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Research Article

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Integrated gully rehabilitation measures enhance soil chemical properties and macrofauna recovery in a Lixisol

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ABSTRACT

Gully erosion may cause serious degradation of soils and disruption of key ecological functions in drylands. This study evaluated manual grading of gullies into bench terraces and their restoration using vegetation treatments to investigate their impact on soil and macrofauna recovery. Plots of 9.75 m in length and 3 m in width were created from three benches of 39 m in length and 3 m in width. The selection of the treatments was based on attributes, drought tolerance, utilization, and maturity period. Pigeon pea (*Cajanus cajan*) intercropped with Dolichos (*Lablab purpureus*) and *S. sesban* intercropped with Super Napier grass (*Cenchrus purpureus* × *Cenchrus glaucum*), Brachiaria grass (*Brachiaria brizantha)* and Mombasa grass (*Panicum maximum* Jacq.) were among the treatments. We sampled soil and macrofauna before and after rehabilitation during the dry and wet seasons. The soil's physicochemical properties included pH, electrical conductivity, carbon fractions, total nitrogen, available phosphorus, exchangeable bases, cation exchange capacity, and bulk density. We hand-sorted the soil macrofauna for identification from monoliths measuring 25 × 25 × 30 cm. The spiders, centipedes, crickets, stick insects, assassin bugs, pot worms, and tiger beetles were recorded as a result of treatment rehabilitation. *S. sesban* + *B. brizantha* treatment had a significant treatment effect on scarab beetle abundance during the wet season. A positive relationship between macrofauna and carbon fractions was noticed, while the soil's

physicochemical properties had no significant treatment effect. Gully rehabilitation with suitable vegetation treatment improves soil and ecosystems.

Keywords: Gully rehabilitation, soil carbon fractions, macrofauna recovery, biomass production, ecosystem restoration, soil health, West Pokot.

1. Introduction

It is increasingly evident that climate change is occurring worldwide, with changes in precipitation patterns and rising temperatures that have resulted in frequent droughts on the one hand and torrential rains and floods on the other. These phenomena are among the key factors that have contributed to reduced agricultural production and land degradation. Drylands occupy about 40% of the world's landmass and support 50% of the global livestock production [1]. With a rising human population, reduced agricultural and grazing lands, and the need for more arable land, drylands are being converted to crops, which accelerates the degradation processes of these lands, resulting in species loss, salinization, and loss of carbon stocks, soil erosion, and ultimately reduced land productivity [2]. Land degradation, one of the significant environmental problems, is a threat to ecosystems, livelihoods, and food security. About 46% of Africa's land area and 65% of Africa's population, estimated at 485 million people, are threatened by land degradation, with an annual value of US$9.3 billion [3]. Moreover, 75-80% of Africa's farmland is degraded, with an average of 30-60 kg ha $^{-1}$ of nutrient loss per year [4]. This impacts food security and livelihoods since agriculture is the primary source of income and food for many communities.

In Kenya, land degradation affects about 80% of the country's total land area. About 30–40% of Kenya's semi-arid lands are reported to be degraded at a rapid rate, while 2% of the semi-arid lands have been completely degraded [5]. Chepareria ward is one of the many rapidly degrading communities in West Pokot County undergoing serious land degradation. As a matter of fact, some parts of the ward have deep gullies covering over 50% of the total area. This is primarily due to human activities, notably deforestation and excessive grazing, which have significantly impacted the local ecology. Soil erosion is estimated to have caused 123 t ha $^{-1}$ of soil loss [6]. Gully erosion is a significant

environmental hazard that leads to loss of fertile topsoils and degradation of land and ecosystem services [7]. Gully erosion is characterized by the concentration of water flow in a narrow channel, which deepens and widens the gully walls [8]. Integrated gully rehabilitation measures include mechanical measures (sand dams and terraces), vegetative measures, and bioengineering measures, which help gully bank stability, surface cover, and surface runoff control and promote vegetation growth.

Soil macrofauna is a generic term that comprises various groups of invertebrates with distinct ecological roles, such as bioturbators (e.g., ants and earthworms), herbivores, predators, fungivores, and detritivores [9]. Soil macrofauna improve the soil physicochemical and biological properties by promoting soil structure, fertility, and decomposition of organic matter [10]. The macrofauna community structure changes provide important information on the conservation status of other species and biodiversity as whole. Therefore, integrated gully rehabilitation measures will have a significant impact on the community structure of macrofauna. The combined use of mechanical and vegetative rehabilitation measures is expected to result in increased macrofauna abundance and diversity and significant changes in their distribution patterns.

Soil organic carbon (SOC) is a vital component of the soil organic matter (SOM) and an essential contributor to soil fertility, water retention, nutrient cycling, aggregation, and biota. SOC is an essential component of the carbon cycle and, therefore, a crucial contributor to the carbon balance of the ecosystem [11]. Changes in SOC content provide valuable information on the short- and long-term dynamics of the soil quality and its responses to individual influences and management interventions. However, changes in total SOC content tend to be slow, and thus SOC is considered a conservative soil property. This phenomenon is explained by different turnover rates of SOC fractions and the contribution of each fraction to the overall SOC content [12].

SOC is a controlled pool with carbon in different organic, inorganic, and mineral forms. SOC can be partitioned into SOC fractions based on their accessibility and stability, and each of these fractions plays a critical role in the carbon cycle. Labile carbon is the readily available and easily degradable fraction of SOC, and it is the largest contributor to the overall SOC content. It is well established that labile carbon is highly correlated with recent litter inputs and organic matter addition to the soil, and thus it serves as an

important energy source for soil biota and a vital contributor to the nutrient cycle. Due to its ready availability, labile carbon responds to changes in vegetation, litter input, and management practices much faster than the total SOC and therefore can be used as an indicator of early recovery of the soil's functional properties [13]. Non-labile carbon is the stable fraction of SOC that is relatively resistant to microbial decomposition. The turnover time of non-labile carbon is long, and thus this fraction plays a significant role in the long-term storage of carbon in the soil. The combined consideration of labile and non-labile fractions of SOC provides more meaningful information on the short- and long-term dynamics of carbon in the soil than the analysis of total SOC [14].

Land degradation and erosion processes decrease the input of organic matter into the soil and, consequently, reduce SOC content in the degraded soils [15]. At the same time, rehabilitation interventions that reduce soil loss and facilitate vegetation recovery have the potential to increase the input of organic matter into the soil and improve the SOC content [16]. Therefore, the analysis of the changes in SOC, labile carbon, and non-labile carbon can provide valuable insights into the processes of soil rehabilitation and recovery following land degradation.

