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 vegetation type and charcoal production affect SOC and TN 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 and both distant from and proximate to sites of active charcoal production, we estimate that woodlands in Mabalane District store on average 19 ± 10 (± 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 Miombo woodlands in the region. Our analysis shows that woodland type does not directly influence the amount of SOC and TN stored in soil, and that soil proximate to 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 plots. 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
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Manuscript.doc [Manuscript File]

Figure_3A_ Piles of Collospermum mopane _2-column fitting image.jpg [Figure]

Figure_3B_ Kiln with charcoal already extracted_2-column fitting image.jpg [Figure]

Figure_4A_Androstachys_forest_3-column fitting.jpg [Figure]

Figure_4B_Combretum_woodland 3-column fitting image.jpg [Figure]

Figure_4B_Mopane_woodland 3-column fitting image.jpg [Figure]

Research Data Related to this Submission

There are no linked research data sets for this submission. The following reason is given:
Data will be made available on request

Dear Dr. Dan Binkley, Editor-in-Chief of Forest Ecology and Management

Please find enclosed our article entitled “Effect of charcoal production and land cover type on soil organic carbon (SOC) and total nitrogen (TN) in dry woodlands of southern Mozambique” to be considered for publication in Forest Ecology and Management.

In this manuscript we highlight our understanding of the impacts of charcoal production on soil organic carbon and total nitrogen in dry woodlands of southern Africa, and demonstrate some localized impacts of charcoal production. We also discuss the implications of our findings in the light of emerging carbon-based payments for ecosystem services programmes in the region. Our study revealed that soils at kiln sites had twice the amount of SOC and TN compared to non-charcoal plots.

This manuscript is an original, unpublished work and is not being considered for publication elsewhere. All authors accept responsibility for the manuscript and have agreed to its submission to Forest Ecology and Management. If you consider the manuscript appropriate for your journal, we have no conflicts of interest to disclose.

We believe that this study can foster important progress in understanding the impact of disturbance on African woodland ecosystems functioning.

Thank you for dedicating time to our manuscript.

On behalf of the authors, sincerely

Sá Nogueira Lisboa (corresponding author)

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Highlights

- Soil in the charcoal kilns had twice the amount of Soil Organic Carbon (SOC) and Total Nitrogen (TN) compared with non-charcoal plots.
- Charcoal production has a positive relationship with increased pools of SOC and TN in Mopane woodland.
- The woodland type alone does not affect the amount of SOC and TN in dry study area.
- The SOC content in the three woodland types of our study area is smaller (more than half) than previous studies reflected in other semi-arid woodlands.

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 vegetation type and charcoal production affect SOC and TN 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 and both distant from and proximate to sites of active charcoal production, we estimate that woodlands in Mabalane District store on average 19 ± 10 (± 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 Miombo woodlands in the region. Our analysis shows that woodland type does not directly influence the amount of SOC and TN stored in soil, and that soil proximate to 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 plots. 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 (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, 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 one of the most promising mechanism driving the conservation of tropical forests (Venter and Koh 2011).

Charcoal is the main source of energy for urban populations across sub-Saharan African countries, resulting in an important economic activity at national scale to the value of approximately 2–3% of GDP of SSA countries (International Energy Agency 2014). Charcoal is primarily produced in rural areas and provides affordable energy to 70–90% of the urban population (International Energy Agency 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 Mopane woodlands in southern Africa (Makhado et al. 2014; Baumert et al. 2016; Zorrilla-Miras et al. 2018; Smith et al. 2019). In Mabalane District, the focus of this study, external large-scale operators and local rural households engage actively in charcoal production (Baumert et al. 2016), with wealthier households producing comparatively more charcoal (Smith et al. 2019). Charcoal production is associated with increases in some aspects of well-being (such as greater assets ownership) (Zorrilla-Miras et al. 2018), although benefits from charcoal production do not equate to improvements in the aggregate well-being of households, when well-being is measured across different dimensions such as health, education and living standards (Vollmer et al. 2017).

