

Effect of charcoal production and woodland type on soil organic carbon and total nitrogen in drylands of southern Mozambique

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Abstract

African woodland ecosystems function as important reservoirs for soil organic carbon (SOC) and total nitrogen (TN). However, these ecosystem functions are particularly sensitive to social-ecological factors, the impacts of which remain understudied. Here, we examine how SOC and TN and other soil properties vary across woodland types and how charcoal production, the main

source of woodland disturbance in the study area, changes these factors in dry woodlands of southern Africa, focusing on three woodland ecosystems that represent the main types in southern Mozambique: *Androstachys* forest, *Combretum* woodland and Mopane woodlands. Drawing on data from soil surveys at 0-5 cm and 0-30 cm depth in different vegetation types as well as both distant from and proximate to sites of active charcoal production, we estimate that these woodlands in Mabalane District store on average 19 ± 10 (\pm SE) Mg ha⁻¹ of SOC, and 2.2 ± 0.9 Mg ha⁻¹ of TN at 0-30 cm, significantly lower than values reported for other woodlands in the region such as Miombo. Our analysis shows that the woodland types do not differ in terms of the amount of SOC and TN stored in soil, and that soil in the charcoal kilns had twice the amount of SOC (30.0 ± 1.8 Mg ha⁻¹) and TN (4.5 ± 0.5 Mg ha⁻¹) compared with non-charcoal soils. This study adds to our understanding of the impact of charcoal production on soil SOC and TN in dry woodlands of southern Africa, and demonstrates some localised impacts of charcoal production. We discuss the implications of our findings in the light of emerging carbon-based payments for ecosystem services programmes in the region.

Keywords: soil carbon, nitrogen, charcoal production, mopane woodland

1. Introduction

Woodland management, especially the harvesting of biomass for wood fuels, can significantly affect soil carbon (C) storage (Nave et al., 2010; James and Harrison, 2016), and charcoal production in particular is a significant driver of woodland degradation across sub-Saharan Africa (SSA) (Chidumayo and Gumbo, 2013; Sedano et al., 2016). The effects of woodland management on SOC and TN are important to understand, not only because these are often key variables determining soil fertility, but also because of global climate change and the role soils can play as a source or sink for C on a global scale (Johnson and Curtis, 2001).

Moreover, there is great interest among policymakers in the potential of carbon-based payments for ecosystem services (PES) to reduce carbon emissions from deforestation and forest degradation and protect forests in tropical countries (Baker et al., 2010). As a result, many projects aim to reduce carbon emissions from deforestation, forest degradation, and forest management, as well as enhance or conserve existing forest carbon stocks (known as REDD+, Angelsen et al. (2009)) which is currently regarded as one of the most promising mechanisms driving the conservation of tropical forests (Venter and Koh 2011).

The majority of C and N in arid and semiarid systems resides belowground (Liu et al. 2010), and factors such as woodland type and charcoal production in these pools play an important role in the variation of soil organic carbon and total nitrogen. However, there is a limited number of studies focusing on the content of C and N in soils of different woodland types in southern Africa (Williams et al., 2008). Charcoal is the main source of domestic energy for urban populations across SSA countries, resulting in an important economic activity at national scale to the value of approximately 2–3% of GDP of SSA countries (IEA, 2014). Charcoal is primarily produced in rural areas and provides affordable energy to 70–90% of the urban population (IEA, 2014). Its production provides a considerable amount of employment in rural areas, allows for a quick return on investments and is often practised in conjunction with agriculture (Ogundele et al., 2011; Sedano et al., 2016; Jones et al., 2016; Smith et al., 2017).

Charcoal production is an income-generating activity for rural populations living near dry forests and woodlands in SSA, usually associated with urban areas that have a demand for charcoal (Zulu and Richardson, 2013; Makhado et al., 2014; Baumert et al., 2016; Zorrilla-Miras et al., 2018; FAO, 2017; Smith et al., 2019). Despite the economic benefits of charcoal production, much concern has been expressed about the impacts on human health and the environment that follow its process through the chain of production to consumption. Specifically related to local environmental conditions, during tree harvesting for charcoal production,

changes take place in the structure and function of woodland ecosystems that reach beyond simply the removal of biomass (Kalaba et al., 2013). Tree harvesting also alters plant litter inputs to soil and modifies the soil environment, which may alter the composition and function of microbial communities (Hassett and Zac, 2005). Giller (2001) noted that charcoal additions do not stimulate only microbial population growth and activity in soil, but also plant-microbe interactions through their effects on nutrient availability and modification of habitat. However, the highest impacts of charcoal production on the soils occur locally at the charcoal site, and to a lesser extent in the surrounding area of the kiln, where the wood has been harvested (Chidumayo and Gumbo, 2013). Previous studies have concluded that, at kiln sites, charcoal production provides higher nutrient content in the soil than in surrounding sites (Chidumayo, 1994, Coomes and Miltner, 2016), as well as improved soil chemical and physical properties (Chidumayo, 1991; Oguntunde et al., 2008; Ogundele et al., 2011; Wahabu et al., 2015; Coomes and Miltner, 2016) because of the presence of fine charcoal particles in the kiln soil (Chidumayo and Gumbo, 2013). However, the changes in SOC and TN as result of charcoal production remains largely unquantified and poorly understood, and this is especially true in the context of semi-arid woodlands in Mozambique.

Soil organic carbon is defined as carbon in soils derived from the decay of plant and animal residues, living and dead microorganisms, as well as soil biota (Scharlemann et al., 2014) and, when considered in combination with its associated nutrients (nitrogen, phosphorus and sulphur), can contribute to the resilience of soil/plant systems (Baldock, 2007). SOC and TN vary between vegetation types because of different inputs, and varying levels of chemical and physical protection of organic molecules. This heterogeneity can mask the impacts of different land uses and so needs to be included in the ecosystem resilience assessment. Furthermore, understanding potential C and N storage capacities will help to predict the quantity of C and N that can be sequestered by specific terrestrial ecosystems, and assess the impact of natural and

anthropogenic events on C and N storage (Jackson et al., 2017). This is particularly needed in Mabalane District where woodland types are distinctive and intermixed with forest, all with differing ecosystem structure and varying levels of disturbance caused by charcoal production that may affect the SOC and TN levels.

