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Spatial variation of soil macrofauna and nutrients in tropical agricultural systems influenced by historical charcoal production in South Nandi, Kenya

Solomon Kamau[a,b,*], Edmundo Barrios[b], Nancy K. Karanja[a], Fredrick O. Ayuke[a], Johannes Lehmann[c,d]

[a] Department of Land Resource Management and Agricultural Technology, College of Agriculture and Veterinary Sciences, University of Nairobi, P.O. Box 29053-00625, Nairobi, Kenya
[b] World Agroforestry Centre,United Nations Avenue, P.O. Box 30677-00100, Nairobi, Kenya
[c] Soil and Crop Science, Cornell University, Ithaca, NY 14853, USA
[d] Atkinson Center for a Sustainable Future, Cornell University, Ithaca, NY 14853, USA

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ABSTRACT

The charcoal sector constitutes an important source of employment and revenue for many tropical agroecosystems. Better understanding of the effects of charcoal-making is thus warranted to guide actions aimed at minimising environmental externalities. Conversion of trees to charcoal eliminates canopy effects associated with the living trees while at the same time creates new conditions in and around spots where the charcoal is produced due to increased concentration of pyrogenic organic matter (PyOM). It is unclear, whether such unintentional PyOM additions play a role in the abundance and distribution patterns of soil macrofauna. A study was conducted in South Nandi (Kenya) to assess effects of PyOM on soil macrofauna, taking advantage of abandoned traditional earth-mound charcoal kilns, where *Croton megalocarpus* Hutch. and *Zanthoxylum gilletii* (De Wild.) P.G.Waterman trees were used in charcoal making. Soil and soil macrofauna samples were collected at increasing distances from the centre of the spots. Total C, non-pyrogenic C (non-PyC) and total N progressively increased with increasing distance from the centre of the spots, whereas soil pH, pyrogenic C (PyC), available P and exchangeable K decreased. The number of earthworms and centipedes in *Z. gilletii* spots (119 and 14 individuals m^{-2}, respectively) was twice as high as in kilns where *C. megalocarpus* was used. Notably, while the number of earthworms in spots rich in *Z. gilletii* PyOM significantly increased with increasing distance from the centre of the spots, the opposite trend was observed for centipedes. In contrast, no significant differences in the spatial distribution of earthworms or centipedes were found in spots rich in *C. megalocarpus* PyOM. Furthermore, beetles, termites and crickets were significantly higher in *C. megalocarpus* than *Z. gilletii* spots, but sampling distance also had no significant influence. As hypothesised, source of PyOM played a major role in determining soil properties and macrofauna distribution patterns thus showing the value of abandoned charcoal-making spots in contributing to a mosaic of soil conditions that could ultimately affect soil productivity in tropical agricultural systems.

1. Introduction

Similar to many tropical agroecosystems world-wide, the charcoal sector significantly contributes to Kenya's economy with 1.6 billion US dollars per year, employing close to 900 000 people in production and trade (SEI/UNDP, 2016). In these agroecosystems, it is a common practice that trees are felled and charcoal made on site (). Smallholder farmers deliberately retain indigenous trees during conversion of forest to cultivated land or intercrop trees with annual crops for fuel, fodder, timber and fruits among other products (Nyaga et al., 2015; Kamau et al., 2017). Some trees are harvested to make charcoal for household consumption or for sale to supplement household income. Charcoal making is usually done by traditional earth-mound kilns, where pieces of felled trees and branches are carbonised at 360 °C to 470 °C for several days (Coomes and Miltner, 2016). Once charcoal making is complete, these kilns are usually abandoned. This practice possibly creates a mosaic of soil conditions in such areas because during the process of charcoal production a substantial amount of soil organic

* Corresponding author at: Department of Land Resource Management and Agricultural Technology, College of Agriculture and Veterinary Sciences, University of Nairobi, P.O. Box 29053-00625, Nairobi, Kenya.
E-mail address: solkam08@gmail.com (S. Kamau).

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matter (SOM) is lost in and around the charcoal-making spots (kilns) (Ketterings and Bigham, 2000; Knicker, 2007). Furthermore, large amounts of pyrolysed materials, often referred to as pyrogenic organic matter (PyOM), also remain *in situ* after charcoal production (Güereña et al., 2015) which may bring about changes in the structure and composition of soil biota. On the other hand, soil biota could modify the properties of PyOM/biochar through, for example, fragmentation into smaller pieces after ingestion by large organisms such as earthworms which increases their surface area and thus enhances or limits further effects of PyOM on other soil biota (Gomez-Eyles et al., 2013). Apart from the effects of PyOM, operations during kiln construction or the intense heat during charcoal production could also cause soil biota to suffer dramatic short or long-term alteration in such areas. Soil biota are essential components of the soil ecosystem as they drive vital soil functions such as nutrient cycling, soil structure modification, biological control of soil borne pests and diseases among others (Barrios, 2007; Brussaard et al., 2007). Thus, changes in soil biota could have profound effects on productivity of low-input farming systems which are characteristic to agriculture in tropical Africa.