Despite the economic benefits of charcoal production, much concern has been expressed about the environmental consequences that follow its production. 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 not only affect microbial population and activity in soil, but also plant microbe interaction through their effects on nutrient availability and modification of habitat. However, the highest impacts of charcoal production on the soils occur locally at the kiln 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 charcoal fines 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.

SOC 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 enxofre), can contribute to the resilience of soil/plant systems (Baldock 2007). SOC and TN vary between vegetation types because of different inputs, different levels of chemical and physical protection of organic molecules and so on. This heterogeneity can mask the impacts of different land uses and so needs to be included in the ecosystems 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, Gaza province, southern Mozambique, 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.

The specific objectives of this study were twofold: (1) to assess the effect of woodland type on SOC and TN; 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 interspersed with discrete patches of *Androstachys johnsonii*, *Combretum spp.* and *Boscia albitrunca* dominated woodlands, with a C4 grass layer (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 ^{o}C (MAE 2005). There are marked dry and wet seasons, with most precipitation falling between October and April. 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). Our seven study villages had similar climatic conditions, vegetation types and infrastructure as well as similar human population size, but they 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).

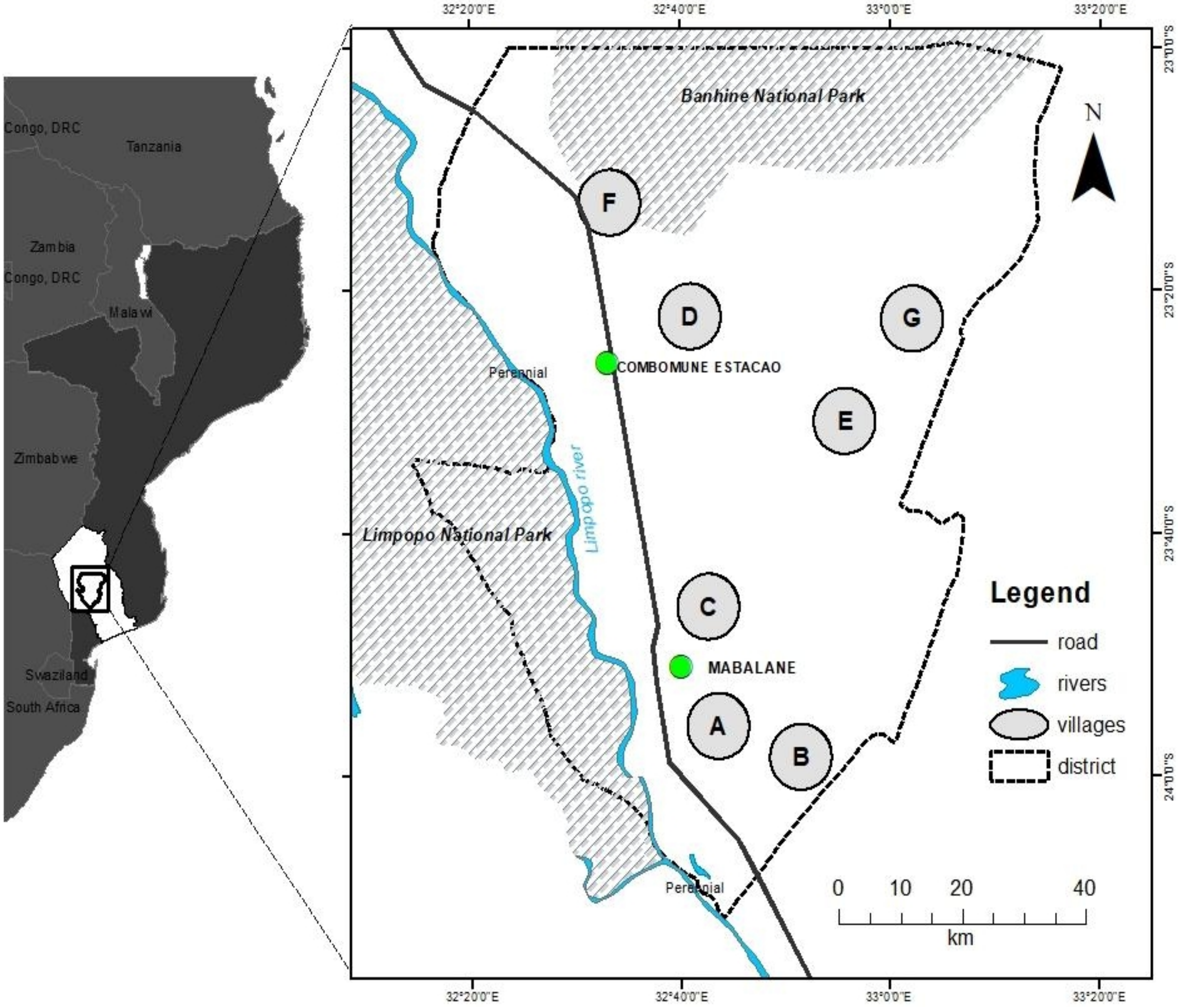

Figure 1: Study area showing the seven villages, the main partially tarred road, main rivers and the Mabalane district boundaries. The main local towns (green circles) and national parks.

2.2. Soil sampling

In each village sampled, 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 km^2), using methods described in Woollen et al. (2016). Before collecting soil samples, observations of disturbances were recorded (e.g. recent fires, presence of charcoal kilns or cut stems etc.) and then plots were classified either as charcoal production plots (plots with old or active kilns inside the plot, total n = 45) or as non-charcoal plots (plots without visible kilns nearby for at least 100 m away, total n = 60).

The non-charcoal plots were circular with a diameter of 20 m, with 4 quadrats placed 10 m from the centre in each cardinal direction (North, South, East and West). Within each 1 m^2 quadrat one soil core from the 0-30 cm (520 cm^3) and four soil cores of the 0-5 cm (162 cm^3) depths were extracted (Fig. 2A). The soil samples from the charcoal production plots were collected only from the soil where the charcoal kiln was found in order to catch the real impact of charcoal production and compare to soil from non-charcoal production plots. All sampled kilns were dormant for at least 2 years after charcoal production. In the centre of the area occupied by each old kiln, a 1 m^2 quadrat was placed, and one soil core of 0-30 cm depth (520 cm^3) and four soil cores of 0-5 cm (162 cm^3) depth were extracted following the procedure described in Figure 2B.

