Model-based assessment of soil organic carbon dynamics and potentials for carbon sequestration under integrated soil fertility management and conservation agriculture in Western Kenya

Rolf Sommer

20 April 2017

Rationale

A key message of the 2015 International Year of Soils was that '*soils help to combat and adapt to climate change by playing a key role in the carbon cycle*'. With 1,417,000 Mt C in the 1st meter, soils store more carbon (C) than found in the atmosphere and aboveground biomass combined (FAO 2016). Expectations are high that little positive changes in soil organic carbon (SOC), i.e. a sequestration of C in soils, if implemented worldwide, could offset a significant share – if not all – of the anthropogenic carbon emissions into the atmosphere, and hence mitigate climate change.

However, it is known that unsustainable management practices of soils indeed cause the exact opposite, a loss of SOC. "*With about 33% of the world's soils being degraded, large losses of soil organic matter (SOM) (and hence SOC) have occurred with soils from various global agroecosystems (i.e. croplands, grazing lands, rangelands, peatlands, etc.) having lost 25–75% of their original SOC pool.*" (FAO 2017).

The *Soil Protection and Rehabilitation for Food Security* global program, commissioned by the German Federal Ministry for Economic Cooperation and Development (BMZ) and implemented by GIZ and partners in Benin, Burkina Faso, Ethiopia, India and Kenya, addresses the issue of soil degradation and loss of productivity and its impact on smallholder livelihoods. The primary goal – as the program title implies – is to support and promote the immediate function that protected, fertile soils play in terms of providing and sustaining food security. In addition – taking up the aforementioned idea of SOC sequestration in soils – improved agricultural management practices may have a role to play in terms of climate change mitigation. Besides increased *productivity* and climate change *resilience*, *mitigation* is the third pillar of climate smart agriculture (CSA). To assess the climate smartness of selected GIZ-supported soil protection and rehabilitation measures in the five countries, GIZ engaged CIAT scientists in the project *Climate-smart soil protection and rehabilitation in Benin, Burkina Faso, Ethiopia, India and Kenya*, which builds on CIAT's expertise in both soil science and CSA.

As part of this project, this brief report summarizes a study that investigated to what extent *Integrated Soil Fertility Management* and *Conservation Agriculture* can contribute to climate change mitigation by SOC sequestration. These are two of a range of improved management practices which have been endorsed by some GIZ Soil program country initiatives as promising ways to protect and rehabilitate soils. Given CIAT's long-standing presence in Kenya and the fact that CIAT maintains two long-term trials in which these two improved agricultural management practices are tested for their impact on crop productivity *long term*, Western Kenya was selected as the focus region for this case study.

The study complements five rapid climate smartness assessments of GIZ soil protection and rehabilitation technologies carried out by CIAT scientist in Benin, Burkina Faso, Ethiopia, Kenya and India, and published individually as well summarized together in one document (Birnholz *et al.* 2017).

Material and Methods

Study area

Since 2003, CIAT maintains an on-farm long-term trial that focuses on Integrated Soil Fertility Management (ISFM). The trial – named INM3 – is located in Western Kenya, 50 km northwest of the city of Kisumu at 34° 24' 13.7" E 00° 08' 38.3" N and at an altitude of 1330 m above sea level.

The climate in the study area is sub-humid with a mean annual temperature of 22.5 °C and annual rainfall between 1,200 and 2,206 mm (average 1,727 mm; observation period 1997-2013) distributed over two rainy seasons: a long rainy season that lasts from March until June and a short rainy season from August until December (Figure 1).

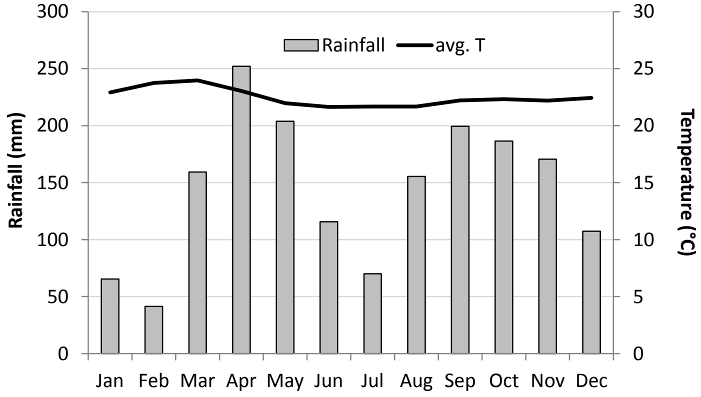

Figure 1: Monthly rainfall and monthly average temperatures at CIAT's INM3 long-term trial

Maize (*Zea mays*) is the dominant staple crop in this region and is often grown intercropped with food legumes, such as common bean (*Phaseolus vulgaris*) or, more recently, soybean (*Glycine max*). The soil has been classified as an Acric Ferralsol, with a clay content of between 56 % (topsoil) and 84 % (subsoil), low CEC and high aluminum saturation, a pH between 4.9 and 5.5, and a topsoil organic matter (SOM) content of between 30 and 45 g/kg. Major growth limiting nutrient are – in the order of importance – phosphorous (P), nitrogen (N) and potassium (Kihara and Njoroge 2013).