This study aims to understand how SOC and TN and other soil properties vary across woodland types and how charcoal production, the main source of woodland disturbance in the study area, changes these factors. The specific objectives of this study are twofold: (1) to assess the variation of SOC and TN across woodland types; and (2) to study the effect of charcoal production on SOC and TN.

2. Material and Methods

2.1. Study area

Our study area encompasses seven villages in Mabalane District, Gaza Province, in southern Mozambique (Fig. 1). The main woodland type is dry tropical woodland, consisting of Mopane woodlands (*Colophospermum mopane* (Benth.) J. Léonard) interspersed with discrete patches of *Androstachys johnsonii* Prain, *Combretum spp.* and *Boscia albitrunca* (Burch.) Gilg & Gilg-Ben. dominated woodlands, with a C4 grass layer such as *Panicum maximum* Jacq and *Hyparrhenia hirta* L. (Woollen et al., 2016). The area has a semi-arid climate, with a mean annual rainfall of 505 mm/year and an average annual temperature of 24 °C (MAE 2005). There are marked dry and wet seasons, with most precipitation falling between October and April. Our seven study villages, located in Mabalane District (Fig. 1), had similar climatic conditions, vegetation types and infrastructure as well as similar human population size, but were at different stages of charcoal production, from villages with a long history of commercial charcoal production (more than 10 years) to villages not yet involved in commercial production (Baumert et al., 2016). The last census reported about 43 800 people living in Mabalane District (Instituto

Nacional de Estatística, 2017). Mabalane District is the main charcoal production area supplying Maputo, the capital of Mozambique (Luz et al., 2015).

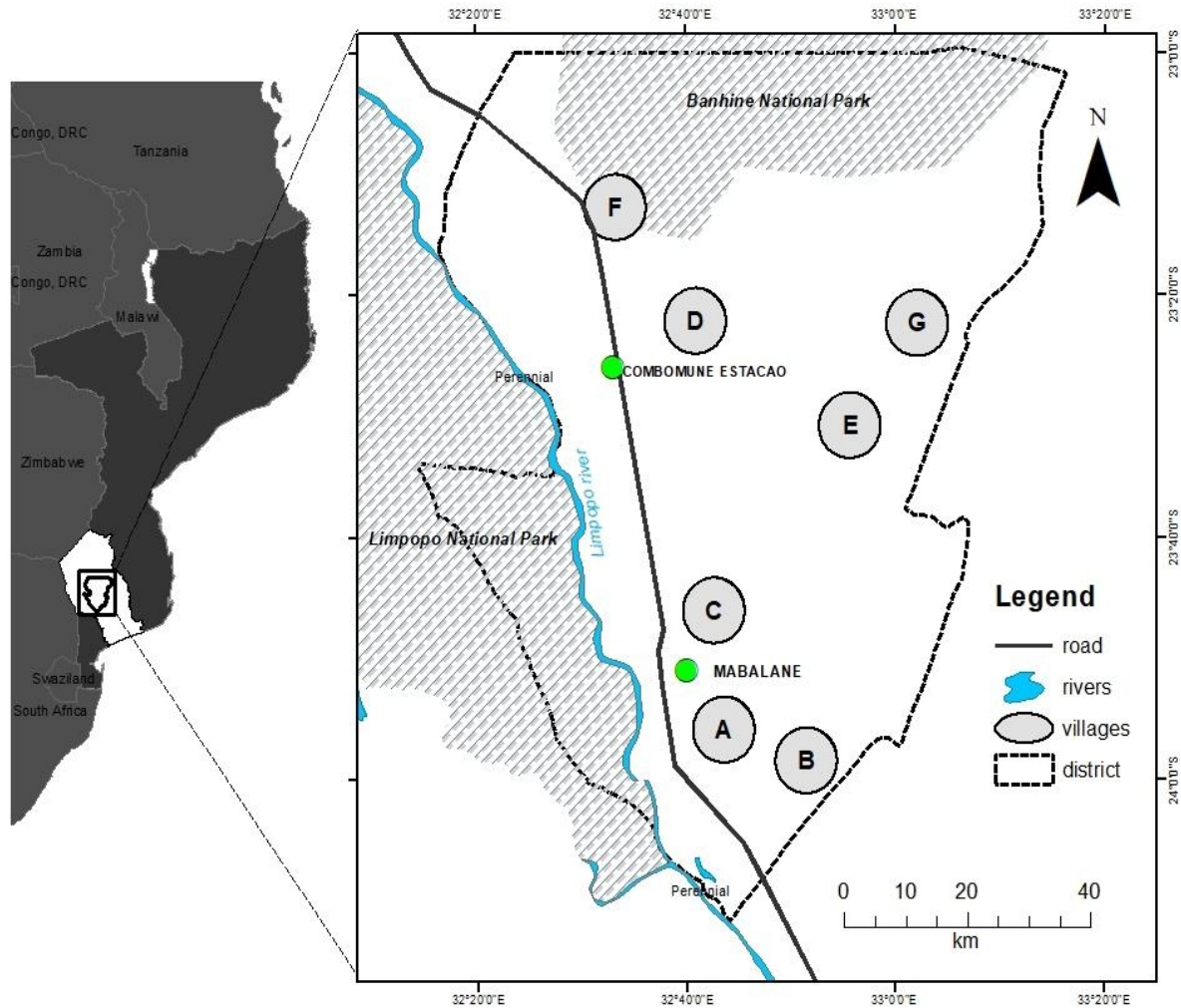


Figure 1: Study area showing the seven villages (A-G), the main partially tarred road, main rivers and the Mabalane district boundaries. The main local towns (green circles) and national parks.

