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Effects of charcoal-enriched goat manure on soil fertility parameters and growth of pearl millet (*Pennisetum glaucum* L.) in a sandy soil from northern Oman

Melanie Willich [a,**], Anne Kathrin Schiborra [b],
Laura Quaranta [b], Andreas Buerkert [a,*]

[a] *Organic Plant Production and Agroecosystems Research in the Tropics and Subtropics, Universität Kassel, Witzenhausen, Germany*
[b] *Animal Husbandry in the Tropics and Subtropics, Universität Kassel, Witzenhausen and Georg-August-Universität Göttingen, Göttingen, Germany*

Abstract

The effect of charcoal feeding on manure quality and its subsequent application to enhance soil productivity has received little attention. The objectives of the present study therefore were to investigate the effects of (i) charcoal feeding on manure composition, and (ii) charcoal-enriched manure application on soil fertility parameters and growth of millet (*Pennisetum glaucum* L.). To this end, two experiments were conducted: First, a goat feeding trial where goats were fed increasing levels of activated charcoal (AC; 0, 3, 5, 7, and 9 % of total ration); second, a greenhouse pot experiment using the manure from the feeding trial as an amendment for a sandy soil from northern Oman. We measured manure C, N, P, and K concentrations, soil fertility parameters and microbial biomass indices, as well as plant yield and nutrient concentrations. Manure C concentration increased significantly ($P < 0.001$) from 45.2 % (0 % AC) to 60.2 % (9 % AC) with increasing dietary AC, whereas manure N, P, and K concentrations decreased ($P < 0.001$) from 0 % AC (N: 2.5 %, P: 1.5 %, K: 0.8 %) to 9 % AC (N: 1.7 %, P: 0.8 %, K: 0.4 %). Soil organic carbon, pH, and microbial biomass N showed a response to AC-enriched manure. Yield of millet decreased slightly with AC enrichment, whereas K uptake was improved with increasing AC. We conclude that AC effects on manure quality and soil productivity depend on dosage of manure and AC, properties of AC, trial duration, and soil type.

Keywords: activated charcoal, goat manure, microbial biomass C, SOC, subtropical soils

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1 Introduction

Under the arid subtropical conditions of the Batinah region in northern Oman, regular additions of organic soil amendments such as manure and compost, and careful irrigation management are determining soil productivity and sustainability of cropping systems. It is well known that microbial activity, and consequently soil organic matter (SOM) turnover, is strongly affected by wet-dry cycles (Lundquist *et al.*, 1999a,b). High microbial turnover is often reflected in rapid decomposition of organic matter (OM) followed by a breakdown of soil fertility (Ghoshal & Singh, 1995; Zech *et al.*, 1997; Wichern *et al.*, 2004). One possibility to counteract soil organic matter decay under year-round conditions of high mineralisation is the exploitation of the *terra preta* concept (Glaser *et al.*, 2001, 2002), adding charred organic material to the soil. Key features of biochar (BC) amended soils are higher levels of

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[*] Corresponding author
Email: tropcrops@uni-kassel.de
Phone: +49 5542 98 1228; Fax: +49 5542 98 1230

[**] Current affiliation: College of Agriculture, Forestry and Natural Resource Management, University of Hawai'i at Hilo, Hilo, HI, USA

SOM, enhanced nutrient retention capacity, and higher moisture-holding capacity than in the surrounding soils (Glaser *et al.*, 2001; Lehmann & Rondon, 2006; Liang *et al.*, 2006). However, in order to substantially affect the aforementioned physico-chemical soil parameters, large quantities of charred material are needed, particularly in view of possible losses through wind and water erosion. Also, there is still little knowledge about the nutrient release dynamics from BC used as a manure-amendment which is subsequently applied to soils. In many cases it is unclear whether BC is benefiting plants by providing nutrients or inhibiting plant growth by sequestering them (Mukherjee & Zimmerman, 2013). In contrast to BC, activated carbon or charcoal (AC) is a homogeneous, technically refined type of BC with effects on soil properties similar to those of BC (Lehmann & Rondon, 2006; Braendli *et al.*, 2008). AC is produced from coal, peat, bamboo, coconut shells or other organic materials by incomplete combustion followed by steam activation (Braendli *et al.*, 2008). It is used as a strong sorbent for a wide range of organic compounds in many different applications such as gas and water purification, medicine, sewage treatment, and air filters (Norit Americas Inc., 2006). It is well documented that BC or AC can be used effectively as a gastrointestinal absorbent for treating forage-induced intoxications such as mycotoxins (Buck & Bratich, 1986; Huwig *et al.*, 2001). Positive effects on feed intake and nutrient utilisation were also reported for animals feeding on low quality forages containing compounds such as alkaloids, phenols, and terpenes (Banner *et al.*, 2000; Poage *et al.*, 2000; Rogosic *et al.*, 2006). However, so far BC studies primarily addressed effects of BC addition to soils (Glaser *et al.*, 2002; Lehmann & Rondon, 2006), whereas little is known about the effect of AC as feed additive on manure quality, and how ingested, manure-bound AC affects soil properties, C sequestration, and plant growth. Recent results by Ingold *et al.* (2011) suggest that charcoal-enriched manure has a greater recalcitrant capacity than AC mixed with faeces outside the animal. Moreover, manure-bound AC seems better suited for no-till applications as it is less likely to disintegrate and erode from soil if bound to a carrier.