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

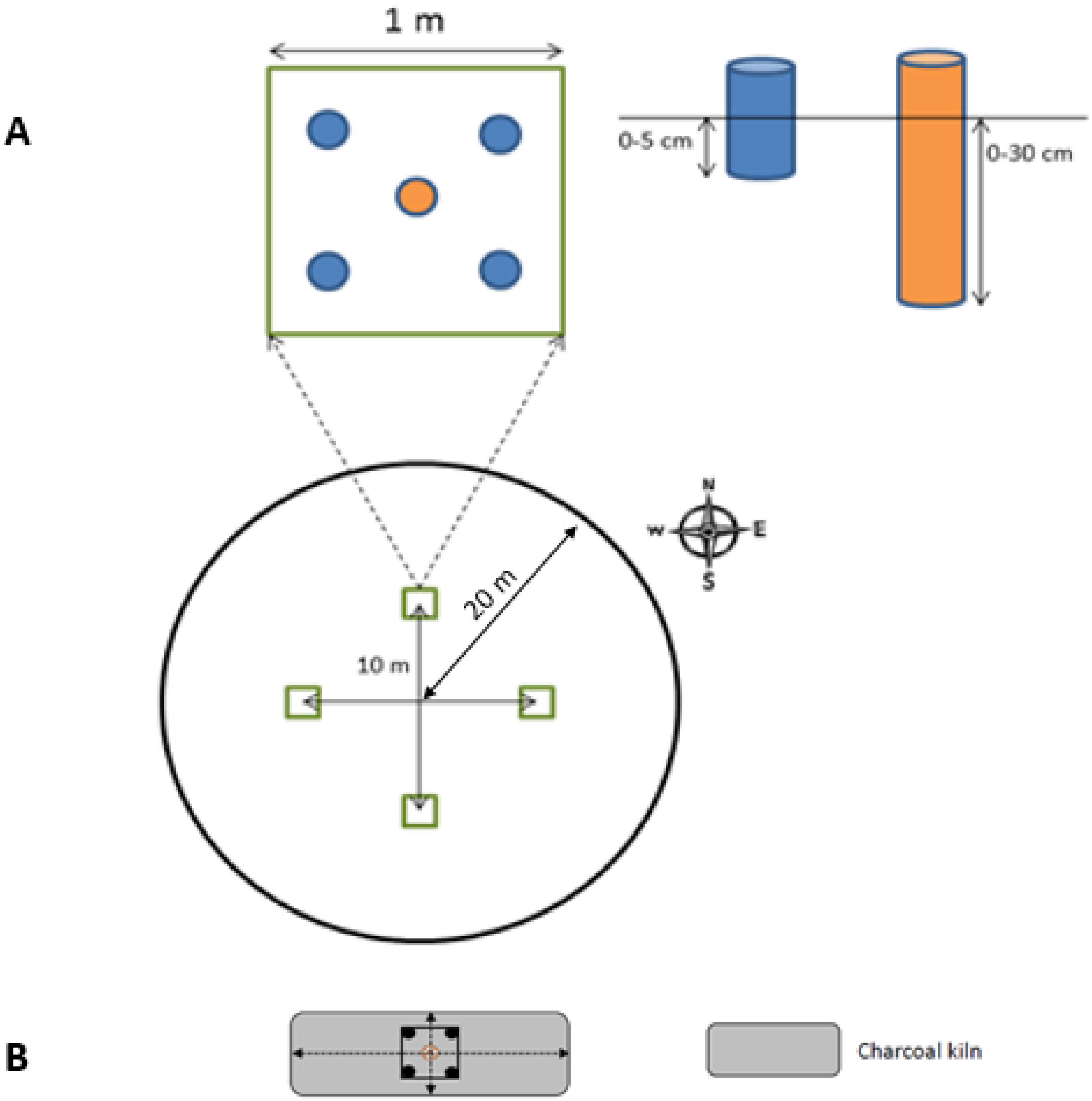

Figure 2: Layout of soil sample plot in the (A) non-charcoal sites and (B) charcoal sites in Mabalane District, southern Mozambique.

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, by *Colophospermum mopane*) and Boscia woodland (BW, 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) (Figure 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 at 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 according to their dominant woodland types post-hoc, 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) (Table 1). These were further divided into those plots that had had charcoal activity, and those that did not (i.e. the non-charcoal plots). Thereby, the total sample size for Mopane woodland were 68, where 45 plots had charcoal activity. Combretum woodland had 24 samples and Androstachys 13 plots. Only Mopane woodland had charcoal activity, because *Colophospermum mopane* is a target species for charcoal production in the area due to its high density and therefore high quality charcoal (Chavana 2014; own data). Therefore, comparisons between charcoal and non-charcoal sites were only performed within Mopane woodland samples. Similarly, we compared between woodland types only using the non-charcoal plots, to eliminate the impact of charcoal activity in the comparison.

Table 1: Number of plots sampled within the three dominant woodland types, the number of sampled plots with evidence of charcoal activity (visible kilns inside), and those without (i.e. non-charcoal plots). Mabalane District, southern Mozambique.