In Mabalane District, Gaza Province, southern Mozambique, (the focus of this study), external large-scale operators and local rural households engage actively in charcoal production. External operators produce the greatest proportion of charcoal in the study area (Baumert et al., 2016), with wealthier local households producing comparatively more charcoal than poorer ones (Smith

et al., 2019). Current charcoal production in the study area by either local or external operators is done using a traditional earth kiln with an average length of 14.1 m, width of 3.8 m and height of 1.3 m, built with mopane trees of diameter at breast height ranging from 12 to 17 cm. The kiln size in the study area is much larger than those from central Mozambique, that Sedano et al. (2016) found to have an average width of 2.2 m and average height of 1.2 m. The practice of charcoal making leaves a substantial amount of small charcoal particles in the kiln scars that remain for many years (Fig. 2). The kiln scars are covered by grasses, similar to the grasses of the open areas of the local Mopane woodland, while sprouted mopane surrounds the kiln scars as soon as one year following charcoal production. There is not much observed soil erosion at the charcoal sites, likely due to the relatively flat nature of the study terrain. Evidence of grazing pressure around or within the kiln was considered to be low, since the livestock density in the area was already low with adequate grazing area available in closer proximity to the villages, far from the studied kilns. Charcoal production in the study area is associated with increases in some aspects of well-being such as greater asset ownership (Zorrilla-Miras et al., 2018). However, it is not associated with improved overall well-being, when measured using a combination of variables such as health, education, food security, and household living conditions (Vollmer et al., 2017).

2.2. Soil sampling

In each village sampled in the dry season, soil samples were collected from a total of 105 circular plots (n =15 plots per village), located within a 5 km radius from the centre of each village (78.5 km²), using methods described by Woollen et al. (2016). Before collecting soil samples, observations of disturbances were recorded (e.g. recent fires, evidence of soil erosion, presence of charcoal kilns or cut stems etc.) and then plots were classified either as charcoal production

162 plots (plots with old or active kilns inside the plot, total $n = 45$) or as non-charcoal plots (plots
163 without visible kilns nearby for at least 100 m away, total $n = 60$).

164 The non-charcoal plots were circular with a diameter of 20 m, with 4 quadrats placed 10 m from
165 the centre in each cardinal direction (North, South, East and West). Within each 1 m² quadrat,
166 one soil core from the 0-30 cm (520 cm³) and four soil cores of the 0-5 cm (162 cm³) depths
167 were extracted (Fig. 3A). The soil samples from the charcoal production areas were collected
168 within a 1 m² quadrat placed at the centre of the charcoal kiln scar, in order to identify the real
169 effect of charcoal production and compare with soil from non-charcoal production areas. The
170 study investigated long-term effects (≥ 2 years after charcoal production), all sampled kilns were
171 dormant for at least 2 years after charcoal production. In the centre of the area occupied by each
172 old kiln, a 1 m² quadrat was placed. One soil core of 0-30 cm depth (520 cm³) and four soil cores
173 of 0-5 cm (162 cm³) depth were extracted following the layout described in Fig. 3B.

174 The sample depth of the 0-30 cm sample and the tube diameter were recorded for bulk density
175 calculations later. Each sample bag was labelled with the plot ID, subplot (N, S, E, W or C), the
176 depth (5 or 30 cm), and the date. Soils were then weighed to determine their wet weight (weight
177 before drying) and then air dried. The wet samples in each plot and at each depth were then
178 mixed together and sub-sampled using a riffle splitter. This created two samples (0-5 cm and 0-
179 30 cm) for each plot or kiln.

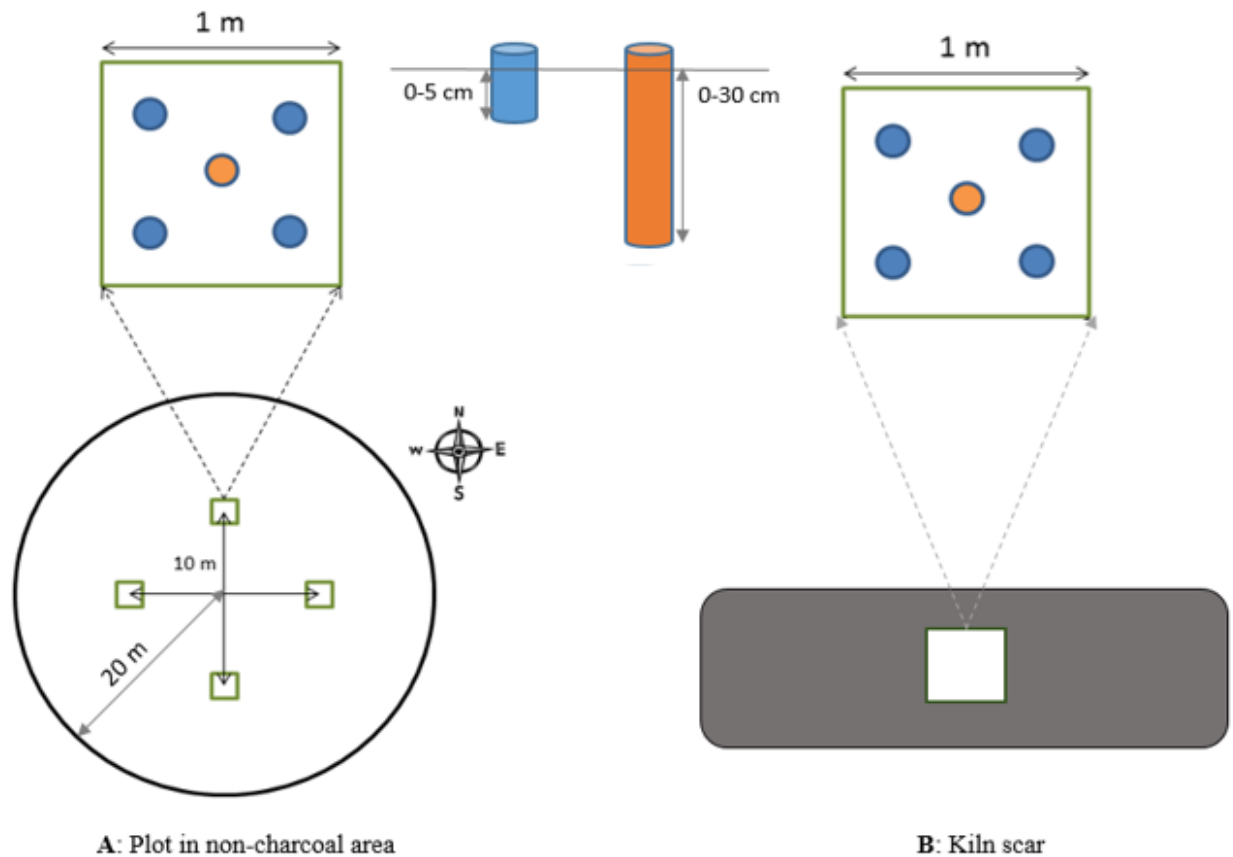


Figure 3: Layout of soil sample plot in the (A) non-charcoal sites and (B) charcoal sites (kiln scar) in Mabalane District, southern Mozambique.