The objectives of this study consisting of a goat feeding trial followed by a greenhouse pot experiment were (i) to determine if AC fed daily to goats had negative effects on animal performance and how ingested AC affects the nutrient composition of the manure, and (ii) to measure AC-manure effects on soil microbial biomass, nutrient and water retention capacities, and growth of a test crop under controlled conditions.

2 Materials and methods

2.1 Soil collection and characterisation

Soil (0–40 cm) was collected from a private experimental farm (24º20′ N, 56º46′ E) located on the northeastern Batinah coast of the Sultanate of Oman (Siegfried *et al.*, 2013). The soil had been classified as a mixed hyperthermic typic Torrifluvent (US Soil Taxonomy, Al-Farsi, 2001) derived from recent fluviatile wadi deposits with a gravel-rich subsoil and partly coverage by aeolian sand veneers. The soil had a coarse texture (82 % sand, 16 % silt, 2 % clay), a $\mathrm{pH_{H_2O}}$ of 8.5, a bulk density of 1.44 $\mathrm{g\,cm^{-3}}$, a total C content of 12.7 $\mathrm{g\,kg^{-1}}$, an organic C content (C_{org}) of 4.9 $\mathrm{g\,kg^{-1}}$, a total N content of 0.6 $\mathrm{g\,kg^{-1}}$, a $CaCO_3$ content of 6.5 %, a C : N ratio of 21.2, an Olsen P of 0.04 $\mathrm{g\,kg^{-1}}$, and $K_{(CAL)}$ of 0.26 $\mathrm{g\,kg^{-1}}$. Before the experiment started, the soil was air dried, sieved (< 2 mm) and shipped to Germany.

2.2 Experimental design

2.2.1 Goat feeding and manure collection

Manure was derived from a feeding trial with four male boer goats (*Capra aegagrus hircus* L.; 22.8 ±3.9 kg) conducted at the Department of Animal Sciences, Georg-August-Universität Göttingen. In this trial, each goat was offered increasing levels of AC (0, 3, 5, 7, 9 % of total diet, dry matter basis) together with concentrate feed over five consecutive 14-day-periods (one AC level per 14-day-period, in increasing order) and effects on feeding behaviour and goats' health and faecal excretion patterns were observed (Quaranta *et al.*, 2013). To this end, the goats were kept in individual cages and fed twice per day with a mixture of 50 % hay (*Lolium perenne* L.) and 50 % concentrate, while hay was offered after concentrate was completely taken up. The concentrate was composed of 35 % barley, 35 % wheat, 15 % rapeseed extraction meal, and 15 % sugar beet molasse chips. AC powder was mixed with the ground ingredients at 0 (control), 6, 10, 14, and 18 % level (corresponding to 0, 3, 5, 7, and 9 % of total diet, dry matter basis) and pressed into pellets. AC powder was manufactured from coconut shells followed by steam activation (AquaSorb® CP1, Jacobi Carbons Service GmbH, Premnitz, Germany) and contained 92.1 % C, 0.1 % N, 0.03 % P, and 0.8 % K. It had a pH of 9.1, a particle size of 44 µm, a surface area of 1050 $\mathrm{m^2\,g^{-1}}$, and a total pore volume of 0.62 $\mathrm{cm^3\,g^{-1}}$ (Jacobi Carbons Service GmbH, Premnitz, Germany). Feed quantity was administered at 1.5 times energy maintenance requirements and adjusted every two weeks according to goats' weight gain.