The study's objective was to assess the changes in soil physicochemical properties and soil macrofauna abundance, richness, and evenness following integrated gully rehabilitation measures in a degraded semi-arid Lixisol. The study aimed to determine changes in the soil's pH, electrical conductivity, organic carbon, labile and non-labile carbon, total nitrogen, available phosphorus, exchangeable bases, cation exchange capacity, and bulk density, and also aimed to assess changes in macrofauna abundance, richness, evenness, and community composition after rehabilitation intervention implementation. This study hypothesized that (i) gully degradation sites had low soil fertility and reduced macrofauna abundance and diversity; (ii) integrated gully rehabilitation interventions had a positive effect on the physicochemical properties of the soil, increasing the levels of soil organic carbon and nutrients while also reducing the bulk density; and (iii) the rehabilitation interventions improved the abundance, richness, and diversity of macrofauna, but the effect varied across the different macrofauna taxa

2. Materials and methods

2.1 Description of the study site

The study was carried out in Chepareria Ward (Fig. 1), which covers an area of almost 495 km^2, with a population of about 57,787 people [17] and is mainly inhabited by the Pokot ethnic group, who practice nomadic pastoralism as their source of livelihood [18]. It is located in Kenya's northwest rangelands, between latitudes 1°15′ and 1°55′N and longitudes 35°7′ and 35°27′ E. Situated at the base of the Kamatira Hills, the ward encompasses the southern floodplains that extend beyond Mount Morpus. The region consists of a plain that gently slopes from 1200 to 1600 meters above sea level. Hills, ridges, and plateaus with peaks of 3000 meters surround the area. Chepareria Ward has a highly seasonal climate [19]. The average annual rainfall is 600 mm, but this varies with altitude. The region is rich in ferromagnesian minerals and is mostly composed of metamorphic bedrock [20]. Rocky soils that are rather shallow and well-drained have evolved from this bedrock. The average annual temperature in West Pokot County ranges from 15 °C to 30 °C at higher elevations and 24 °C to 38 °C in the lowlands.

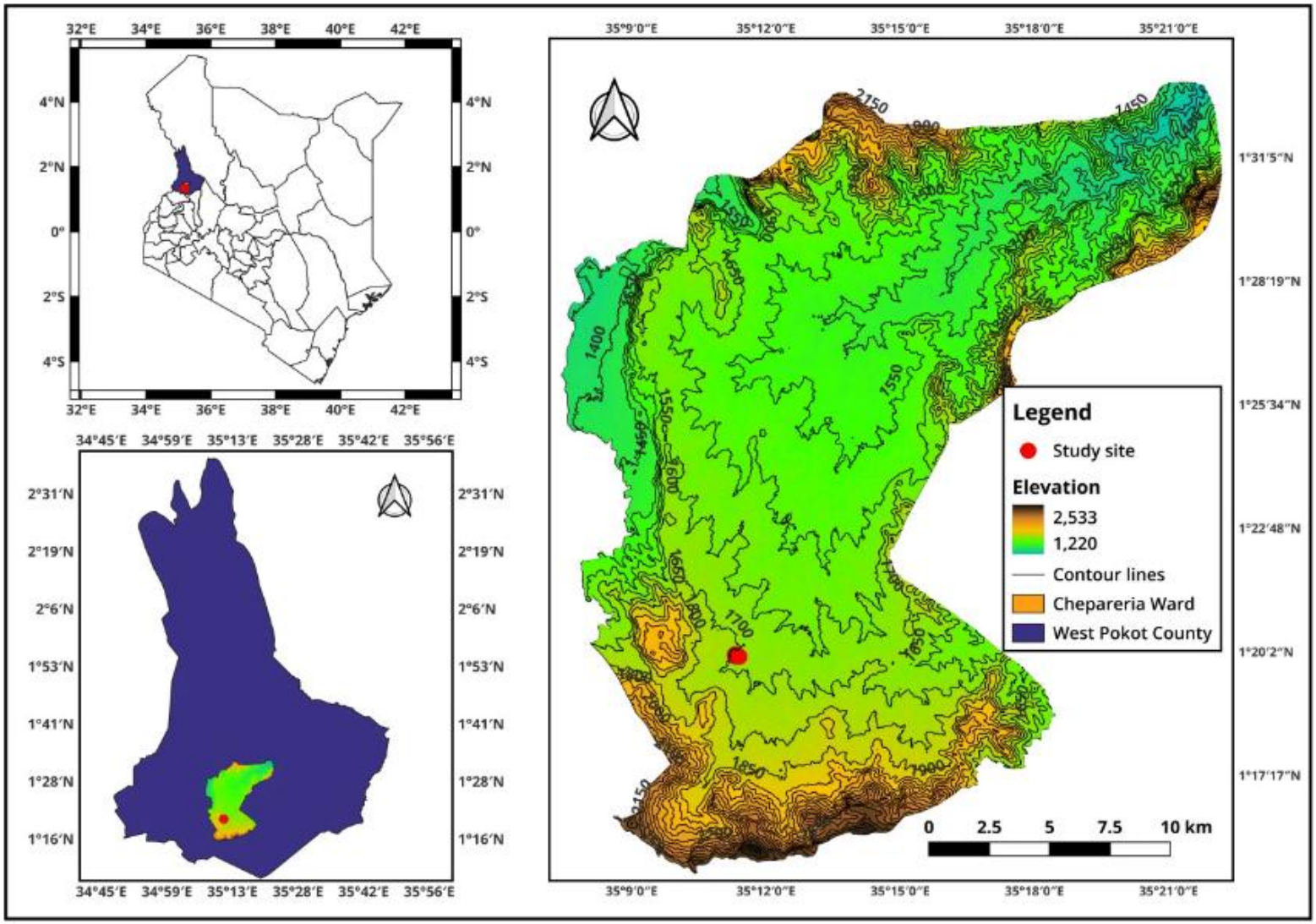


Fig. 1 Location of the study site

2.2 Experimental Design and Layout

2.2.1 Site selection

A survey was conducted, and a gully-prone site was identified that cuts across an area of about 1.5 ha, located in Korelach village, where integrated rehabilitation measures were implemented. The gully site was identified based on severity. The experimental design employed was a Before-After-Control-Impact design: (i) Before - involved collection of baseline data on soil for physico-chemical properties analysis and soil macrofauna abundance and diversity before implementation of integrated gully rehabilitation measures, (ii) After - involved implementation of integrated rehabilitation measures in selected gully-prone site, (iii) Control - involved the identification of nearby gully sites with similar characteristics where no rehabilitation measures were implemented, and (iv) Impact - soil and macrofauna were monitored in both treated and control sites after implementation of rehabilitation measures.

Bench terraces were constructed on the gully faces to encourage gully healing and recovery. Bench terraces are effective soil conservation measures that consist of a series of level strips running across the slope at vertical intervals, supported by risers and banks. The bench terrace dimensions were 3 m wide and 39 m long; the slope of the riser was 1.93 m for easier maintenance, as proposed by [21]. The treatments were laid out on the bench terraces in a randomized complete block design (RCBD), with each bench terrace as a block and replicated three times. A maximum of 3 terraces were constructed on the gully. The plot size for each treatment was 3 m wide by 9.75 m long, separated by 1 m paths.

The treatments used for experimental design included agroforestry trees, fodder grasses and food crops. These were: Sesbania (*Sesbania sesban*), pigeon peas (*Cajanus cajan*), super napier grass (*Cenchrus purpureus* × *Cenchrus glaucum)*, Brachiaria grass (*Brachiaria brizantha*), Mombasa grass (*Panicum maximum* Jacq.) and Dolichos, also known as hyacinth bean (*Lablab purpureus*). To accelerate gully healing and protect the bench terraces, fodder grasses were intercropped with Sesbania, while the two legumes were also intercropped. The criteria used for treatment selection were: (i) attributes – the treatments were selected based on their deep rooting system, which was important in stabilizing the bench terraces and therefore accelerated gully healing, (ii) maturity

duration – the selected trees and grasses took a shorter period to mature and be harvested, (iii) utilization type – the selected treatments were important food and fodder crops, and (iv) drought tolerance – the selected trees and grasses were drought tolerant and therefore suited to the study site. The spacing for Sesbania was 1 m between rows and 50 cm within rows, while pigeon pea was 150 cm between the rows and 50 cm within the rows. Mombasa grass was planted at a spacing of 50 cm between the rows and 50 cm within the rows. In comparison, Brachiaria grass was planted at a spacing of 60 cm between rows and 60 cm within rows, and Super Napier at a spacing of 75 cm between rows and 50 cm within rows. Finally, Dolichos was planted at a spacing of 60 cm between rows and 45 cm within rows.