INM3 is laid out in a split-split-split plot design with four reps (blocks), 44 treatments and 192 plots in total. The first split encompasses plus (4 t dry matter per ha per season) or minus farm yard manure (FYM) application, and the second split factor addresses residue retention (2 t/ha maize stover retained vs. all stover removed). The third split factor comprises three crop rotations, continuous maize (M-M), Tephrosia in the long rainy season followed by maize in the short rainy season (T-M) or vice-versa (M-T), and maize-soybean intercropping (MS). *Tephrosia candida* was used, which is one of the poisonous species of *Tephrosia* with high concentration of rotenone, because it is common in the region and seeds are easily available.

Maize-soybean rotation treatments were not further considered in this study.

Plots received between 0 and 90 kg N/ha/season as urea and 0 or 60 kg P/ha/season as triple super phosphate, with individual levels aliased with the crop rotation treatments. All plots also received 60 kg potassium/ha/season in the form of muriate of potash. The mineral N and P fertilizer application rates were:

- no mineral N (N0), 30 kg N (N30), 60 kg N (N60) and 90 N/ha/season (N90) to the continuous M-M treatments, each together with 60 kg P/ha/season (P60);
- N0 P0, N0 P60 and N30 P60 to the T-M and M-T rotations.

Agronomic management

Land preparation was done by common hand hoeing practice to maximum 20-30 cm depth, with soil disturbance and mixing diminishing with depth. The plant spacing of maize and Tephrosia was 75 cm x 25 cm, with one plant per hill. Throughout the 13 years, maize and Tephrosia were planted between end of March and end of April in the long-rain season, and between beginning of September and beginning of October in the short-rain season. Maize was harvested between mid-August and mid-September and beginning of February and mid-March in the long- and short-rain season, respectively. Maize stovers were removed after harvest and then 2 t/ha re-applied a few days before planting by broadcasting on the soil surface (R+ treatments). This was done to reduce the significant loss of residues during the dry season through consumption/removal by termites. Tephrosia was only harvested a few days before land preparation of the subsequent season, and biomass chopped and spread on the soil immediately. All Tephrosia material was subsequently manually incorporated into the soil. The same was done with maize stovers in the R+ sub-plots.

Farm yard manure, mineral P and potassium fertilizer was applied at planting by broadcasting and incorporation into the soil by hand hoeing (together with the residues, if applicable). One-third of the mineral N fertilizer was applied at planting together with the other fertilizers, and 2/3 when maize reached knee height. At topdressing stage the N-fertilizer was banded near the maize plants. The experiment was kept weed free by hand weeding at least twice a season. Maize stem borers were controlled by pesticides application (Beta-cyfluthrin) once early in the season.

Soil organic carbon measurements

From 2004 onwards, topsoil samples from 0-15 cm depths (N=192) were taken twice a year in-between seasons on all plots, dried, 2-mm sieved and stored for future analysis. Topsoil samples of September 2005, 2007, 2009, 2011, 2013 and 2015 were analyzed for total C and N by total (Duma-type of) combustion technique using an elemental macro-analyzer (*Elementar Vario Max Cube*). As the soils under study are acid, it can be assumed that total carbon (TC) only consists of soil organic carbon compounds while inorganic carbon is absent, i.e. TC = SOC.

Soil organic carbon simulations

To study soil organic carbon dynamics, we furthermore used the crop-soil simulation model, CropSyst (Stöckle et *al.* 2014). This had previously been calibrated to continuous maize and maize-Tephrosia rotation treatments of INM3, using observed weather data, details of the various management practices (e.g. time, type and amount of fertilizer), long-term maize yield and aboveground biomass data, observations of soil moisture dynamics, soil mineral, and nitrous oxide emissions from soils (Sommer *et al.* 2015). For the sake of consistency and briefness, this study focused on simulating the SOM dynamics of four contrasting treatments – the first three of which had also been used in the aforementioned study:

a) "Resource-constrained livestock farmer": FYM+ R- M-M N0
b) "Integrated Soil Fertility Management (ISFM)": FYM+ R+ T-M (or M-T) N30
c) "Intensive maize farmer": FYM- R+ M-M N90
d) "Worst case management": FYM- R- M-M N0

For this study, the multi-pool soil organic matter sub-routine of CropSyst was used, which is based on the CENTURY type of models (Parton *et al.* 1994), in which SOM is subdivided in various conceptual pools (Figure 2).

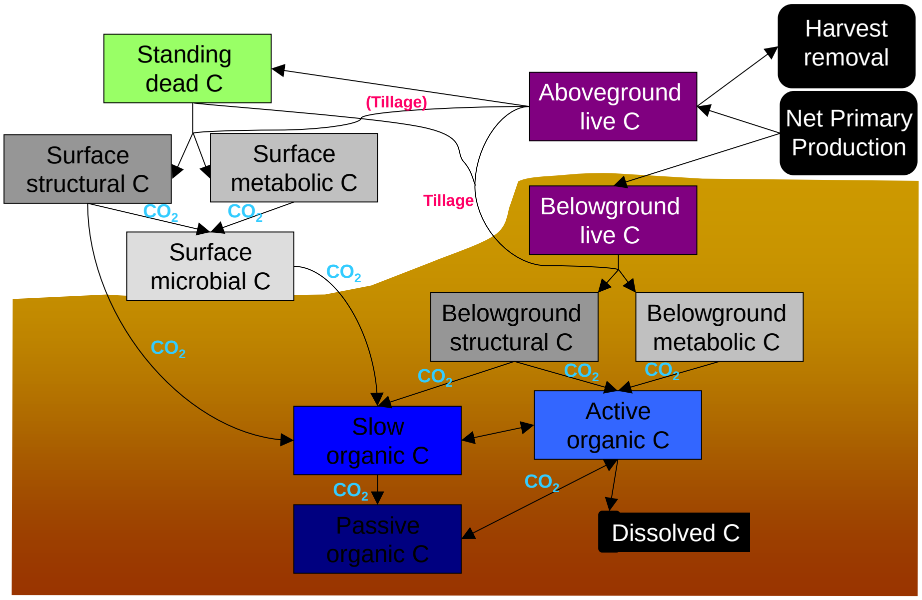

Figure 2: Conceptual sketch of (soil) organic matter cycling and turnover as implemented in the CENTURY type of organic matter routines