Soil macrofauna constitute an important component of soil biota given the significant impact of their activity on soil properties (Lavelle, 1997) and their role as bioindicators of potential unintended impacts of biochar applications to soil (Castracani et al., 2015). Given their larger body size, soil macrofauna are more susceptible to physical damage or destruction, loss of their habitat, and even removal of food substrates (Ayuke et al., 2009; Mbau et al., 2015). For instance, the loss of existing SOM during charcoal making, and its replacement with PyOM, could alter the soil microbial communities and dynamics, and change the carbon substrates and nutrients available for soil macrofauna through a cascade of effects within the soil food web. As noted by Lehmann et al. (2011), if a large proportion of C in pyrolysed materials is chemically stable, the microbes may not be able to readily utilise the C as an energy source. Chemical composition of feedstock also greatly affects the quality of pyrolysed materials (Warnock et al., 2007; Downie et al., 2009; Laird et al., 2009) and thus persistence of C which influence the growth of soil microorganisms. Such changes may in turn affect the abundance and diversity of the soil macrofauna which benefits from feeding on microorganisms found on the PyOM (Domene et al., 2015). High concentration of PyOM in charcoal-making spots may also cause changes in soil physico-chemical properties (Glaser et al., 2002; Oguntunde et al., 2004), which could further affect soil macrofauna. For instance, addition of pyrolysed materials has been shown to alter tensile strength and bulk density of the soil, which can affect the soil water dynamics and gas transport (Lehmann et al., 2011; Masiello et al., 2015). In addition, application of these materials has also been shown to affect soil pH and therefore the amounts of available nutrients such as N, P and cations (Warnock et al., 2007; Ippolito et al., 2015). Therefore, tree-felling and concomitant charcoal production may trigger significant changes in soil chemical and physical properties as well as shifts in soil macrofauna abundance and diversity on these soils for extended periods of time. Such changes, with potential negative effect on soil productivity thus impacting socio-economic welfare of millions of people in Africa, are rarely addressed. In addition, soil fauna are among the least well-studied components of soil biota as affected by PyOM and biochar (Lehmann et al., 2011; Ameloot et al., 2013; Castracani et al., 2015).

Therefore, this study aimed at investigating spatial effects of PyOM on the abundance and distribution patterns of seven key soil macrofauna groups: earthworms, beetles, centipedes, millipedes, spiders, termites and ants. We took advantage of existing charcoal-making spots derived from traditional earth-mound kilns where *Croton megalocarpus* Hutch. and *Zanthoxylum gilletii* (De Wild.) P.G.Waterman had been used for charcoal making *in situ*. We hypothesised that PyOM additions modify soil chemical properties and consequently soil macrofauna abundance and spatial distribution. Given the significant differences in plant tissue quality reported by Kamau et al. (2017) for the same tree species, we expected that this would likely be reflected in charcoal-making spots and hence influence the abundance and spatial distribution of soil macrofauna.

2. Materials and methods

2.1. Description of the study site

The study was conducted in the Kapchorwa region of Nandi County (Kenya) on farmers' fields, approximately 20 km Southwest of Kapsabet town. The region lies along the Kakamega-Nandi forest complex, an extension of the Guinean-Congolian forest (Latitude 0° 10′ 00" N and Longitude 35° 0′ 00" E), at an average altitude 1800 m above sea level (Güereña et al., 2015). Rainfall occurs in a bimodal pattern, with an annual total of about 2000 mm, distributed between April and June (1200 mm) and August and October (800 mm). Temperatures are fairly constant throughout the year with mean minimum and maximum annual temperatures of about 18 and 27 °C, respectively. Soils are classified as kaolinitic Acrisols based on the FAO/UNESCO classification (Recha et al., 2013). The indigenous vegetation is dominated by *Funtumia africana* (Benth.) Stapf, *Prunus africana* (Hook.f.) Kalkman, *Ficus* spp., *Croton* spp., and *Celtis* spp. (Glenday, 2006). The area was originally occupied by a sparse population of former forest dwelling human communities who practiced shifting cultivation, hunting and gathering (Mbau et al., 2015). However, high population growth rate and immigration into the area has reduced average land holding to less than 0.5 ha per household. The farms are dominated by cereal cultivation, with maize and beans being the predominant crops often intercropped with indigenous and exotic trees (Kamau et al., 2017).

2.2. Selection of charcoal-making spots used in the study

Charcoal production in smallholder farms is mainly done onsite where the fuel wood is located (). Typically, wood is pyrolysed at temperatures between 360 °C to 470 °C using the traditional earth-mound kilns (Coomes and Miltner, 2016). Due to the poor conversion ratio and pyrolysis conditions in these kilns, many fragments of pyrolysed materials are left onsite and become incorporated into the soil through cultivation after the kilns are abandoned, creating characteristic concentric rings of PyOM-rich spots. Identification of such charcoal-making spots to be used in the study was guided by participatory action research tools involving randomly-selected farmers within the area of study (Barrios et al., 2012). A total of 52 spots were identified in this process, with an average diameter of about 15 m, which were spread at an area of 28.9 ha. The criteria used in selection of charcoal-making spots to be used in this study were: (i) history of the spots: the type of tree used and the time since charcoal making were known. Each tree species used in charcoal making represented a treatment; (ii) distribution: the charcoal-making spots selected occurred isolated within the farms and thus free from interferences by trees. Only spots where *C. megalocarpus* and *Z. gilletii* were used in charcoal making, fulfilled the selection criteria in the study area. Five spots of each tree type were selected for the study. All the charcoal-making spots had been abandoned 2 years before sampling was conducted. At the time of sampling, all the charcoal-making spots were under maize-beans intercrop.

2.3. Soil macrofauna sampling

The area around selected charcoal-making spots was subdivided into four concentric zones, W, X, Y and Z based on an adaptation of the sampling method used by Kamau et al. (2017). Zone W was located 0.25 m from the centre of the spot, X at the middle of the spot, and Y located at the edge. Zone Z was located away from edge of the charcoal-making spots at an equivalent distance to that between W and Y. Soil monoliths (0.25 × 0.25 × 0.30 m) were collected using the standard Tropical Soil Biology and Fertility Institute (TSBF) method as described

by Anderson and Ingram (1993), in each concentric zone following four transects at right angles from each other, for a total of 16 monoliths per spot. Soil monoliths were hand-sorted in trays and all soil macrofauna seen with the naked eye were collected, counted, weighed and preserved in 75% alcohol, except for the earthworms which were first placed in 75% ethanol and then fixed in 4% formaldehyde and stored in sealed and labelled vials. The preservative solution was replaced when a change in colour was observed. Soil fauna were identified at least to genera or species, except a few (centipedes, earwigs and two of the beetles' families) where the identification keys only allowed identification to family level. Earthworms were further separated into ecological groups: epigeic and endogeic. The abundance of the soil fauna is reported as mean individuals per square metre (individuals m^{-2}).