2.3 Soil sampling and analysis

Soil samples collected before and after rehabilitation of the gullies were taken to the laboratory for analysis of physicochemical properties. Before rehabilitation, a total of thirty-two soil samples were collected following systematic excavation of four soil monoliths along each transect, with a total of eight sampling points towards the end of the long rains in July 2024. Twenty-four soil samples were collected towards the end of the short rains in November 2025 for the dry season, including two soil monoliths per treatment (replicated three times). The same procedure was done towards the end of the long rains in May 2026 for the rainy season. The soil properties analyzed included: soil bulk density and soil texture, soil pH, Electrical conductivity, total nitrogen, soil organic carbon, available phosphorus, cation exchange capacity, and exchangeable bases (calcium, magnesium, potassium, and sodium). Soil pH analyzed by a pH meter with a 1:2.5 (Soil: H_2O) [22]. Electrical conductivity (EC) by the water suspension method [23]. Soil organic carbon by the Walkley-Black method [24]. Total nitrogen by the Kjeldahl method [25]. Available phosphorus was determined using the sodium bicarbonate ($NaHCO_3$) extraction procedure [26]. Exchangeable calcium, magnesium, potassium and sodium were analyzed using the ammonium acetate displacement method at pH 7 [22]. Soil texture analyzed by the hydrometer method [27]

2.4 Soil macrofauna sampling and identification

For initial soil and macrofauna sampling, four soil monoliths measuring (25 by 25 by 30 cm) were excavated along the transect with a total of 8 sampling points during the rainy season in July 2024, following the Standard Tropical Soil Biology and Fertility sampling protocol [28]. The soil monoliths were placed in plastic trays after excavation and large clods were broken down and macrofauna were handpicked. The macrofauna picked were placed in 75% ethanol, except for the earthworms which were placed in 4% formaldehyde. The soil macrofauna identified were separated into major taxonomic groups. After the experiment setup with treatments, soil and macrofauna sampling was carried out towards the end of the long rains in November 2025. Two monoliths were randomly excavated from each treatment, placed on plastic trays with large clods, and macrofauna were collected. Soil macrofauna collection was done similarly to that of the initial sampling.

2.5 Statistical analysis and data management

Soil macrofauna abundance was expressed as the number of individuals per square metre (individuals m^{-2}) by converting the number of individuals collected from each soil monolith to a unit-area basis. Macrofauna community characteristics were assessed using abundance, Shannon diversity index, species richness and evenness. Soil physicochemical and macrofauna data were organized according to treatment, replicate and sampling season and analyzed using R statistical software, version 4.5.2 [29]

Baseline soil physicochemical properties and macrofauna characteristics measured before rehabilitation were summarized using means and standard errors (SE) to describe the initial conditions of the study site. Differences in soil physicochemical properties among the four vegetation rehabilitation treatments were evaluated separately for the dry and wet seasons using one-way analysis of variance (ANOVA). The response variables included pH, electrical conductivity, organic carbon, labile carbon, nonlabile carbon, total nitrogen, available phosphorus, exchangeable K, Ca, Mg and Na, cation exchange capacity, and bulk density. Where significant treatment differences were detected, Tukey's honestly significant difference (HSD) test was used for pairwise comparisons at $\alpha = 0.05$.

Differences among rehabilitation treatments in macrofauna abundance, Shannon diversity, species richness and evenness were evaluated separately for the dry and wet seasons using one-way ANOVA. Individual macrofauna taxa were also compared among treatments. Because the macrofauna abundance data contained a high proportion of zero values, count-based analysis using negative binomial regression was applied where appropriate to account for overdispersion in the count data. Where significant treatment differences were detected, Tukey-adjusted post-hoc comparisons were performed at $\alpha = 0.05$. Results were presented as means ± SE, and statistical significance was considered at $P < 0.05$.

Multivariate relationships between soil physicochemical variables and macrofauna assemblages were further examined using redundancy analysis (RDA), with soil physicochemical properties as explanatory variables and macrofauna taxa as response variables. RDA was used to visualize patterns of association between soil conditions and macrofauna composition across the rehabilitation treatments and sampling seasons.

3. Results

3.1 Soil chemical properties before gully rehabilitation

Soil properties of the baseline soils were presented in (Table 1). The pH was an average of 8.0 ± 0.2, indicating moderately alkaline conditions. Electrical Conductivity (EC) of the soils was an average of 0.10 ± 0.02 (dS m^{-1}). Soil organic carbon was on average 0.80 ± 0.10%, with labile and non-labile carbon on average 0.40 ± 0.10% each. Total Nitrogen was, on average, 0.04 ± 0.01%; available phosphorus was, on average, 1.6 ± 0.2 mg kg^{-1}. Exchangeable potassium was an average of 0.20 ± 0.02 cmol (+) kg^{-1}). High Exchangeable calcium (14.6 ± 1.3 cmol (+) kg^{-1}), magnesium (15.6 ± 0.9 cmol (+) kg^{-1}), and cation exchange capacity (30.6 ± 1.7 cmol (+) kg^{-1}). Bulk density was 1.73 ± 0.04 g cm^{-3}.

Table 1. Baseline soil physicochemical properties of the gully before rehabilitation (means ± SE).

Physicochemical properties	Means ± SE
pH(water)	8.0 ± 0.2

EC (dS m^{-1})	0.1 ± 0.02
Organic C (%)	0.8 ± 0.1
Labile C (%)	0.4 ± 0.1
Nonlabile C (%)	0.4 ± 0.1
Total N (%)	0.04 ± 0.01
Available P (mg kg^{-1})	1.6 ± 0.2
K [cmol (+) kg^{-1}]	0.2 ± 0.02
Ca [cmol (+) kg^{-1}]	14.6 ± 1.3
Mg [cmol (+) kg^{-1}]	15.6 ± 0.9
Na [cmol (+) kg^{-1}]	0.2 ± 0.03
CEC [cmol (+) kg^{-1}]	30.6 ± 1.7
Bulk density (g cm^{-3})	1.73 ± 0.04

Abbreviations: EC-Electrical conductivity, C-carbon, N-nitrogen, P-phosphorus, K-potassium, Ca-calcium, Mg-magnesium, Na-sodium, CEC-cation exchange capacity.

3.2 Soil macrofauna abundance and diversity before gully rehabilitation

The initial abundance and diversity of soil macrofauna before the implementation of gully rehabilitation measures (Table 2). The findings reveal a sparse macrofauna community. Among the macrofauna sampled, termites (Termitidae sp.) were the most dominant group, with an average abundance of 7.9 ± 2.1 individuals m^{-2}. *Lumbricus* earthworms and ants (Formicidae family) also showed a higher abundance, with an average of 4.1 ± 1.6 individuals and 1.8 ± 0.8 individuals m^{-2}, respectively. Other macrofauna types, such as dung beetles (*Aphodius*), reed beetles (*Donacia*), rove beetles *(Fabrius*), longhorn beetles (Cerambycidae), and *Allolobophora* earthworms, occurred at low densities, with most species recording fewer than one individual m^{-2}. The Shannon diversity index was low (0.9 ± 0.1), with species richness of 3.4 ± 0.3 and Pielou's evenness score of 0.8 ± 0.03 also being low.