CropSyst uses a slightly modified CENTURY version, whereas the belowground live C is represented by a *Microbial biomass* pool, while the remaining active, slow and passive pools are represented by *Labile active, Metastable active,* and *Passive SOM pools*, respectively.

Conceptual pools – as the name implies – have no analog in nature, but are mere vehicles to describe the complex nature of organic matter turnover in mathematical terms. The decomposition of carbon from these pools is described by simple first order decay reaction equations, i.e.

$$\frac{dSOM}{dt} = (1-k) * SOM_{t-1}$$

where *dSOM/dt* is the change of a SOM pool over time, *k* is the rate constant and *t* is the time (days). The differential equation of this reaction equation is:

$$SOM = SOM_{t0} * e^{[Ln(1-k)*t]}$$

This basically has two unknowns: *SOM_{t0}* which is the initial amount of SOM and *Ln(1-k)*. Depending on the k-values, thus SOM in the different pools decomposes at different speeds, and thus the SOM-pool's half-life times – the time required to break down 50 % of the initial amount – measured in days (d_{50}) or years (yr_{50}) differ (Table 1).

Table 1: CropSyst soil organic matter pools, their respective default rate constants (k), half-life times (d_{50} and yr_{50}), and standard CN ratios

CropSyst SOM pool	------------- k -------------		---------- Ln(1-k) -----------		d_{50}	yr_{50}	CN ratio
	(day^{-1})	(yr^{-1})	(day^{-1})	(yr^{-1})			
Microbial biomass	0.005	0.839519	-0.005012542	-1.82958	138	0.38	8
Labile active	0.02	0.999373	-0.020202707	-7.37399	34	0.09	25
Metastable active	0.0005	0.166853	-0.000500125	-0.18255	1386	3.8	15
Passive	0.0000185	0.00673	-0.0000185002	-0.00675	37467	102.6	11

The decomposition of the passive pool is exemplarily shown in Figure 3. It takes more than four centuries (hence the name of the original model) to decompose 95 % of the initial organic matter.

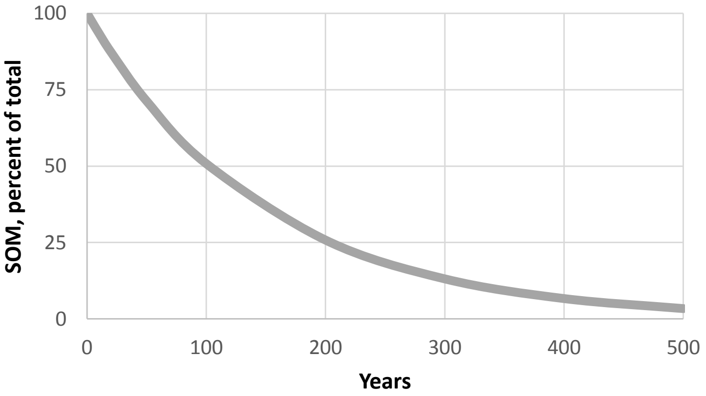

Figure 3: First order decay of a passive soil organic matter pool under optimal conditions

The default rate constants in CropSyst can be modified by the user, which however is not recommended, unless the user has data of decomposition measured under controlled standard conditions in the laboratory.

The decomposition of organic matter in the various pools is then further a function of soil temperature and soil moisture, with minimum, optimum (decomposition not reduced) and maximum thresholds. Furthermore, soil disturbance (tillage) as well as the carbon-nitrogen (CN) ratio of the SOM pools (see Table 1 for defaults) determines the speed of decomposition, as well as the content of lignified, slow and fast-cycling components of biomass added to the soil (analogous to the belowground structural and metabolic C in Figure 2), which is also user-specified. It is thus understood that the percent distribution of SOM in its four pools varies over time in response to the amount and quality of organic matter added.

Sand, silt, clay, bulk density and water holding characteristics are fixed soil parameters that have to be provided by the user in CropSyst for each defined soil layer (Figure 4).

