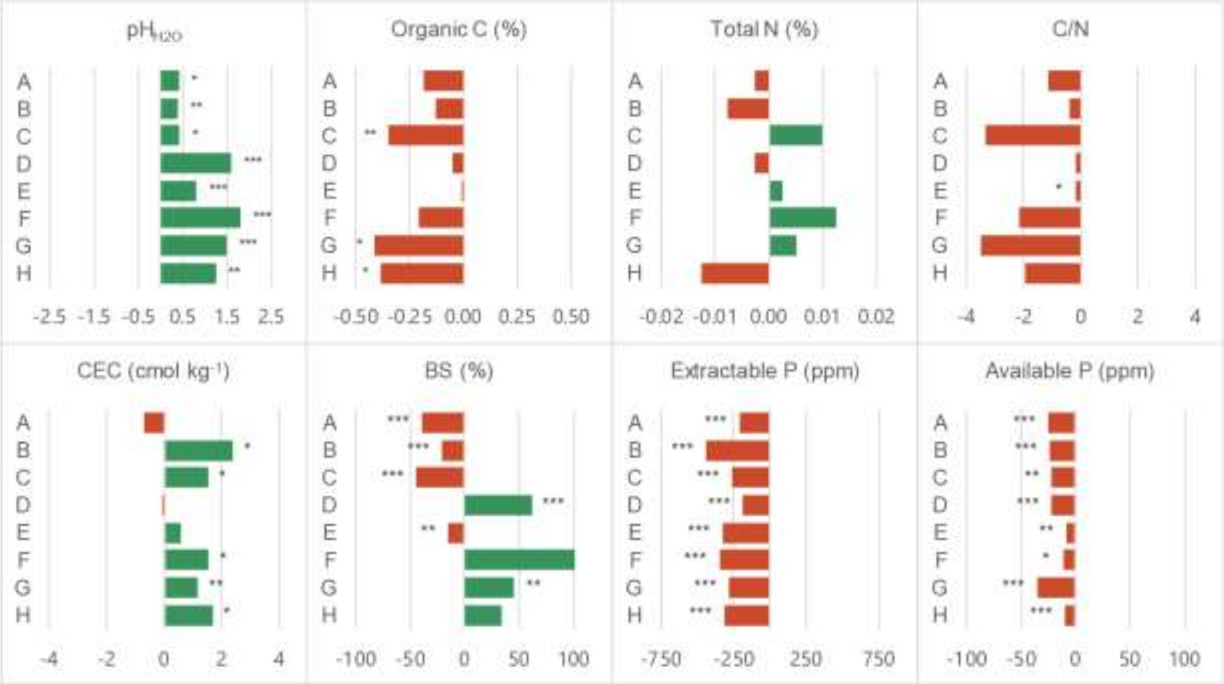
A	B	C	D	E	F	G	H
Control	Mineral Fertiliser	Compost	Dolomite	B+C	B+D	C+D	B+C+D
				Fert. + Compost	Fert. + Dolomite	Compost + Dolomite	Full mix