277 **Table 2.** Initial macrofauna abundance and diversity before gully rehabilitation (means ± SE).

Order	Family	Genus/species	Common Name	Means ± SE
Blattodea (Isoptera)	Termitidae	Termitidae sp	Termites	7.9 ± 2.1
Coleoptera	Scarabaeidae	*Aphodius*	Dung beetles	0.9 ± 0.4
	Cerambycidae	*Cerambycidae sp*	Longhorn beetles	0.2 ± 0.1
	Chrysomelidae	*Donacia*	Reed beetles	0.7 ± 0.3
	Staphylinidae	*Fabrius*	Rove beetles	0.8 ± 0.5
	Ommatidae	Ommatidae sp	Ommatid beetles	0.1 ± 0.1
	Scarabaeidae	Phyliophage	Leaf-feeding insects	0.4 ± 0.3
Hymenoptera	Formicidae	Attini	Leaf-cutter/fungus-growing ants	0.3 ± 0.3
		Formica	Field ants	1.0 ± 0.8
		Formicidae sp	Ants	1.8 ± 0.8
		Solenopsis	Fire ants/thief ants	1.6 ± 1.1
		Tapinoma	Odorous ants	0.9 ± 0.9
Lumbriculida	Lumbricidae	*Allolobophora*	Earthworms	0.4 ± 0.3
		Lumbricus		4.1 ± 1.6
Shannon diversity index				0.9 ± 0.1
Richness				3.4 ± 0.3
Evenness				0.8 ± 0.03

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3.3 Soil physicochemical properties after gully rehabilitation

After the rehabilitation efforts, several significant changes were noticed in the soil's physicochemical properties during the dry season (Table 3). The soil pH decreased slightly from 8.0 to 7.61 and 7.88. Electrical conductivity remained low, between 0.11 and 0.15 (dS m^{-1}). In terms of organic carbon, the content ranged between 0.58% (under Sesbania + Mombasa grass) to 0.86% (under pigeon pea + Dolichos), though these differences were not significant. Minor variations were noticed in non-labile and Labile carbon. Total nitrogen was lower, with an average of 0.02% to 0.03% compared with before rehabilitation, which was 0.04%. Available phosphorus increased from 1.6 mg kg^{-1} before rehabilitation to 11.08 mg (under Sesbania + super napier) and 27.6 mg kg^{-1} (under Sesbania + Mombasa grass and pigeon pea + Dolichos) after rehabilitation. Exchangeable calcium increased from 14.6 cmol (+) kg^{-1} to 18.2 (under pigeon pea + Dolichos) and 20.22 cmol (+) kg^{-1} (under Sesbania + super napier), while exchangeable magnesium decreased from 15.6 cmol (+) kg^{-1} to between 6.98 and 8.55 cmol (+) kg^{-1}. Exchangeable potassium remained relatively stable compared to baseline. The soil physical characteristics improved as bulk density decreased from 1.73 g cm^{-3} before rehabilitation to 1.48 and 1.63 g cm^{-3} after rehabilitation, with the lowest value recorded in plots with Sesbania + Brachiaria.

Table 3. Soil physicochemical properties under different rehabilitation treatments during the dry season (means ± SE).

Soil physicochemical properties	Pigeon pea +Dolichos	Sesbania +Brachiaria	Sesbania +Mombasa	Sesbania +Super Napier	P value
pH(water)	7.61 ± 0.28	7.86 ± 0.23	7.88 ± 0.19	7.87 ± 0.36	0.878
EC (dS m^{-1})	0.12 ± 0.02	0.11 ± 0.02	0.13 ± 0.02	0.15 ± 0.03	0.634
Organic C (%)	0.86 ± 0.14	0.7 ± 0.11	0.58 ± 0.12	0.76 ± 0.15	0.532
Labile C (%)	0.37 ± 0.06	0.33 ± 0.06	0.3 ± 0.05	0.27 ± 0.05	0.655
Nonlabile C (%)	0.24 ± 0.06	0.2 ± 0.04	0.33 ± 0.09	0.23 ± 0.03	0.406
Total N (%)	0.02 ± 0.01	0.02 ± 0.01	0.03 ± 0.01	0.02 ± 0.01	0.915
Available P (mg kg^{-1})	27.6 ± 10.1	22.6 ± 6.8	27.6 ± 12.9	11.1 ± 3.7	0.544
K [cmol (+) kg^{-1}]	0.17 ± 0.01	0.14 ± 0.02	0.14 ± 0.04	0.14 ± 0.02	0.832
Ca [cmol (+) kg^{-1}]	18.2 ± 1.3	18.4 ± 1.7	19.5 ± 1.3	20.2 ± 1.2	0.700
Mg [cmol (+) kg^{-1}]	8.55 ± 0.62	6.98 ± 1.48	7.73 ± 1.79	7.56 ± 1.46	0.888
Na [cmol (+) kg^{-1}]	0.57 ± 0.07^{a}	0.29 ± 0.05^{b}	0.1 ± 0.04^{b}	0.62 ± 0.06^{a}	<0.001
CEC [cmol (+) kg^{-1}]	27.36 ± 1.4	25.95 ± 3.12	27.78 ± 1.87	28.33 ± 0.89	0.853
Bulk density (g cm^{-3})	1.57 ± 0.03^{ab}	1.48 ± 0.03^{b}	1.57 ± 0.02^{ab}	1.63 ± 0.04^{a}	0.034

Within rows, different letters indicate significant differences between vegetation rehabilitative measures ($p < 0.05$; Tukey's HSD)

After rehabilitation, the soil's physicochemical properties recorded several significant changes during the wet season (Table 4). Soil pH slightly decreased from 8.0 to 7.5 and 7.9. Low Electrical conductivity (0.10 dS m^{-1}). organic carbon was 0.70% (under Sesbania +Brachiaria) and 0.90% (under Pigeon pea + Dolichos); labile carbon ranged from 0.30 to 0.40%, while non-labile carbon increased from 0.40 to 0.50%. Total nitrogen content remained low (0.03%). Available phosphorus ranged from 4.2 to 9.9 mg kg^{-1}, decreased during the dry season, but was higher than before rehabilitation 1.6 mg kg^{-1}. Exchangeable potassium increased from 0.20 cmol (+) kg^{-1} to 0.30 cmol (+) kg^{-1}. Exchangeable calcium declined compared to the dry season but was within the moderate ranges. exchangeable magnesium increased from 15.6 cmol (+) kg^{-1} before rehabilitation to 24.9 cmol (+) kg^{-1} (under Sesbania +Super Napier) and 27.03 cmol (+) kg^{-1} (under Sesbania +Mombasa). Cation exchange capacity increased from 30.6 cmol (+) kg^{-1} before rehabilitation to 34.8 cmol (+) kg^{-1} (under Sesbania +Super Napier) to 40.4 cmol (+) kg^{-1} (under Sesbania +Mombasa) after rehabilitation. Bulk density decreased to 1.58 and 1.62 g cm^{-3}, which was lower than before rehabilitation.