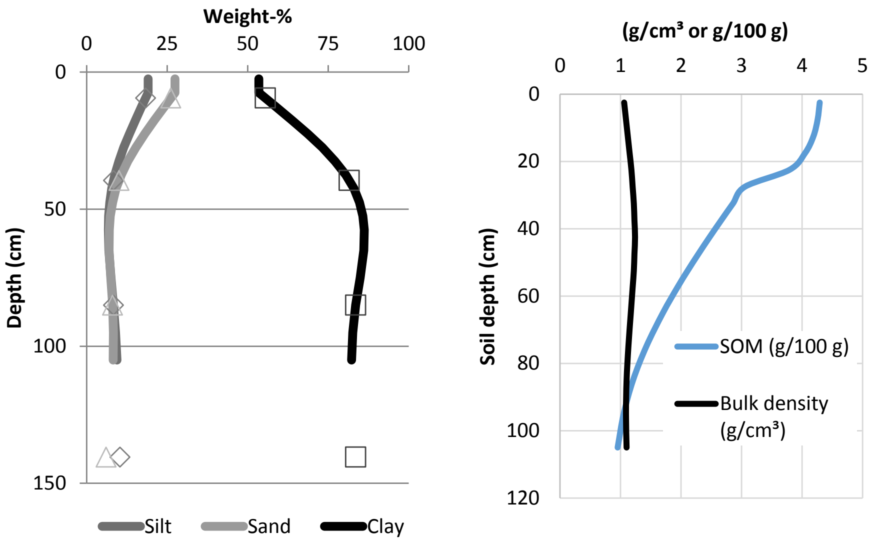

Figure 4: Silt, sand and clay content (left) and bulk density and (initial) soil organic matter content by soil depth as used in the CropSyst simulations (dots are observed values; Jelinski *et al.* unpublished)

Likewise, SOM pools for the defined soil layers have to be initialized, as is the case for total SOM and mineral N content. These are state variables that vary over time in response to the simulated biophysical dynamics. While total SOM and soil mineral N data are usually more easily available, in the majority of cases knowledge about the percent distribution of total SOM in the four pools is absent, even more so, as these cannot be easily measured in the lab by wet chemistry.

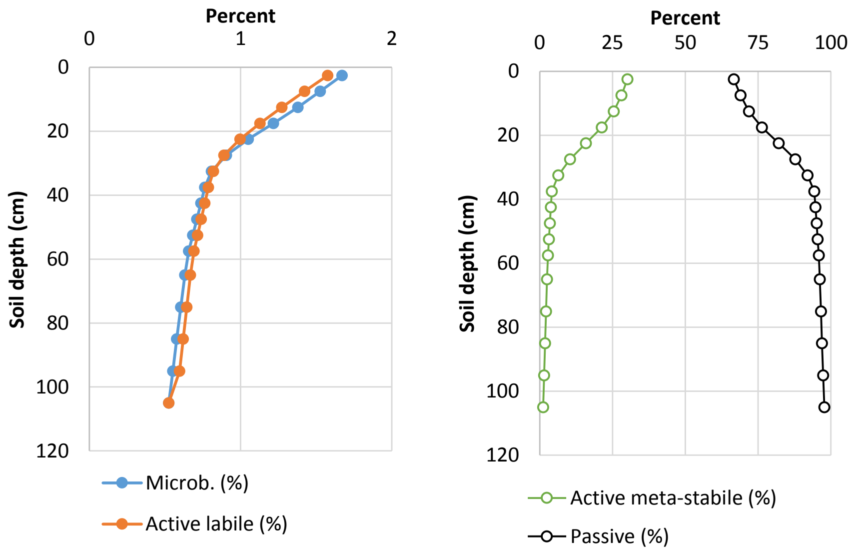

Figure 5: Percentages of the four SOM pools *Microbial biomass, Labile active, Metastable active,* and *Passive* by defined soil layers; each dot represents a distinct layer

To initialize these pools, so-called spin-up runs are usually carried out, which was also the case in this study. Therefore, a simulation of default farm management is run ex-ante (repeatedly) spanning several decades, and resulting percent distribution of SOM in its four pools carried forward to the subsequent simulation – either another round of spin-up or the simulation of the actual time period and management practice at hand.

In our case resulting pool percentages were further manually adjusted, so as to match observed and simulated soil organic matter contents over time. The resulting initial percentages of the four SOM pools are shown in Figure 5.

Scenario analysis and estimation of long term SOC trends

CropSyst simulations were carried out for the four mentioned INM3 treatments (FYM+ R- M-M N0, FYM+ R+ T-M N30, FYM- R+ M-M N90, FYM- R- M-M N0) covering the period 2004 until 2016.

In addition a scenario was set up, in which conservation agriculture was simulated, i.e. zero tillage and full crop residue retention, in combination with mineral N-fertilizer application (90 kg/ha) and continuous cropping of maize. This served to test alternative viable crop management options towards sustainable intensification, i.e. maintaining (or increasing) soil fertility and soil carbon *and* increasing productivity.

This scenario, and in contrast the worst case management (FYM- R- M-M N0), was projected into the future – year 2017-2035 – using CropSyst. Therefore, future synthetic weather data (neglecting a potential impact of climate change) were generated using the ClimGen weather generator software. ClimGen is capable of generating stochastic weather data from existing daily data (Stöckle *et al.* 1999). Management practices, i.e. the time of sowing, fertilizer application, soil tillage (if applicable) and time harvest, were maintained as observed (averages) of the 13 years of observations.

In addition, as a simpler way of predicting future trends, a three-parameter single exponential decay function was used for the selected treatments from the long-term trial to forecast observed SOM stocks of the top 40 cm depth into the future (2017-2035) based on observed trends of 2004-2016:

$$y = a + b * e^{(-ct)}$$

Here, a (t/ha/40 cm), b (unitless) and c (unitless) are curve fitting parameters. Such three parameter function was used successfully by other authors to describe the fate of SOM over time in conventional cropping systems of Western Kenya (Kinyangi 2008; Moebius-Clune *et al.* 2011).

