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Full Length Research Paper

Soil macrofauna indices and their association with physical soil properties under agroforestry systems

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Abstract

Agroforestry technologies such as *Sesbania sesban* or pigeonpea improved fallows have been promoted to restore degraded biophysical soil properties in Sub-Saharan Africa. The objectives of the study were to evaluate the effect of improved fallows on soil macrofauna species indices, abundance of earthworms and related physical soil properties. A randomized complete block design, replicated three times, was used with five treatments (*S.sesban*, pigeonpea, *S.sesban* + *Panicum maximum,* pigeonpea + *P.maximum* and *P.maximum*). Soil macrofauna was sampled using 25 × 25 × 25 cm steel monoliths. Aggregate stability was calculated using mean weight diameter. Soil aggregate stability and infiltration rate were significantly different (P<0.05). The highest aggregate stability and infiltration rate were observed in *S. sesban* as compared to *P. maximum. P. maximum* + *S.sesban* had the highest soil macrofauna species richness than *P. maximum*. Earthworm abundance was highest on *S.sesban* than other treatments. The highest positive significant correlation was recorded on soil macrofauna species evenness and diversity while the least was observed on aggregate stability and macrofauna species richness. *S.sesban* or pigeonpea improved fallows is recommended for restoring soil macrofauna and physical soil properties in South Africa.

Keywords: aggregate stability, agroforestry, improved fallows, pigeonpea, *Sesbania sesban*, soil macrofauna.

INTRODUCTION

Soil is a source of various ecosystem services that benefits the human population and permits ecosystems to function properly (Wall et al., 2012; Baveye et al., 2016). The soil is well known for being the biggest pool of biodiversity as it houses a range of micro and macrofauna. According to Marichal et al. (2014) and Lavelle et al. (2016), soil macrofauna is vital in ecosystem regulation by controlling soil structure. In addition, they modify soil aggregation, which will improve infiltration and alters soil water retention characteristics (Lavelleet al., 2014; Bottinelli et al., 2015). Macrofauna may be utilized as a biological indicator of the effects of land-use practices on soil physical properties (Rousseau et al., 2013). Various studies have been carried out to identify bioindicators related to certain land-use practices through ascertaining relationships between bioindicators and ecosystems functions and services of the soil (Rousseau et al., 2013; Lavelle et al., 2014; Marichal et al., 2014). Despite these studies, the rampant deforestation and conversion of forests into agricultural lands has led to a reduction in soil macrofauna, which has negatively impacted aggregate stability, bulk density and infiltration rate of the soil

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(Velăsquez at al., 2012: Lavelle et al., 2016).
Agroforestry systems (AFS) mimic natural forests in forest cover and litter abundance (Oliveira, 2018). To our knowledge, no studies in South Africa have focused on the effects of AFS (mainly improved fallows using legume tree species such as *S.sesban* and pigeonpea) on soil macrofauna organisms and related physical soil properties. Land use practices related to AFS, which include integrating legume trees into agricultural lands have shown to increase soil macrofauna abundance and diversity (Pauli et al., 2011; Kamau et al., 2017). This study focused much on earthworm macrofauna abundance since they are considered as ecosystem engineers and are known for maintaining soil structure. Earthworms are fundamental actors in soil biodiversity, and they will probably be an essential key in the growth of sustainable farming systems in the future (Bertrand et al., 2015). The impact of macrofauna on soil physical properties and soil structure formation has been studied (Sankar and Patnaik, 2018; Melman et al., 2019). Earthworms are known as ‘ecosystem engineers’ due to their major function in reworking the soil. They can alter soil structure by biological as well as physicochemical variations due to burrowing and casting processes, which have a significant influence on infiltration (Sankar and Patnaik, 2018). The objectives of the study were to: (1) Evaluate the impacts of improved fallows on soil macrofauna species indices and related physical soil properties. (2) Evaluate the abundance of earthworms in improved fallows and *P.maximum* grass in KwaZulu-Natal, South Africa. The hypothesis for the study was that improved fallows would promote soil macrofauna species richness, abundance and diversity, evenness, and improve aggregate stability, bulk density and infiltration rate.