Woodland type	Total sampled plots	Plots with evidence of kilns	non-charcoal plots
Mopane woodland (MW)	68	45	23
Combretum woodland (CW)	24	-	24
Androstachys forest (AF)	13	-	13
Entire sample	**105**	**45**	**60**

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 (<2mm; 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:

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

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, one-way analysis-of-variance (ANOVA) was used to determine the effect of woodland type (AF, CW and MW) on SOC, TN, sand, clay, silt, clay plus silt, bulk density and C:N ratio, using only the data from the non-charcoal plots. Before performing ANOVA, we tested for data homogeneity of variance and normality of data using the Levene and the Shapiro-Wilk test, respectively. Data were transformed into log or/and root square in order to force to normality. If significant effects were observed by ANOVA, a least significant difference (LSD) test was used.

Secondly, one-way ANOVA was performed to compare averages of SOC, TN, sand, clay, silt, clay plus silt, bulk density and C: N ratio between charcoal production plots and non-charcoal plots. All data first were tested for normality using the Shapiro-Wilk and Kolmogorov-Smirnov tests. Log transformation was applied where necessary to these parameters, leading to near normal distributions. From the total sample plot dataset, some plots of 0 - 5 cm depth were excluded from analyses due to errors in measurements, missing data or no C and N analyses. All analyses were performed at 5% of significance level using R software version 3.1.3 (R core team 2015).

3. RESULTS

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

The results of the effect of woodland type on SOC, TN and other soil parameters are presented in Figure 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 they exist for both SOC and TN at 30 cm depth. The average SOC and TN stock (± Standard Error) at 30 cm for the entire samples 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 at 30 cm was significantly higher in MW with a mean 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 at 30 cm was also smaller in CW than in MW and AF. The soil texture at both 5 and 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. Figure 5 shows that most of the CpS content is stored in the surface layer, and more than 57% of CpS content stored at the deeper layer was contributed by the CpS content of the surface layer. Soil bulk density (BD) was higher in MW at 30 cm depth, while at 5 cm depth BD were not significantly different amongst woodland types.