Results and Discussion

Observed and simulated topsoil organic carbon contents

After thorough calibration, CropSyst simulations produced SOC trends that closely matched observed dynamics. Simulations were in the majority of cases within the uncertainty range expressed by the standard error of the mean of observed SOC.

All three continuous maize treatments lost SOC in the top 15 cm of soil over time, irrespectively of residues retained or manure and mineral fertilizer applied (Figure 6). This was expected for the “worst case” management (FYM- R- M-M N0), but came as a surprise for the "resource-constrained livestock farmer" (FYM+ R- M-M N0) and the "intensive maize farmer" (FYM- R+ M-M N90) practices, which either received significant amounts of manure, or where residues were partly retained and mineral N fertilizer (besides P and K) applied. Only the treatment maintained SOC similar to the initial content of 24.2 g/kg, in which maize was rotated with the green manure cover crop Tephrosia, and where manure and mineral fertilizer was applied and crop residues retained. This meant that only a rather intense form of ISFM – i.e. FYM+ R+ T-M/M-T N30 – would meet aspirations that an increase in soil fertility would also be visible in high(er) levels of SOC. Yet, all treatments missed the aspirational target of soil organic carbon *sequestration*, as is often assumed to take place under ISFM.

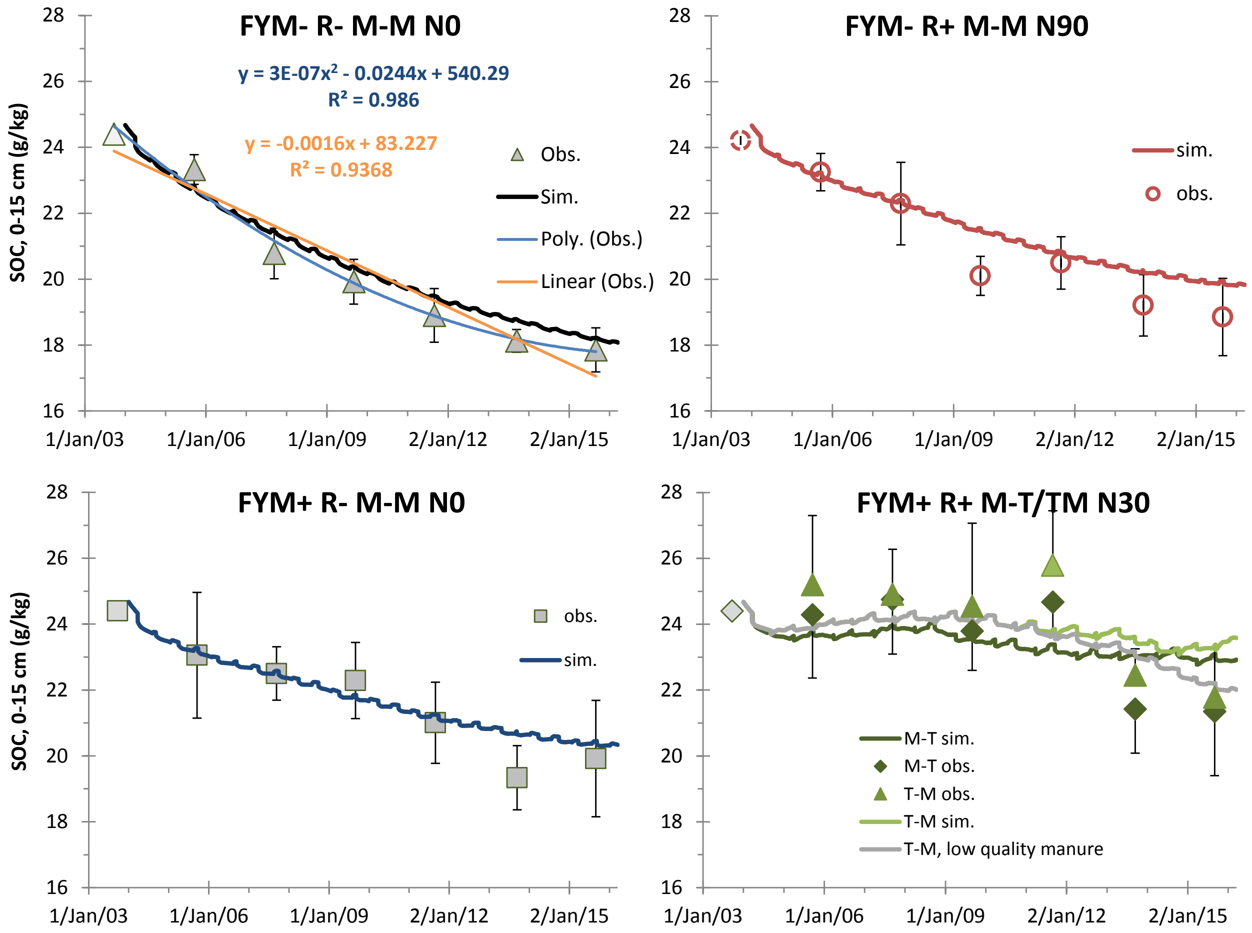

Figure 6: Observed and simulated organic carbon contents in the top 15 cm of soil; bars are standard errors

Observed losses decreased in the order *worst case* > *intensive maize farmer* > *resource-constrained livestock farmer* > *ISFM*. That meant in terms of avoiding SOC losses, applying manure would be favorable over mineral fertilizer (Figure 6). However, differences were small.

