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Long-Term Integrated Systems of Green Manure and Pasture Significantly Recover the Macrofauna of Degraded Soil in the Brazilian Savannah

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Abstract: Healthy soil biota is the key to meeting the world population's growing demand for food, energy, fiber and raw materials. Our aim is to investigate the effect of green manure as a strategy to recover the macrofauna and the chemical properties of soils which have been anthropogenically degraded. The experiment was a completely randomized block design with four replicates. Green manure, *Urochloa decumbens*, with or without application of limestone and gypsum, composed the integrated systems. The macroorganisms as well as the soil fertility were analyzed after 17 years of a process of soil restoration with the aforementioned systems. The succession of *Stizolobium* sp. with *Urochloa decumbens*, with limestone and gypsum, was teeming with termites, beetles and ants. This integrated system presented the most technically adequate indexes of diversity and uniformity. Multivariate models showed a substantial increase in the total number of individuals due to the neutralization of harmful elements and the gradual release of nutrients by limestone and plaster. These conditioners have undergone multiple chemical reactions with the substrate in order to balance it chemically, thus allowing the macroinvertebrates to grow, develop, reproduce and compose their food web in milder microclimates. It was concluded that the integration of green manure together with grass is an economical and environmentally correct strategy to restore the macrofauna properties of degraded soil in the Brazilian savannah.

Keywords: *Cajanus* sp.; *Canavalia* sp.; *Urochloa decumbens*; macroorganisms

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1. Introduction

Experts rely on a healthy soil biota as the key to meeting the increasing world population's demand for food, energy, fiber and raw materials [1]. Soil fauna consists of micro-, meso- and macroorganisms. Macroorganisms are living things larger than 2 mm in body diameter. The groups of macroinvertebrates proposed by specialists because of their ability to modify soil aggregates are bioturbators, reorganizers and weathering agents of clay minerals. Bioturbators refer to mobilizing and structuring agents of organic and mineral compounds. Ants, beetles, earthworms and termites are highly effective bioturbators in the production and molding of biogenic aggregates through their habits of foraging, tunneling, digging and nesting. Ecologists recognize them as the greatest soil engineers. Reorganizers are likely to alter soil structure by redefining internal organizational patterns of primary particles. Annelids and termites, in particular, process clay minerals via mandibular crushing and intestinal transition, respectively, consequently transforming them into pellet-shaped feces strengthened by chemical and physical bonds. Saliva and mucus membranes reorient precast micro-, meso- and macroaggregates, thus collaborating with the rehabilitation of soil properties; aging, drying and coating make newly formed biogenic aggregates naturally stronger. Weathering bioagents refer to macroinvertebrates able to modify clay mineralogy, making them either expansive, adsorptive or absorptive due to shifts in the ratio of tetrahedral to octahedral blades [2–7].

Irrespective of functional group, soil-dwelling macroinvertebrates offer a wide range of valuable ecological services that continuously improve agriculture, for instance, cycling of nutrients, decomposition and preservation of long-lasting pools of soil organic matter, mitigation of greenhouse gases threatening the environment and public health, promotion of microbial symbiosis between crop plants and microorganism and improvement of absorption and retention of water and gaseous exchanges through pores. These benefits are extremely relevant to optimize the functioning of the soil as global support for the growth and development of floral and faunal components [8].

Abundance, diversity, evenness and richness are paramount ecological aspects of macrofauna. They vary drastically with soil biological, chemical and physical properties. Hence, any disturbance by atypical pedoclimatic or anthropogenic forces on the environment causes several negative impacts on trophic relationships among ants, beetles, earthworms, termites and other aboveground and underground macroinvertebrates. Macroorganisms are sensitive to land use and management practice, so they are useful bioindicators of degradation events by erosion, salinization, pollution, desertification, etc. [9–13].

The presence of cover vegetation on the soil provides greater food availability and, consequently, the establishment of taxonomic groups aiming to colonize the soil, which improve the physical structure and act in the initial decomposition processes of plant residues. With the increase in the colonization of edaphic fauna in the areas under rehabilitation, the organisms reach a standard that is very close or even higher than that of being under native vegetation [14]. These authors report that in the Brazilian savannah research, the use of grass might have favored the emergence of organisms due to the greater layer of dry matter in different degrees of decomposition, sheltering organisms with different survival strategies.

Food and energy top the list of mankind's earliest and most essential goods and services. Hydroelectric power, especially, offers key benefits to civilizations from around the world, mainly including primary production of renewable energy and improvement of quality of life. Yet, large-scale plants for the generation of electricity in both low-income and high-income countries can easily devastate natural resources, such as soil and water. When the soil is under degradation by either pedoclimatic or anthropogenic forces, a study of physical, chemical and biological properties is necessary to select suitable management practices to restore it. The rehabilitation of degraded soil, traditionally performed using mechanical, physical or chemical techniques, may be expensive and detrimental to the environment. The development and implementation of alternative strategies are, therefore, necessary for both economic and environmental reasons [15].

Our multidisciplinary team from the School of Engineering at São Paulo State University (Unesp) has, for a long time, been studying and developing environmentally friendly and cost-effective technologies to monitor and mitigate events of degradation in the Brazilian savannah. This mixed woodland–grassland landscape is the country's second largest biome in terms of area, behind the Amazon jungle. In the past years, there have been studies in order to develop the promising agricultural frontiers of crop–livestock–forest frameworks in tropical zones [16,17]. There have been, nonetheless, very few studies reported in the literature focusing on the recovery of degraded sites [18–25].

When planning the recovery of degraded soil, the main objective to be achieved is the establishment of an A horizon so that, from there, the process is catalyzed by the biosphere, giving the possibility of the emergence of other horizons, according to natural conditioning. In soil restoration work, the initial activity is to identify and characterize the active degradation processes and analyze their environmental consequences. Thus, it is necessary to use indicators that allow us to qualify and quantify the degree of existing degradation in the area to be restored as well as to monitor the evolution of soil rehabilitation through these indicators afterwards.