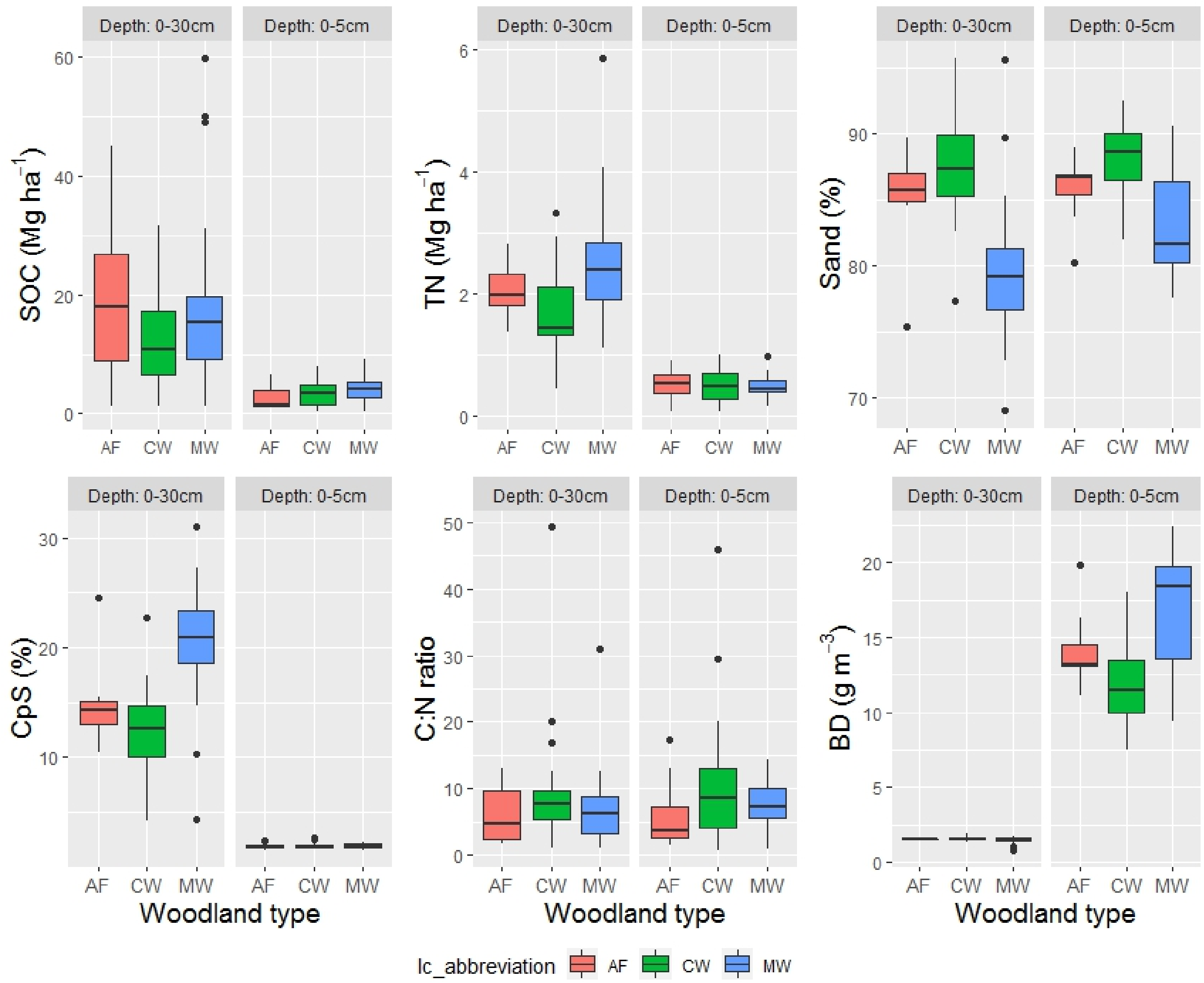

Figure 5: Comparison of mean soil organic carbon (SOC), total nitrogen (TN) and other soil parameters (sand content, clay plus silt (CpS), C:N ration and bulk density (BD)) among woodland types at both depth 0-5 and 0-30 cm. Mabalane District, southern Mozambique.

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 Figure 6. Charcoal production significantly affected SOC and TN in the 0-30 cm layer ($P < 0.001$). SOC and TN at 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 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%).