2.3. Dry woodland ecosystem classification

The dry woodlands were classified into four types based on a ground assessment (Woollen et al., 2016), each of them represented by a dominant tree species: *Androstachys* forest (AF, dominated by *Androstachys johnsonii*), *Combretum* woodland (CW, dominated by *Combretum spp*), *Mopane* woodland (MW, dominated by *Colophospermum mopane*) and *Boscia* woodland (BW, dominated by *Boscia spp*). Plots were randomly located prior to woodland analysis, with the result that *Boscia* woodland existed in only four plots. Since this would not allow for a robust statistical analysis, *Boscia* woodland was excluded from the analysis. A woodland map distinguishing the three remaining woodland types was created based on the

classification of multi-temporal Landsat 8 data (images from May and Oct 2014) and ALOS PALSAR 2 HV backscatter (Oct/Nov 2014) (Fig. 4).

Woodland classification was created using a Support Vector Machine classifier implemented in ENVI version 5.2 (Exelis Visual Information Solutions, Boulder, Colorado) utilizing 430 training polygons of ground data based on our observations data from 105 plot. The training polygons were drawn in Google Earth Pro on the 2014 image. Twenty-five percent of the ground data were set aside and used for validation purposes. The classification had an overall accuracy of 87 % (Kappa coefficient 0.8) and was effective in distinguishing different woodland types. Amongst woodland type, the two dominant classes (Mopane and Combretum woodlands) were easily distinguished with a separability of 1.9 – 1.99, whereas the less dominant classes had a separability of 1.1 (Woollen et al., 2016).

2.4 Sample size

The sampled plots were classified post-hoc according to their dominant woodland types, determined by the dominant tree species present in the plot. The total sample (n = 105) was then classified into those occurring in *Androstachys* (AF), *Combretum* (CW) or Mopane woodland (MW). These were further divided into those plots that had charcoal production and those that did not (i.e. the non-charcoal plots). The total sample size for Mopane woodland was 68, where 45 plots had charcoal activity. Combretum woodland had 24 samples and *Androstachys* 13 plots. Only Mopane woodland had charcoal production, because *Colophospermum mopane* is a target species for charcoal production in the study area due to its high wood density (1.064 g cm^{-3}) and therefore high quality charcoal (Chavana, 2014). Therefore, comparisons between charcoal kilns scars and non-charcoal plots were only performed within Mopane woodland (Fig. 4). Similarly,

we compared woodland types only using the non-charcoal plots, to eliminate the impact of charcoal activity in the comparison.

2.5. Soil analyses

All soil sub-samples were dried in an oven at 60-70°C until constant weight, the dry soil sample sieved to a < 2 mm fraction and weighed. Dry weights and fresh volumes were used in bulk density calculations. Soil texture was analysed according to the Olsen method (Olsen et al., 1954), dividing particles following specificities of soil particle diameter (d): clay ($d < 0.002$ mm), silt ($0.002 < d < 0.05$ mm) and sand ($0.05 < d < 2$ mm), and calculating the percentage of each diameter. All sieved soil samples (< 2 mm; $n = 105$ each) were ball-milled to a fine powder and analysed using Walkley and Black's method (Walkley and Black, 1934) and the Kjeldahl's method (Jackson 1976) to give % C and % N, respectively. Total SOC (Mg ha^{-1}) and TN (Mg ha^{-1}) were determined as follows:

$$SOC = BD \times \%C \times d \times K \times G \quad (\text{Eq. (1)})$$

where BD is bulk density (g cm^{-3}), $\%C$ is percent total carbon, d is depth (m), K is a scaling factor (in this case 100 to get per hectare values), and G is the fraction of the soil which was <2 mm (i.e. not gravel). For G , a mean soil fraction for each sample was obtained by sieving and weighing the gravel fraction, and used to correct for the presence of gravel to avoid overestimation of soil C stocks. The gravel fraction did not contain any organic C, but consisted mainly of quartz minerals. The same formula was used to compute TN with %N. The average of SOC and TN was estimated for all the samples from non-charcoal plots using a proportion of the

area occupied by each woodland type, as determined by the woodland map, based on Mandallaz (2007) and Seifert and Seifert (2014).

2.6. Statistical analysis

In the first analysis, a Kruskal-Wallis one-way ANOVA was used to test the significance in the variation of SOC, TN, sand, clay plus silt, bulk density and C:N ratio amongst woodland type (AF, CW and MW), using only the data from the non-charcoal plots. Before performing the Kruskal-Wallis test, we tested for data homogeneity of variance and normality of data using the Levene and the Shapiro-Wilk test, respectively. If significant effects were observed by ANOVA, a least significant difference (LSD) test was used.

Secondly, we used non-paired samples in a two-tailed Wilcoxon test in order to compare averages of SOC, TN, sand content, clay plus silt content (CpS), bulk density (BD) and C: N ratio between kilns scars plots and non-charcoal plots. All data were initially tested for normality using the Shapiro-Wilk and Kolmogorov-Smirnov tests. From the non-charcoal total sample plot dataset ($n = 60$), seven plots of 0-5 cm depth were excluded from analyses due to errors in measurements, missing data or no C and N analyses. A comparison between 0-5 cm and 0-30 cm layers was made by taking the difference between the two layers for each parameter to be compared. All analyses were performed at 5% of significance level using functions available in the packages *ggplot2* (Wickham, 2009) and *ggpubr* (Kassambara, 2019) of the R Environment (R Development core team, 2015).