2.4. Soil and PyOM chemical analyses

Fragments of PyOM were collected from charcoal-making spots at the points where soil monoliths were excavated. The PyOM collected was air dried in the field before being transferred into paper bags for laboratory analysis. Once in the laboratory, the samples were further dried in the oven at 60 °C to a constant weight, ground and passed through a 2 mm sieve and stored in bags. In addition, after removal of soil macrofauna, soil from each of the 4 monoliths by sampling zone was thoroughly mixed, and a sample of about 500 g collected for analysis. The PyOM samples were analysed for C, N, P, K, Ca and Mg (expressed as mg per g of PyOM dry weight) as well as lignin and polyphenol (expressed as percentage values). Total C and N were determined by FLASH 2000 NC Analyser (ThermoFisher Scientific, Cambridge, UK) while P, K, Ca and Mg were extracted through a closed-vessel microwave-assisted digestion system (Miller, 1998) and determined using inductively coupled plasma atomic emission spectroscopy (Isaac and Johnson, 1998). Lignin content was analysed using the acid detergent fibre method while total polyphenols were measured by the Folin-Denis method (Anderson and Ingram, 1993). Soil parameters measured included: total N and C, plant-available P and bases (Ca, Mg and K) (expressed as mg per g of soil dry weight except P, expressed as mg per kg of soil dry weight) and soil pH. Total C and N were determined using NC Analyser, while P and the bases were extracted following Mehlich-3 procedure (Mehlich, 1984) and determined using inductively coupled plasma atomic emission spectroscopy. Soil pH was determined using a pH metre with a soil-water ratio of 1:2.5 (Anderson and Ingram, 1993). Soil PyC was determined using partial least-squares (PLS) regression analysis of mid-infrared (MIR) spectroscopy data using spectral calibration from previous work done in the same study area by Güereña et al. (2015).

2.5. Statistical analyses

All statistical analyses were carried out using R software version 3.2.2 (R Core Team, 2015). Soil macrofauna abundance data was modelled using generalised linear mixed models (GLMM) as a function of source of PyOM and zone of sampling, including the replicates as a random factor using R package lme4 (Bates et al., 2015). Several models were built based on the formula (Variable ~ Species + Zone + Species: Zone + (1|Replicate: Species), such that terms could be added or removed from the model. The term 'Species' referred to the tree species used in charcoal making, whereas 'Zone' was the sampling zone as related to the distance from the centre of charcoal-making spots. Negative binomial regression analysis was chosen as an extension of the Poisson distribution to allow for the count data with a significant proportion of zero values. When analysis of variance (ANOVA) showed significant main or interactive effects, Tukey's post-hoc comparisons were performed at $\alpha = 0.05$. Further, relative differences in soil chemical parameters between zones in charcoal-making spots (W, X and Y) and away from the spot (Z) were assessed.

Table 1
Quality parameters (mean ± SE) of PyOM fragments collected in charcoal-making spots (n = 5).

Parameter	*Croton megalocarpus*	*Zanthoxylum gilletii*	*p*-value
C (mg g^{-1})	587.0 ± 4.0^{a}	572.0 ± 3.0^{a}	0.257
N (mg g^{-1})	7.9 ± 0.7^{a}	6.9 ± 1.1^{a}	0.443
P (mg g^{-1})	**0.4 ± 0.1^{b}**	**0.7 ± 0.1^{a}**	**0.012**
K (mg g^{-1})	**1.9 ± 0.2^{b}**	**2.8 ± 0.1^{a}**	**0.050**
Ca (mg g^{-1})	**20.1 ± 4.9^{a}**	**11.2 ± 0.3^{b}**	**0.010**
Mg (mg g^{-1})	**1.3 ± 0.1^{b}**	**2.0 ± 0.4^{a}**	**0.035**
C/N	58.0 ± 5.9^{a}	60.3 ± 10.4^{a}	0.852
C/P	**1296.9 ± 81.4^{a}**	**582.3 ± 76.1^{b}**	**0.015**
L (%)	37.6 ± 3.5^{a}	39.2 ± 2.7^{a}	0.819
PP (%)	0.1 ± 0.1^{a}	0.2 ± 0.1^{a}	0.064
L/N	48.2 ± 4.6^{a}	58.0 ± 5.0^{a}	0.305
PP/N	**0.1 ± 0.03^{b}**	**0.3 ± 0.2^{a}**	**0.044**
(L + PP)/N	48.2 ± 4.6^{a}	58.2 ± 4.8^{a}	0.077

Within rows, means followed by different lower case letters in superscript are significantly different at $p < 0.05$ (n = 5). Values marked in bold are significant. Means were separated based on Tukey's honest significant difference (HSD) test.

3. Results

3.1. Quality parameters of PyOM fragments

The elements P, Mg and K were significantly higher in PyOM derived from *Z. gilletii* (0.7, 2.0 and 2.8 mg g^{-1}, respectively) compared to *C. megalocarpus* (0.4, 1.3 and 1.9 mg g^{-1}, respectively) (Table 1). On the contrary, Ca was higher in *C. megalocarpus* PyOM (20.1 mg g^{-1}) than that in *Z. gilletii* PyOM (11.2 mg g^{-1}). Thus, due to its lower P content, the C/P ratio of *C. megalocarpus* PyOM was more than double the value recorded in *Z. gilletii* PyOM. The ratio PP/N was significantly higher in *Z. gilletii* PyOM than in *C. megalocarpus* PyOM.