MATERIALS AND METHODS

The study was carried out at Empangeni, KwaZulu-Natal, South Africa, between November 2016 to November 2018 at Owen Sithole College of Agriculture (28.6391° Sand 31.9400° E). The mean annual rainfall for this area is approximately 867 mm and falls mostly in the summer from November to April. The mean maximum temperature is 30°C, while the mean minimum temperature is 12°C with an altitude of 450 m. Fig 1 present the total rainfall received during the trial period. Soil samples were collected from 20 cm depth and analyzed for pH, N, P, K and organic carbon using method explained by International Institute of Tropical Agriculture IITA, (1979). The results are shown in Table 1. The soils are classified as ferralsols by the Food and Agriculture Organization of the United Nations (FAO) classification system (Faye, 2010). The soil physical and macrofauna data was collected from 5 treatments (Table 2). The treatments were assigned to plots measuring 8m x 6 m, replicated three times in a randomized complete block design (RCBD) in November 2016.

Soil physical properties measurement

Next to each macrofauna sampling pit, a metal ring (7 cm diameter) was driven vertically into the soil surface to a depth of 5 cm using a hammer to determine soil bulk density. Soil collected within this ring was also used for determining field moisture by taking a sub-sample of soil from each ring in the lab and drying at 105 °C for 24hrs. The sample left was then sieved through 8 mm by gently breaking soil clods along the natural planes of fracture, and then air-dried. A sub-sample of 40 g of air-dried soil was wet-sieved following the procedure explained by Elliott (1986). The soil was spread on a 2 mm sieve and submerged in deionized water for 5 min for slaking. The soil was then cautiously, submerged repeatedly in water for a total of 50 oscillations during a 2 min time frame. The aggregate fraction remaining at the top of the sieve was rinsed into a pre-weighed aluminum pan, then oven-dried at 60 °C and weighed. This process was repeated on the soil passing through each sieve with a 250 μm and a 53 μmmesh sieve. As a result, four aggregate size fractions were obtained: large macroaggregates (> 2 mm), small macroaggregates (250-2000 μm), microaggregates (53-250 μm) and silt + clay (< 53 μm). Aggregate stability was then calculated according to van Bavel (1949), using mean weight diameter (MWD). Soil infiltration count was determined from double rings in the net plot. Infiltration rate was ascertained to have been reached when five similar successive readings were obtained (Rene et al., 2012)

Soil macrofauna measurement

The soil macrofauna was collected using a modified Tropical Soil Biology and Fertility (TSBF) method (Anderson and Ingram, 1993). A soil monolith measuring 25 cm × 25 cm was excavated to a depth of 25 cm and all material (soil and surface residues) was hand-sorted to collect visible macro-invertebrates (> 2 mm). These were stored in 70% ethanol and returned to the lab for identification. Specimens were classified to the level of order (or phylum for earthworms, family for Coleoptera). The different soil taxa encountered and abundance of each were used to calculate species richness (S = total number of taxonomic groups) as well as the Shannon index of diversity (H; Shannon, 1948).

$$H' = -\sum_{i=1}^{S} p_i \ln p_i$$

Where *pi* is the proportion of the species belonging to the *i*th order in each sample.

Table 1. Soil characteristics at Owen Sithole Agricultural College, Empangeni.

Soil characteristic	Value
Nitrogen (%)	0.23
Organic carbon (%)	3.31
Phosphorus (mg kg^{-1})	6.63
Potassium (mg kg^{-1})	139.00
Calcium (mg kg^{-1})	1393.75
Magnesium (mg kg^{-1})	745.75
Copper (mg kg^{-1})	2.98
Total cations (cmolkg^{-1})	13.48
pH (KCl)	5.03
Clay (%)	35.00

Table 2. Description of the treatments studied at Owen Sithole College of Agriculture, located in KwaZulu-Natal Province, established from November 2016 to November 2018.