Interestingly, it mattered in which sequence Tephrosia and maize were rotated. Growing Tephrosia during the long rainy season resulted in slightly higher SOC contents than growing it in the short rainy season. This effect, even though small, was picked up by the model as well, and can be attributed to higher biomass produced in the long rainy season as compared to the short-rain season, which was then incorporated into the soil contributing to SOC.

The sudden drop of SOC in 2013 as compared to 2009 in the FYM+ treatments could be a consequence of (unintended) manure application of inferior quality. This is supported by a simulations run (gray line; lower right Figure 6) in which the quality of manure was reduced from 2011 onwards from its standard N-content of 1.75 % to merely 0.69 % as was observed by Margenot *et al.* (2017) in 2014.

For the FYM- R- M-M N0 treatment in Figure 7, two types of regressions were applied to describe time trends: one linear and one polynomial (cubic) regression. Obviously, the polynomial type of regression equation yielded a higher R^2 than the linear regression. The increase in R^2 was however very little. Visually it seemed that the polynomial would describe the decrease in SOC over time better; meaning the loss of SOC tended to be somewhat higher in the beginning, starting to level off later-on.

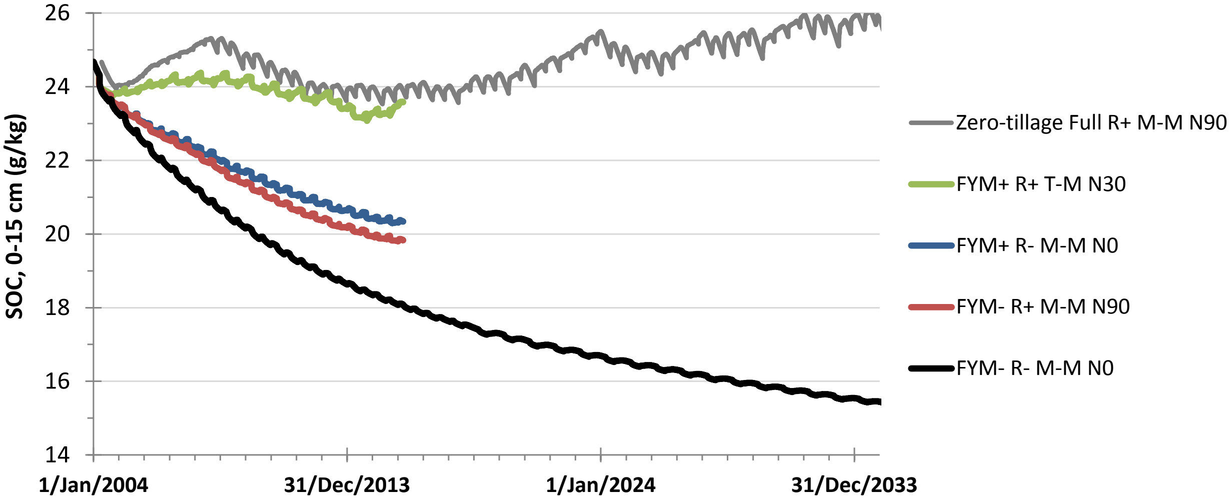

Figure 7: Simulated organic carbon contents in the top 15 cm of soil of the four observed treatments as well as a hypothetical conservation agriculture treatment comprising zero-tillage, full maize residue retention and an application of 90 kg N/ha mineral fertilizer

Figure 7 also displays the topsoil SOC content of the hypothetical conservation agriculture treatment comprising zero-tillage, full maize residue retention and an application of 90 kg N/ha mineral fertilizer per season. According to this simulation – and in agreement with commonly observed changes under CA (Baker *et al.* 2007) – such treatment would stimulate an increase of SOC in the top 10 cm above the initial levels in the long run. However, weather patterns and subsequent ups and downs in the produced total biomass also showed its impact on the topsoil SOC content, oscillating over the simulated 31 years.

Yet, under such CA treatment, in the absence of incorporation of residues to deeper layers, as is the case under common tillage practice, simulations revealed that the soil layer from ~10 to 30 cm depth lost significant amounts of SOC over time (Figure 8). In agreement with observations (data not shown), there were no notable changes of SOC simulated for the soil layers below 40 cm depths, which permitted us to focus on assessing changes in SOC of the top 40 cm only.

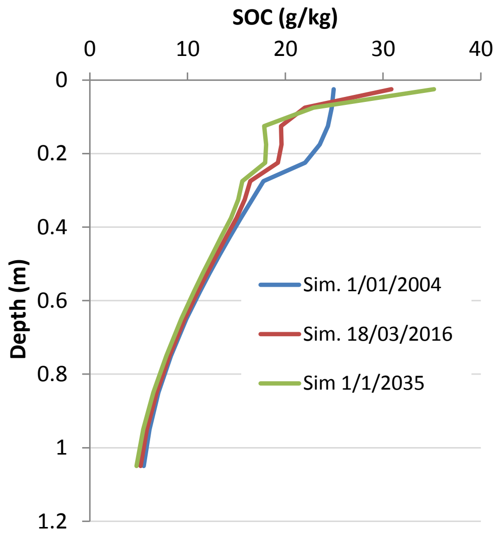

Figure 8: SOC contents of the 1.1 m soil profile under a conservation agriculture treatment comprising zero-tillage, full maize residue retention and an application of 90 kg N/ha mineral fertilizer – initial (1 Jan 2004) and its changes over time, i.e. after ~12 years and 31 years.