3.2. Effect of charcoal making on soil chemical properties

Seven of the nine soil chemical parameters measured were significantly affected by charcoal making, and the magnitude of the differences depended on the type of tree used in charcoal making and the sampling zone (Table S1). Total C, non-PyC and total N were higher in spots where *C. megalocarpus* was used in charcoal making (37.0 mg, 34.0 mg and 3.5 mg g^{-1}, respectively) than in *Z. gilletii* spots (29.9 mg, 25.6 mg and 2.6 mg g^{-1}, respectively) (Table 2). On the other hand, PyC, P and K were higher in spots rich in *Z. gilletii* PyOM (4.4 mg, 27.2 mg and 0.5 mg g^{-1}, respectively) than those rich in *C. megalocarpus* PyOM (3.6 mg, 18.0 mg and 0.4 mg g^{-1}, respectively). Sampling zone significantly affected soil pH, PyC, available P and exchangeable K, with the magnitude of the differences decreasing with increasing distance from the centre of the spot (Fig. 1). Higher differences in soil pH were recorded in spots rich in *Z. gilletii* PyOM and progressively declined from 6.7 in zone W at the centre of the spot to the lowest 6.2 in zone Z away from the spot. PyC concentration was greatest, 6.8 and 4.9 mg g^{-1}, at the centre of *Z. gilletii* and *C. megalocarpus* charcoal-making spots respectively, compared to 1.8 mg g^{-1} away from the spots. In this case, the proportion of PyC in total C was highest, 23% and 14%, at the centre of the spots compared to 6% and 5% away from the spots, respectively. Soil available P in the spots was greatly affected by tree species and sampling zone. This element was highest at the centre (zone W) of *Z. gilletii* charcoal-making spots (44.4 mg kg^{-1}) and progressively declined to 18.6 mg kg^{-1} in zone Z outside the charcoal-making spots. The concentration of available P in soil at the centre of *Z. gilletii* spots was therefore more than twice as high as in the soil outside the spot. A similar, but less contrasting soil available P pattern was observed across sampling distances in *C. megalocarpus* spots. Soil exchangeable K also showed a general decreasing concentration gradient from zone W to Z.

Table 2
Soil chemical properties (mean ± SE) as influenced by the charcoal-making spots (n = 5).

Soil chemical parameter	*Croton megalocarpus*					*Zanthoxylum gilletii*				
	Sampling zone									
	W	X	Y	Z	Mean[a]	W	X	Y	Z	Mean[a]
pH (water)	6.34 ± 0.23[a]	6.30 ± 0.22[a]	6.14 ± 0.23[a]	6.04 ± 0.24[a]	6.21 ± 0.11[A]	**6.67 ± 0.09[a]**	**6.63 ± 0.06[a]**	**6.33 ± 0.01[b]**	**6.23 ± 0.02[b]**	6.47 ± 0.07[A]
Total C (mg g^{-1})	36.39 ± 5.39[a]	35.58 ± 4.68[a]	36.98 ± 5.36[a]	39.10 ± 5.76[a]	**37.01 ± 2.5[A]**	29.25 ± 6.14[a]	29.34 ± 3.45[a]	30.13 ± 3.78[a]	31.00 ± 4.93[a]	**29.93 ± 3.4[B]**
PyC (mg g^{-1})	**4.93 ± 0.30[a]**	**3.95 ± 0.87[a]**	**3.71 ± 1.01[a]**	**1.78 ± 0.79[b]**	**3.60 ± 0.3[B]**	**6.81 ± 0.27[a]**	**5.33 ± 1.07[a]**	**3.67 ± 0.72[b]**	**1.77 ± 0.80[c]**	**4.40 ± 0.4[A]**
PyC (as% of Total C)	**13.51 ± 3.19[a]**	**11.10 ± 3.01[a]**	**10.03 ± 3.63[ab]**	**4.50 ± 0.60[b]**	**9.79 ± 1.2[B]**	**23.28 ± 5.80[a]**	**18.17 ± 6.08[ab]**	**11.74 ± 4.02[bc]**	**5.71 ± 0.81[c]**	**14.73 ± 1.5[A]**
Non-PyC (mg g^{-1})	32.00 ± 5.13[a]	32.74 ± 4.41[a]	33.56 ± 3.91[a]	37.67 ± 5.18[a]	**33.99 ± 1.9[A]**	23.43 ± 9.80[a]	24.21 ± 10.44[a]	26.41 ± 7.01[a]	28.36 ± 8.14[a]	**25.60 ± 3.2[B]**
Total N (mg g^{-1})	3.30 ± 0.60[a]	3.30 ± 0.50[a]	3.50 ± 0.60[a]	3.70 ± 0.60[a]	**3.45 ± 0.27[A]**	2.50 ± 0.50[a]	2.50 ± 0.40[a]	2.60 ± 0.40[a]	2.60 ± 0.60[a]	**2.55 ± 0.39[B]**
Extractable P (mg kg^{-1})	**20.35 ± 3.54[a]**	**21.14 ± 4.00[a]**	**16.69 ± 1.54[ab]**	**13.70 ± 1.21[b]**	**17.97 ± 1.46[B]**	**44.40 ± 8.52[a]**	**25.57 ± 4.58[ab]**	**20.34 ± 1.93[b]**	**18.57 ± 0.25[b]**	**27.22 ± 3.01[A]**
Extractable K (mg g^{-1})	**0.47 ± 0.05[a]**	**0.44 ± 0.05[a]**	**0.41 ± 0.05[a]**	**0.35 ± 0.05[b]**	**0.42 ± 0.02[B]**	**0.57 ± 0.02[a]**	**0.55 ± 0.03[a]**	**0.47 ± 0.04[ab]**	**0.44 ± 0.03[b]**	**0.51 ± 0.02[A]**
Extractable Ca (mg g^{-1})	2.51 ± 0.49[a]	2.34 ± 0.44[a]	2.48 ± 0.53[a]	2.62 ± 0.59[a]	2.49 ± 0.24[A]	2.09 ± 0.04[a]	2.17 ± 0.07[a]	2.12 ± 0.01[a]	2.12 ± 0.29[a]	2.13 ± 0.22[A]
Extractable Mg (mg g^{-1})	0.29 ± 0.02[a]	0.29 ± 0.03[a]	0.28 ± 0.02[a]	0.28 ± 0.03[a]	0.29 ± 0.01[A]	0.30 ± 0.02[a]	0.30 ± 0.03[a]	0.27 ± 0.02[a]	0.27 ± 0.02[a]	0.29 ± 0.01[A]

[a] This mean gives aggregate effect of tree species used in charcoal-making. Within rows, means in bold and followed by different letters in superscript are significantly different at $p < 0.05$ (n = 5). Uppercase letters indicate the differences based on tree species used in charcoal making while lowercase letters indicate the differences within sampling zones. Means were separated based on Tukey's honest significant difference (HSD) test.