With the aim of studying the influence of bioindicators on soil recovery and proposing an appropriate use for them, this work intended, with macroorganisms as indicators, to evaluate the biological properties of an Oxisol that has been in the process of recovery for 17 years with the use of liming, gypsum and plant species. The hypotheses of this work were that the combination of the use of liming, gypsum and plant species in a long run would restore the soil with a high degree of degradation and that the soil macroorganisms would be good indicators of the progress in the rehabilitation of this soil.

2. Materials and Methods

The field experiment was carried out at the Teaching, Research and Extension Farm of the School of Engineering, at São Paulo State University (Unesp), located in the municipality of Selvíria, state of Mato Grosso do Sul, Midwest Brazil, coordinates 20°22′ S and 51°22′ W and elevation of 317 m. According to the Brazilian Soil Classification System, the soil of the area is a sesquioxides-rich, eutrophic red Latosol, with sandy–loamy texture, corresponding to an Oxisol [26,27].

The earthworks and dam foundation required to install the Ilha Solteira Hydroelectric Power Plant made the site under investigation drastically degraded. The soil substantially excavated at an 8.6 m depth remained exposed since the 1970s. In the early 1990s, after a long period of natural rehabilitation, native species of grasses, shrubs and trees spontaneously grew at low density on the mixed woodland–grassland biome.

The tests planning to restore the degraded soil consisted of combinations of genera of green manures with a tropical species of pasture, with or without administration of limestone and/or agricultural gypsum, as detailed in Table 1.

Table 1. Characterization of an integrated system planned to recover physical, chemical and macrofaunal properties of an anthropogenically degraded site in the Brazilian savannah.

Code	Integrated System *
NC	Exposed soil; negative control
SMB	Soil under native vegetation with cultivation of *Urochloa decumbens*
MPB	Succession of *Stizolobium* sp. and *U. decumbens*
GFPB	Succession of *Cajanus* sp., *Canavalia* sp. and *U. decumbens*
CMPB	Succession of *Stizolobium* sp. and *U. decumbens* with limestone
CGFPB	Succession of *Cajanus* sp., *Canavalia* sp. and pasture of *U. decumbens* with limestone
CGeMPB	Succession of *Stizolobium* sp. and *U. decumbens* with limestone and gypsum
CGeGFPB	Succession of *Cajanus* sp., *Canavalia* sp. and *U. decumbens* with limestone and gypsum
PC	Forest; positive control

* Each plot was 10 m in length by 10 m in width, totaling 400 m^2 per test.

A border of 2 m on all sides of each 10 m × 10 m plot was disregarded (assessed area 64 m^2), and replications were 2 m apart from each other. Each test comprised four replicates and the experiment was a completely randomized block design. Exposed soil and native forest were references for potential contrasting.

Before the installation of the experimental field, the conventional preparation consisted of subsoiling, plowing and harrowing. From 1992 to 1999, for the sowing of green manure, the soil was prepared with plowing by using plow and leveling harrows. The chemical and physical characterization consisted of carrying out sampling at the depths of 0.00–0.20 and 0.20–0.40 m, according to Quaggio et al. [28] and Teixeira et al. [29].

The amendment of natural soil fertility of the experimental field consisted in carrying out the application of dolomitic limestone of 70% neutralizing power and agricultural gypsum at 1850 and 580 kg per hectare, respectively, aiming to improve the saturation of exchangeable cations to approximately 70%. The limestone was incorporated into the soil with the use of a harrow. In mid-1992, the sowing and the cultivation of the genera of green fertilizers, *Cajanus* sp., *Canavalia* sp. and *Stizolobium* sp., at a density of 10 seeds per meter was performed. In order to produce biomass faster for the recovery of the biological and chemical properties of the soil, the cutting-off of the N-fixing plants at the beginning of flowering was performed while maintaining as much agricultural residues as possible on the soil surface. In 1996, the liming of the experimental plots with a saturation of exchangeable cations out of the critical range of 50–70%, reported by Quaggio et al. [28], for crop plants growing in tropical zones was carried out. In 1999, the sowing of *U. decumbens* on no-tillage systems consisting of agricultural residues gradually released from the green manures throughout the harvest seasons running from 1992 to 1999 was finally performed. The management of pasture consisted of cutting it off to avoid overgrazing.

Annually, the soil physical and chemical properties and the dry mass plant productivity were analyzed. With 17 years of the influence of the treatments, in addition to these attributes of the soil and plants, the evaluation of soil macrofauna was added to the investigation. This biological attribute characterizes a dynamic property of the soil; therefore, the objective was the study in space. Because it is dynamic and greatly influenced by temperature and humidity conditions, the proposal was the relative analysis of the results and the use of two controls (native vegetation and soil with a high degree of degradation under natural recovery). The evaluation was carried out in winter and summer. With 14 to 15 years of implementation of treatments for soil recovery, with the influence of treatments, native tree plant species began to appear spontaneously in the study area. This aspect was an indicator of the improvement of soil conditions, and we decided to add the analysis of a soil biological attribute, in this case its macrofauna. At 17 years old, native tree vegetation grew at a high density, indicating a change in the edaphic conditions of the soil, which could favor and/or influence the appearance of species of organisms. In the periods of winter and summer, with 17 years of soil under the recovery system, the sampling of soil-dwelling macroinvertebrates was formally performed, according to Velasquez and Lavelle [30]. In order to collect macrofauna, square-shaped traps (0.3 m length by 0.3 m width by 0.3 m height) were placed at 0.00–0.05, 0.05–0.10 and 0.10–0.20 m depths. Afterwards, the collected monoliths were carefully introduced into polyethylene flasks containing alcoholic solution at 200 mL L^{-1}, and then they were transferred to the Laboratory of Soil Science, Unesp, for further analytical procedures of macrofauna technical assessment. The sampling of experimental plots, exposed soil and native forest for characterization of chemical properties was performed simultaneously, according to Quaggio et al. [28].

The technical assessment of macroinvertebrates comprised the visual count and the taxonomic identification of orders or classes as well as the calculation of total abundance and indexes of Shannon, Simpson and Pielou [31,32].

