Title: Simulation of the impacts of restoration techniques on soil organic carbon content and structure in West Africa

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Abstract

The main objective of this study was to evaluate two restoration techniques, “stone rows” and “stone rows + tree planting” on soil organic carbon (SOC) sequestration and structure in terms of water stable aggregates as well as the time required to restore soil fertility. The Carbon, Aggregate and Structure Turnover (CAST) model was used to model the changes of SOC content and water stable aggregate formation under the two restoration techniques. Field experiments used for calibration of the model were conducted using a randomized block design. Soil samples were class fractionated followed by a micro-aggregate isolation procedure. The two restoration techniques contributed significantly to improving soil total carbon content. By running five year simulation of the “stone rows”, the estimated total carbon input was 27 Mg ha^{-1} of which 6.1 Mg ha^{-1} were sequestered in the soil and 20.7 Mg ha^{-1} were released as CO_2. In “stone rows + planting”, the total SOC content after five years was estimated to be 22.96 Mg ha^{-1}, which was broken down to 15.43 Mg ha^{-1} aggregated carbon and 26.60 Mg ha^{-1} CO_2. Fifty-year simulations showed a SOC increase to 54.8 Mg ha^{-1} in “stone rows”, and to 86.0 Mg ha^{-1} in “stone rows + planting”. This means that natural grassland vegetation slowly improves soil carbon content and soil quality, but with trees behind stone rows, the result will be about 50% higher.

Key words: water stable aggregates, carbon, restoration, modelling, stone rows, tree planting

1. Introduction

The causes of land degradation and desertification are both natural and anthropogenic. Degradation processes are driven by dry conditions and various human actions resulting in depletion of soil and reduced fertility of billions of hectares of range- and cropland throughout the world. Almost 40% of the world's agricultural land has been significantly degraded, affecting farming and grazing productivity as well as the livelihoods of more than 1 billion people in 100 countries (IDRC, 2008).

Africa is one of the continents facing the most severe consequences of desertification and land degradation since two-thirds of its land is already degraded (UNCCD, 2013), affecting 65% of the entire African human population. Furthermore, land degradation in Africa is occurring despite the efforts frame of the United Nations Convention on Combating Desertification (UNCCD) to combat desertification. In Burkina Faso for example, 1,198,000 ha (17.5%) of forest were lost between 1990 and 2010 (FAO, 2010) and almost 24% of the soils have turned into bare incrusted soils (zipellés) in central and northern Africa (Zougmoré et *al*., 2004).

The urgency to restore degraded ecosystems in Africa has been recognized by international organizations and the scientific community, resulting in the development of various restoration techniques (Kagambèga et *al.*, 2011a). Soil treatment and water harvesting techniques are often used, such as deep ploughing, creation of half-moon micro-catchments, or building up simple stone rows (Zougmoré et *al.*, 2003). These techniques have been shown to be effective in decreasing surface runoff, controlling erosion and improving soil fertility and revegetation of degraded landscapes (Kagamèbga et *al*., 2011b; Yaméogo et *al*., 2011). Enhancement of natural regeneration processes is attained by simply protecting land (ITTO, 2002) and tree planting has been used to accelerate natural regeneration processes.

Soil fertility is related to carbon and water stable aggregate contents (Six et *al.*, 2000; Paul et *al.*, 2013). Most work on water stable aggregates and soil fertility has been carried out for agricultural soils (e.g. Six et al., 2000; Boogar et *al*., 2014). Afforestation has been shown to increase soil organic carbon (SOC) content (Gong et *al.*, 2013), however, the impacts on soil structure and water stable aggregates are not well known. There has been increased interest in the scientific literature regarding the restoration of degraded agricultural soils using carbon amendments and agro-ecological practices such as conservation tillage (Mrabet, 2002; Kösters et *al.*, 2013).

Giannakis et *al.* (2014) used the CAST model to simulate the impact of carbon amendments in agricultural soils on water stable aggregate distribution and carbon sequestration. The CAST model (Stamati et *al.*, 2013) is based on the concept soil aggregation and disaggregation where macro-aggregates are formed around silt-clay particles, micro-aggregates and particulate organic matter. The CAST model can identify the factors affecting carbon sequestration and turnover in soils and ascertain the response of soil to land use and climate change as well as agro-ecological practices (Li e*t a*l., 2016; Apostolakis e*t* al., 2017).

The overall objective was to assess the impact of two soil restoration techniques, “stone rows (SR)” and “stone rows + tree planting (SRP)” on carbon sequestration and soil structure and to assess the time required to restore fertility using the CAST model.