3.3. Effect of charcoal making on soil macrofauna abundance

The abundance and spatial distribution of soil macrofauna was mainly affected by the type of tree used in charcoal making (Table S2). The average number of earthworms in charcoal-making spots rich in *Z. gilletii* PyOM (118.5 individuals m^{-2}) was more than twice the number recorded in spots rich in *C. megalocarpus* PyOM (47.2 individuals m^{-2}) (Table 3). While the number of earthworms in spots rich in *Z. gilletii* PyOM significantly increased with increasing distance from the centre of the spots, there was no significant spatial differences found in spots rich in *C. megalocarpus* PyOM. Notably, the differences observed in the number of earthworms in spots rich in *Z. gilletii* PyOM can be attributed to endogeic earthworms which were dominant. There were no significant spatial distribution differences in epigeic earthworms. Higher number of centipedes were also found to be associated with *Z. gilletii* charcoal-making spots (14.0 individuals m^{-2}). This was twice the number recorded in spots rich in *C. megalocarpus* PyOM (7.0 individuals m^{-2}). Notably, the numbers decreased with increasing distance from the centre of spots rich in *Z. gilletii* PyOM. On the other hand, although beetles, termites and crickets were significantly higher in spots rich in *C. megalocarpus* PyOM, there were no spatial differences in their numbers (Table 3). Abundance of ants, earwigs, millipedes and spiders were not significantly different across the spots.

4. Discussion

4.1. Effects of in-field charcoal production and PyOM on soil chemical properties

It is likely that in-field charcoal production generated significant amounts of PyOM that contributed to the high soil pH and PyC at the centre of the spots where charcoal was produced (zone W). Changes in soil pH as a result of increased concentration of pyrolysed materials are frequently reported (Glaser et al., 2002; Ameloot et al., 2013). These changes could be brought about by, but not limited to, presence of negatively charged functional groups such as phenolic, carboxyl and hydroxyl, and high ash content in the pyrolysed material (Chintala et al., 2014). The negative charges in the functional groups can bind H^+, and thus potentially affect soil pH. In addition to the PyOM, ash could have contributed to the observed differences in soil pH. During charcoal preparation, sealing of the traditional earth-mound kilns is often not uniform and air leaks may occur and lead to complete burning of some of the charcoal (FAO, 1987) therefore increasing the concentration of ash in such spots. The production of compounds such as oxides, hydroxides and carbonates in the ash could also bind H^+ ions from the soil solution and therefore contribute to increased soil pH. The mode of charcoal removal from these traditional kilns is usually accomplished by raking charcoal radially towards the outside of the kiln. This is a typical practice that facilitates extinguishing fire from all of the charcoal pieces to avoid re-ignition. In order to retrieve the charcoal that might have been buried in the process of opening the kiln, the mixture of PyOM, ash and burned soil are further spread out. Such a phenomenon could have contributed to the spread of PyOM and ash, and therefore the observed trends in pH and PyC from the centre of charcoal-making spots towards the outside.

Besides changing soil pH and PyC, PyOM and ash could also have contributed to the observed trends in soil P and K. Since pyrolysis mainly leads to losses of C, N, O and H, nutrients that volatilize at greater temperatures such as P, K and other metals in the wood are expected to remain in PyOM (Enders et al., 2012). Higher concentration of P and K are thus expected to be found at the centre of the spots where the kilns were located. It is important to note that while leaves from the trees harvested for charcoal making are locally used as a thin interface between the wood being carbonised and the soil which is used to seal the kiln, their contribution to the nutrients in and around the kiln is likely to be small. The practice of raking the charcoal during retrieval