Firstly, the Shapiro–Wilk and Bartlett procedures were run to check if the data set was normal and the distribution and homogeneous were in random variance, respectively. The effects of integrated systems of green manure species with tropical pasture with or without application of limestone and gypsum on the soil macrofauna and chemical properties were tested using a one-way analysis of variance. Then, the treatments were compared by mean values by post-hoc Tukey's HSD test. Other methods of applying non-traditional statistics to track and understand multivariate patterns included the Pearson product-moment correlation test, PCA and MRA. The Pearson product-moment correlation test measured the strength and direction of linear associations between macrofaunal and chemical properties. Prior to running the PCA, the Bartlett's test of sphericity tested if the original data set was reliable. Then, the Kaiser–Meyer–Olkin procedure was used to test the significance of eigenvalues of principal components needed to reduce the dimensionality of the original data set while preserving as much statistically understandable variability as possible into orthogonally rotated subsets with absence of multicollinear variables and ambiguities. A factorial map was customized to contrast macrofaunal and chemical properties of the soil before and after recovery by long-term integrated systems of species of green manures with tropical pasture. MRA was performed to figure out the relationship between independent variables and predictors; the criteria for selection of significant multiple regression models were AIC (Akaike information criterion), BIC (Bayesian information criterion) and Radj2 (Adjusted Rˆ2). The software used for statistical computing and graphics was R software [33].

3. Results

The chemical composition of the exposed soil mainly consisted of high contents of H^+ and Al^{+3} and low contents of Presin, K, Ca, Mg and SOM. These properties caused the saturation of exchangeable cations to be predictably low in the environment before starting the process of restoration (Table 2). Additionally, the physical composition was replete with micropores, thus presenting a high degree of compaction by mechanical forces of earthworks and dam foundations visible on the deforested landscape. The highest apparent density was at the deepest depth of 0.20–0.40 m.

Table 2. Chemical and physical properties of soil degraded by earthworks and dam foundations for the establishment of a hydroelectric power plant in the Brazilian savannah, before the installation of the experiment, in 1992.

Property	**Depth (m)**	
	0.00–0.20	0.20–0.40
Presin (mg dm^{-3})	1.00	0.00
Organic matter (g dm^{-3})	7.00	4.00
pH	4.0	4.20
K (cmolc dm^{-3})	0.20	0.20
Ca (cmolc dm^{-3})	2.00	2.00
Mg (cmolc dm^{-3})	1.00	1.00
Potential acidity (cmolc dm^{-3})	20.00	20.00
Sum of exchangeable cations (cmolc dm^{-3})	3.20	3.20
Cation-exchange capacity (cmolc dm^{-3})	23.20	23.10
Saturation of exchangeable cations (%)	14.00	14.00
Total porosity (m^3 m^{-3})	0.34	0.33
Macroporosity (m^3 m^{-3})	0.09	0.07
Microporosity (m^3 m^{-3})	0.25	0.26
Soil bulk density (kg m^{-3})	1.60	1.74

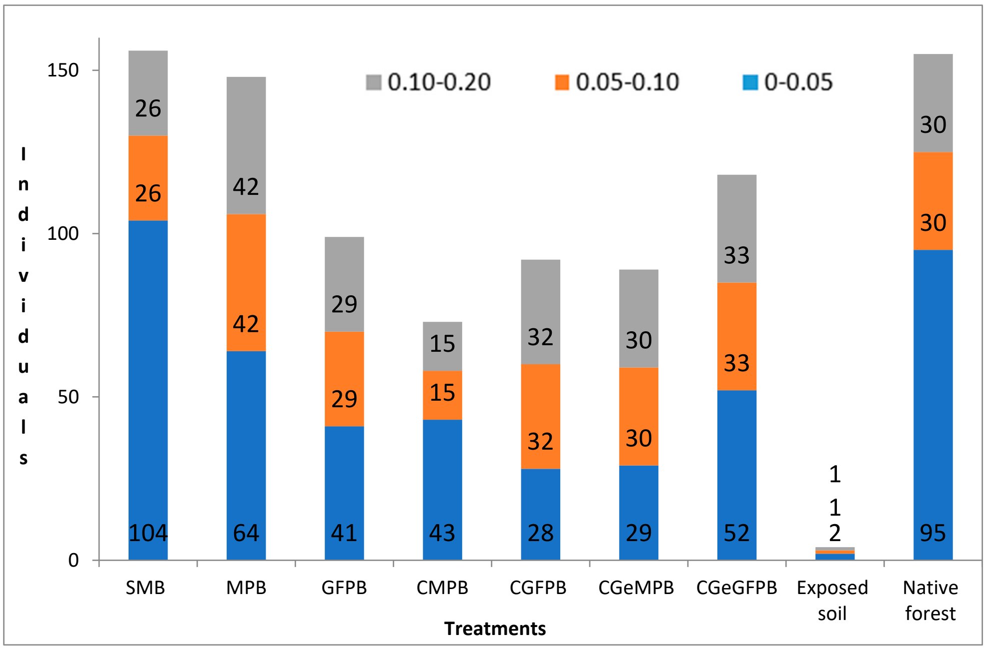
The integrated systems, exposed soil and native forest, collectively, yielded about 2210 macroinvertebrates making up the orders or classes Aranae, Coleoptera, Dermaptera, Diplopoda, Isoptera, Haplotaxida, Hemiptera, Hymenoptera and Orthoptera; eggs and larval stages of arthropods taxonomically unidentified were other elementary components of heterogeneous macrofauna of the site under investigation.

Figure 1A–D show the numbers of individuals and orders, organized by treatments and seasons of the year studied. Regardless of the treatment, a greater number of termites (Winter: 359, 133, 1333; Summer: 419, 438, 438) were found in the soil depths of 0.00–0.05, 0.05–0.10 and 0.10–0.20 m, respectively.