Key findings to date

STUDY #2 Fertilizer and amendments field experiment

Change in soil properties

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



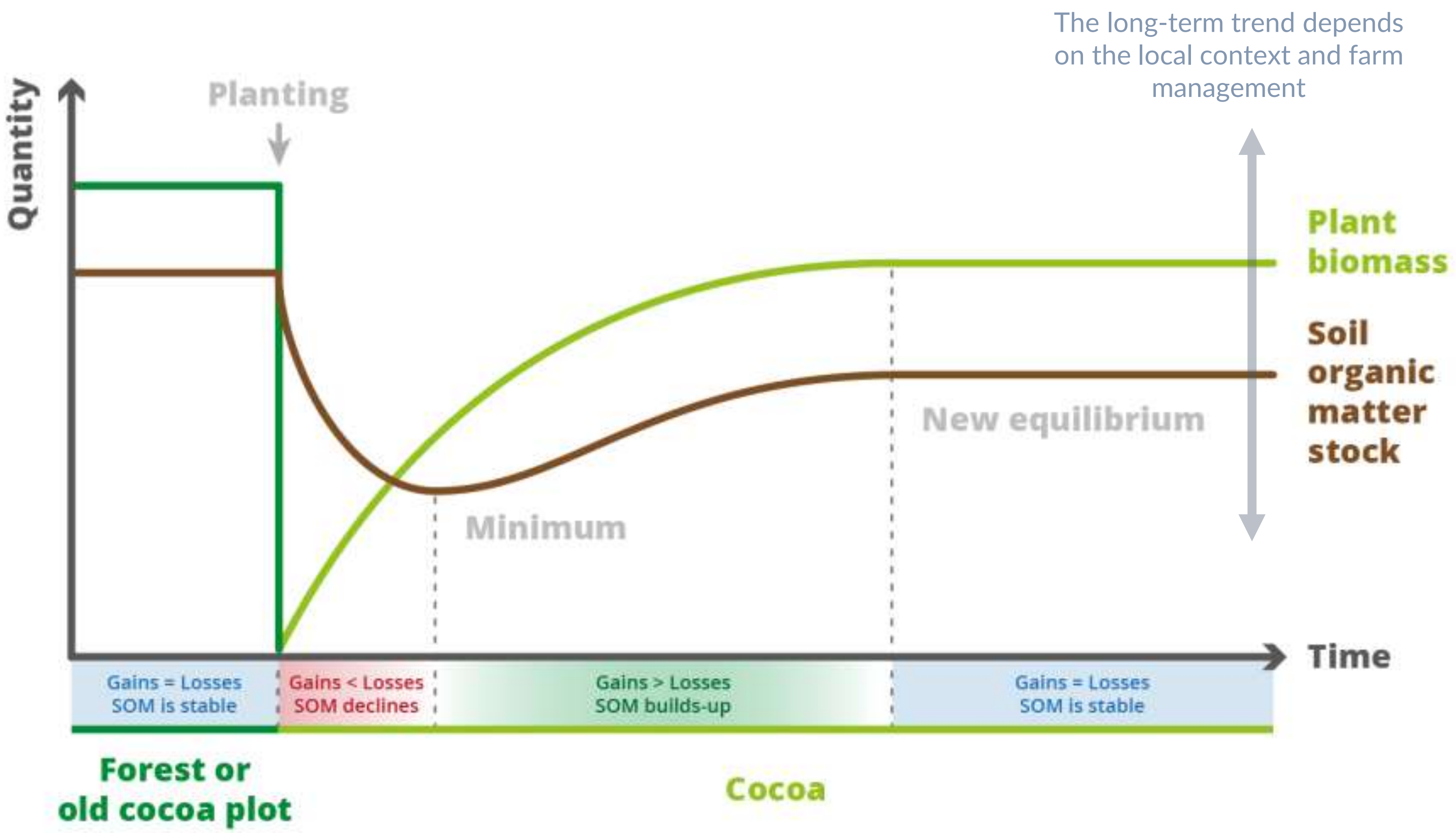
A	B	C	D	E	F	G	H
Control	Mineral Fertiliser	Compost	Dolomite	B+C	B+D	C+D	B+C+D
				Fert. + Compost	Fert. + Dolomite	Compost + Dolomite	Full mix