318 **Table 4**. Soil physicochemical properties under different rehabilitation treatments during the wet season (means ± SE)

Soil physicochemical properties	Treatments				
	Pigeon pea + Dolichos	**Sesbania +Brachiaria**	**Sesbania +Mombasa**	**Sesbania +Super Napier**	**P value**
pH(water)	7.5 ± 0.3	7.9 ± 0.3	7.7 ± 0.2	7.9 ± 0.4	0.821
EC (dS m^{-1})	0.1 ± 0.02	0.1 ± 0.02	0.1± 0.01	0.1 ± 0.03	0.855
Organic C (%)	0.9 ± 0.2	0.7 ± 0.09	0.7 ± 0.1	0.7 ± 0.2	0.589
Labile C (%)	0.4± 0.1	0.3 ± 0.1	0.3 ± 0.1	0.4 ± 0.1	0.945
Nonlabile C (%)	0.4 ± 0.1	0.4 ± 0.1	0.5 ± 0.1	0.5 ± 0.13	0.830
Total N (%)	0.03 ± 0	0.03 ± 0.01	0.03 ± 0	0.03 ± 0.01	0.941
Available P (mg kg^{-1})	9.9 ± 2.7	6.9± 1.7	4.2± 0.7	6.0 ± 0.9	0.156
K [cmol (+) kg^{-1}]	0.3 ± 0.03	0.3 ± 0.03	0.3 ± 0.04	0.3 ± 0.02	0.756
Ca [cmol (+) kg^{-1}]	9.9 ± 0.8	10.8 ± 0.8	11.1 ± 1.0	8.0 ± 0.6	0.058
Mg [cmol (+) kg^{-1}]	26.2 ± 1.0	25.9 ± 1.2	27.03 ± 1.7	24.9 ± 1.5	0.753
Na [cmol (+) kg^{-1}]	1.3± 0.4	1.8± 0.4	2.0 ± 0.3	1.6 ± 0.3	0.620
CEC [cmol (+) kg^{-1}]	37.8 ± 1.7	38.7 ± 2.2	40.4 ± 2.8	34.8 ± 1.9	0.350
Bulk density (g cm^{-3})	1.58 ± 0.03	1.62 ± 0.03	1.62 ± 0.05	1.58 ± 0.05	0.889

319 Within rows, different letters indicate significant differences between vegetation rehabilitative measures ($p < 0.05$; Tukey's HSD)

3.4 Soil macrofauna abundance and diversity after gully rehabilitation

The macrofauna community was observed during the dry season following the rehabilitation efforts (Table 5). Compared with the baseline conditions, the rehabilitation led to the emergence of several macrofauna taxa that were not present before rehabilitation. Notable new species included jumping spiders (*Mizaga),* plate-thigh beetles (*Eucinetus*), water scavenger beetles (*Hydrophilus*), white grubs (*Scarabaeiform*), soil centipedes *(Haplophilus*), assassin bugs (*Brontostoma*), field crickets (*Gryllus*), and stick insects (*Extatosoma*). Termites remained the most abundant macrofauna group after rehabilitation, showing a significant increase to a maximum of 204.8 ± 177.6 individuals m^{-2}, a great increase compared to the baseline level of 7.9 ± 2.1 individuals m^{-2}. However, the differences observed in post-rehabilitation between the different treatments were not statistically significant ($P = 0.324$). Likewise, the population of *Formica* ants increased, with abundances of 24.0 and 51.2 individuals per square meter, compared to just 1.0 ± 0.8 individuals per square meter before rehabilitation. Despite the greater presence of various macrofauna groups, metrics such as total macrofauna abundance, species richness, Shannon diversity, and evenness did not show statistically significant improvements ($P > 0.05$). The Shannon diversity index changed from 0.0 to 0.3, species richness ranged from 1.0 to 2.0, and evenness scores were 0.5 and 0.7, all of which remained lower than the diversity indices recorded at baseline.

339 **Table 5**. Macrofauna abundance (individuals m^{-2}), Shannon diversity, richness, and evenness under different rehabilitation treatments in
340 the dry season (means ± SE).

Soil Macrofauna Description				**Treatments**				
Order	**Family**	**Genus/Species**	**Common Name**	**Pigeon pea+Dolichos**	**Sesbania +Brachiaria**	**Sesbania +Mombasa**	**Sesbania +Super Napier**	**P-value**
Araneae	Argyronetidae	*Mizaga*	Jumping spider	2.72 ± 2.72	0 ± 0	3.2 ± 3.2	0 ± 0	0.582
Blattodea (Isoptera)	Termitidae	Termitidae sp.	Termite	204.8 ± 177.6	20.8 ± 20.8	0 ± 0	0 ± 0	0.324
Coleoptera	Eucinetidae	*Eucinetus*	Plate-thigh beetle	4.8 ± 3.2	3.2 ± 3.2	3.2 ± 3.2	0 ± 0	0.54
	Hydrophilidae	*Hydrophilus*	Water scavenger beetle	0 ± 0	3.2 ± 3.2	0 ± 0	0 ± 0	0.413
	Scarabaeidae	*Scarabaeiform*	White grub (scarab beetle larva)	0 ± 0	0 ± 0	3.2 ± 3.2	0 ± 0	0.413
Geophilomorpha	Geophilidae	*Haplophilus*	Soil centipede	3.2 ± 3.2	0 ± 0	0 ± 0	0 ± 0	0.413
Hemiptera	Reduviidae	*Brontostoma*	Assassin bug	0 ± 0	0 ± 0	0.2 ± 0.2	0 ± 0	0.413
Hymenoptera	Formicidae	*Formica*	Wood ant	36.8 ± 16	24 ± 9.6	51.2 ± 14.4	28.8 ± 8	0.461
Orthoptera	Gryllidae	*Gryllus*	Field cricket	0 ± 0	3.2 ± 3.2	0 ± 0	0 ± 0	0.413
Phasmatoda	Phasmatidae	*Extatosoma tiaratum*	Giant prickly stick insect	4.8 ± 4.8	0 ± 0	0 ± 0	0 ± 0	0.413
		Extatosoma	Stick insect	3.2 ± 3.2	0 ± 0	0 ± 0	0 ± 0	0.413
Richness				2 ± 0.5	1.3 ± 0.3	1.7 ± 0.2	1 ± 0	0.188
Shannon				0.3 ± 0.2	0.1± 0.1	0.3 ± 0.1	0 ± 0	0.219
Evenness				0.5 ± 0.2	0.7 ± 0	0.7 ± 0.1	1±0	0.621

341 Within rows, different letters indicate significant differences between vegetation rehabilitative measures ($p < 0.05$; Tukey's HSD)

The macrofauna community after rehabilitation during the wet season (Table 6). Compared with both the baseline and the dry-season observations, the wet season supported a more abundant and taxonomically diverse macrofauna community. Several beetle groups, including darkling beetles (*Tenebrionidae*), leaf beetles (*Chrysomelidae*), rove beetles, scarab beetles (*Scarabaeidae*), tiger beetles (*Cylindera*) and longhorn beetles (*Cerambycidae*), were recorded in greater numbers than before rehabilitation. Among these, *Scarabaeidae* was the only group that differed significantly among the post-rehabilitation observations between the different treatments ($P = 0.004$), with abundances ranging from 8.0 individuals in Sesbania + Mombasa to 80.0 individuals m^{-2} in Sesbania + Brachiaria. Pot worms (*Enchytraeidae*), which were absent before rehabilitation, reached abundances of up to 93.3 ± 31.3 individuals m^{-2} in plots with pigeon peas + Dolichos. Similarly, *Formica* ants remained abundant during the wet season, with densities reaching 88.0 ± 56.8 individuals m^{-2} in Sesbania + super napier. Termites occurred at much lower densities than those observed during the dry season. Macrofauna diversity also improved after rehabilitation, with the Shannon diversity index increasing from the baseline value of 0.9 to 1.1 while species richness increased from 3.4 before rehabilitation to 3.83 species in plots with Sesbania + Brachiaria. Evenness remained within the same range as before the rehabilitation of the gully.