In the winter, after 17 years of influence of the treatments, the soil with native vegetation cover with subsequent cultivation of *U. decumbens* had an inexpressive number of spiders, adult millipedes and ants but an impressive number of termites at a depth of 0.00–0.05 m depth. These macroinvertebrates collaboratively caused the SMB to yield a total abundance greater than that of the exposed soil, where macroorganisms under harsh microclimate were notably scarce, regardless of the depth. Similarly, succession of *Stizolobium* sp. with *U. decumbens*, without conditioning by regular administration of limestone and gypsum, also yielded a great number of termites but an insignificant number of beetles. These macroinvertebrates provided the MPB with acceptable indexes of diversity, dominance and evenness, in comparison to other integrated systems and native forest, where spiders, adult millipedes and crickets were absent beneath litterfall. The integrated system of *Cajanus* sp., *Canavalia* sp. and *U. decumbens*, without limestone and gypsum, was seemingly microclimatically selective for termites, ants, beetles and stinkbugs. Moderate indexes of diversity and evenness reflected the GFPB's ecological aspects, thus distinguishing it from the others. Technically similar to SMB, MPB and GFPB, the succession of *Stizolobium* sp. with *U. decumbens*, without limestone and gypsum, also had a remarkable abundance of termites but inexpressive counts of ants, spiders, beetles, white grubs and adult millipedes. Yet, CMPB had a satisfactory diversity of bioturbators, reorganizers and weathering agents of clay minerals.

Winter

(**A**)



(**B**)

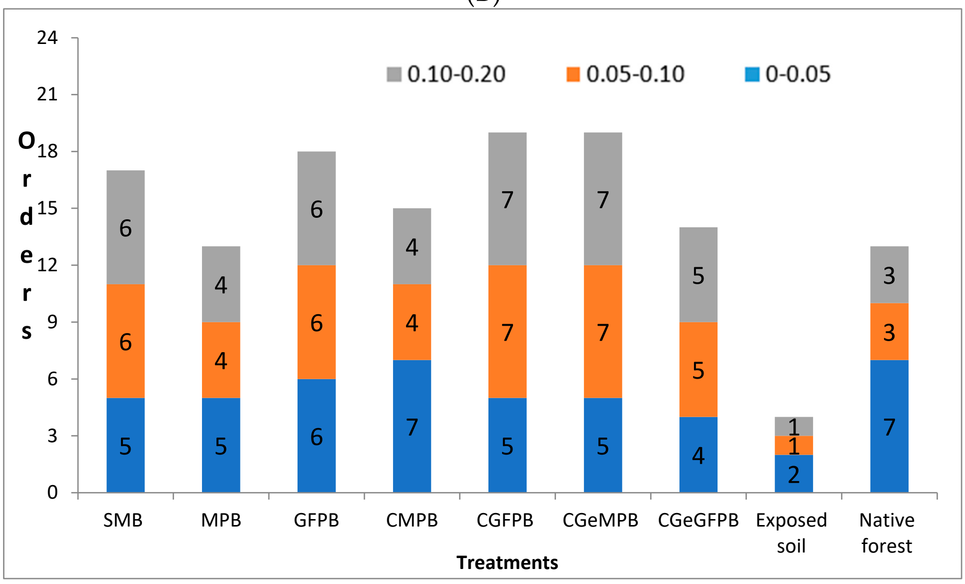
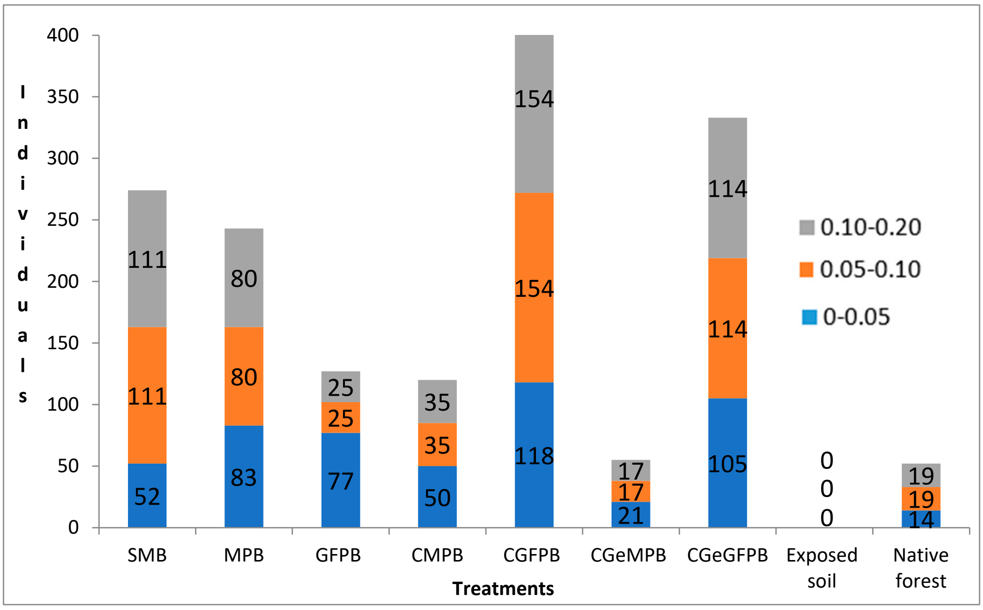


Figure 1. *Cont.*

Summer

(**C**)



(**D**)

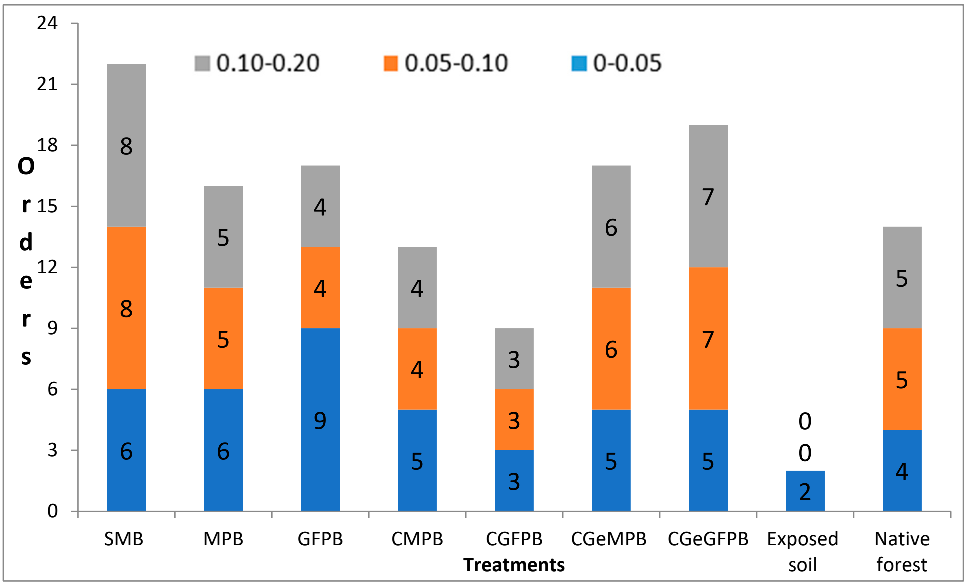


Figure 1. Time–space profiles of macroinvertebrates at different depths for (**A**) individuals—winter; (**B**) orders—winte, (**C**) individuals—summer; and (**D**) orders—summer at a site of Brazilian savannah recovered for 17 years by integrated systems of green fertilizers with pasture, with or without application of limestone and gypsum.