Treatments	Description and establishment
Panicum maximum + *Sesbania sesb*an	The *P. Maximum* seeds were planted at a rate of 7.5 $kgha^{-1}$ intercropped with transplanted three months old *S. sesban* seedlings at 1 m x 1 m spacing with a total plant population of 10 000 plants ha^{-1}
Panicum maximum + Pigeonpea	The *P. maximum* seeds were planted at a rate of 7.5 $kgha^{-1}$ intercropped with Pigeonpea which was sown as seed at a spacing of 1 m x 1 m which translates to 10 000 plants ha^{-1}
Panicum maximum	*P. maximum* seeds were planted at a rate of 7.5 $kgha^{-1}$ with an inter-row spacing of 0.25 m planted in rows (control)
Sesbania sesban	Three months old *S. sesban* seedlings were transplanted at 1 m x 1 m spacing making a total plant population of 10 000 plants ha^{-1}
Pigeonpea	Pigeonpea was sown as seed at a spacing of 1 m x 1 m which translates to 10 000 plants ha^{-1}

DATA ANALYSIS

The data obtained on soil fauna richness, diversity, evenness and abundance, and soil physical properties were subjected to analysis of variance (ANOVA) with GenStat Release 18.2, VSN International Limited, Hempstead, UK to determine significant treatment effects. Where significant differences were noted on soil macrofauna and physical soil properties the multiple comparisons using Fisher protected least significant difference (Lsd) was used. Pearson correlation coefficients (r) for the seven soil physical and macrofauna were computed using R software version 4.0.1 (R Development Core Team, 2020).

RESULTS

Effects of agroforestry systems on aggregate stability, bulk density and infiltration rate

Aggregate stability data showed similar trends to the infiltration rate, with the highest aggregate stability (9.87 m mm^{-1}) and infiltration rate (32 mm hr^{-1}) observed in *S. sesban* as compared to *P. maximum* which had the lowest values (8.01 m mm^{-1} and 23.10 mm hr^{-1} respectively). Meanwhile, bulk density was also affected significantly ($P<0.05$) by the agroforestry system, such that the highest bulk density was experienced in *P. maximum*, while the lowest was experienced on *S.sesban* (Table 3).

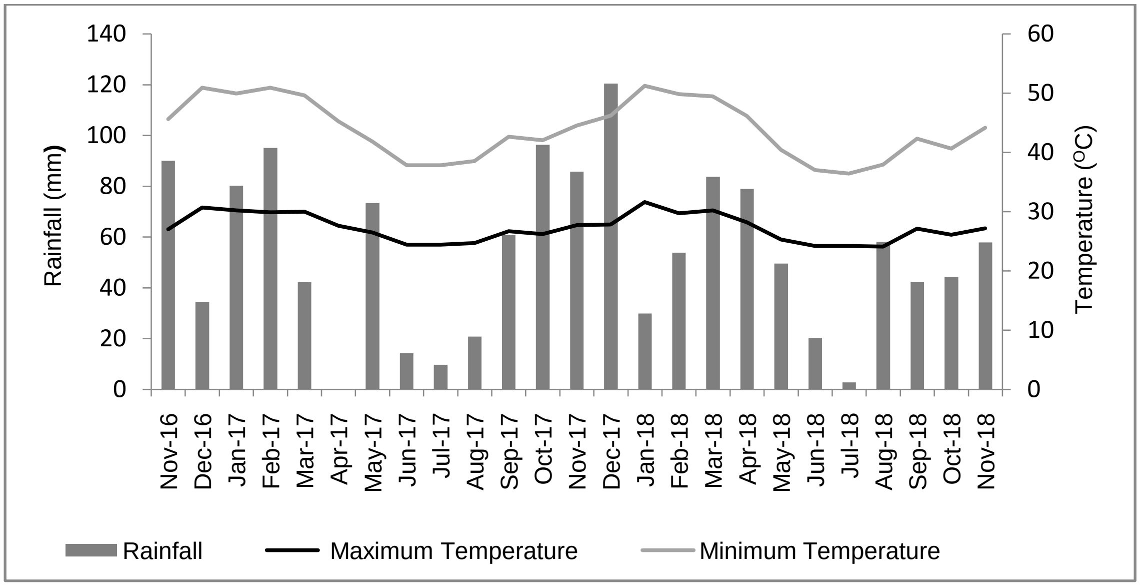

Fig 1. Climatic data recorded at Owen Sithole Agricultural College from November 2016 to November 2018.