2. Material and methods

2.1 Study area

The experiment was conducted on a endo-petric skeletal lixisol in the rural township of Dissin near the Total and Partial Reserves of Fauna of Bontioli, south-western part of Burkina Faso between the latitudes of 05°01’W and 4°26’W and longitudes of 12°01'N and 12°23'N. The climate is south-sudanian with the wet season in the summer-fall and the dry in winter-spring. The average annual rainfall is 1000 mm (1997 to 2007) and fluctuated between 900 mm and 1200 mm. The annual mean temperature is 29°C (Kaboré et *al.*, 2015). Extensive grazing and agriculture without fallow periods are the prevailing land uses, causing degradation of soil and vegetation cover.

2.2 Experimental setup

The experiment included two treatments and a control situated on fallow land on a slight slope (randomized block design with three replicates each). It was assumed that the control plots represented background soils and the data collected from these plots were used as a base-line for the evaluation of the impact of the restoration measures. The data from the control plots could therefore be used as initial conditions in the model regarding SOC content in order to assess the efficacy of restoration. The two treatments were stone rows (Figure 1) with natural vegetation (SR) and stone rows with densely planted of seedlings of the native tree *Piliostigma thonningii* (SRP). The planting density was about 5000 plants/ha. The dimensions of each plot were 20 m x 35 m (700 m^2) and the stone rows were situated on the downhill side of the slight slope of the plots. The slope fluctuated between 2 to 3%. The blocks were separated by 15 m while the plots within a block were separated by 5 m. The entire research site was protected from animals through fencing. The tree species *P. thonningii* was chosen because it is a pioneer species of fallow land colonization in Burkina Faso. The rural population is using it mainly for medicinal purposes. Its wood is also used as firewood and for house construction. The experiment started in May 2011.

2.3 Soil sampling and analysis

Soil samples were collected in May 2011 to determine the initial conditions. Soil samples for the modelling the impact of the two treatments were collected in October 2014. One composite sample from 0-15 cm depth was constituted with the soil taken on the uphill side, downhill side and the middle of each plot. The pipette method was used to determine soil texture (Loveland and Whalley, 1991). The pH was measured in a 1:2.5 soil/water suspension described by Sahilemedhin and Taye (2000). The Kjeldahl method (NKT) was used to analyse total nitrogen (Bremner, 1965) and the Bray1 method for total available phosphorus (van Reeuwijk, 2002). Potassium was extracted with ammonium acetate-extractable cations and analysed by atomic absorption spectrometry.

Wet-sieving was used to determine the content and size distribution of water stable aggregates followed by sand correction (subtracting the sand particles of given size class) according to the fractionation procedure described by Stamati (2012). The size class fractionation was followed by micro-aggregate isolation described by Lichter et *al.* (2008). The procedure is summarized in Figure 2. Finally, the carbon content of water stable aggregate size classes and bulk soil was analysed by the Walkley-Black method (Mylavarapu, 2015).

2.4 Data analysis

The normality of the data was verified using the Shapiro–Wilk test at alpha-level 0.05. An analysis of variance was conducted using the XLSTAT 7.5 software. The null hypothesis of the equality of the means was tested using the Newman-Keuls test at the 95% significance level.

2.5 Simulation of the restoration process

2.5.1 The CAST model

The CAST models (Stamati et *al.*, 2013) simulate the evolution of aggregation and disaggregation processes using three particle size classes: the silt-clay (AC1< 53 µm), micro-aggregates (AC2, 53-250 µm) and macro-aggregates (AC3,> 250 µm). The aggregation process is initiated when soil plant residue is colonized by microbes. These decomposers exude the binding material for soil particles, bacteria and fungi to form macro-aggregates around Particulate Organic Matter (POM). Further decomposition of macro-aggregate POM is encrusted within silt-clay aggregates, forming in these way micro-aggregates within macro-aggregates (AC2 and AC3). Biodegradation of macro-aggregate incorporated organic matter (OM) reduces their stability and increases the export of microbial biopolymers. Under slaking events, these macro-aggregates break down and release micro-aggregates, silt–clay aggregates and POM. The aggregation and dis-aggregation cycle starts again when new plant residues enters the soil. The CAST model uses the RothC carbon pools (Coleman and Jenkinson, 1999): Decomposable Plant Material (DPM), Resistant Plant Material (RPM), Microbial Biomass (BIO), Humified Organic Matter (HUM) and Inert Organic Matter (IOM). The AC1 aggregate type is consisting of BIO, HUM and IOM. The AC2 aggregate type is consisting of BIO, HUM, IOM and fine DPM and RPM pools. The AC3 aggregate type is consisting of BIO, HUM, IOM and fine and coarse deriving DPM and RPM pools. Each carbon pool decomposes into CO_2, BIO and HUM with a first-order process. The inert matter pool represents is recalcitrant and similar to biochar. The clay content of the soil determines the breakdown of organic matter into CO_2, BIO and HUM (Coleman and Jenkinson, 1999). The CAST model also simulates the changes in bulk density and porosity. Table 1 summarizes the abbreviations reported in this manuscript.