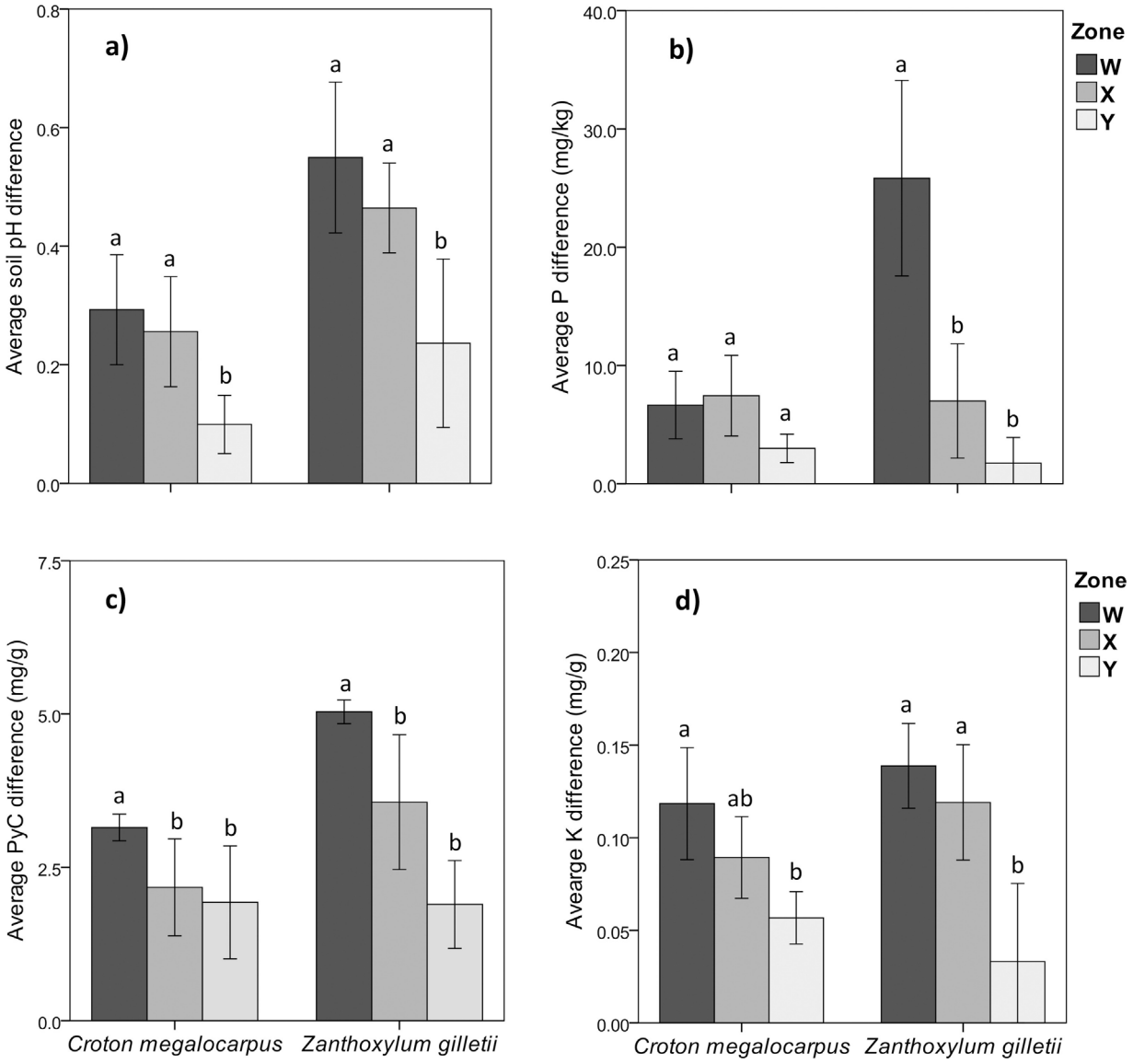

Fig. 1. Absolute differences in pH, available P, Pyrogenic C and exchangeable K in zones W, X and Y in charcoal-making spots compared to Z away from the spots (means and standard errors). Different letters indicate significant differences between the zones within a given tree species at $p < 0.05$ (n = 5). Means were separated based on Tukey's honest significant difference (HSD) test.

from the kilns mentioned earlier, could have also contributed to the spread of PyOM, ash and burned soil and thus the observed progressive decline in P and K from the centre towards the outside of PyOM-rich spots. Several studies have reported similar results. For instance, Chidumayo (1994a) reported that carbonisation of wood in miombo woodland in Zambia using traditional earth kilns resulted in higher soil pH, P and K. Similarly, Oguntunde et al. (2004) in Ghana reported that soil pH, P, Ca and Mg were higher in charcoal production sites compared to the adjacent soil. Nevertheless, the feedstock plays an important role in determining the amounts of nutrients returned into the soil in such cases. For instance, wood with higher amounts of non-volatile nutrients will be expected to produce PyOM with higher concentrations of these nutrients. Physiological differences among trees influence their ability to retain nutrients in the wood (Chidumayo, 1994b), hence the type of tree used in charcoal making will greatly affect the amounts of nutrients in PyOM and their concentration in these spots. It is therefore likely that higher amounts of soil available P in *Z. gilletii* spots could have resulted from higher concentrations of P in the wood of this tree, as indicated by the quality characteristics of the PyOM. However, it should be noted that differences in production practices could affect soil properties of the abandoned charcoal kilns. Thus, other differences between the charcoal-making spots instead of, or in addition to, chemical quality attributes of individual tree species may cause the observed differences in soil properties. For instance, considerable amounts of C and N are lost from the soil in and around the kiln in the process of charcoal production likely through direct heat (Ketterings and Bigham, 2000; Knicker, 2007) or operations during kiln construction (digging, loading and unloading). This could, to some extent, explain the observed variation in concentration of these elements.

4.2. Effects of charcoal production on soil macrofauna abundance and distribution

In this study, high concentration of PyOM (as indicated by the higher PyC) in the charcoal-making spots had contrasting effects on different soil macrofauna groups. Among these, earthworms, which are known to rely heavily on soil organic matter as a source of energy or to feed on the microbes growing on this substrate or their metabolites (Shan et al., 2010, 2013), showed the clearest trends. The low soil C,

Table 3
Soil macrofauna abundance (mean number of individuals m^{-2} ± SE) as influenced by charcoal-making spots (n = 5).