Table 3. Effects of different agroforestry systems on aggregate stability, bulk density and infiltration rate at Owen Sithole Agricultural College, KwaZulu-Natal: Means in each column with different superscripts are significantly different (P<0.05), according to Fisher`s protected Lsd.

Treatment	Aggregate stability (mmm^{-1})	Bulk density (gcm^{-3})	Infiltration rate ($mmhr^{-1}$)
S. sesban	9.87 a	1.06 a	32.00 a
Pigeonpea	9.65 a	1.10 a	29.00 b
P. maximum +*S. sesban*	9.39 a	1.12 a	29.47 b
P. maximum + pigeonpea	9.82 a	1.13 a	28.00 b
P.maximum	8.01 b	1.31 b	23.10 c
$LSD_{(0.05)}$	1.034	0.037	1.902
P-value	0.003	<.001	<.001
CV	4.3	6.2	4.2

Effects of *S.sesban* or pigeonpea improved fallows on soil macrofauna

The total number of recorded individuals was 2504, from which *S.sesbania* (725) had the highest total abundance, while *P.maximum* (200) recorded the least (Figure 2). Twenty-one taxonomic groups were identified, with Oligochaeta and Technomyrmex being the most abundant (1006 and 474 individuals, respectively) (Figure 3). Soil macrofauna species richness was significantly different (P<0.05) across treatments. *P. maximum* + S.sesban (18.89) had the highest soil macrofauna species richness than all other treatments while *P. maximum* (7.89) recorded the least. Meanwhile, no significant differences (P<0.05) were observed in soil macrofauna species diversity and evenness with treatments containing legume trees (p =0.375 and 0.380, respectively (Table 4). Significant difference (P<0.05) was observed on earthworm abundance as shown by the following order *S.sesban* ≥ *P.maximum* + *S.sesban* >*P.maximum*+ pigeonpea ≥ pigeopea>*P.maximum* (Figure 4).

The correlation of physical soil properties and soil macrofauna

The results showed that bulk density was negatively correlated with aggregate stability and infiltration rate.

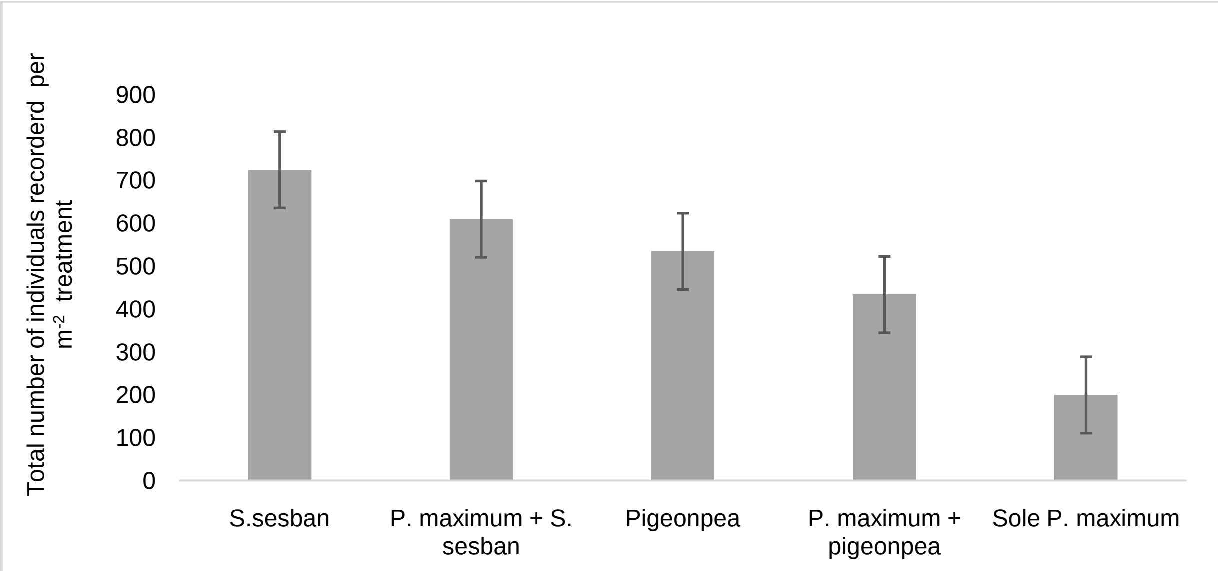

Fig. 2. Soil macrofauna species abundance at Owen Sithole Agricultural College (total count per m^2).