Feeding behaviour (consumption rate, refusals) and manure characteristics (colour, odour, consistency) were observed during the first five days of each period. At days 8 to 10 of each 14-day-period, goats were equipped with faecal collection bags, which were attached by harnesses. The complete amount of manure in the collection bags was sampled twice daily before each feeding, weighted and stored immediately at −20 °C.

2.2.2 *Greenhouse trial*

A greenhouse trial over 12 weeks with six replicates was carried out using the manure produced in the feeding trial: Treatments were (i) manure with 0 % AC in goat feed (control), (ii) manure with 3 % AC in goat feed, (iii) manure with 5 % AC in goat feed, (iv) manure with 7 % AC in goat feed, and (v) manure with 9 % AC in goat feed. In the following, these treatments will be referred to as AC 0 (or control), AC 3, AC 5, AC 7, and AC 9, respectively. For all treatments, 4.2 kg dry soil was filled into respective PVC pots (17.5 cm diameter, 22 cm height).The experiment was fertilised equivalent to 160 kg N ha^{-1} and thus received between 6.4 t (AC 0) and 9.4 t (AC 9) of manure per hectare depending on the AC treatment. Per pot, this amounted to 15.3 g (AC 0), 19.5 g (AC 3), 20.6 g (AC 5), 21.0 g (AC 7), and 22.1 g (AC 9) manure. Prior to the treatment application, soil and manure were analysed separately for microbial and chemical properties. From this analysis, the initial values for soil and all manure treatments were determined. Two days before sowing, the water content was adjusted to 40 % water holding capacity (WHC), which was gravimetrically controlled and adjusted every third to fourth day throughout the experiment, so that the water content remained at >35 % of WHC. One day before sowing, the manure treatments were buried at 5 cm soil depth. In each pot, ten seeds of millet (*Pennisetum glaucum* L.) were sown at 2 cm depth, and thinned to four seedlings nine days later. Millet was chosen as indicator plant, because it grows well under greenhouse conditions and is fertility responsive. Climatic conditions were regulated to 28 ±1 °C during the day and 16 ±1 °C during the night with a 12/12 h day/night light regime and a light summation per day of at least 120 klx. The pots were re-randomized every fourth day throughout the duration of the trial.

2.3 *Analytical methods*

2.3.1 *Manure nutrient contents*

Upon thawing, manure samples were oven dried to constant weight at 60 °C and ground with a ball mill, then homogenized, and combined to form a composite sample for each AC level. Two subsamples per treatment were analysed for C and N contents using a Vario MAX elemental analyser (Elementar GmbH, Hanau, Germany). The concentrations of P and K were determined photometrically (P; Hitachi U-2000, Hitachi Co Ltd., Tokyo, Japan) and by flame photometry (K; Instrument Laboratory 543, Bedford, USA) in coloured ash solution (32 % HCl) after burning the manure in a muffle furnace (550 °C, 24 h; Murphy & Riley, 1962). Organic matter was calculated as difference between dry weight (105 °C, 24 h) and ash content of a sample.

2.3.2 *Soil organic carbon and total N*

Before any soil samples were taken, plant roots were thoroughly removed. For capacity reasons, four out of the six replicates were randomly assigned from each treatment for soil analyses. Total C and N of soil was determined by gas chromatography after dry combustion to CO_2 and N_2 using a Vario Max CN analyser (Elementar GmbH, Hanau, Germany). Carbonate ($CO_3{}^{2-}$) was measured gas-volumetrically after addition of 1:2 diluted 32 % HCl. Soil organic carbon was calculated as difference between total C and CO_3-C.

2.3.3 *Microbial biomass indices*

Microbial biomass C (Vance *et al.*, 1987) and microbial biomass N (Brookes *et al.*, 1985) were measured on fresh soil by chloroform fumigation extraction with 0.5 M K_2SO_4 and subsequent analysis of organic C and total N using a CN analyser (Multi N/C 2100S, Analytik Jena AG, Jena, Germany). Microbial biomass C was calculated as E_C/k_{EC}, where E_C is (organic C extracted from fumigated soils) – (organic C extracted from non-fumigated soils), and k_{EC} is 0.45 (Wu *et al.*, 1990). Microbial biomass N was calculated as E_N/k_{EN}, where E_N is (total N extracted from fumigated soils) – (total N extracted from non-fumigated soils), and k_{EN} is 0.54 (Brookes *et al.*, 1985).