3. RESULTS

3.1. Soil Organic Carbon, Total Nitrogen stocks and soil parameters among woodland type

The results of the variation of SOC, TN and other soil parameters across woodland type are presented in Fig. 5. The data indicate that there are no statistically significant differences ($P >$

0.05) in SOC and TN between woodland types at 5 cm depth, but there are differences for both SOC and TN at 30 cm depth. The average carbon and nitrogen content for the entire sample from the 0-30 cm layer is 0.45% and 0.05%, respectively. The average SOC and TN stock (\pm Standard Error) for the 0 – 30 cm layer for all plots is 16.85 ± 4.02 Mg ha⁻¹ SOC (8.81 to 24.89 Mg ha⁻¹ at 95% confidence interval) and 1.98 ± 0.19 Mg ha⁻¹ TN (1.6 to 2.7 Mg ha⁻¹ at 95% CI). TN for the 0-30 cm layer was significantly higher in MW with an average of 2.59 ± 0.25 Mg ha⁻¹, almost twice as large as CW (1.66 ± 0.17 Mg ha⁻¹), although no difference from AF was observed ($P > 0.05$). SOC content for the 0-30 cm layer was also higher in MW and AF than in CW. The soil texture at both 0-5 and 0-30 cm varied significantly among woodland type. For example, clay plus silt (CpS) content was significantly higher in MW than in CW and AF for both depths 5 and 30 cm. Fig. 5 shows that most of the CpS content ($\text{CpS}_{5\text{cm}} = 14\%$ and $\text{CpS}_{30\text{cm}} = 16\%$) is stored in the surface layer, and more than 85% of CpS content stored at the deeper layer was contributed by the CpS content of the surface layer. Soil bulk density (BD) was not significantly different amongst woodland types either at 0-30 or at 0-5 cm depth, however was higher at 0-5 cm than 0-30 cm depth.

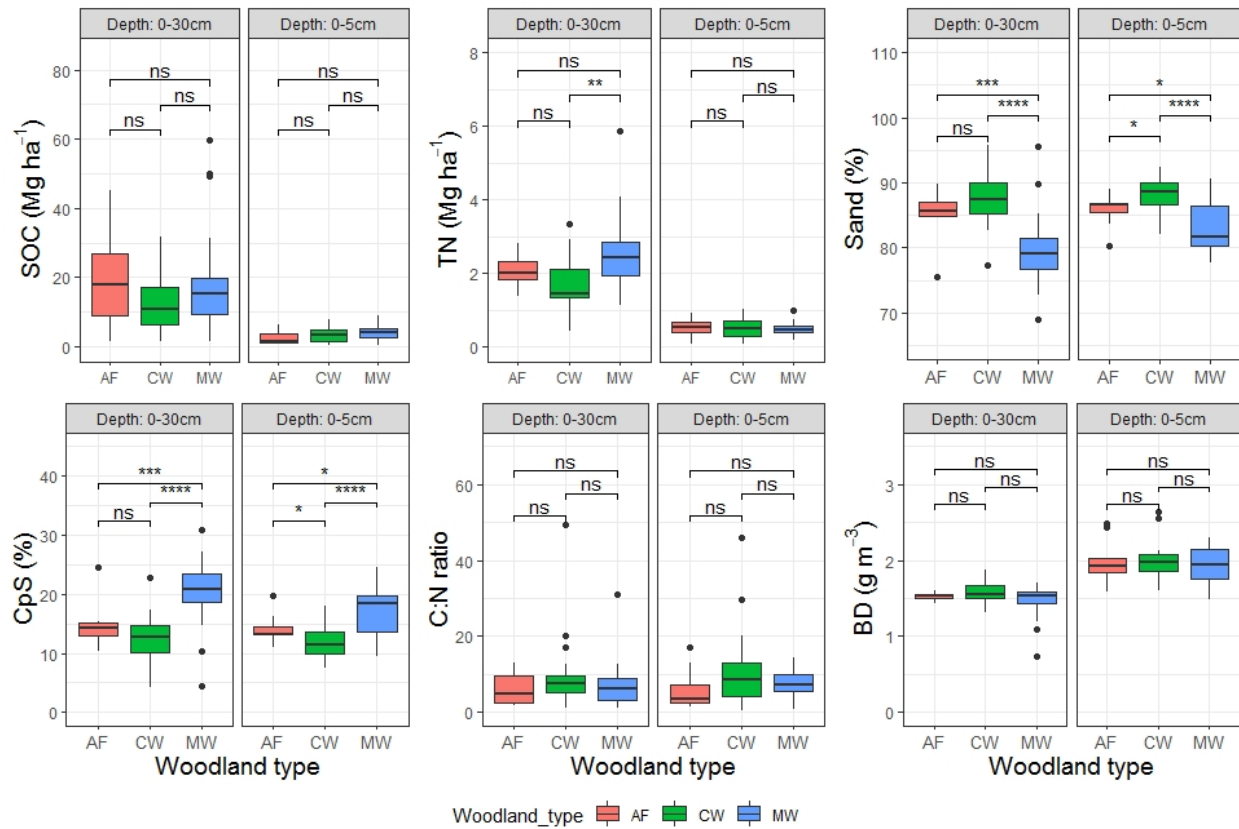


Figure 5: Comparison of mean soil organic carbon (SOC), total nitrogen (TN), sand content, clay plus silt (CpS), C:N ratio and bulk density (BD), among woodland types at both depth 0-5 and 0-30 cm. Mabalane District, southern Mozambique. (***) denote significant at $\alpha = 0.001$, (**) denote significant at $\alpha = 0.01$, (*) denote significant at $\alpha = 0.05$, (ns) denote not statistically significant at $\alpha = 0.05$.