The integrated system of *Cajanus* sp., *Canavalia* sp. and *U. decumbens* with limestone was also microenvironmentally suitable for the growth, development and reproduction of termites and ants. This succession had moderate indexes of diversity and evenness. The integrated system of *Stizolobium* sp. with *U. decumbens*, with limestone and gypsum, interestingly was richer in termites, eggs and larval stages of arthropods taxonomically unidentified than other integrated systems but poorer in beetles, white grubs and adult centipedes. Evidently, the composition of the net of macroinvertebrates was dependent on the microclimate. The integrated system of *Cajanus* sp. *Canavalia* sp. and *U. decumbens* with limestone and gypsum also predominantly consisted of termites and had a relatively low count of adult centipedes and spiders, which are typical natural predators of mesoinvertebrates and macroinvertebrates in tropical, subtropical and temperate zones. The native forest was the genuine habitat of termites, earthworms, beetles, ants and stinkbugs. These macroinvertebrates grew at a relatively similar quantity. Generally, in the winter after 17 years in recovery, the integrated system of *Stizolobium* sp. with *U. decumbens* with limestone and gypsum provided the macrofauna from the top depth with the most technically pleasing indexes of diversity, dominance and evenness (Table 3).

Table 3. Ecological features of macrofauna of the Brazilian savannah site restored by integrated systems of green manures with pasture with or without application of limestone and gypsum after 17 years in recovery.

Integrated System	Period of Sampling							
	Winter				Summer			
Index	Diversity	Dominance	Evenness	Total Abundance (Ind m^{-2})	Diversity	Dominance	Evenness	Total Abundance (Ind m^{-2})
Exposed soil	0.10 e	1.00 a	1.00 a	0.15 c	0.00 h	0.00 h	0.00 f	0.00 i
SMB	1.61 b	0.11 b	0.23 b	3.58 a	0.97 c	0.40 c	0.54 b	5.70 c
MPB	1.61 b	0.15 b	0.29 b	2.90 b	0.85 d	0.35 d	0.47 c	5.35 d
GFPB	0.79 d	0.67 a	0.82 a	2.05 b	1.20 b	0.48 b	0.55 b	3.65 e
CMPB	1.95 a	0.23 b	0.37 b	1.93 b	0.65 e	0.23 e	0.40 c	2.60 f
CGFPB	1.61 b	0.54 a	0.70 a	3.18 a	0.20 g	0.30 d	0.18 e	7.93 a
CGeMPB	1.61 b	0.68 a	0.85 a	1.55 b	1.41 a	0.74 a	0.88 a	1.68 g
CGeGFPB	1.39 c	0.15 b	0.34 b	2.45 b	0.39 f	0.12 f	0.24 d	5.95 b
Native forest	1.95 a	0.33 b	0.44 b	3.58 a	0.60 e	0.35 d	0.43 c	1.08 h
F (5%)	4000 *	1190 *	1403 *	0910 *	6447 *	4828 *	3430 *	4591 *
CV (%)	2.14	7.69	5.85	14.37	6.60	12.20	7.46	0.62

Mean values followed by the same letters in the column do not differ according to post-hoc Tukey's HSD test; * significative by the post-hoc Tukey's HSD test at $p < 0.05$. CV (%): coefficient of variation.

In the summer, with 17 years of influence of the treatments, soil with cover of native vegetation with subsequent cultivation of *U. decumbens* retained a great number of termites and insignificant numbers of ants, white grubs, adult centipedes and beetles at a depth of 0.00–0.05 m. Unlike in the winter, with 17 years of influence of treatments, SMB had no counts of spiders, earwigs, adult millipedes, earthworms, stinkbugs and crickets, probably due to the morphophysiological sensitiveness of these macroinvertebrates to the constantly increasing temperature in the substrate. The succession of *Stizolobium* sp. with *U. decumbens* continued to have a predominance of termites over beetles, white grubs, ants and earwigs, making up the smaller insect orders, Coleoptera, Hymenoptera and Dermaptera, respectively. These macroorganisms enabled the MPB to have a higher total abundance compared to native forest and exposed soil, where macrofauna did not exist. Indeed, soil degraded by mechanical forces of earthworks and dam foundations was the harshest microclimate for the growth, development, reproduction and residence of functional groups of bioturbators, reorganizers and weathering agents of clay minerals. Technically similar to MPB, the integrated system of *Cajanus* sp., *Canavalia* sp. and *U. decumbens* also appeared to be microclimatically suitable for termites, geophages definitely predominant over beetles, white grubs, adult centipedes, earwigs, earthworms, stinkbugs, ants and crickets.

For all indices (diversity, dominance, uniformity, abundance) and two seasons of the year studied, there was a statistical difference. The exposed soil had less diversity and abundance of individuals, unlike the native forest and treatments with combinations of green manure + limestone + gypsum.

In the summer period, there was a greater number of termites in the superficial soil layer, followed by a smaller number of ants, lacrals and beetles. The results obtained in the exposed soil treatment characterize this as the least favorable environment for the development of soil fauna; consequently, the others were favorable and resilient in the recovery process.

Regarding the seasons, summer, due to the higher incidence of solar radiation and abundant precipitation (tropical climate), favored a greater number of individuals and the abundance of some treatments studied, such as combinations of green manure + limestone + gypsum.