Key findings to date

STUDY #3 Chronosequence

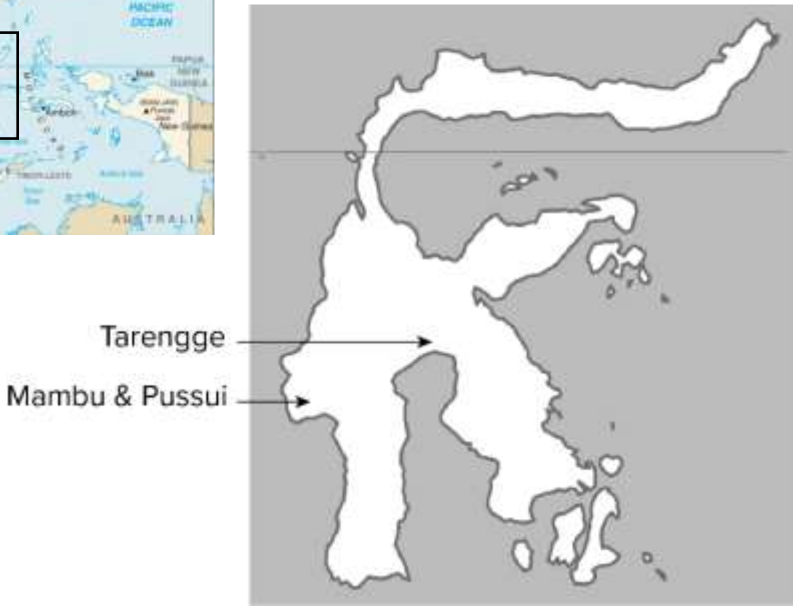
Conceptual / Hypothetical SOM dynamics in cocoa farms

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 results in SOM gains.
6. Ultimately, a new equilibrium can be reached.



Key findings to date

STUDY #3 | C and N chronosequence



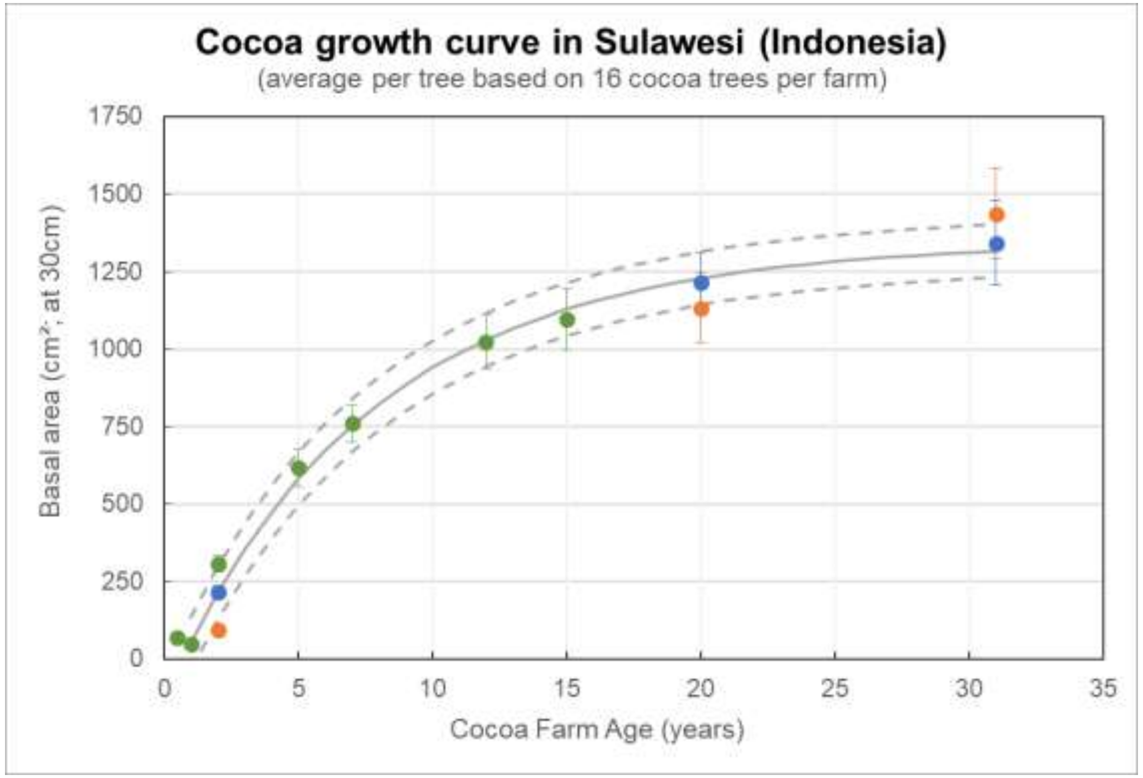
- 3 locations in Sulawesi
- 13 cocoa farms + 1 adjacent forest
- Ranging from 0.5 to 31 years old
- Trunk measurements (16 cocoa trees)
- Soil samples at 5 depths (0-100 cm)