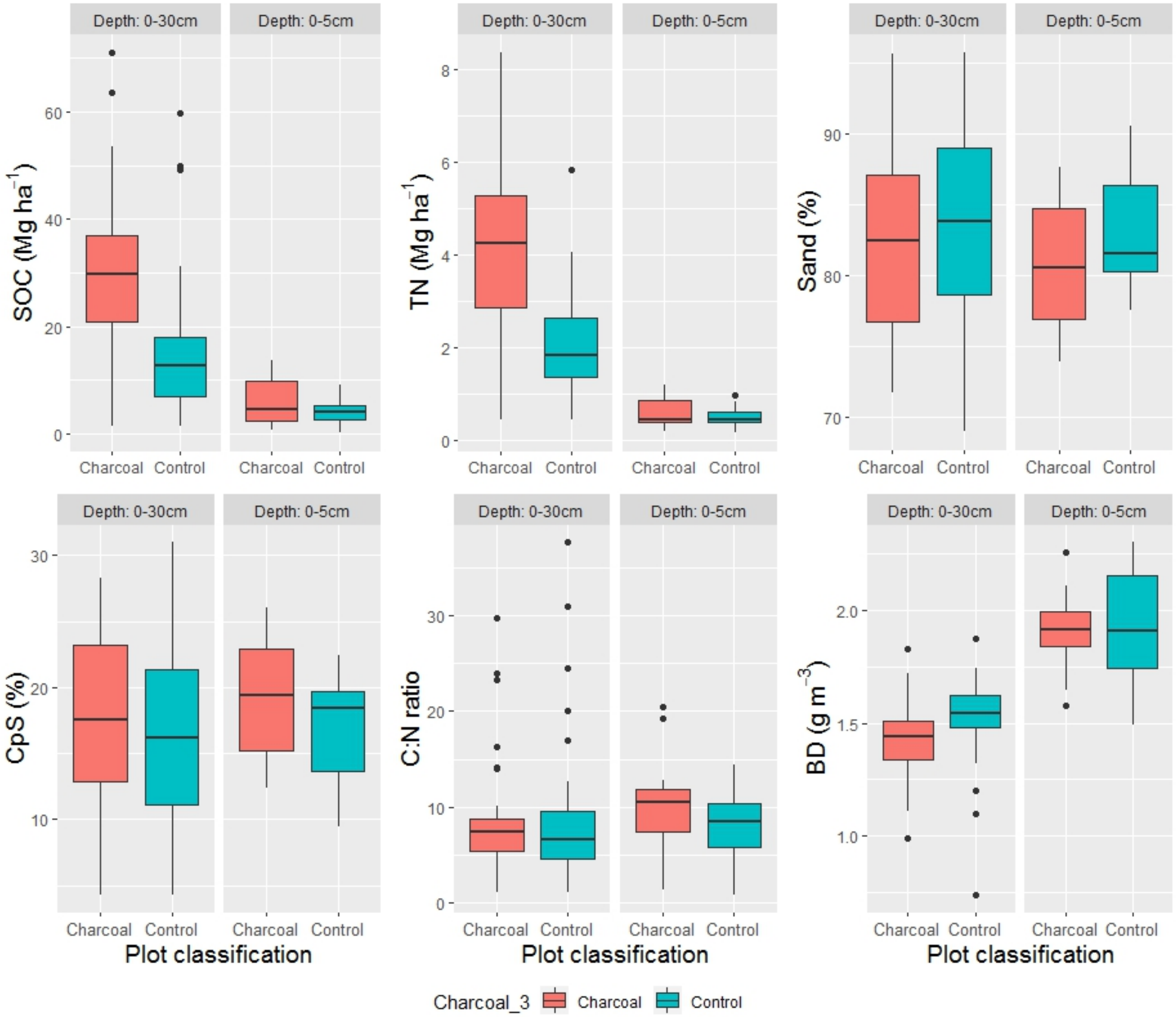

Figure 6: Comparison of soil organic carbon, total nitrogen and other soil parameters between the charcoal plots and non-charcoal plots (control) in Mopane woodlands at both depth 0-5 cm and 0-30 cm. Mabalane District, southern Mozambique.

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 amount in the non-charcoal plots (1.52 ± 0.03 g cm^{-3}) than the charcoal plots (1.42 ± 0.03 g cm^{-3}). All soil parameters (CpS, bulk density and C:N ratio) within charcoal production sites in the surface layer were much higher than in deeper layers, while the opposite was observed for non-charcoal sites. 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 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 might be due to the mutual effect of the original soil content and the tree species have on soil. There were no observed effects of woodland type in the 5 cm layer, which may be due to the effect 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 Zambia, 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, shrubs 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-N_2-fixing and depend more on fungal symbiotic associations (Hogberg et al. 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 Zambian 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). 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 2014). This may be 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 comparable 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 kiln sites compared to the non-charcoal plots but only at the deeper layer. This result is in line with Nigusse and Kissi (2011) who found that in deeper layers of the soils after charcoal production the reservoirs of SOC and TN were bigger than non-charcoal sites. Our similar findings may be due to comparable climate conditions and soil composition to those of Nigusse and Kissi (2011).