3.2. Soil Organic Carbon and Total Nitrogen between charcoal sites and non-charcoal sites

The effect of charcoal production on SOC and TN is presented in Fig. 6. Charcoal production sites had significantly different SOC and TN in the 0-30 cm layer ($P < 0.001$). SOC and TN at 0-30 cm depth were significantly twice as high in the charcoal production plots than in non-charcoal plots ($P < 0.001$). However, at the 5 cm depth charcoal production did not have any effect on either SOC or TN ($P > 0.05$). Within the 0-30 cm layer, SOC had lower variability in

the charcoal plots (CV = 47%) than non-charcoal plots (CV = 81%), while TN had higher variability in charcoal plots (CV = 73%) than non-charcoal plots (CV = 54%).

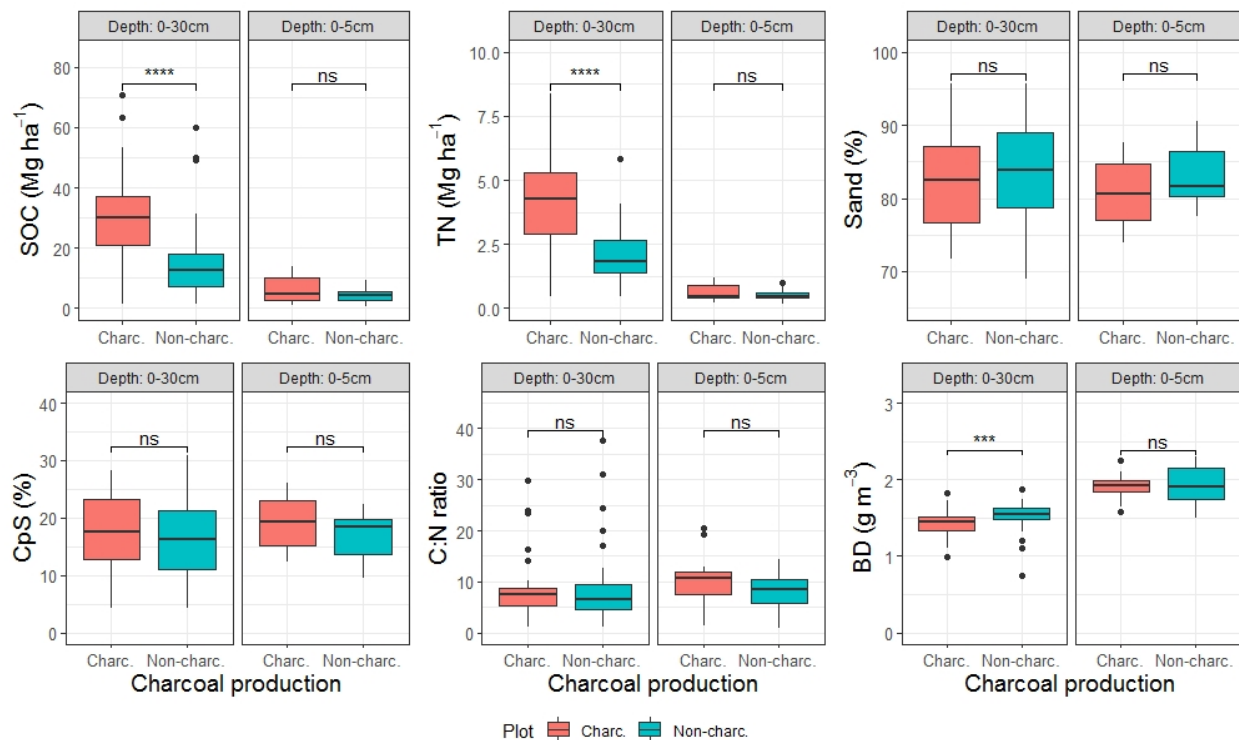


Figure 6: Comparison of soil organic carbon, total nitrogen and other soil parameters between the charcoal (kiln scars) and non-charcoal plots in Mopane woodlands at both depth 0-5 cm and 0-30 cm. Mabalane District, southern Mozambique. (***) denote significant at $\alpha = 0.001$, (**) denote significant at $\alpha = 0.01$, (*) denote significant at $\alpha = 0.05$, (ns) denote not statistically significant at $\alpha = 0.05$.

Charcoal production appeared not to have any effect on the C: N ratio and soil texture, neither at the surface layer nor at deeper layers ($P > 0.05$). However, bulk density (BD) was shown to be affected by charcoal production only at deeper layers ($P < 0.05$), with a slightly higher density in the non-charcoal plots ($1.52 \pm 0.03 \text{ g cm}^{-3}$) than the charcoal plots ($1.42 \pm 0.03 \text{ g cm}^{-3}$). All soil parameters (CpS, BD and C:N ratio) within charcoal production plots in the surface layer were much higher than in deeper layers, while the opposite was observed for BD and C:N ratio in the

non-charcoal plots. For instance, at deeper layers the bulk density decreased by 7% from non-charcoal to charcoal plot, while sand content, clay content, silt content and C:N ratio decreased in 2, 5, 17 and 3% respectively.

4. DISCUSSION

4.1. Relationship between woodland type and Soil Organic Carbon and Total Nitrogen

There were significant variations in SOC and TN stocks at the 0-30 cm depth across woodland types, which is consistent with earlier findings (e.g. Jobbagy and Jackson, 2000; Rossi et al., 2009; Wang et al., 2009; Fu et al., 2010). These soil differences between woodland types are due to the long process of soil formation dependent on rock characteristics and the long history of natural and human forces such as climate (Ganuza and Almendros, 2003; Garcia-Pausas et al., 2017), topography (Garcia-Pausas et al., 2007), vegetation, land use (Ganuza and Almendros, 2003; Sugihara et al., 2015) and soil management (Post and Kwon, 2000). There were no observed effects of woodland type in the 0-5 cm layer, which may be due to the effect that varying land use practices have on organic matter over the long term, like fire or animal grazing. Factors which affect the dynamic of C and N turnover in MW have previously been explored through experimental studies in Zimbabwe, showing that volume of organic matter input from litter determines soil fertility (Mlambo et al., 2005; 2007; 2008; and 2010). Furthermore, nutrient enrichment of soils may vary with grass, shrub and tree species: e.g. patches with leguminous trees may contain more soil N than patches with non-leguminous species that may also affect SOC dynamics (Scholes and Archer, 1997; Breulmann et al., 2012). However, all the species dominating each woodland type (*Androstachys johnsonii*, *Combretum* spp and *Colophospermum mopane*) are non-N₂-fixing and depend more on mycorrhizal symbiotic associations (Hogberg and Pearce, 1986). Despite AF and MW being different in terms of structure and species

composition, our results revealed that these two woodlands store similar amounts of SOC and TN at both the 0-5 cm and the 0-30 cm layer.