2.3.4 *Soil physico-chemical parameters*

Soil pH (H_2O) was measured using a glass electrode at a 1:2.5 soil-to-water ratio. Water holding capacity (WHC) of the soil was calculated as gravimetrical difference following complete saturation with deionized water and subsequent drying (105 °C, 24 h). For the determination of cation exchange capacity (CEC), 2.5 g soil were saturated with 30 ml 0.1 M $BaCl_2$ buffered (pH 7) solution and shaken for 2 h. Then, samples were centrifuged (Centrikon T-124, Kontron Instruments, Milan, Italy) at 9000 rpm for 15 minutes, and filtered through a black band filter. K and Na were measured according to Murphy & Riley (1962) with a flame photometer (Flame Photometer 543, Instrumentation Laboratory, Bedford, MA, USA). Concentrations of Ca, Mg, and Al were determined by atomic absorption spectrometry (AAS 906AA, GBC Scientific Equipment, Melbourne, Australia). CEC was calculated as the sum of the exchangeable cations (K, Na, Ca, Mg, Al) and expressed in cmol kg^{-1}.

2.3.5 Plant nutrient uptake and biomass yield

At day 29, 36, 43, 58, 65, and 81 after sowing, shoot height was determined after stretching the longest leaf. Upon harvest, plants were cut above soil surface, dried (60 °C, 24 h), and ground with a ball mill. While a subsample was analysed for total C and N with a Vario MAX elemental analyser (Elementar, Hanau, Germany), the remainder of the samples were further dried to constant dry weight (105 °C, 24 h). Subsequently, 1.5 g dry matter was ashed in a muffle furnace (550 °C, 24 h) and dissolved in concentrated HCl for colorimetric analysis of P and K using the ascorbic acid method described by Murphy & Riley (1962). Individual plants per pot were treated as subsamples, pooled and values reported as averages per plant.

2.4 Statistical analysis

Significance of treatment effects was tested by analysis of variance (ANOVA) and post-hoc test statistics (Tukey HSD). Arithmetic means were compared at $P < 0.05$ using contrasts. All statistical analyses and graphs were performed using the statistical packages Statistica 7.0 (StatSoft GmbH, Hamburg, Germany), SPSS 17.0 (SPSS Inc., Chicago, IL, USA) and Sigma Plot (Systat Software Inc., San José, CA, USA).

3 Results

3.1 Manure quality and faecal scores

Based on feeding behaviour observations, intake of concentrate was not affected by AC concentration (Quaranta *et al.*, 2013). Percentage of manure C increased significantly with the amount of AC fed to goats while N and P concentrations steadily decreased (Table 1).

The increase in C and decline in N resulted in a widened CN ratio with rising AC levels in the goat feed. Manure K concentration was significantly lower in AC-manure compared with the control. AC addition to the feed also affected manure consistency, colour and odour (Table 2).

Table 2: *Mode faecal scores of goat manure from the feeding trial with AC (n = 4).*

	AC in goat feed (%)				
	0	*3*	*5*	*7*	*9*
consistency	3	3	4	4	4
colour	2	3	3	3	4
odour	2	1	1	1	1

AC: activated charcoal fed to goats in % of total ration.
Consistency: 1 ≙ Diarrhoea, 2 ≙ Soft, 3 ≙ Normal, 4 ≙ Hard
Colour: 1 ≙ Light, 2 ≙ Normal, 3 ≙ Dark, 4 ≙ Very dark/black
Odour: 1 ≙ Mild, 2 ≙ Normal, 3 ≙ Strong

Table 1: *Mean carbon and nutrient contents of goat manure from the feeding trial with AC. Values in parentheses represent ± one standard error of the mean (n = 2). Significance of treatment effects at $P < 0.05$ based on contrast tests.*

AC in goat feed (%)	*C* (%)	*N* (%)	*P* (%)	*K* (%)	*CN ratio*
0	45.2 (0.1)	2.5 (0.1)	1.5 (0.0)	0.8 (0.0)	18 (0.3)
3	51.4 (0.0)	2.0 (0.0)	1.2 (0.0)	0.5 (0.1)	26 (0.3)
5	56.7 (0.1)	1.9 (0.0)	1.1 (0.1)	0.5 (0.0)	30 (0.4)
7	57.9 (0.2)	1.8 (0.0)	1.0 (0.1)	0.7 (0.0)	32 (0.0)
9	60.2 (0.5)	1.7 (0.0)	0.8 (0.0)	0.4 (0.0)	35 (0.1)
Contrasts					
Manure –AC *vs.* +AC	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
High AC *vs.* low AC	< 0.001	0.006	0.002	0.175	< 0.001
CV (%)	10	15	23	28	22

CV: mean coefficient of variation between replicates of one column. AC: activated charcoal fed to goats in % of total ration. High AC = 9 %, low AC = 3 %.