Table 1

2.5.2 Simulations

The model set up required inputs of climatic conditions (temperature, precipitation, evapotranspiration), above ground plant derived C (litterfall) and soil properties such as bulk density, soil depth, and particle size distribution. Moreover, data of the initial conditions were used by the model, such as the water stable aggregate distribution in the three classes (AC1, AC2 and AC3) and their respective SOC content. After a three-year application of the two restoration techniques, soil samples were analysed for SOC and water stable aggregates from both plots. These data were used for the model calibration through the calibration of carbon decomposition rates, the macro- and micro- aggregate formation and the fragmentation rate of the fresh plant material. Five-year simulations for the two techniques were used to describe the impact of the SR and SRP. Since the CAST model successfully described the carbon and aggregate dynamics of the experiment, a 50-year scenario was conducted with the calibrated model, in order to reach steady state conditions and assess the long-term impact of the two restoration techniques on the degraded soil.

3 Results

3.1 Soil analyses

3.1.1 Initial soil physical and chemical characterization

The initial physical (Table 2) and chemical (Table 3) soil parameters did not show significant differences, both treatments and control contained about 70% sand and 30% finer particles (silt and clay), pH was slightly acidic (5.50-5.54) and total nitrogen (0.04%) and organic matter (0.9%) were low.

Table 2

Table 3

3.1.2 Development of water stable aggregates

The large macro-aggregates (LAC3), the medium macro-aggregates (MAC3), the small macro-aggregates (SAC3) and the micro-aggregates (AC2), showed no significant differences between the treatments (Figure 3). The silt-clay sized micro-aggregates (AC1) showed a significant difference ($p<0.001$) between treatments. Thus, SRP increased this fraction by 47% and 63%, respectively, in relation to the control.

3.1.3 Development of carbon content in aggregate size classes

The carbon content in the SRP treatment was significantly higher than the control in small macro-aggregates (SAC3), micro-aggregates (AC2) and silt-clay size classes (AC1), while SR showed significant increases compared to the control in the silt-clay size class only (AC1) (Figure 4). There were no significant differences between the treatments in the large (LAC3) and medium sized aggregates (MAC3).

3.2 Simulations

3.2.1 Water stable aggregate distribution and soil carbon in the stone rows treatment

The CAST model was initialized using the carbon content measured in the control plots and calibrated using the measured data from the SR treatment (the crosses on Figure 5) obtained after three years of treatment. At the calibration time (36 months) the SOC in the control was 6.5 Mg ha^{-1} and it was split between 3.9 Mg ha^{-1} as POM and 2.6 Mg ha^{-1} in the silt-clay fraction. At the same time (after 36 months), SOC in the SR treatment was calibrated to be 10.5 Mg ha^{-1} (Figure 5), and it was split between 5.2 Mg ha^{-1} as POM and 5.3 Mg ha^{-1} in the silt-clay fraction.

The whole simulation was extended to five years in order to evaluate the impact of the SR treatments on soil restoration in terms of carbon sequestered in the different aggregate size classes over a longer period than the experimental three years. The model results over the five-year simulation showed a continued increase in carbon content of AC1 to 5.5 Mg ha^{-1} and a total content of 12.6 Mg ha^{-1} while the carbon content of AC2 and AC3 levelled off after a slight increase the first two to three years (Fig 5). During the five year simulation, the estimated total carbon input to the SR treatment was 27 Mg ha^{-1} of which 6.1 Mg ha^{-1} were sequestered in the soil and 21 Mg ha^{-1} were released as CO_2 (Table 4).