Soil organic carbon stocks at 0-40 cm

Given the SOC increases in the top 10 cm and concurrent decreases of SOC in the following 20 cm of soil under CA, the top 40 cm soil SOC stocks (t/ha) of this scenario and that of *ISFM* were not different (green and gray lines in Figure 9).

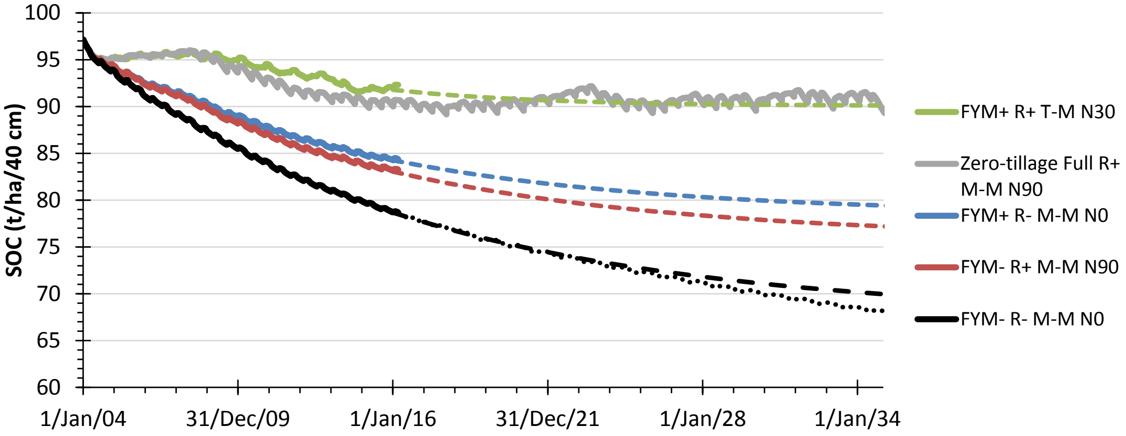

Figure 9: Simulated (CropSyst) and further projected (three-parameter exponential decay function) SOC stocks in the top 40 cm of soils, bold and dotted black line = CropSyst simulation; dashed lines = decay function

In the *worst case management* scenario (black line in Figure 9), losses of SOC did not level off even after some 30 years. There was some little divergence visible in the projections based on CropSyst and that based on the three-parameter exponential decay function, with the latter drawing a somewhat less pessimistic picture of losses SOC over time than the CropSyst simulations.

SOC stocks of the other four simulations indeed tended to level off, latest after some 30 years. Year-2035 SOC stocks of the *resource-constrained livestock farmer* (FYM+ R- M-M N0) and the *intensive maize farmer* (FYM- R+ M-M N90) ranged between 77-79 t/ha/40 cm, while the *ISFM* and *CA* treatments leveled off at about 90 t/ha/40 cm, but already some 15-20 years earlier.

Carbon balance

Comparing SOC stocks at the beginning of the trial with those predicted 31 years later, the five treatments lost between 7 and 27 t C/ha in the top 40 cm of soil (Table 2).

Table 2: Predicted losses of SOC stocks in the top 40 cm of soil of the four studied treatments in CIAT's INM3 long-term trial as well as a hypothetical CA treatment over a period of 31 years and average annual losses of carbon, respective CO_2 equivalents, and average annual avoided losses by adoption of ISFM or CA

Treatment	**Description**	**SOC difference 2004-2035**	**Average annual loss of SOC**	
		t C/ha	**t C/ha/yr**	**t CO_2e/ha/yr**
FYM- R- M-M N0	Worst case management	-27.2	-0.88	-3.22
FYM- R+ M-M N90	Intensive maize farmer	-19.9	-0.64	-2.36
FYM+ R- M-M N0	Resource-constrained livestock farmer	-17.7	-0.57	-2.09
FYM+ R+ T-M N30	ISFM	-7.0	-0.23	-0.83
ZT Full R+ M-M N90	Conservation agriculture	-7.6	-0.24	-0.90
Avoided losses			**0.33-0.65**	**1.20-2.38**

Expressed as average losses, the *worst case management* triggered losses of almost 0.9 t C per year. SOC losses of the *intensive maize farmer* system were also high with on average 0.64 t C/ha/yr, while *CA* and *ISFM* systems losses were reduced to 'only' 0.24 and 0.23 t C/ha/yr, respectively. Hence, by adopting ISFM or conservation agriculture, carbon emissions in the range of approximately 0.33 to 0.65 t/ha/yr could be avoided[1].

Overall discussion and conclusions

It is not surprising to see that poorly managed crop land loses considerable soil organic carbon over time. This has been reported repeatedly elsewhere (Don *et al.* 2010, Smith 2008). However, the still significant losses of SOC in systems where considerable amounts of mineral fertilizer were applied and some 2 tons of crop residues per hectare retained each season, or in systems with inputs of 4 t/ha/season farm yard manure, is more than surprising. It is often assumed that with such notable

---

[1] *0.33 t/ha/yr is the difference between FYM+ R- M-M N0 and ZT Full R+ M-M N90, i.e. the smallest observed difference, while 0.65 t/ha/yr is the largest observed difference between FYM- R- M-M N0 and FYM+ R+ T-M N30.*

inputs, soil fertility (and soil organic carbon) can be maintained (Lal 2004; Bationo *et al.* 2007), which our results show, is apparently not the case in the humid tropical environment of Western Kenya. ISFM and CA practices perform comparably better, but still even these systems lose SOC for quite some time until a lower, new equilibrium is reached, as our prediction show.