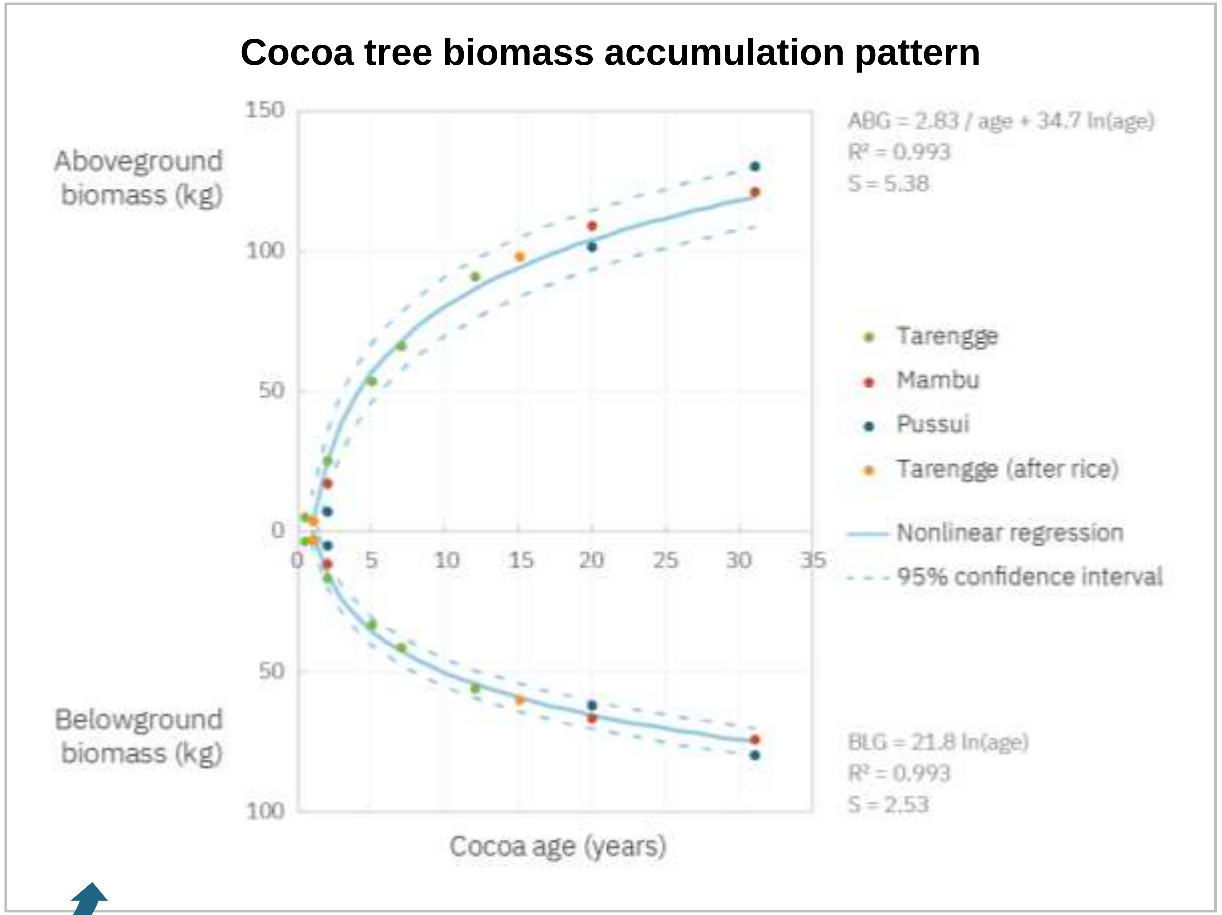
Location	Farm code	Age (years)
Tarengge	A	0.5
	B	1
	C	2
	D	5
	E	7
	F	12
	G	15
Mambu	H	2
	I	20
	J	31
Pussui	K	2
	L	20
	M	31
	Forest	-