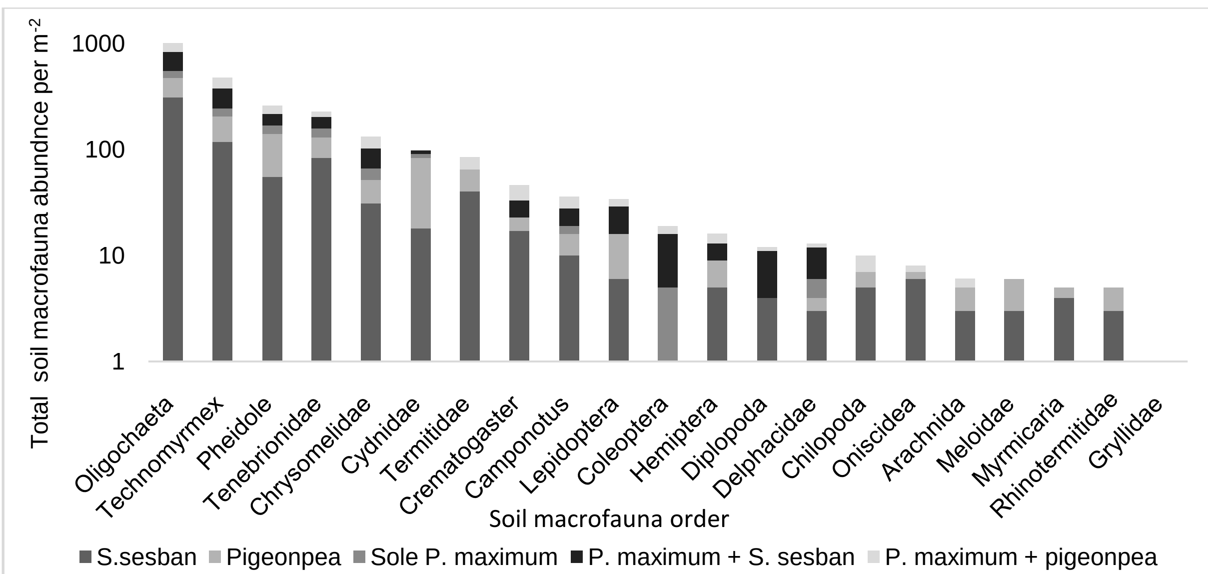

Fig. 3. Soil macrofauna abundance recorded across each treatment.

Species richness had a significant ($P<0.01$) negative correlation with species diversity and species evenness ofr^2 = 0.71 and 0.70, respectively. The soil macrofauna species index had the highest significant ($P<0.001$) positive correlation between species diversity and species evenness (r^2 = 0.99; Table 5).

DISCUSSION

The results of the study showed that agroforestry systems (improved fallows) could affect physical soil properties significantly. Aggregate stability, bulk density and infiltration rate are among the generally used soil physical properties indicators. The improvement in aggregate stability, bulk density and infiltration rate could be attributed to the formation and addition of humus from the decomposition of high-quality litter provided by *Sesbania sesban* and pigeonpea trees from all the treatments which had trees as compared to *P.maximum* grass. Land use practices that conserve soil, such as agroforestry systems (improved fallows) frequently supplies with

Table 4. Soil macrofauna indices recorded at Owen Sithole Agricultural College; Means in each column with different superscripts are significantly different (P<0.05), according to Fisher`s protected Lsd.