3.2 Soil physico-chemical parameters

Irrespective of AC treatment, manure addition to the soil did not affect SOC concentrations (Table 3).

By the end of the trial, however, the SOC concentration in soils treated with AC-enriched manure was significantly higher than in soils which received manure without dietary AC. In contrast, soil total nitrogen (TN) concentrations remained constant with only marginal increases for the two highest AC treatments. Consequently, the soil CN ratio tended to increase with increasing AC fed. Water holding capacity tended to increase with AC-enriched manure. The increase of the average WHC from the initial soil to the soils amended with the two lower AC treatments (3 and 5) was 3 %, and statistically not significant. However, in the soils of the two higher AC treatments (7 and 9) WHC increased by 9 and 25 % as compared with the initial soils' WHC; and by 6 and 21 % as compared with the soils that received un-amended manure. CEC dropped by 2 % in soils treated with AC 9 manure, and by 6 % in soils treated with AC 7 manure as compared with the control. However, compared with the initial soils' CEC, average CEC of the AC 9 treatment was still slightly higher (9.7 and 10 cmol kg^{-1}, respectively). There was no difference in pH level between the initial soil and the soil that received un-amended manure (both pH 8.5), but pH was significantly lower in soils that received AC-enriched manure.

3.3 Soil microbial biomass

AC-enriched manure applications did not affect microbial biomass C (Table 4). Compared with the initial value, mean microbial biomass C concentrations were nevertheless higher in all manure amended soils, except for soils that received AC 5 manure, where microbial biomass C was slightly lower than in the initial soil (4 %) and considerably lower than in all other fertilised soils (26 %). Microbial biomass N was significantly higher in all manure treated soils than before manure application. With increasing manure AC levels, microbial biomass N decreased by 36 % from 28 µg g^{-1} (AC 3) to 18 µg g^{-1} (AC 9). The ratio of microbial biomass C to SOC indicated an increase from initially 2 % to 3 % in the soils of the AC 5 and AC 7 treatments, respectively, and declined in the soils of the AC 9 treatment again to about 2 %. The contribution of K_2SO_4-extractable N to total N decreased during the 12 weeks of the experiment from 4.6 % to 2.3 % and was lowest in the two higher AC treatments (AC 7 and 9).

Table 3: *Mean concentrations of soil organic carbon (SOC) and total nitrogen (TN); CN ratio, water holding capacity (WHC) and cation exchange capacity (CEC) of soil samples. Values in parentheses represent ± one standard error of the mean (initial concentrations before treatment application: n = 4; treatment replicates: n = 4). Significance of treatment effects at P* < 0.05 *based on contrast tests.*

	SOC (mg g^{-1} soil)	*TN* (mg g^{-1} soil)	*CN ratio*	*WHC* (%)	*CEC* (cmol kg^{-1} soil)	*pH*
Initial concentrations	4.9 (0.6)	0.6 (0.0)	21 (0.7)	32 (2)	9.7 (0.3)	8.5 (0.0)
Manure (% AC fed)						
0	3.7 (0.8)	0.5 (0.0)	22 (0.8)	33 (3)	10.2 (0.2)	8.5 (0.0)
3	4.3 (0.3)	0.5 (0.0)	22 (0.4)	33 (3)	10.2 (0.1)	8.4 (0.0)
5	4.6 (0.8)	0.5 (0.0)	23 (0.2)	33 (2)	10.2 (0.1)	8.3 (0.0)
7	5.9 (0.8)	0.6 (0.0)	23 (0.1)	35 (2)	9.6 (0.2)	8.4 (0.0)
9	6.2 (0.5)	0.6 (0.0)	23 (0.3)	40 (1)	10.0 (0.2)	8.3 (0.1)
Contrasts						
Initial *vs.* treatment	NS	NS	NS	NS	0.073	0.001
Manure −AC *vs.* +AC	0.040	0.062	NS	NS	NS	0.004
High AC *vs.* low AC	0.050	0.092	NS	0.044	NS	NS
CV (%)	31	12	4	14	4	1

CV: mean coefficient of variation between replicates of one column. AC: activated charcoal fed to goats in % of total ration.
High AC = 9 %, low AC = 3 %. Treatment: all manures. NS: not significant.