Taxa	Family	Common name	*Croton megalocarpus*					*Zanthoxylum gilletii*				
			Sampling zone									
			W	X	Y	Z	Mean[a]	W	X	Y	Z	Mean[a]
Insects												
Hymenoptera	Formicidae	Ants	4.7 ± 2.0^{a}	4.7 ± 3.4^{a}	6.0 ± 4.2^{a}	6.7 ± 2.7^{a}	4.5 ± 4.3^{A}	0.0^{a}	2.0 ± 2.0^{a}	2.0 ± 2.0^{a}	2.0 ± 2.0^{a}	1.5 ± 1.5^{A}
Coleoptera	(Total number)	Beetles	26.7 ± 5.0^{a}	28.7 ± 7.0^{a}	24.7 ± 8.6^{a}	42.0 ± 8.0^{a}	**30.6 ± 3.4^{A}**	12.0 ± 4.0^{a}	28.0 ± 2.0^{a}	14.0 ± 4.7^{a}	26.5 ± 10.9^{a}	**17.5 ± 3.4^{B}**
	Carabidae		0.0^{a}	0.0^{a}	0.0^{a}	2.7 ± 0.6^{a}	**0.7 ± 0.3^{B}**	2.0 ± 0.3^{a}	4.0 ± 0.5^{a}	0.0^{a}	0.0^{a}	**1.5 ± 0.3^{A}**
	Curculionidae		0.0^{a}	0.0^{a}	0.0^{a}	0.0^{a}	**0.0^{B}**	0.0^{a}	4.0 ± 1.2^{a}	0.0^{a}	10.0 ± 6.2^{a}	**3.5 ± 0.9^{A}**
	Elateridae		0.7 ± 0.2^{a}	1.3 ± 0.6^{a}	0.7 ± 0.6^{a}	5.3 ± 1.2^{a}	2.0 ± 0.9^{A}	2.0 ± 0.6^{a}	4.0 ± 0.3^{a}	2.0 ± 0.2^{a}	0.0^{a}	2.0 ± 0.5^{A}
	Scarabaeidae		15.3 ± 3.2^{a}	9.3 ± 4.6^{a}	12.7 ± 5.6^{a}	21.3 ± 5.2^{a}	**14.7 ± 2.7^{A}**	4.0 ± 2.6^{a}	4.0 ± 1.3^{a}	4.0 ± 2.1^{a}	10.2 ± 3.0^{a}	**5.5 ± 1.6^{B}**
	Staphylinidae		10.7 ± 1.3^{a}	18.0 ± 1.9^{a}	11.3 ± 2.3^{a}	12.7 ± 2.1^{a}	13.2 ± 1.9^{A}	10.0 ± 1.1^{a}	10.0 ± 1.8^{a}	8.0 ± 2.0^{a}	12.0 ± 2.9^{a}	10.0 ± 2.5^{A}
	Tenebrionidae		0.0^{a}	0.0^{a}	0.0^{a}	0.0^{a}	0.0^{A}	0.0^{a}	2.0 ± 0.6^{a}	0.0^{a}	0.0^{a}	0.5 ± 0.3^{A}
Isoptera	Termitidae	Termites	8.7 ± 4.2^{a}	33.3 ± 11.3^{a}	10.7 ± 5.7^{a}	25.3 ± 5.5^{a}	**19.5 ± 3.9^{A}**	8.0 ± 6.0^{a}	6.0 ± 4.0^{a}	12.0 ± 6.6^{a}	0.0^{a}	**6.5 ± 3.5^{B}**
Orthoptera	Gryllidae	Crickets	1.3 ± 0.1^{a}	0.7 ± 0.1^{a}	2.0 ± 0.2^{a}	2.0 ± 0.1^{a}	**1.5 ± 0.5^{A}**	0.0^{a}	0.0^{a}	1.0 ± 0.1^{a}	0.0^{a}	**0.3 ± 0.3^{B}**
Dermaptera	Forficulidae	Earwigs	0.7 ± 0.1^{a}	0.7 ± 0.1^{a}	0.7 ± 0.1^{a}	0.0^{a}	0.5 ± 0.3^{A}	0.0^{a}	0.0^{a}	0.0^{a}	2.0 ± 0.3^{a}	0.5 ± 0.5^{A}
Hemiptera	Coreidae	True bugs	0.0^{a}	0.0^{a}	0.0^{a}	2.0 ± 0.3^{a}	**0.5 ± 0.3^{B}**	2.0 ± 0.5^{a}	8.0 ± 3.1^{a}	2.0 ± 0.2^{a}	0.0^{a}	**3.0 ± 0.7^{A}**
Isopoda	Porcellionidae	Woodlice	0.0^{a}	0.0^{a}	0.0^{a}	0.7 ± 0.3^{a}	0.2 ± 0.2^{A}	2.0 ± 1.3^{a}	0.0^{a}	2.0 ± 1.0^{a}	0.0^{a}	1.0 ± 0.4^{A}
Earthworms[b]												
Oligochaeta	(Total number)	Earthworms	55.9 ± 24.8^{a}	47.4 ± 16.3^{a}	44.7 ± 15.7^{a}	40.6 ± 17.3^{a}	**47.2 ± 7.6^{B}**	**68.0 ± 18.7^{c}**	**86.0 ± 12.3^{c}**	**130.0 ± 14.8^{b}**	**190.0 ± 16.3^{a}**	**118.5 ± 9.8^{A}**
	(Epigeic)		16.6 ± 4.9^{a}	14.7 ± 7.0^{a}	22.7 ± 8.1^{a}	20.6 ± 10.3^{a}	18.7 ± 3.2^{A}	12.0 ± 4.7^{a}	22.0 ± 6.4^{a}	26.0 ± 9.1^{a}	20.0 ± 5.1^{a}	20.0 ± 3.4^{A}
	(Endogeic)		39.3 ± 23.7^{a}	32.7 ± 14.8^{a}	22.0 ± 9.2^{a}	20.0 ± 8.6^{a}	**28.5 ± 6.4^{B}**	**56.0 ± 14.9^{c}**	**64.0 ± 19.8^{c}**	**104.0 ± 10.3^{b}**	**170.0 ± 13.6^{a}**	**98.5 ± 9.4^{A}**
Myriapods												
Chilopoda	Scolopendridae	Centipedes	8.7 ± 3.4^{a}	9.3 ± 4.8^{a}	2.0 ± 1.5^{a}	7.3 ± 2.3^{a}	**6.8 ± 1.6^{B}**	**20.0 ± 6.1^{a}**	**18.0 ± 7.2^{a}**	**12.0 ± 5.9^{ab}**	**6.0 ± 4.2^{b}**	**14.0 ± 2.4^{A}**
Diplopoda	Trigoniulidae	Millipedes	1.3 ± 0.9^{a}	5.3 ± 2.1^{a}	2.7 ± 1.1^{a}	4.7 ± 3.4^{a}	3.3 ± 1.1^{A}	2.0 ± 2.0^{a}	2.0 ± 2.0^{a}	2.0 ± 2.0^{a}	6.0 ± 2.9^{a}	3.0 ± 2.1^{A}
Arachnids												
Araneae	Araneidae	Spiders	2.0 ± 1.8^{a}	2.7 ± 2.2^{a}	4.0 ± 1.6^{a}	3.3 ± 2.2^{a}	3.0 ± 1.0^{A}	0.0^{a}	2.0 ± 1.5^{a}	0.0^{a}	4.0 ± 4.0^{a}	1.5 ± 0.6^{A}