Treatment	Species richness	Species diversity	Species evenness
P. maximum	7.89a	1.513a	0.4067a
Pigeonpea	12.33bc	1.643a	0.4433a
Pigeonpea + *P. maximum*	13.55c	1.467a	0.3967a
S.sesban	13.78 c	1.330a	0.3600a
S.sesban + *P. maximum*	18.89d	1.203a	0.3267a
$Lsd_{(0.05)}$	4.007	0.5470	0.1498
p-value	<.001	0.375	0.380
CV	20.5	22.3	22.6

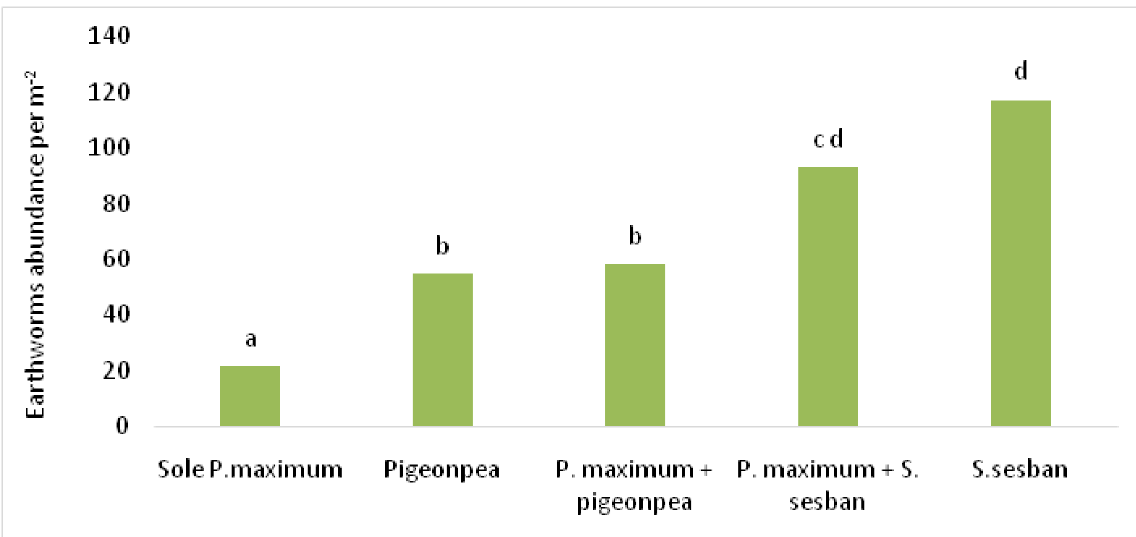

Fig. 4. Earthworm abundance at Owen Sithole.

organic matter, which was very important in preserving a good soil structure (Portella et al., 2012; Suárez et al., 2018). The difference observed in treatments with tree legume against *P.maximum* in terms of aggregate stability and bulk density maybe attributable to continuous additions of quality organic matter through litter fall from *S.sesban* and pigeonpea. According to Ayres et al. (2009), different tree species and surrounding conditions around the tree systems affect soil parameters differently. Tree cover from *S.sesban* and pigeonpea lessened soil degradation by diminishing the rain drop effect and spontaneous shift in relative humidity. High quality organic matter from *S.sesban*, pigeonpea added into the soil through leaf litter is the main food source for microbes, which helps in enhancing aggregate stability as well as pore size distribution and due to less dense decomposing organic matter constituents as compared to mineral constituents which will lead to a reduction in soil bulk density (Portella et al., 2012). This might be the reason why treatments that had tree legumes (*S.sesban*, pigeonpea) had significantly lower bulk density than *P.maximum*. In addition, continuous accumulation of plant litter from *S.sesban* and pigeonpea trees promoted a higher infiltration rate, explaining why greater infiltration rate was recorded for *S.sesban*, pigeonpea and both intercrops as compared to *P.maximum*. This indicates that aggregate stability, bulk density and infiltration rate are altered by types of land use practices and management employed (Negasa et al., 2017). A decrease in bulk density is an indicator of less compaction and higher soil porosity. These changes have been recorded by Amusan et al. (2006), who found that bulk density of

Table 5. Pearson correlation coefficients (r) for seven soil physical and macrofauna* = P<0.05, ** = P<0.01, *** P<0.001, BD= Bulk density, AG= Aggregate stability, IR= infiltration rate SR = Species richness, SD = Species diversity, TA = Total abundance and EVS = Evenness.