Table 4: *Mean concentrations of K_2SO_4-extractable organic carbon and nitrogen and microbial biomass carbon and nitrogen of soil samples. Values in parentheses represent ±one standard error of the mean (initial concentrations before treatment application: n = 4; treatment replicates: n = 4). Significance of treatment effects at* $P < 0.05$ *based on contrast tests.*

	K_2SO_4-*C* (µg g^{-1} soil)	K_2SO_4-*N* (% TN)	*Microbial biomass C* (µg g^{-1} soil)	*Microbial biomass C* (% SOC)	*Microbial biomass N* (µg g^{-1} soil)
Initial concentrations	104 (7)	4.6 (0.0)	111 (6)	2.3 (0.3)	6 (0.2)
*Manure (% AC fed)**					
3	74 (6)	n.d.	158 (32)	n.d.	28 (4)
5	89 (5)	2.8 (0.6)	107 (19)	3.0 (0.8)	20 (6)
7	99 (5)	2.1 (0.2)	148 (37)	3.2 (1.3)	20 (4)
9	88 (2)	2.1 (0.3)	125 (14)	1.9 (0.1)	18 (1)
Contrasts					
Initial *vs.* treatment	0.020	0.002	NS	NS	0.024
High AC *vs.* low AC	0.056	n.d.	NS	n.d.	NS
CV (%)	12	35	39	64	41

* Values for 0 % AC are missing. n.d.: not determined. CV: mean coefficient of variation between replicates of one column. AC: activated charcoal fed to goats in % of total ration. High AC = 9 %, low AC = 3 %. Treatment: all manures. NS: not significant.

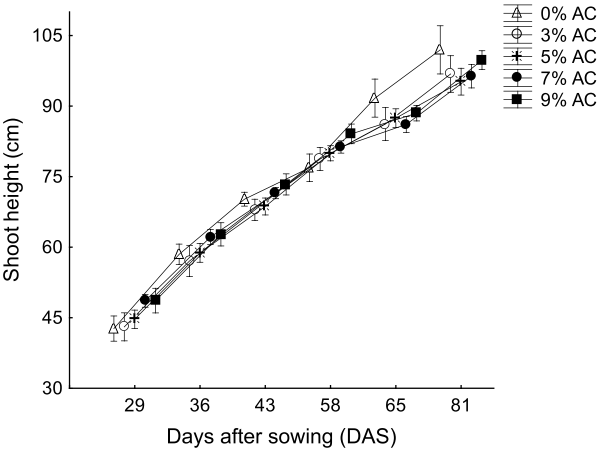

Fig. 1: *Effects of AC-amended manures on millet shoot growth. Data points show means (n = 6) ± one standard error at P <* 0.05 *measured 29, 36, 43, 58, 65, and 81 days after sowing. AC: activated charcoal fed to goats in % of total ration.*

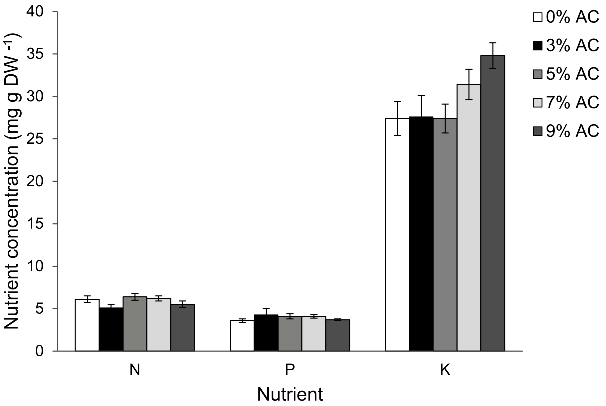

Fig. 2: *Effects of AC-amended manures on nitrogen (N), phosphorus (P), and potassium (K) concentration of millet shoot dry matter at harvest. Data show means (n = 6) and ± one standard error. AC: activated charcoal fed to goats in % of total ration.*

3.4 Plant growth and nutrient concentrations

No significant effects of manure AC enrichment on millet growth were found after twelve weeks (Fig. 1).