The integrated system of *Cajanus* sp., *Canavalia* sp., *Stizolobium* sp. and *U. decumbens* with limestone and gypsum had significant indexes of Shannon, Simpson and Pielou, which were dependent on the specific abundance of termites. The native forest provided the macrofauna with the highest indexes of diversity and evenness in the winter. However, it was not technically and ecologically efficient in protecting spiders, white grubs, adult millipedes, earthworms and crickets from potential adversities of climatic changes in the summer. Apparently, similarly to the integrated systems, in the native forest there were also termites at the highest population density, possibly due to the acidity of the soil beneath litterfall. Globally, in the summer, *Stizolobium* sp. with *U. decumbens* with limestone and gypsum remained the most effective succession to provide the macroinvertebrates dwelling through the depth of 0.00–0.05 m with the most balanced indexes of diversity, dominance and evenness. Irrespective of succession, termites have been also persistently predominant at the depths of 0.05–0.10 and 0.10–0.20 m. The presence of termites in the treatments studied, including in the forest, is due to the genetic characteristic of the savannah soil, which is acidic, and termites are an indicator organism of soil acidity.

Other relevant groups dwelling abundantly through deep depths were beetles, white grubs and ants. By contrasting the periods of winter and summer, macroinvertebrates significantly moved from the top towards the deep depths of the soil. The migratory behavior of macroorganisms to deeper layers of the soil in the summer probably occurred because the more superficial layers reached higher temperatures.

The integrated systems significantly improved the chemical properties of the soil, in contrast to the reference (Table 4) 0–0.05 m depth with the largest availability of Presin, while the exposed soil had the lowest content of this macronutrient after several years of experimentation. In addition, CGeGFPB, CGFPB and MPB were apparently the most efficient integrated systems in concentrating Presin in the deepest depths of 0.05–0.10 and 0.10–0.20 m. The integrated systems had a relatively similar content of organic matter, regardless of the depth. Soil under the process of recovery had higher absolute values of pH in comparison to exposed soil and native forest, certainly due to the neutralization of H^+ by limestone undergoing multiple reactions with the soil to balance it chemically. The integrated systems of either *Canavalia* sp. or *Stizolobium* sp. with *U. decumbens* caused the top depth of 0.00–0.05 m to have the highest K content. Meanwhile, soil under *Stizolobium* sp. with *U. decumbens* with limestone and gypsum had lower K content when compared to the soil beneath litterfall from native forest.

Irrespective of soil depth, the native forest was the microclimate with the highest absolute values of Al^{+3}, potential acidity and CEC, lowest absolute values of SEC and saturation of exchangeable cations. Soils in the Brazilian savannah are generally high in potential acidity.

The Pearson product-moment correlation test accurately tracked significant correlations between macrofaunal and chemical properties of the site in the Brazilian savannah that were successfully recovered by successions of green manures and pasture with and without conditioning by limestone and gypsum (Figure 2). Amongst the main linear relationships, stinkbugs had positive correlations with termites (r = 0.50), earthworms (r = 0.75), beetles (r = 0.60), earwigs (r = 0.80), eggs (r = 0.80) and total of individuals (r = 0.45) but negative correlation with spiders (r = −0.45). Termites had a positive correlation with total of individuals (r = 0.95). The total of orders negatively correlated with potential acidity (r = −0.95). The saturation of exchangeable cations had a negative correlation with Al^{3+} (r = −0.75). SOM positively correlated with Presin (r = 0.85), K (r = 0.95), Mg (r = 0.85) and SEC (r = 0.65). The total of individuals had positive linear relationships with pH (r = 0.50), Presin (r = 0.50), K (r = 0.50), Mg (r = 0.70) and Ca (r = 0.50) but a negative linear relationship with Al^{3+} (r = −0.50). In line with the multivariate patterns recognized through the Pearson product-moment correlation test, principal component analysis robustly divided the high complexity net of linear associations between macrofaunal and chemical properties of restored soil into the subsets PCI, PCII, PCIII, PCIV and PCV. The explanations for these components are chemical neutralization of toxic elements, diversity of food sources on the soil, biological decomposition of organic matter, unavailability of aboveground biomass and predatory activity, respectively. These components collaboratively retained about seventy-five percent variance within orthogonally rotated subsets without the presence of collinear variables (Table 5).

Table 4. Chemical properties of Brazilian savannah soil restored by integrated systems of green manures with pasture with or without application of limestone and gypsum after 17 years in recovery.