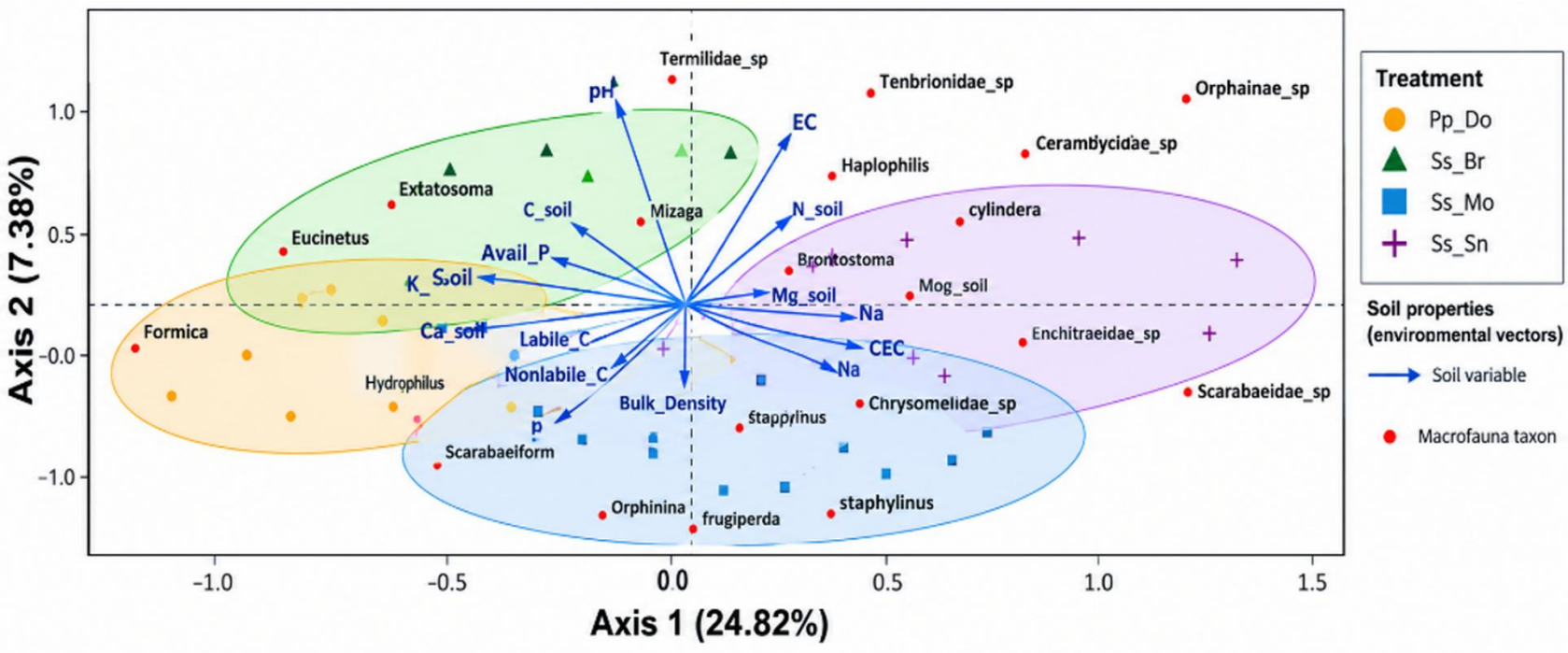
Table 6.Soil macrofauna abundance (individuals m^{-2}), Shannon diversity, richness, and evenness under different rehabilitation treatments in the wet season (means ± SE).

Soil Macrofauna Description				Treatments				
Order	**Family**	**Genus/Species**	**Common name**	**Pigeon pea + Dolichos**	**Sesbania + Brachiaria**	**Sesbania + Mombasa**	**Sesbania + Super Napier**	**P - value**
Blattodea (Isoptera)	Termitidae	*Termitidae* sp	Termite	0 ± 0	0 ± 0	2.67 ± 2.67	0 ± 0	0.413
Coleoptera	Tenebrionidae	*Tenebrionidae* sp	Darkling beetle	0 ± 0	2.67 ± 2.67	0 ± 0	0 ± 0	0.413
	Chrysomelidae	*Chrysomelidae* sp	Leaf beetle	0 ± 0	8.00 ± 8.00	5.33 ± 3.37	0 ± 0	0.483
	Cerambycidae	*Cerambycidae* sp	Longhorn beetle	2.67 ± 2.67	0 ± 0	0 ± 0	0 ± 0	0.413
	Staphylinidae	*Staphylinus*	Rove beetle	13.3 ± 6.4	26.7 ± 8.9	5.3 ± 3.4	18.7 ± 10.5	0.292
		Staphylinus sp		0 ± 0	5.33 ± 5.33	0 ± 0	0 ± 0	0.413
	Orphninae	*Orphnina*	Scarab beetle	0 ± 0	0 ± 0	18.67 ± 18.67	0 ± 0	0.413
	Orphninae	*Orphninae* sp		0 ± 0	5.33 ± 5.33	0 ± 0	0 ± 0	0.413
	Scarabaeidae	*Phaenomeridina*		0 ± 0	0 ± 0	8.00 ± 8.00	0 ± 0	0.413
		Scarabaeidae sp		16.0 ± 7.2[b]	80.0 ± 24.4[a]	8.0 ± 5.5[b]	24.0 ± 9.0[b]	0.004
	Cicindelidae	*Cylindera*	Tiger beetle	0 ± 0	13.3 ± 13.3	10.7 ± 10.7	21.3 ± 21.3	0.744
Enchytraeida	Enchytraeidae	*Enchytraeidae* sp	Pot worm	93.3 ± 31.3	53.3 ± 26.7	29.3 ± 14.0	10.7 ± 5.3	0.076
Geophilomorpha	Geophilidae	*Haplophilis*	Soil centipede	2.67 ± 2.67	0 ± 0	0 ± 0	0 ± 0	0.413
Hemiptera	Reduviidae	*Brontostom*a	Assassin bug	0 ± 0	10.67 ± 6.75	0 ± 0	0 ± 0	0.089
Hymenoptera	Formicidae	*Formica*	Ant	29.3 ± 20.4	2.67 ± 2.67	24.0 ± 16.4	88.0 ± 56.7	0.283
		Formicidae sp		5.33 ± 5.33	0 ± 0	0 ± 0	10.67 ± 10.67	0.544
Lepidoptera	Noctuidae	*frugiperda*	Fall armyworm	0 ± 0	0 ± 0	13.33 ± 13.33	0 ± 0	0.413
	Argyronetidae	*Mizaga*	Moth	0 ± 0	0 ± 0	5.33 ± 5.33	5.33 ± 5.33	0.582
Shannon index				0.90 ± 0.11	1.10 ± 0.17	0.78 ± 0.26	0.80 ± 0.26	0.681
Richness				3.00 ± 0.26	3.83 ± 0.48	2.83 ± 0.65	3.00 ± 0.68	0.571
Evenness				0.84 ± 0.07	0.82 ± 0.07	0.90 ± 0.04	0.88 ± 0.00	0.804

Within rows, different letters indicate significant differences between vegetation rehabilitative measures ($p < 0.05$; Tukey's HSD).