Same ages

Key findings to date

STUDY #3 Chronosequence





Allometric relationship

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

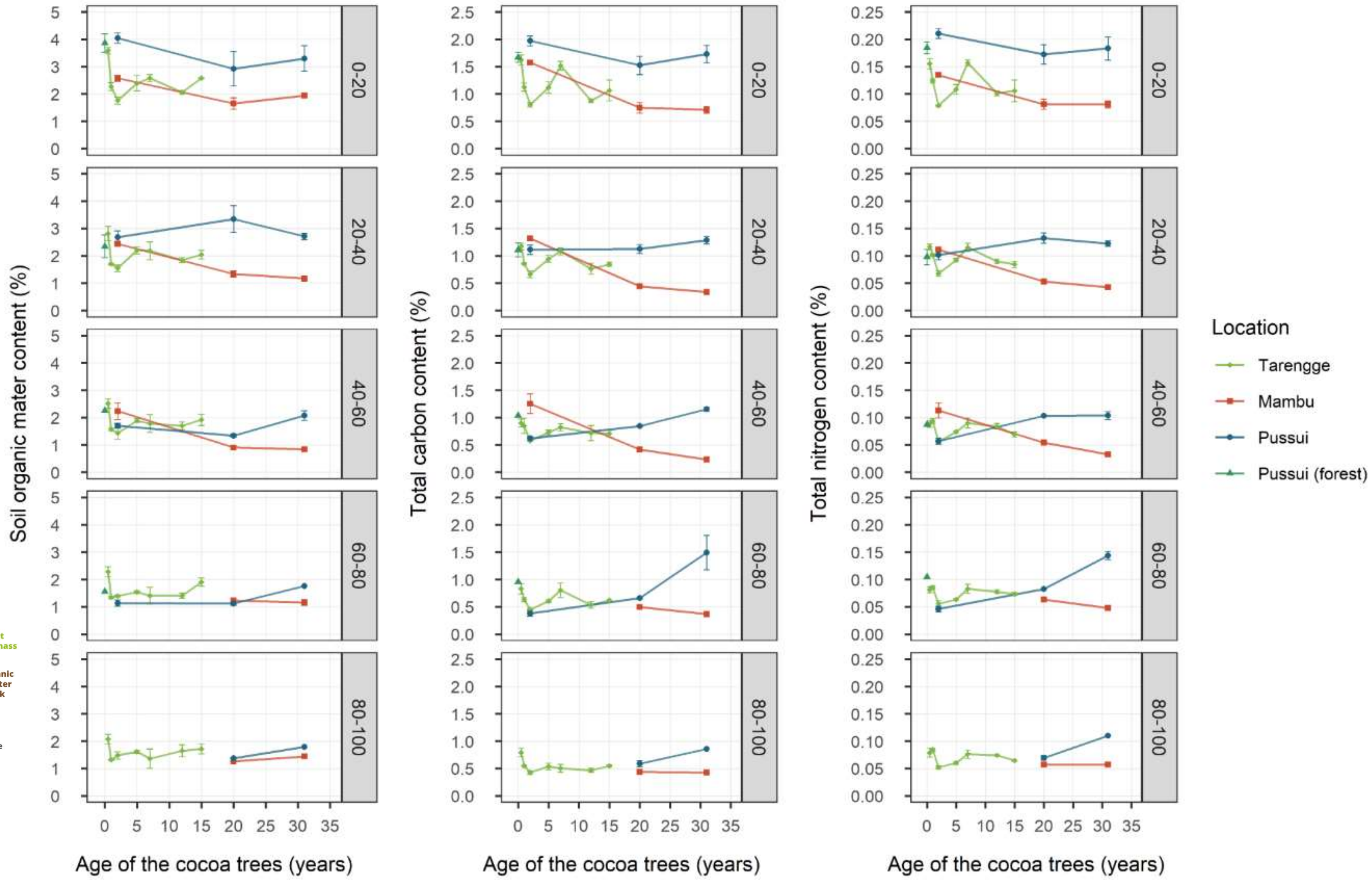
Key findings to date

STUDY #3 C and N chronosequence

SOM
(adjusted LOI)

Total C

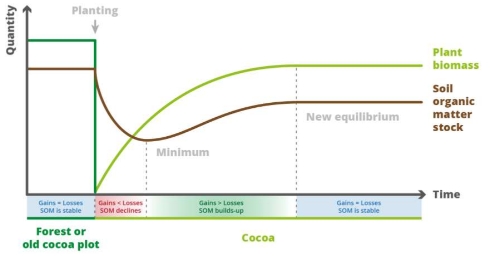
Total N



CONTENTS (%)