Clay content showed a significant positive correlation with SOC and TN at 30 cm in the non-charcoal sites but it was non-significant in the charcoal sites. This suggests that the highest SOC and TN stocks observed in the charcoal site 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 surface soil, an unexpected outcome, although our result is in line with similar findings by Oguntunde et al. (2004). Chiti et al. (2014) in their study on effect of selective logging on SOC dynamics in central and western Africa, state that the topsoil is the most susceptible layer to change after some 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 is in agreement with Nigussie and Kissi (2011) and Oguntunde et al. (2004), but inconsistent with findings by other authors, e.g. Ogundele et al. 2011; Wahabu et al. 2015, who report a significant soil texture 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, what would produce the aggregation of those particles to form sand-sized particles, thus leading to a different structured soil (Oguntunde 2008; Wahabu et al. 2015). Our findings could be explained by the lower content of clay and silt 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 the charcoal production is leached by rainfall.

Finally, we observed no significant changes in soil bulk density as a result of charcoal production, aligning with findings from Ueckert et al. (1978). Our observed changes in soil bulk density are higher than 28% from Fontodji et al. (2009).

4.3. Implications of the SOC stocks under charcoal production for forest 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 sub-Saharan Africa (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 is 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 climate change mitigation programs, and consider reporting and verification efforts as the first step to reduce carbon emission uncertainties in SSA.

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

According to Woollen et al. (2016), to avoid increased intensification, the charcoal frontier must continue to expand to new areas of exploitation and allow for regeneration of woodlands to occur. Although many native species are extremely slow growing, most of charcoal species in

SSA can as well regrow after charcoal production (Chidumayo 1993). For instance, *C. mopane* stumps have relatively fast regeneration rates (Mushove and Makoni 1993; Potgieter et al. 2006), and an adaptive co-management approach could contribute to an effective and quicker restoration of dry woodlands. The use of payments, compensation and co-investment, initiatives such as REDD+ could minimise charcoal intensification by promoting effective and quicker restoration practices and at the same by reducing local dependence on charcoal providing communities with a modest opportunity benefit as job and income (Ghazoul et al. 2010; Bayrak and Marafa 2016). Climate change mitigation programs can provide direct and indirect incentives including both monetary (e.g. carbon payments) and non-monetary benefits (e.g. land tenure arrangements, building infrastructure, promotion of local community charcoal institutions etc.) (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 tackled. Technical challenges include providing alternative tree species for desired charcoal quality (Woollen et al. 2016), promotion of good charcoal production and restoration techniques, and finding viable and cheap policies to overcome the government's lack of capacity to control the legal production of charcoal and promote 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 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, caution, must be taken in the interpretation of the potential effect of charcoal production in 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)), SOC and TN does not change significantly in our arid study area between MW and AF. On the contrary, we found that CW has smaller (almost half) SOC and TN stocks than MW. The SOC content in the three woodland types of our study area is smaller than previous studies in other semi-arid woodlands. We found that MW disturbed by charcoal production stores double SOC than 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 the soil texture did not change significantly between charcoal and non-charcoal plots.

These are important findings for Mozambique's current implementation of its 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 Mabalane District. The highlighted positive effect of charcoal production on SOC for REDD+ schemes reported in this study would be improved with a comprehensive data collection on all the carbon pools, as well as the non-CO2 emission that our method did not assess. Charcoal production has a positive relationship with increased pools of SOC and TN in Mopane woodland.

This study is unique in collecting and analysing a large set of data related to SOC and TN in dry woodland landscapes, as well as in assessing charcoal production effects on SOC and TN 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 on its C storage potential under disturbance mainly by charcoal production in dry woodlands of sub Saharan Africa. We make an important contribution to the debate on the implication of dry woodlands carbon pools on potential emerging programs of carbon-based payments for ecosystem services.

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Figure 3: Charcoal production in Mopane woodland, Mabalane District, southern Mozambique. **A**: Piles of *Collospermum mopane* being prepared for charcoal production in a kiln; **B**: Kiln with charcoal already extracted. Charcoal production plots samples were collected in these areas, in the middle of the kiln.

Figure 4: Dominant woodland types in the study area, Mabalane District, southern Mozambique. **A**: Androstachys forest; **B**: Combretum woodland; **C**: Mopane woodland.