Integrated System	P_{resin}	SOM	pH	K	Ca	Mg	H + Al^{3+}	Al^{3+}	SEC	CEC	SEC/CEC
	(mg dm^{-3})	(g dm^{-3})		(mmolc dm^{-3})							%
Soil Depth (m)	**0.00–0.10**										
Exposed soil	3.00 ^{D}	4.75 ^{C}	5.00 ^{A}	0.25 ^{C}	2.00 ^{C}	2.75 ^{A}	19.75 ^{A}	0.75 ^{A}	5.50 ^{A}	25.25 ^{C}	22.75 ^{AB}
SMB	6.75 ^{AB}	10.75 ^{AB}	5.00 ^{A}	1.00 ^{AB}	5.00 ^{AB}	4.25 ^{B}	23.75 ^{A}	1.75 ^{A}	10.25 ^{AB}	34.00 ^{BC}	29.50 ^{A}
MPB	7.25 ^{AB}	11.00 ^{AB}	5.00 ^{A}	1.25 ^{B}	5.5 ^{AB}	5.25 ^{C}	25.25 ^{A}	1.75 ^{A}	12.00 ^{AB}	37.25 ^{BC}	32.00 ^{A}
GFPB	7.75 ^{AB}	10.00 ^{AB}	5.00 ^{A}	0.75 ^{AB}	5.25 ^{AB}	4.25 ^{B}	24.75 ^{A}	1.75 ^{A}	10.25 ^{AB}	35.00 ^{BC}	28.75 ^{A}
CMPB	8.00 ^{AB}	11.75 ^{B}	5.00 ^{A}	1.00 ^{AB}	6.25 ^{AB}	5.00 ^{BC}	25.25 ^{A}	1.75 ^{A}	12.25 ^{B}	37.50 ^{BC}	32.50 ^{A}
CGFPB	7.00 ^{AB}	11.00 ^{B}	5.00 ^{A}	1.00 ^{AB}	5.50 ^{A}	4.50 ^{B}	23.5 ^{A}	1.25 ^{A}	12.00 ^{AB}	35.50 ^{BC}	33.50 ^{A}
CGeMPB	8.75 ^{A}	10.75 ^{AB}	4.75 ^{A}	1.00 ^{AB}	5.50 ^{A}	4.50 ^{B}	25.00 ^{A}	2.00 ^{A}	11.00 ^{AB}	36.00 ^{BC}	30.25 ^{A}
CGeGFPB	7.25 ^{AB}	9.00 ^{AB}	5.00 ^{A}	1.00 ^{AB}	4.00 ^{ABC}	3.25 ^{A}	24.50 ^{A}	2.25 ^{A}	8.25 ^{AB}	32.70 ^{AB}	24.50 ^{AB}
Native forest	4.25 ^{C}	12.75 ^{B}	4.00 ^{B}	1.00 ^{AB}	2.50 ^{AB}	2.75 ^{A}	36.50 ^{B}	6.75 ^{B}	5.75 ^{AB}	42.25 ^{A}	13.00 ^{C}
F-value	2.83 *	3.78 *	16.00 *	2.70 *	7.33 *	2.19 *	14.99 *	11.70 *	3.94 *	6.95 *	5.49 *
CV (%)	15.17	12.00	3.43	9.90	10.58	14.28	9.19	13.97	13.27	9.87	11.89
MSD	1.01	0.95	0.40	0.33	0.59	0.77	5.60	0.58	1.04	8.31	1.37
	0.10–0.20										
Exposed soil	3.00 ^{A}	3.25 ^{B}	4.25 ^{AB}	0.25	1.00 ^{B}	1.00 ^{A}	22.50 ^{BC}	2.25 ^{A}	2.25 ^{B}	19.70 ^{A}	9.25 ^{BC}
SMB	3.00 ^{A}	5.00 ^{B}	4.50 ^{AB}	0.20	4.25 ^{A}	2.00 ^{C}	20.75 ^{AB}	1.50 ^{A}	6.25 ^{A}	23.50 ^{A}	24.00 ^{A}
MPB	3.75 ^{A}	6.25 ^{AB}	4.25 ^{AB}	0.25	3.75 ^{A}	2.00 ^{C}	24.25 ^{C}	2.75 ^{A}	6.00 ^{AB}	21.7 ^{A}	20.75 ^{AB}
GFPB	3.00 ^{A}	6.75 ^{AB}	5.00 ^{B}	0.25	3.50 ^{A}	1.50 ^{B}	22.00 ^{BC}	1.75 ^{A}	5.25 ^{AB}	22.70 ^{A}	19.50 ^{ABC}
CMPB	4.75 ^{B}	5.75 ^{AB}	4.75 ^{AB}	0.25	3.75 ^{A}	2.00 ^{C}	23.00 ^{BC}	2.25 ^{A}	6.00 ^{AB}	22.70 ^{A}	21.25 ^{AB}
CGFPB	3.75 ^{A}	5.75 ^{AB}	4.75 ^{AB}	0.25	3.75 ^{A}	2.50 ^{D}	21.50 ^{BC}	1.50 ^{A}	6.50 ^{A}	24.5 ^{A}	23.75 ^{A}
CGeMPB	3.00 ^{A}	4.75 ^{AB}	5.00 ^{B}	0.25	3.50 ^{A}	1.75 ^{BC}	21.25 ^{B}	1.25 ^{A}	5.50 ^{AB}	22.20 ^{A}	20.75 ^{AB}
CGeGFPB	5.00 ^{B}	4.50 ^{AB}	4.75 ^{AB}	0.25	2.25 ^{AB}	1.25 ^{A}	18.75 ^{A}	2.25 ^{A}	3.75 ^{AB}	21.70 ^{A}	12.50 ^{ABC}
Native forest	3.00 ^{A}	8.00 ^{A}	4.00 ^{A}	0.25	1.00 ^{B}	1.00 ^{A}	32.75 ^{D}	7.75 ^{B}	2.25 ^{B}	30.20 ^{B}	6.75 ^{C}
F-value	0.43	4.11 *	2.84 *	1.12	9.15 *	2.64 *	68.16 *	7.83 *	6.36 *	7.79 *	10.83 *
CV (%)	19.05	10.76	9.15	18.88	11.45	12.00	4.07	17.31	12.60	9.04	11.89
MSD	0.98	0.67	1.00	0.50	0.55	0.47	2.32	0.77	0.73	5.00	1.23
	0.20–0.40										
Exposed soil	2.00 ^{A}	3.00 ^{A}	5.00 ^{AB}	0.20	1.00 ^{B}	1.00 ^{A}	21.50 ^{A}	2.00 ^{A}	2.00 ^{A}	23.50 ^{A}	9.25 ^{AB}
SMB	3.00 ^{AB}	3.75 ^{ABC}	4.50 ^{AB}	0.17	2.50 ^{AB}	1.25 ^{A}	21.00 ^{A}	1.50 ^{A}	3.75 ^{AB}	24.75 ^{A}	16.00 ^{ABC}
MPB	3.00 ^{AB}	4.50 ^{BC}	4.75 ^{AB}	0.12	2.50 ^{AB}	1.50 ^{A}	21.00 ^{A}	1.50 ^{A}	4.00 ^{AB}	25.00 ^{A}	16.75 ^{ABC}
GFPB	2.00 ^{A}	3.25 ^{AB}	5.00 ^{AB}	0.17	1.75 ^{AB}	1.25 ^{A}	21.75 ^{A}	2.25 ^{A}	3.00 ^{AB}	24.75 ^{A}	12.75 ^{ABC}
CMPB	2.00 ^{A}	4.00 ^{ABC}	5.20 ^{AB}	0.20	3.25 ^{A}	2.00 ^{B}	21.25 ^{A}	1.75 ^{A}	5.25 ^{AB}	26.50 ^{A}	20.00 ^{BC}
CGFPB	3.00 ^{AB}	5.00 ^{C}	5.00 ^{AB}	0.20	3.50 ^{A}	2.00 ^{B}	20.75 ^{A}	1.50 ^{A}	5.75 ^{AB}	26.50 ^{A}	22.00 ^{C}
CGeMPB	2.00 ^{A}	3.50 ^{AB}	5.00 ^{AB}	0.12	2.25 ^{AB}	1.25 ^{A}	21.00 ^{A}	1.75 ^{A}	3.50 ^{AB}	24.50 ^{A}	14.75 ^{ABC}
CGeGFPB	2.00 ^{A}	4.00 ^{ABC}	5.00 ^{AB}	0.17	2.00 ^{AB}	1.25 ^{A}	21.75 ^{A}	2.25 ^{A}	3.25 ^{AB}	25.00 ^{A}	13.75 ^{ABC}
Native forest	4.00 ^{B}	7.00 ^{D}	4.00 ^{A}	0.22	1.00 ^{B}	1.00 ^{A}	31.00 ^{B}	7.75 ^{B}	2.00 ^{A}	33.00 ^{B}	7.00 ^{BC}
F-value	5.40 *	22.80 *	2.67 *	1.99	4.08 *	1.26 *	21.38 *	28.22 *	3.58 *	13.45 *	5.41 *
CV (%)	14.34	10.29	9.50	27.20	13.72	12.92	6.33	9.16	14.51	5.90	11.38
MSD	1.03	1.23	1.10	0.12	0.58	0.48	3.40	0.40	0.74	3.68	1.05