Table 4

3.2.2 Water stable aggregate distribution and soil carbon in the stone rows + planting treatment

The CAST-model was calibrated to simulate the impact of soil restoration of the SRP treatment after three years (36 months), and SOC in the SRP treatment was 14.5 Mg ha^{-1} (Figure 6), and it was split between 5.6 Mg ha^{-1} as POM and 8.9 Mg ha^{-1} in the silt-clay fraction. The following five-year simulations show that SOC content can be expected to increase to 20.8 Mg ha^{-1} (Figure 6). The total organic carbon input was 41.1 Mg ha^{-1} over the five years where 14.2 Mg ha^{-1} were stored in the soil and 26.6 Mg ha^{-1} were released as CO_2 (Table 4). This means that tree planting can increase the annual carbon input to the system by 14.1 Mg ha^{-1} (52% more than the stone rows) (Table 4) causing an increase of carbon sequestration in the soil of 8.1 Mg ha^{-1} (132% compared to stone rows) as well as an increase of 6 Mg ha^{-1} (29% extra) in CO_2 emission. While the increase in POM between the SR and SRP treatments remained about the same, the increase of silt-clay total carbon was 3 times larger in the SRP treatment compared to SR.

The SOC in the CAST model is the sum of the aggregated carbon in AC1, AC2 and AC3 as well as the particulate plant derived organic carbon, which is the sum of DPMc, RPMc and RPMf. The total SOC content after five years was estimated to be 22.96 Mg ha^{-1} (Figure 6), which was broken down to 15.43 Mg ha^{-1} aggregated carbon and 7.53 Mg ha^{-1} plant derived organic matter (POM). This means that about 1/3 of the total carbon input to the system has not undergone fragmentation and thus it was unavailable for sequestration. It is evident that organic degradation processes are not being favoured under the climatic conditions in Burkina Faso. Even though the area receives significant rainfall (1000 mm/yr), the soil is very sandy and well drained, conditions not favourable to retaining soil moisture. Furthermore, the rainy season is only about four months long, which leaves the soil very dry for about eight months.

3.2.4 Fifty-year simulations of the development in soil carbon content

Fifty-year simulation of the two systems show that the total accumulation of SOC after 50 years was 54.8 Mg ha^{-1} for the SR treatment (Figure 7). Of these BIO and HUM comprised 88.1% (BIO = 15.3 Mg ha^{-1} and HUM = 33.0 Mg ha^{-1}) and the aggregated and un-aggregated POM the remaining (POM-ag = 4.3 Mg ha^{-1} and POM-un-ag = 2.2 Mg ha^{-1}). The simulation shows a continuous accumulation for BIO, HUM and SOC while the POM components reach steady state after 4 years for the aggregated POM and after 12 yrs for the un-aggregated. Similarly, for the SRT treatment the total accumulation of SOC after 50 years was simulated to be 86 Mg ha^{-1}. BIO and HUM comprised 87% of SOC (BIO = 23.5 Mg ha^{-1} and HUM = 51.0 Mg ha^{-1}) while the aggregated and un-aggregated POM the remaining (POM-ag = 5.0 Mg ha^{-1} and POM-un-ag = 6.4 Mg ha^{-1}). The simulations also shows a continuous accumulation for BIO, HUM and SOC while the POM components reach steady state after 4 years of treatment for the aggregated POM and 20 yrs. for the un-aggregated. These simulations highlight the importance of processes and differences between the two treatments. Both treatment favour HUM accumulation over BIO. It should also be noted, that both aggregated and un-aggregated POM reach steady state in both treatments even though the time to steady state differs between treatments. For both treatments, about 82-83% of the input was converted to CO_2.

4 Discussion

There was a clear difference in the total soil carbon content in the three plots, showing lowest content in the control, medium content behind the stone rows, and highest content behind the stone rows with planting of *P. thonningii* (Figure 3). The vegetation having better humidity conditions behind the stone row is without doubt the main cause of this difference. In the SR treatment, there was a strong colonization of the space by herbaceous species, and in the SRP treatment in addition to the herbaceous cover, there were the leaves and root turnover of *P. thonningii* trees. These results are consistent with those of Diedhou et *al.* (2009) and those of Yélémou et *al.* (2013) who noticed increased carbon and nitrogen content under *P. thonningii* in the semi-arid zone of Senegal and in Burkina Faso, respectively. They explained this increase by increased litter and root biomass. Similarly, Jandl et *al.* (2007) and Li et *al*. (2016) reported that afforestation is a major contributor to carbon sequestration in arid areas. The large impact of trees can be explained by Iyamuremye et *al.* (2000), who reported that the content of nitrogen and hemicelluloses in the leaves of *P. Piliostigma* is high while lignin is low compared to other trees in Senegal. This chemical composition of the leaves makes them difficult to decompose which could explain the higher carbon content and high POM stocks in *P. Piliostigma* plots.

The observed silt-clay fraction carbon content was higher compared to other fractions in all treatments. The SOM of this fraction is strongly associated with the mineral particles and may be physically protected against biodegradation (Plante et *al.*, 2006; Traoré et *al.* 2015). According to Six et *al.* (2002) and Traoré et *al.* (2007), the labile carbon was part of the macro-aggregates that provide minimal physical protection since they are composed by plant residues. This fraction is sensitive to agricultural practices and affected by land degradation processes (Wei et *al.*, 2013).