Nevertheless, towards the end of the experiment plants from the AC-enriched manure treatments showed a slightly smaller growth compared with plants amended with control manure. Plant aboveground biomass yield was on average 9.4 g DM per plant and remained unaffected by AC-manure. Nitrogen concentrations in plant material ranged between 5.1 (AC 3) and 6.4 mg g^{-1} DM (AC 5) and did not significantly differ between manure treatments (Fig. 2). Plant P concentration was with 4.3 ± 0.7 mg P g^{-1} DM highest for the AC 3 manure treatment and lowest in plants fertilised with AC 0 manure (3.6 ± 0.2 mg g^{-1} DM) and AC 9 enrichment (3.7 ± 0.1 mg g^{-1} DM), but these differences were not statistically significant. Plant K concentrations tended to increase with AC concentration: control (27 ± 2.0 mg g^{-1} DM), AC 3 (28 ± 2.5 mg g^{-1} DM), AC 5 (27 ± 1.7 mg g^{-1} DM), AC 7 (31 ± 1.8 mg g-1 DM), and AC 9 manure treatment (35 ±1.5 mg g^{-1} DM), however, they only significantly differed between the control and AC 9 ($P = 0.027$).

4 Discussion

4.1 Effects of AC feeding on manure nutrient contents and faecal scores

Feeding AC is widely used in veterinary medicine to treat animals suffering from diarrhoea and different types of intoxication (Buck & Bratich, 1986). The use of AC in the daily diet of ruminants that feed on plants containing secondary compounds like phenolics or terpenes, which can reduce feed intake and decrease nutrient utilisation, was examined in several studies (Banner *et al.*, 2000; Villalba *et al.*, 2002). Even at higher AC levels than those of our study, effects of AC supplementation on feed intake (Rogosic *et al.*, 2006, 2008) and nutrient utilisation (Murdiati *et al.*, 1991; Van *et al.*, 2006) were negligible or positive and there is no experimental evidence of negative effects on animal health such as constipation (Villalba *et al.*, 2002). In our study AC intake did not affect feed ingestion by goats. This is in accordance with other studies that did not find differences in feed intake due to AC feeding (Van *et al.*, 2006; Alkindi *et al.*, 2013). As expected, with increasing AC rate faeces colour changed to dark, odour was reduced, and the consistency turned to hard, without any sign that the goats' digestion or health were negatively affected.

Our data confirm that daily feeding of goats with significant amounts of AC is physiologically feasible. We assume that AC is inert in the animals' organism, meaning that it is not digested or absorbed by the animal. This assumption is reflected by the results showing a linear increase in faeces C concentration with increasing AC supplementation. The decline in faeces N and P concentrations with increasing AC supplementation reflect a dilution effect due to higher amounts of excreted AC.

4.2 Effects of AC-enriched manure on soil fertility parameters and microbial biomass indices

AC-enriched manure increased SOC by up to 68 %, while the soil TN pool remained unaffected. The AC effect on SOC was particularly pronounced, because the SOC in the soil treated with control manure was lower than in the initial soil. Our applications ranged between 0.4 t AC ha^{-1} (AC 3) and 1.4 t AC ha^{-1} (AC 9), assuming that the difference in manure C concentration between the control manure and the AC-enriched manures derived from the undigestible AC. Sradnick *et al.* (2013) conducted a field trial on the same soil. They applied 15 t dry goat manure ha^{-1} (control) and compared this with (i) goat manure and 2.5 % AC (AquaSorb® CP1) as feed additive, which corresponded to 1.65 t ha^{-1}, and (ii) goat manure mixed with AC (AquaSorb® CP1; 1.7 t ha^{-1}). After the first seven months season, they reported an increase in SOC from 7.6 (initial) to 9.1 (control), 10.6 (i), and 10.5 mg g^{-1} (ii); and an increase in TN from 0.4 (initial) to 0.6 (control), 0.7 (i), and 0.6 mg g^{-1} (ii). The positive relationship between AC-enriched manure and soil TN concentrations found by these authors may be caused by the larger input of both manure and AC, as compared with our application rates. AC-manure effects on the soil CN ratio were surprisingly small, most likely because the application doses were too low. It is often discussed that the widening of CN ratios in biochar amended soils can lead to immobilisation of N (Lehmann *et al.*, 2003; Ding *et al.*, 2010; Nelson *et al.*, 2011; Kloss *et al.*, 2014). The results of this study show that TN did not differ significantly between treatments, hence we assume that differences in the immobilisation of N played a negligible role in overall nutrient availability. The WHC of AC-manure amended soils increased by up to 25 % (AC 9) compared with the manure amended or initial soil. The sensitivity of our soil towards manure-induced changes in WHC supports data of Rawls *et al.* (2003), who found the highest response of water retention to changes in soil organic matter on sandy soils with low SOC contents. AC-manure application did not increase soil pH, but even decreased it by up to 0.4 units. This is in contrast to other findings that show clear pH increases following BC additions (Kloss *et al.*, 2014). However, most studies on biochar effects on soil quality were conducted on highly weathered acid soils (Glaser *et al.*, 2002; Lehmann *et al.*, 2003; Steiner *et al.*, 2007), where the well-known proton buffering capacity of BC was effective. This is consistent with findings of Kloss *et al.* (2014), where the application of biochar increased the pH of an acid Planosol from 5.3 to 6.9 after seven months, whereas biochar addition at the same rate to an alkalic Chernozem only led to a minor pH increase from 7.4 to 7.6. Similarly, Liu *et al.* (2012) found on a German Cambisol of pH 6 a significant increase in pH and CEC as response to the addition of compost, but not of BC. Our results are in accordance with data by Ingold *et al.* (2015), who recorded a slight pH decrease of 0.1 units after AC-enriched manure addition to the same soil under field conditions. Similarly, the CEC in their study declined from 10.2 cmol kg^{-1} to 9.4 cmol kg^{-1} after manure addition, and to 9.5 cmol kg^{-1} after the addition of AC-enriched manure (Ingold, unpublished data). These results are in contrast to numerous reports showing considerable CEC increases after BC amendment, an effect attributed to surface oxidation of BC particles as well as a higher charge density in BC-rich soils (Liang *et al.*, 2006). Recently, Slavich *et al.* (2013) showed on an Australian acid Ferralsol that the application of BC increased soil pH, but did not affect the pH-dependent CEC.