	BD	AG	IR	SR	SD	TA	EVS
BD	1	-0.26	-0.62*	-0.13	-0.27	-0.68**	-0.30
AG	-0.26	1	0.50	0.57**	-0.43	-0.10	-0.41
IR	-0.62*	0.50	1	0.35	-0.12	0.38	-0.11
SR	-0.13	0.57*	0.35	1	-0.71**	-0.29	-0.70**
SD	-0.29	-0.43	-0.12	-0.71**	1	0.73**	0.99***
TA	-0.68**	-0.10	0.38	-0.29	0.74**	1	0.75***
EVS	-0.30	-0.41	-0.12	-0.70**	0.99***	0.75**	1

cacao agroforestry plantation (1.32 g cm^{-3}) was significantly lower than natural forest (1.49 g cm^{-3}). Ramesh et al. (2013), observed a 7% reduction in bulk density as compared to the control plot (without tree plantation) under the hilly ecosystems of Northeast India.

S.sesban + *P.maximum* had the greatest soil macrofauna species richness than all other treatments, while *P.maximum* had the least. Treatments containing tree legumes (*S.sesban* and pigeonpea) resulted in dense canopy cover that promoted a high species richness of soil macrofauna. The lack of significant differences between all the treatments in terms of species diversity and evenness is hard to explain at the present moment and thus needs further investigation. Improved fallows appeared to support overall soil macrofauna abundance and species richness; however, the results show that *S.sesban* + *P.maximum* and *S.sesban* had the highest soil macrofauna abundance and species richness. Soil moisture, as well as temperature changes, may impact soil macrofauna dynamics (Doblas-Miranda et al., 2009), hence the variation of species richness among the treatments notable *S.sesban* + *P.maximum* versus *P.maximum* could be possibly caused by the difference in terms of moisture and temperature.

Oligochaeta (earthworms) is the main constituent of soil macrofauna communities in most ecosystems (Bhadauria and Saxena, 2010). Earthworm abundance under *S.sesban and S.sesban* + *P.maximum* were almost four times greater than the control (*P.maximum* grass). Higher earthworm abundance observed under *S.sesban* and *S.sesban* + *P.maximum* corroborates with previous studies, which suggest that higher quality organic matter inputs are usually associated with higher earthworm populations (Briones and Schmidt, 2017; Prayogo et al., 2019). In another similar study conducted by Cardinael et al. (2019), higher earthworm abundance was recorded on AFS as compared to natural grass (control). Treatments containing *S.sesban* recorded higher earthworm abundance probably is because of higher quality leaf litter than pigeonpea. Organic materials from plants, which include leaves, twigs and dead roots, are the primary food energy source of earthworms and other macrofauna (Rosa et al., 2015; Korboulewsky et al., 2016; Yatso and Lilleskov, 2016). Hence, the addition of higher quality of organic matter from *S.sesban* would be anticipated to support larger and more active soil macrofauna communities, such as earthworms, as evidenced by the results from the study (Abail and Whalen, 2018). *S.sesban* and pigeonpea leaf litter on the soil surface helps in soil temperature and moisture regulation that created a favorable environment for soil macrofauna such as earthworms. Earthworms enhance soil porosity through opening tunnels within the soil profile (Medina-Sauza et al., 2019). This may explain the lower bulk density and higher infiltration rates in *S.sesban,* which had a higher abundance of earthworms than *P.maximum* (control). Earthworms ingest a large quantity of soil and dead plant residues, hence helping in the mixing of organic matter and mineral soils, which will improve aggregate stability (Bertrand et al., 2015). The build-up of organic matter will result in higher water retention capacity of the soil and subsequently, have an effect on earthworms.

CONCLUSION

This study showed that improved fallows of *S.sesban* and pigeonpea, as well as their intercrop with *P.maximum* enhanced aggregate stability, infiltration rate, soil macrofauna species richness and earthworm abundance than *P. maximum* grass. Soil bulk density was lowered by improved fallows; however, no significant differences were observed on soil macrofauna species diversity and evenness. The highest positive significant correlation was experienced on soil macrofauna species evenness and diversity whilst the least was observed on aggregate stability and soil macrofauna species richness. The use of AFS such as *S.sesban* as improved fallows is recommended for restoring soil macrofauna and physical soil properties in South Africa.

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