The initial carbon content at the restoration site was very low but simulations suggest that it can be increased twofold in five years without doing more than establishing low stone rows and keeping it free of grazing. If, on top of establishing the stone rows, it is also possible to plant trees it is possible to double the restoration speed. The results of this study are very encouraging, making it attractive to restore degraded soils by establishing stone rows and planting a high density of tree seedlings. Therefore, soil restoration using stone rows and tree planting is an applicable method.

The turnover time of the various carbon fractions calibrated in the CAST model showed that the carbon turnover is significantly larger for most of the parameters in the African soils compared to the natural restoration processes in Greece and the USA (Stamati et *al.*, 2013). This suggests that even though the African soils can accumulate carbon in a short period, the organic matter cannot be decomposed fast enough in order to produce humus that will increase soil fertility. A possible explanation for the reduced fragmentation and humification rates between the different soils is related to soil composition and climate. For instance, even though the annual precipitation of Burkina Faso is about 1000 mm, which is higher than the ones in Greece and USA, it falls within a short period and there is a 7-8 month period of dry season. The combination of long dry season and the fact that the soils of Burkina Faso are very sandy (78% to 88% sand), which means that they drain freely and do not have a sufficient water holding capacity, results in reduced SOM fragmentation. This is in line with the results of Davidson and Janssens (2006) and Wei et *al.* (2013).

5 Conclusion

This work is to our knowledge the first study, which simulated the evolution of carbon in soils during soil restoration in Western Africa. The empiric results showed that SR and SRP contributed to improve soil carbon content and simulations suggest that the carbon content can be increased two-fold in five years only by establishing a low stone row and keeping it free of grazing for five years. With additional planting of trees, it is possible almost to double the pace of restoration of degraded soils in Burkina Faso.

The results from field measurements and the CAST modelling show that SR, and especially SRP, can be used as a means of soil restoration.

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Table 1. Summary of the abbreviations used in the text.

Abbreviation	Definition
AC1	Silt-clay sized aggregates (< 53 µm)
AC2	microaggregates (53-250 µm)
AC3	macroaggregates (> 250 µm)
LAC3	Large macroaggregates (> 2000 µm)
MAC3	Medium macroaggregates (1000–2000 µm)
SAC3	Small macroaggregates (250–1000 µm)
mM	Microaggregates with macroaggregates
Sc-M	Easily dispersed silt-clay fraction
BIO	microbial Biomass
CAST	Carbon Aggregation and Structure Turnover model
DPM	Decomposable Plant Material
DPMc	coarse Decomposable Plant Material
HUM	Humified Organic Matter
IOM	Inert Organic Matter
POM	Particulate Organic Matter
cPOM	Coarse Particulate Organic Matter
fPOM	Fine Particulate Organic Matter
RPM	Resistant Plant Material
RPMf	fine Resistant Plant Material
RPMc	coarse Resistant Plant Material
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SR	Stone Rows
SRP	Stone Rows + tree Planting

Table 2: Initial soil texture in the experimental plots (3 replicates).

Treatments	Clay (%)	Silt (%)	Sand (%)
tone rows	10.08	19.14	70.77
Stone rows+ planting	9.59	20.16	70.24
Control	9.92	20.60	69.48
F statistic	***0.16***	***0.99***	***0.52***
P-value	***0.86***	***0.43***	***0.62***

Table 3. Initial soil chemical characteristics in the experimental plots (3 replicates).

Treatments	pH	Organic matter (%)	Extractable phosphorus (mg/kg)	Available K(meq/100g)	Total N (%)	C/N
Stone rows	5.52	0.90	1.12	36.88	0.04	12.21
Stone rows + planting	5.54	0.92	1.08	31.56	0.04	12.39
Control	5.50	0.86	1.02	32.95	0.04	12.74
F statistic	***0.02***	***0.09***	***0.23***	***0.64***	***0.36***	***0.08***
P-value	***0.986***	***0.917***	***0.805***	***0.558***	***0.715***	***0.9207***

Table 4. Carbon fluxes (Mg ha^{-1}) in the two treatments over five years.

Treatment	Input (total)	SOC initial	SOC final (after 5 y)	Storage	CO_2 emissions
Stone rows	27.0	6.51	12.65	6.14	20.70
Stone rows + planting	41.1	6.51	22.96	15.43	26.60

SOC = Soil organic carbon