SOC and TN stocks from all woodland types in this study were clearly lower than those found in other semi-arid woodlands, for example Miombo woodland in central Mozambique (Woollen et al., 2012) and Malawi (Walker and Desanker, 2004). Moreover, the SOC and TN stocks in the MW sites in the study area are also lower than estimations of 34.09 Mg ha⁻¹ of SOC and 6.75 Mg ha⁻¹ of TN found in Zimbabwe MW (Mlambo et al., 2007). Furthermore, our findings contrast with those of other studies, which reported higher SOC stocks in AF (Molotja et al., 2011; Khavhagali and Ligavha-Mbelengwa, 2009; Magalhães, 2017; Tchaúque, 2018). The lower SOC and TN stock observed in this study can be attributed to several factors such as low productivity under variable moisture and temperature, erratic rainfall and low soil water-holding capacities at the study site (Evan and Ehleringer, 1994; Scholes and Archer, 1997; Lal 2004). This may also be due to high level of lignin in the organic matter of MW (Mlambo et al., 2010), or organic matter in AF that decays at a slower rate in the study area, due to high concentrations of lignin and low concentrations of soluble carbohydrates (Molotja et al., 2011). The same reason may be attributed to the comparably low SOC and TN stocks recorded in MW against figures for other Miombo regions (Walker and Desanker, 2004; Woollen et al., 2012).

4.2. Effects of charcoal production on Soil Organic Carbon and Total Nitrogen

Our results show that charcoal production doubled levels of SOC and TN stock in charcoal plots compared to the non-charcoal plots but only at the deeper layer. This result is in line with Nigussie and Kissi (2011) who found that in deeper layers of soils following charcoal production the reservoirs of SOC and TN were larger than at non-charcoal sites in southwest Ethiopia. Our similar findings may be due to comparable climate conditions and soil composition to those of Nigussie and Kissi (2011). We suggest this trend is applicable to the above-ground biomass as

demonstrated by Kalaba et al. (2013) who reported an increase of 10.5 to 64.3 Mg ha⁻¹ of stem carbon stocks in miombo recovery sites after 5 to 44 years of charcoal production, respectively. Clay content showed a significant positive correlation with SOC ($r = 0.26$, $P < 0.05$) and TN ($r = 0.25$, $P < 0.05$) at 0-30 cm in the non-charcoal plots but it was non-significant in the charcoal plots. This suggests that the highest SOC and TN stocks observed in the charcoal plots is not attributed to clay content but are more likely due to the presence of carbon and nitrogen-rich charcoal or charred biomass coming from the charcoal process. For both SOC and TN stocks our findings suggested no significant effects of charcoal production at the soil surface, an unexpected outcome, although our result is in line with findings by Oguntunde et al. (2004). Land use systems such as agriculture cannot be attributed as the main factor that led to this finding as there was no evidence of agriculture in the charcoal production area. This is due to the dry climate conditions and the low soil quality, which forces the farmers to grow crops only along the riverbeds and only during the wet season. Therefore, the charcoal production areas were not farmed after charcoal production as at many other sites (see Jones et al., 2017). Instead, as noticed earlier, they are abandoned as degraded woodlands and only in rare circumstances used for livestock grazing. Chiti et al. (2014) in their study on the effect of selective logging on SOC dynamics in central and western Africa, observe that the topsoil is the most susceptible layer to change after disturbance. However, this was not observed in this study, likely because soil texture was not significantly changed by charcoal production in this layer type, suggesting that the earth kiln method used by charcoal producers may not change the soil texture of MW soil. This result agrees with findings from Nigussie and Kissi (2011) and Oguntunde et al. (2004), but is inconsistent with findings by other authors, e.g. Ogundele et al. (2011); Wahabu et al. (2015), who report a significant clay and silt content increase at kiln sites compared to adjacent soils. The change in soil textures could be the result of clay and silt particles being exposed to high temperatures that would produce the aggregation of those

particles to form sand-sized particles, thus leading to a different soil structure (Oguntunde, 2008; Wahabu et al., 2015). Our findings could be explained by the lower clay and silt content in these soils. One hypothesis for increase of C and N content in the deeper soil layer could be that C and N coming from charcoal production is leached by rainfall.

Finally, we observed significant decrease in soil BD at 0-30 cm layer as a result of charcoal production. Our finding is in line with results from Fontodji (2009) in West Africa. However, our observed decrease of soil BD is much lower (7%) than the 28% from Fontodji et al. (2009), perhaps due the differences in soil properties between our study site and West Africa.

4.3. Implications of the SOC stocks under charcoal production for woodland management and climate change mitigation effects

The estimation of SOC stocks provided in this study has wider implications for the management of dry woodlands in SSA. It allows, in part, estimation of their contribution to global carbon stocks, crucial information for climate change mitigation policies such as carbon trade strategies and payment for ecosystem services schemes (e.g. the REDD+ program). REDD+ provides incentives to developing countries in the tropics to contribute to climate change mitigation and represents a major financial boost for conserving tropical forests (Venter and Koh, 2011). Much of REDD+ financing to date has been directed to promoting REDD+ “readiness”, i.e. assisting countries in designing, preparing, and early piloting of mitigation measures (Holmer et al., 2017). Most of the SSA countries involved are currently pilot countries, in the stages of finalizing their required monitoring, report and verification methods (MRV). However, Sedano et al. (2016) highlight the importance of incorporating charcoal-specific monitoring strategies in the context of REDD+ and other programs focused on mitigating climate change, and consider reporting and verification efforts as the first step to reduce carbon emission uncertainties in SSA.