[a] The mean gives an aggregate effect of the tree used in charcoal making.
[b] Earthworms were further separated into ecological groups: epigeic, endogeic and anecic groups. In this study, there were no anecic groups recovered. Within rows, means in bold and followed by different letters in superscript are significantly different at $p < 0.05$ (n = 5). Uppercase letters indicate the differences based on tree species used in charcoal making while lowercase letters indicate the differences within the sampling zones. Means were separated based on Tukey's honest significant difference (HSD) test.

and even more the low non-PyC contents (likely more important than PyC as an energy source for soil biota) could have made the soil in charcoal-making spots a less desirable substrate for earthworms. In *C. megalocarpus* spots where total C and non-PyC was significantly higher than in *Z. gilletii* spots, the presumably negative effects of PyOM appeared to be lower, given that the abundance of earthworms was not significantly different between the four sampling zones. Of the two ecological groups of earthworms found in this study, the endogeic group, which ingests substantial amounts of organic matter and mineral soil were the most affected and this was especially conspicuous in *Z. gilletii* charcoal-making spots. In a study by Topoliantz and Ponge (2003) where the authors were looking at the response of earthworms (*Pontoscolex corethrurus*) to charcoal application, it was reported that the burrows made by the earthworms in the soil + charcoal treatment could have been created as the earthworms pushed charcoal particles aside, perhaps, in search of charcoal-free soil. However, although PyOM could be a less desirable substrate as an energy source, it has been proposed that earthworms could selectively ingest it for other purposes. For instance, Lehmann et al. (2011) suggested that earthworms can ingest biochar particles to help in grinding food in their gizzard, a function similar to that of sand. In addition, its ingestion may benefit earthworms indirectly by enhancing production of earthworm's digestive enzymes from microbial communities or for its detoxifying and liming properties (Topoliantz and Ponge, 2003). Therefore, if all conditions are held constant, the quality of PyOM could be an important determinant of the earthworms' preference for such a material. In this study, if the earthworms were ingesting PyOM, then it is likely that they preferred the PyOM from *Z. gilletii* tree over that from *C. megalocarpus* given the significant differences in earthworm abundance recorded between the soils affected by PyOM made from these two tree species. The quality of PyOM can also be measured by the concentration of toxic substances such as polycyclic aromatic hydrocarbons (PAHs), dioxins, among other compounds (Hale et al., 2012). Though it is unlikely that these toxic compounds could have had a significant influence on the current population of soil macrofauna given the relatively long period of time the PyOM had stayed in the field before sampling was conducted, we cannot rule out such a possibility. The differences observed in earthworm abundance could also be attributed to the influence of PyOM on soil conditions. For instance, studies have reported changes in soil chemical and physical properties as a result of PyOM accumulation from charcoal production (Oguntunde et al., 2004; Coomes and Miltner 2016). In the current study, progressive decrease in pH towards outside of the charcoal-making spots may have accounted for the observed earthworm trends. Additionally PyOM/biochar has also been demonstrated to alter soil tensile strength and bulk density, which can affect the hydrodynamics and gas transport in the PyOM/biochar-rich soil (Lehmann et al., 2011; Masiello et al., 2015). In other studies, application of PyOM/biochar has been shown to affect soil albedo, thus possibly affecting soil temperature and moisture (Castracani et al., 2015). Although soil moisture and temperature were not measured in these spots, we believe that the variation in these parameters may have also contributed to the differences observed in earthworm abundance.

In contrast to earthworms, a significant number of centipedes was recorded in charcoal-making spots, particularly those rich in *Z. gilletii* PyOM. Apart from food, habitat provision has been reported to play a big role in determining the abundance of soil organisms. Pyrolysed materials such as PyOM provide niches for soil microfauna (protozoa, tardigrades and nematodes) and mesofauna (mites and collembola) to access resources and thrive (Lehmann et al., 2011). Since centipedes are known to be predators, this could suggest that their high numbers in charcoal-making spots could have, perhaps, been a consequence of increased prey abundance. There was no spatial variation or definite patterns in abundance of ants, beetles, termites, crickets, earwigs, millipedes and spiders. This could be due to the fact that these groups of macrofauna are relatively mobile, and therefore may not have been directly affected by PyOM.

5. Conclusion

The study has shown that soils in the charcoal-making spots were rich in PyC, P and K, which all progressively decreased with increasing distance from the centre of the spots. However, total C and N and non-PyC progressively increased with distance from the centre of the spots. All soil macrofauna studied (except centipedes) were lower in charcoal-making spots, perhaps due to negative effects of the charcoal production process on them. One reason may be that PyC, which was higher in these spots, was too recalcitrant to support soil microbial growth, and therefore reducing the abundance of soil macrofauna such as earthworms which feed on microbes growing on such substrates and/or their metabolites. Therefore, assessments in agricultural landscapes dominated by charcoal production need to consider the differential effects of *in situ* production of charcoal in contributing to a mosaic of soil conditions influencing soil macrofauna abundance and distribution. Moreover, it would be important that farmers should set aside a central place where charcoal production can be done repeatedly without necessarily moving into new areas in order to reduce negative effects of charcoal production on soil macrofauna. Further research is needed to assess short-term vs. long-term effects of *in situ* charcoal production on ecological functions driven by soil macrofauna in such a mosaic of soil conditions and thus the potential effects of such activities on the socio-economic welfare smallholder farmers in Africa and other regions where charcoal making is prevalent.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apsoil.2017.07.007.

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