5 depths

3-5 samples per farm X depth



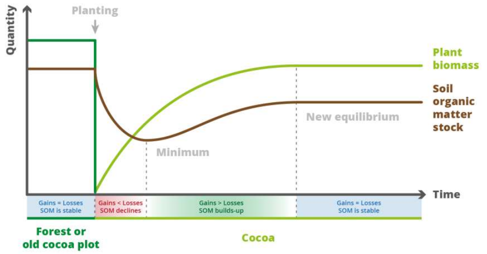
Key findings to date

PAPER 3 | C and N chronosequence

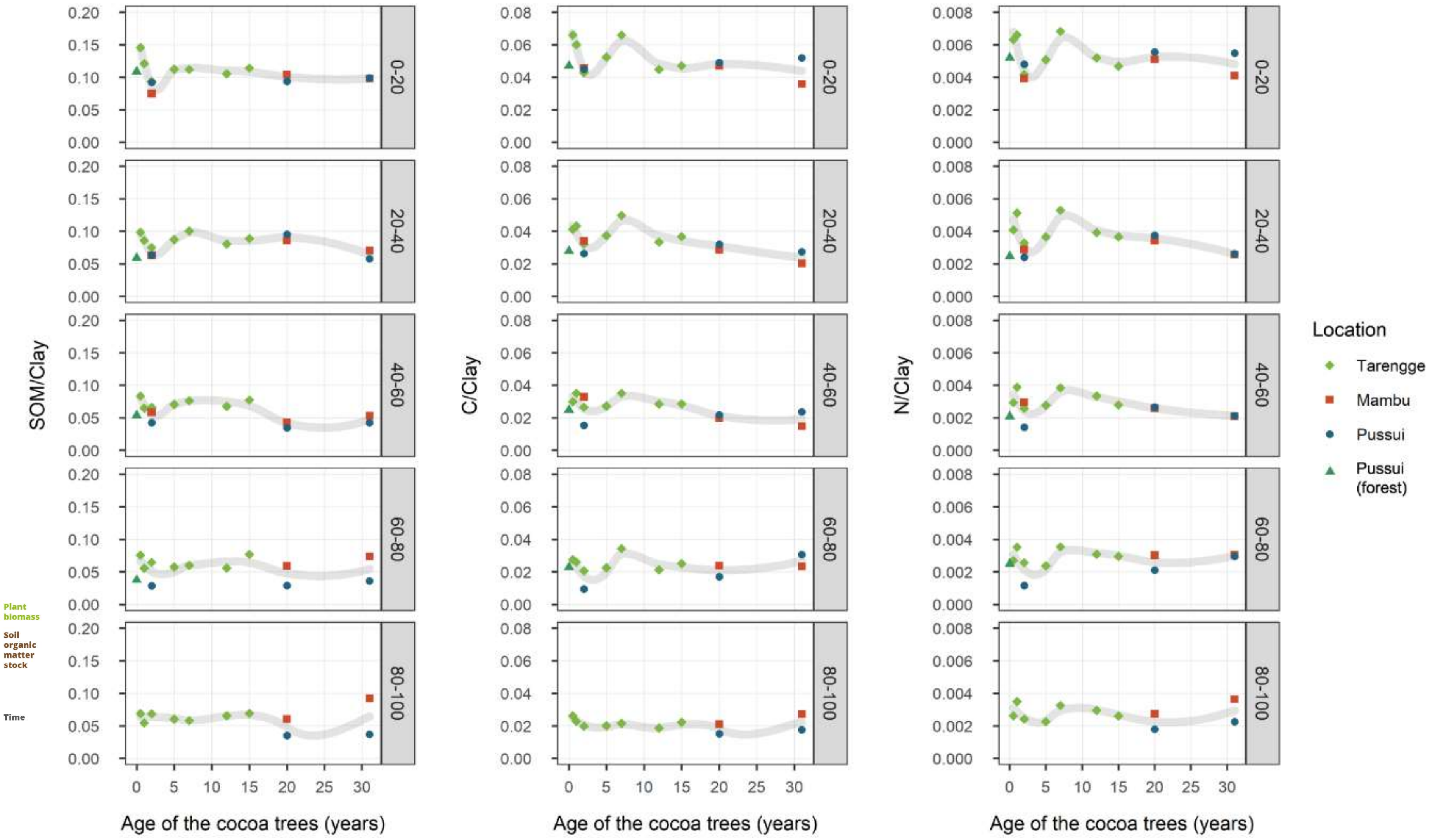
Results adjusted for clay content

5 depths