3.5 Relationship between soil macrofauna and soil chemical properties

The Redundancy Analysis (RDA) (Fig. 2) showed that the first two axes explained 32.20% of the constrained variation (Axis 1 = 24.82%; Axis 2 = 7.38%). The Pigeon pea + Dolichos treatment was associated mainly with Ca, K, labile C, non-labile C and Available P, whereas Sesbania + Brachiaria was associated with pH and EC. Sesbania + Mombasa grass was closer to bulk density, while Sesbania + Super Napier was associated with N, Na, and CEC. Macrofauna taxa differed along soil gradients, indicating community composition differences in relation to the physicochemical conditions created by the different rehabilitation treatments.



392 **Fig. 2** RDA of soil physicochemical properties and macrofauna

4. Discussion

4.1 Effects of integrated gully rehabilitation measures on soil properties

The baseline survey indicated that gully soils were severely degraded with very low organic carbon, labile and non-labile carbon, total nitrogen, and Available phosphorus. Additionally, the soils had a relatively high bulk density, suggesting that the topsoil had been lost due to erosion. Consequently, the degraded soils had low organic matter and a decreased capacity to store carbon. These results are consistent with the characteristics of degraded gully soils, where continued erosion leads to reduced active and stable pools of carbon, reduced soil structure, and reduced biological activity [30]. The baseline soil survey provides a reference point that was used to evaluate the changes that occurred following the integrated gully rehabilitation using the before-after-control-impact (BACI) design. The integrated gully rehabilitation resulted in increased SOC and its fractions, suggesting that the rehabilitation measures had initiated the recovery process of the stable pool of carbon. Although the changes recorded in the study were marginal, they indicate that the rehabilitation interventions have the potential to increase soil carbon through vegetative cover and litter addition, as demonstrated by similar studies. The study revealed that the rates at which SOC increased following the rehabilitation intervention were slow. SOC sequestration is a slow process, especially in the early stages of ecosystem recovery. The rapid rise in the labile carbon pool during the early phases of revegetation is fuelled by the comparatively high rate of litter and fine root input into the soil. This finding is consistent with the observation that labile carbon responds faster to changes in management and environmental conditions than the total SOC. Over time, the interactions between the plant litter and the mineral soil can lead to the formation of more stable carbon pools that are less susceptible to microbial decomposition [31]. Consequently, significant increases in stable carbon pools will only be recorded after decades of rehabilitation and recovery [32]. The observed minor changes in the SOC content could also be attributed to seasonal variations in vegetation and ecology. The increase in SOC recorded during the wet season suggests that carbon sequestration had commenced in the relatively short time since rehabilitation began.

The comparison of the soil properties before and after rehabilitation indicated that the interventions had changed several soil properties. Specifically, the soils in the gully were initially characterized by low available phosphorus, total nitrogen, and high bulk density, which probably limited plant establishment and natural recovery. Following the rehabilitation interventions,

available phosphorus increased significantly during the dry season compared to the baseline survey. Concurrently, the bulk density decreased from 1.73 g cm^{-3} before rehabilitation to between 1.48 and 1.63 g cm^{-3} after rehabilitation. These results suggest that the rehabilitation interventions had a positive effect on the soil, facilitating the improvement of several soil properties. However, the treatment effect varied between soil properties and seasons. Except for exchangeable sodium and dry-season bulk density, no significant treatment effects were recorded for all other measured properties. The variations recorded in the available phosphorus, calcium, magnesium, potassium, and cation exchange capacity (CEC) between the dry and wet seasons further suggest that these properties were influenced by the season in addition to rehabilitation treatments. These results are consistent with a similar study that reported that the rehabilitation of degraded gullies follows a slow and gradual improvement trajectory, with different properties responding differently to the rehabilitation interventions depending on the vegetation cover [33].

4.2 Effects of integrated gully rehabilitation measures on soil macrofauna recovery

Prior to the rehabilitation interventions, the macrofauna community was characterized by low abundance, moderate species richness, and low diversity. The community had 14 taxa which were identified from six insect orders, namely Blattodea, Coleoptera, Hymenoptera, Lepidoptera, Lumbriculida, and associated families, as well as Termitidae and *Lumbricus* earthworms. The *Termitidae* species and *Lumbricus* earthworms dominated, while beetles, ants, and other arthropods were recorded in low abundance. The low values of the Shannon diversity and species richness, along with evenness, indicated a basic community with a few predominant species before recovery. The results indicated that gully erosion had substantially compromised habitat quality, which in turn had decreased the richness, diversity, and evenness of the macrofauna population. The decline in vegetation and organic matter resulted in the unavailability of crucial resources, including food and nesting materials, which significantly impacted the community structure of macrofauna. Similar negative effects of gully erosion on the soil biological properties have been reported elsewhere [34]. The study by [34] noted that degraded landscape sites tended to have fewer macrofauna species due to the loss of organic

matter, stable soil structure, and favorable temperature and moisture regimes that accompany extensive erosion. Following the rehabilitation interventions, the treatment effect on the macrofauna community was inconsistent across species during the dry season. Even though total abundance, species richness, and Shannon diversity were not significantly different among treatments, the rehabilitation interventions had a significant effect on the taxonomic composition of the macrofauna community. During the dry season, 11 macrofauna taxa were recorded from the rehabilitated plots. The treatments did not restore the presence of *Aphodius* dung beetles, *Donacia* reed beetles, *Fabrius* rove beetles, *Ommatidae* beetles, *Phyliophage* leaf-feeding insects, *Attini*, *Solenopsis, Tapinoma*, and *Allolobophora* earthworms recorded before rehabilitation. The absence of these taxa might be attributed to the combined effect of the dry season and the short period available for colonization and recolonization. It is well established that ecological restoration interventions do not lead to immediate recovery of all ecological components, but rather some species recover faster than others depending on their dispersal ability, reproductive potential, and other factors [35]. However, the rehabilitation treatments recorded the presence of new groups of macrofauna, including *Mizaga* (jumping spiders), *Hydrophilus* (water scavenger beetles), *Scarabaeiform* white grubs, *Haplophilus* soil centipedes, *Brontostoma* assassin bugs, *Gryllus* field crickets, and *Extatosoma* stick insects. The presence of these new taxa suggests that the restored sites can support a wide range of predators, decomposers, and herbivores not present in the degraded gully. This change was probably facilitated by the addition of perennial grasses and legumes that provided more litter, root mass, and, consequently, a diverse range of habitats that favored the colonization by these macrofauna groups. Similar observations have been made in ecological restoration studies where increased litter and root mass following revegetation interventions have facilitated the colonization of new macrofauna taxa even before significant changes in overall biodiversity are recorded [36].

During the dry season, the abundance of *Formica* ants was exceptionally high, recording an abundance of 51.2 ± 14.4 individuals m -2 in the Sesbania + Mombasa treatment. Water scavenger beetles (*Hydrophilus*), field crickets (*Gryllus*), and plate-thigh beetles (*Eucinetus*) were also abundant in the rehabilitated plots with perennial vegetation. Although the treatment effect on the abundance of these groups was not significant, their presence suggests that the rehabilitation interventions have started to create favorable habitats for several macrofauna taxa. In general, the recovery of soil macrofauna communities following ecological rehabilitation

interventions requires time due to the slow development of vegetation cover, litter, and root mass that provide habitat and sustenance for these organisms [37]. One of the interesting observations recorded in this study was the exceptionally high abundance of termites in the pigeon pea + Dolichos treatment during the dry season. The treatment recorded 204.8 ± 177.6 individuals m^{-2} of termites, compared to an average of 7.9 ± 2.1 individuals m^{-2} before rehabilitation. Termites are considered ecosystem engineers due to their ability to break down plant material and transfer significant amounts of organic matter to the lower soil profiles through their burrows [38]. The presence of these termites suggests that the treatment has provided favorable habitats for these organisms following the rehabilitation interventions. However, the high variance recorded in termite abundance among the replicates suggests that the distribution of these insects was uneven, possibly due to differences in the extent of vegetation establishment and organic matter availability in the various rehabilitated gullies.