As a result of its recalcitrance, biochar-C is largely unavailable to soil microbes, but changes in soil physico-chemical properties and biologically available labile C compounds deriving from BC may accelerate microbial biomass and its activity (Warnock *et al.*, 2007; Steinbeiss *et al.*, 2009; Anderson *et al.*, 2011). The increase in microbial biomass may lead to a temporal immobilisation of mineral N, as shown for instance by Bargmann *et al.* (2014). Sradnick *et al.* (2013) reported for the same soil similar microbial biomass C and microbial biomass N. Their findings for microbial biomass C support our results. We detected a significant increase in microbial biomass N that arose from manure application; microbial biomass N decreased with increasing AC enrichment, possibly due to decreased availability of N with a widening treatment CN ratio.

4.3 Effects of AC-enriched manure on plant growth, yield, and nutrient concentrations

Under the controlled conditions of this study growth of millet was fast and no tillering occurred likely due to limited light intensity. For the last two measurements of plant height, we observed growth retardation for all plants grown on soils amended with AC-manure as compared with the control group. Often discussed as a reason for plant yield reductions after charcoal applications is N immobilisation that leads to N deficiency in plants (Lehmann *et al.*, 2003; Deenik *et al.*, 2011; Kloss *et al.*, 2014) which may have been the case in the last period of our study. Previous work has shown an increase in plant nutrient availability and growth after biochar incorporation across a range of soils (Glaser *et al.*, 2002; Lehmann *et al.*, 2003; Steiner *et al.*, 2007; Liu *et al.*, 2012). However, differences in the substrate and pyrolysis conditions greatly affect BC characteristics and its effects on key soil parameters such as CEC and nutrient content (Glaser *et al.*, 2002; Gaskin *et al.*, 2008, 2010; Alburquerque *et al.*, 2014) which may thus be study specific. Charcoal-induced reductions or zero effects on plant growth were also reported (Gaskin *et al.*, 2010; Jones *et al.*, 2012; Güerena *et al.*, 2013; Kloss *et al.*, 2014). Also, micronutrient deficiencies after pH-induced decreases in micronutrient availability were found (Bolan *et al.*, 2003).

5 Conclusions

Based on our experiment we conclude that short-term feeding of goats with diets containing up to 9 % AC in the ration is possible without negative effects on animal health, while the excretion of C into manure could be increased. Applied as a low-cost feed additive at this rate, charcoal may have positive effects on animal health (endoparasites and related internal intoxication leading to diarrhoea). Most soil fertility parameters and microbial biomass indices remained unaffected by AC-manure application, except for SOC, pH, and microbial biomass N. WHC tended to increase with AC enrichment of manure. Yield of millet remained unaffected by AC enrichment, whereas K uptake was improved with increasing AC application. Main responsible factors may have been soil type, dosage of manure and AC, properties of AC, and duration of the trial.

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