Losses tend to be somewhat higher in the beginning than later-on (Figure 6), which basically justified using a three-parameter single exponential decay function. However, this type of forecasting is apparently slightly beatifying realities; it levels off at a slightly higher SOC equilibrium and earlier than our CropSyst-based simulations would suggest.

In conclusion, it thus must be stated that none of the tested systems does actually constitute a soil carbon sink, i.e. **true net carbon sequestration is absent**. In return, that does not mean that ISFM or CA do not contribute to climate change mitigation. The contrary: avoiding SOC losses thru such improved management practice means less CO_2 emissions to the atmosphere, which mitigates climate change. Our model-based predictions of avoided losses range between 1.20-2.38 t CO_2e/ha/yr.

Nevertheless, as long as soils are not true C-sinks, they do not serve to offset greenhouse gas emissions elsewhere, off- or on-farm, e.g. those occurring through enteric fermentation of ruminants and the release of CH_4 or nitrous oxide emissions from soils.

Two aspects are however worth mentioning in that respect:

1.) The tested cropping systems are “mainstream” soil conservation and soil fertility management. Both best-bets – *ISFM* and *CA*, could be improved by providing for a better, and more continuous protection of the soil by inclusion of a green manure cover crop that better covers the soil than the tall and rather “shadow-less” Tephrosia. Also a proper crop rotation including more than just maize, Tephrosia and soybean (data not shown), seems advisable.

2.) Not shown in this study – the tested best-bet systems (ISFM an CA) do outperform common farmer practice by a factor 2-4 in terms of maize productivity, which is a consequence of vastly improved soil fertility, nutrient use efficiency, and water infiltration and use. They also provide for better yield stability, with crops better withstanding ins-season and late-season dry spells. Thus, these systems are very successful in achieving their primary goals, which is enhanced productivity and resilience.

Therefore, both ISFM and CA cropping systems are climate smart, with a potential to further improve on the third pillar of climate smart agriculture – climate change mitigation.

References

Baker, J.M., Ochsner, T.E., Venterea, R.T., Griffis, T.J. 2007. Tillage and soil carbon sequestration – What do we really know? Agriculture, Ecosystems and Environment 118, 1-5.

Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B., and Kimetu, J. 2007. Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agricultural Systems 94, 13-25.

Birnholz, C., Braslow, J., Koge, J., Notenbaert, A., Sommer, R., Paul, B. 2017. Rapid climate smartness assessment of GIZ soil protection and rehabilitation technologies in Benin, Burkina Faso, Ethiopia, Kenya, and India. Working Paper. CIAT Publication No. 431. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. 84 p. https://cgspace.cgiar.org/handle/10568/80678

Don, A., Schumacher, J., Freibauer A. 2010. Impact of tropical land-use change on soil organic carbon stocks – a meta-analysis. Global Change Biology 17, 1658–1670.

FAO 2016. Soils and climate change. Soils: key to unlocking the potential of mitigating and adapting to climate change. http://www.fao.org/3/a-i6478e.pdf

FAO 2017. Global Symposium on Soil Organic Carbon. GSOC17 http://www.fao.org/global-soil-partnership/resources/highlights/detail/en/c/461896/

Kihara, J., Njoroge, S. 2013. Phosphorus agronomic efficiency in maize-based cropping systems: A focus on western Kenya. Field Crops Research 150, 1-8.

Kinyangi, J.M. 2008. Soil degradation, thresholds and dynamics of long-term cultivation: from landscape biogeochemistry to nanoscale biogeocomplexity. PhD Thesis. Cornell University. 175 p. http://hdl.handle.net/1813/8228

Lal, R. 2004. Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. Science 304, 1623-1627.

Margenot, A.J., Sommer, R. Parikh, S.J. 2017. Changes in soil phosphatase activities across a lime-induced pH gradient depend on management history. Submitted for publication.

Moebius-Clune, B.N., van Es, H.M., Idowu, O.J., Schindelbeck, R.R., Kimetu, J.M., Ngoze S., Lehmann, J., Kinyangi, J.M. 2011. Long-term soil quality degradation along a cultivation chronosequence in western Kenya. Agriculture, Ecosystems and Environment 141 (2011) 86–99

Parton, W.J., Ojima, D.S., Cole, C.V., Schimel, D.S. 1994. A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. In: Quantitative modeling of soil forming processes, Soil Science Society of America, Madison, pp 147-167

Smith P. 2008. Soil Organic Carbon Dynamics and Land-Use Change. pp 9-22 in Braihmoh, A.K. and Vlek, P.L.G (eds.): Land Use and Soil Resources. Springer. 254pp.

Sommer, R., Mukalama, J., Kihara, J., Koala, S., Winowiecki, L. and D. Bossio 2015. Nitrogen dynamics and nitrous oxide emissions in a long-term trial on integrated soil fertility management in Western Kenya. Nutr. Cycl. Agroecosyst. DOI: 10.1007/s10705-015-9693-6

Stöckle, C.O., Campbell, G.S., Nelson, R., 1999. ClimGen Manual. Biological SystemsEngineering Department, Washington State University, Pullman, WA

Stöckle C.O., Kemanian A.R., Nelson, R.L., Adam, J.C., Sommer, R., Carlson, B. 2014. CropSyst model evolution: From field to regional to global scales and from research to decision support systems. Environmental Modelling & Software 62, 361-369.