406 When assessing the impact of charcoal production on forest and woodlands, most studies in SSA
407 focus on the impacts on forest degradation (e.g. Kalaba et al., 2014; Ndegwa et al., 2016; Sedano
408 et al., 2016) and soil properties (Ogondunde et al., 2008; Ogondunde et al., 2011; Wahabu et al.,
409 2015). Due to the strong relationship observed between TN and SOC, this study highlights the
410 importance of considering both SOC and TN in these assessments, since we found that charcoal
411 production can double both SOC and TN stocks in the areas where charcoal production occurs
412 (charcoal kilns).

413 The intensification of woodland resource use, for example in charcoal production, results in
414 degradation and sometimes complete deforestation leading to negative impacts on human well-
415 being, as well as loss of habitat and biomass. According to Woollen et al. (2016), to avoid
416 increased intensification the charcoal frontier must continue to expand to new areas of
417 exploitation and allow for regeneration of the woodlands to occur. Although many native woody
418 species are extremely slow-growing, particularly in arid and semi-arid regions such as our study
419 area, most charcoal species in SSA can regrow after charcoal production (Chidumayo, 1993). For
420 instance, *C. mopane* stumps have relatively fast regeneration rates (Mushove and Makoni, 1993;
421 Potgieter et al., 2006), and an adaptive co-management approach could contribute to an effective
422 and quicker restoration of the dry woodlands. The use of payments, compensation and co-
423 investment initiatives such as those promised in the context of REDD+ could minimise charcoal
424 intensification by promoting effective and quicker restoration practices and at the same time by
425 reducing local dependence on charcoal by providing communities with a modest alternative
426 opportunities for income-generation (Ghazoul et al., 2010; Bayrak and Marafa, 2016). Climate
427 change mitigation programs can provide direct and indirect incentives including both monetary
428 (e.g. carbon payments) and non-monetary benefits (e.g. formalizing and strengthening land
429 tenure, building infrastructure, promotion of local community charcoal institutions etc.)
430 (Anderson and Zerriff, 2014; Bayrak and Marafa, 2016). However, the potential contribution of

restored woodlands to mitigate climate change, as well as help address the technical, social, policy and economic challenges that exist in the SSA countries also need to be understood. Technical challenges include providing alternative tree species for desired charcoal quality (Woollen et al., 2016), promotion of good charcoal production and restoration techniques, finding viable and cheap policies to overcome the government's lack of capacity to control the legal production of charcoal and promoting sustainable charcoal production (Zorrilla-Miras, 2018; Jones et al., 2016). Economic and policy challenges include unclear rights to land, poor market infrastructure (Norfolk, 2004; Vollmer et al., 2017; Zorrilla-Miras, 2018; Jones et al., 2016), corruption in the charcoal value chain, and labour shortages (Baumert et al., 2016). Accounting for carbon pools, and the non-CO₂ emissions from charcoal avoidance or improved practices, is needed in order to fully evaluate the overall contribution of charcoal production under REDD+ schemes.

5. Conclusion

Our findings show that charcoal production has the potential to double the SOC and TN stock in abandoned kilns which means that ecosystem functioning is temporarily improved by charcoal production in the study area. However, this study is purposefully narrowly focused on localized ecosystem impacts and did not investigate the other ways that the charcoal process and commodity chain exacerbate climate change. Therefore, caution must be taken in the interpretation of the potential effect of charcoal production when developing management strategies and carbon-based payment of ecosystem service such as those linked to the REDD+ programme.

Additionally, our study reveals that despite there being distinctive woodland types (Androstachys forest (AF), Combretum woodland (CW) and Mopane woodland (MW)), there were no significant differences observed in SOC and TN levels among woodland types. On the contrary,

we found that CW had significantly smaller (almost half) TN stocks than MW and AF. The SOC content in the three woodland types in our study is smaller than previous studies in other semi-arid woodlands. We found that MW disturbed by charcoal production stores double the SOC compared to non-disturbed MW, much more carbon than AF, and is comparable to the SOC stock reported for Miombo woodlands in southern Africa. However, future investigation of the relationship between SOC and litter (including dead wood) and land management practices is needed to further understand the drivers of ecosystem functioning in dry woodlands of Mozambique, particularly where there is no charcoal production activity. We also found that SOC and TN magnitudes are explained by clay content. However, the effect of charcoal production on soil properties (texture and bulk density) was less clear, given that we did not find significant differences in soil texture between charcoal and non-charcoal plots.

These are important findings for sub-Saharan African nations, which are in the process of updating and implementing monitoring, report and verification methods (MRV) that could assume that AF and MW woodland types have similar soil C and N storage capacity, at least in areas with the same climate, soil and geological conditions as our study area. The highlighted positive effect of charcoal production on SOC for REDD+ schemes reported in this study could be improved with comprehensive data collection from all the carbon pools, as well as the non-CO₂ emissions that our method did not assess.

This study is unique in collecting and analysing a set of data related to SOC and TN in dry woodland landscapes, as well as in assessing charcoal production effects on SOC and TN levels related to land use management. This study therefore contributes to a better understanding of the role of dry woodland in C and N cycles at the local scale and improving our knowledge about its C storage potential under disturbance, mainly by charcoal production in dry woodlands of sub-Saharan Africa. We view this as an important contribution to the discussion on implications of dry woodland carbon pools on the design of proposed REDD+ programs.

481

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487

488 **6. References**

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720

721 **Figure 2:** Charcoal production in Mopane woodland, Mabalane District, southern Mozambique.

722 **A:** Piles of *Collospermum mopane* being prepared for charcoal production in a kiln; **B:** Kiln with
723 charcoal already extracted. Charcoal production plots samples were collected in these areas, in
724 the middle of the kiln.

725

726 **Figure 4:** Dominant woodland types in the study area, Mabalane District, southern Mozambique.

727 **A:** *Androstachys* forest; **B:** *Combretum* woodland; **C:** Mopane woodland.

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CONFLICT OF INTEREST DECLARATION

We have no conflict of interest to declare!