3-5 samples per farm X depth



SOM/clay (adjusted LOI) | **Total C/clay** | **Total N/clay**



Key findings to date

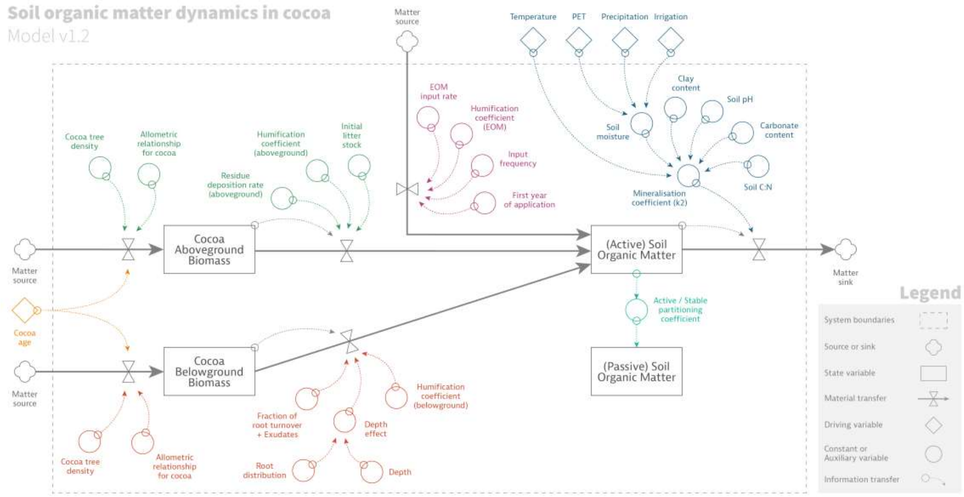
STUDY #4 | Modelling SOM long-term dynamics

The model:

- Adaptation of the AMG soil model

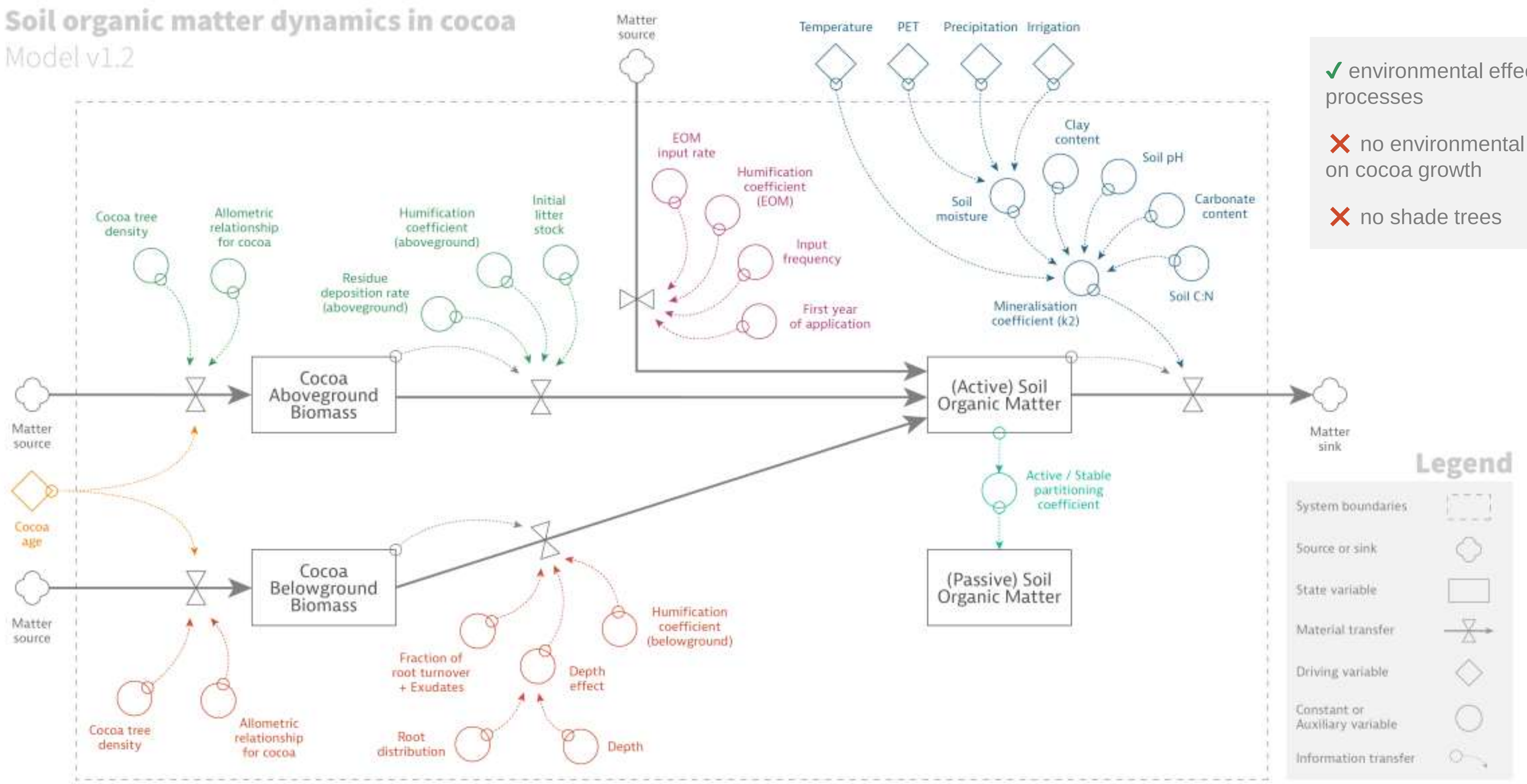
Procedure:

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



✓ environmental effects on soil processes

✗ no environmental effects on cocoa growth

✗ no shade trees