The ant community showed remarkable resilience throughout the study period, with ant abundance being relatively high throughout the study period. Prior to rehabilitation, five ant taxa, including *Attini*, *Formica*, *Formicidae* sp., *Solenopsis*, and *Tapinoma*, were recorded, although their abundance was generally low. During the dry season, only Formica was abundant across all treatment plots. The low abundance of other ant taxa does not necessarily indicate that these groups were absent; instead, it can be attributed to their ability to change their distribution patterns in response to changes in the local environment. For example, ants are highly mobile organisms, and their distribution is often dictated by the availability of resources rather than local environmental conditions [39]. Another observation was the absence of earthworms following rehabilitation, even though they were present before rehabilitation. Before rehabilitation, Lumbricus (4.1 ± 1.6 individuals m^{-2}) and Allolobophora (0.4 ± 0.3 individuals m^{-2}) were recorded in the soil but were absent after rehabilitation. Earthworms are highly sensitive to changes in moisture, and their survival depends on the suitable soil structure, litter, and organic matter for them to burrow [40]. Several studies have reported that earthworms are among the last macroinvertebrates to colonize disturbed or degraded sites due to their limited dispersal ability and specific habitat requirements [41].

The wet season showed the effects of rehabilitation on the macrofauna community. The rainfall received during the wet season provided optimal moisture conditions that supported vegetation growth and litter accumulation, which enhanced macrofauna recovery. After rehabilitation, 18

519 macrofauna taxa were recorded during the wet season, 14 taxa were recorded before
520 rehabilitation and 11 taxa were recorded during the dry season. Notably, several of the taxa
521 recorded during the wet season were absent during the dry season and prior to rehabilitation.
522 The observed increase in the number of taxa following rehabilitation suggests that the
523 interventions had a positive effect on macrofauna recovery. The new taxa recorded following
524 rehabilitation included *Tenebrionidae (*darkling beetles), *Chrysomelidae* (leaf beetles),
525 *Staphylinus* rove beetles, *Orphnina*, *Phaenomeridina*, *Cylindera* tiger beetles, *Enchytraeidae*
526 potworms, and Spodoptera *frugiperda* fall armyworms, among others. The emergence of these
527 new taxa suggested that improved habitat conditions, including vegetation cover and litter,
528 following rehabilitation contributed to their recolonization. The increased rate of litter
529 decomposition and microbial activity during the wet season probably created additional
530 resources that favored the establishment of these taxa [42].

531 Even though the study did not record significant differences in biodiversity, richness, and
532 evenness between the treatments, several observations suggest that the rehabilitation
533 interventions have had a positive effect on the macrofauna community compared to the dry
534 season. Specifically, the Sesbania + Brachiaria treatment had the highest Shannon diversity
535 and species richness among all the treatments. This observation suggests that the combined
536 use of perennial grasses and legumes can create favorable habitats that promote biodiversity
537 conservation. In general, increased plant diversity favors increased litter quality and quantity
538 as well as root biomass, which in turn improve soil quality and create favorable habitats for a
539 wide range of macrofauna taxa [35]. The most remarkable observation during the wet season
540 was the occurrence of Scarabaeidae beetles. The abundance of this group varied between the
541 treatments, with the highest abundance recorded in the Sesbania + Brachiaria treatment, which
542 had 80.0 ± 24.4 individuals m^{-2} of these beetles. Remarkably, before rehabilitation, only one
543 species of scarab beetle, namely Aphodius, was recorded at very low abundance. After
544 rehabilitation, several scarab-related taxa, including *Scarabaeidae* sp., *Orphnina*, *Orphninae*
545 sp., *Phaenomeridina*, and several others, were recorded from the rehabilitated plots. Scarab
546 beetles are generally regarded as significant contributors to the decomposition process in
547 agroecosystems [43]. The observed increase in the abundance of this group following
548 rehabilitation suggests that increased vegetation cover and improved litter conditions favored
549 their establishment in the study area. This observation is consistent with the findings of a similar
550 study that reported that the abundance of scarab beetles increased following revegetation

interventions due to increased litter availability [44]. Another important observation was that the community structure of the scarab beetles changed following rehabilitation. Specifically, before rehabilitation, Aphodius was the only scarab beetle species recorded, with no other species observed. Following rehabilitation, a wide range of scarab-related taxa were recorded from the experimental plots, suggesting that the community structure was changing. This change in Scarabaeidae community structure was probably a reflection of the overall improvement in the habitat conditions brought about by the rehabilitation interventions. Similar changes in Scarabaeidae community structure have been reported in other studies examining the effect of land use changes on the distribution patterns of soil macrofauna [45].

5. Conclusion

The findings suggest that integrated gully rehabilitation measures improved the soil condition of the degraded gully. After rehabilitation, changes in soil carbon fractions (organic, labile and non-labile) revealed gradual improvement of the degraded soil condition relative to the initial degraded state. Other soil chemical and physical properties were also altered indicating that the rehabilitation measures had a broader impact of improvement on the degraded gully soil. The soil available phosphorus increased relative to the initial state, especially during the dry season while the soil bulk density decreased indicating amelioration of the physical condition of the rehabilitated soil. However, the response of individual soil properties varied with treatments and season. Most of the chemical properties did not vary significantly with treatments. However, exchangeable sodium and dry-season bulk density revealed significant treatment effects. The results suggest that integrated gully rehabilitation can lead to improvement in soils beyond changes in carbon fractions as some aspects of soil fertility and its physical condition were improved. Thus, the approach offers a viable option for restoring degraded gully sites and creating enhanced conditions for vegetation establishment and sustainable soil functioning. In addition, the findings suggest that integrated gully rehabilitation measures restored the gradual re-establishment of soil macrofauna communities as they created enhanced conditions for their occurrence. The degraded gully prior to rehabilitation supported a relatively simple macrofauna community with low abundance, diversity and species richness. After rehabilitation, the community structure became more diverse with additional taxa recorded in the rehabilitated plots and higher species richness was also recorded during the wet season relative to the initial state. However, macrofauna abundance

and diversity indices did not vary significantly with the rehabilitation treatments. Nevertheless, the presence of new macrofauna taxa and the marked increase in scarab beetles in the Sesbania + Brachiaria treatment suggest that rehabilitation created better conditions for the return and establishment of soil fauna.

The positive association between the recovery of macrofauna community and improvements in soil carbon fractions and physicochemical properties supports the proposition. However, further assessment is needed to determine if the changes will lead to sustained improvement in soil fertility and its physical condition.

Abbreviations

RDA-Redundancy Analysis

EC-Electrical Conductivity

C-Carbon

Mg-Magnesium

Na-sodium

BD-Bulk density

SE-Standard Error

ANOVA-Analysis of Variance

Authors Contribution Statement

Calister Kerubo Osuma: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing-original draft, Writing-review and editing.

Solomon Kamau: Supervision, Methodology, Validation, Writing-review and editing.

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Competing interest

The authors declare that they have no conflict of interest related to this study

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Declaration of competing interest

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Data availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request

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