Mean values superscripted by the same capital letters are not significantly different according to post-hoc Tukey's HSD test; * $p < 0.05$. CV (%): coefficient of variation; MSD: minimal significant difference.

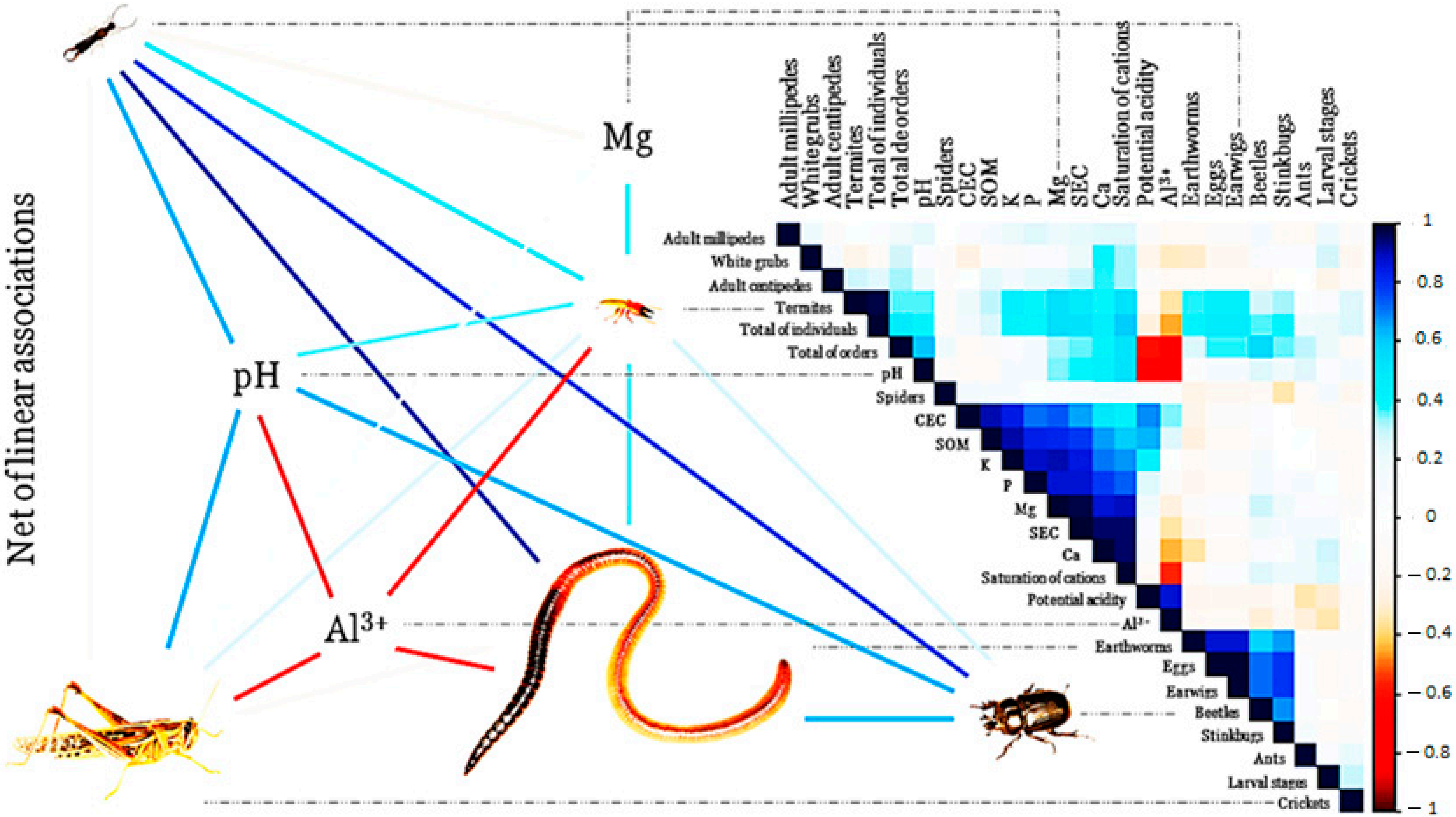


Figure 2. Correlogram for the linear associations between macrofaunal and chemical properties of the Brazilian savannah restored soil by long-term integrated systems of green manures with pasture with or without application of limestone and gypsum. Blue cells show positive linear associations between analytical variables placed along with the lines and columns in the data-to-viz card, while the red color represents negative linear associations. A few of the linkages of the net of linear associations are hard to read, but solid lines exist for macrofaunal and chemical properties at statistically understandable correlations.

Table 5. Principal component (PC) analysis for the macrofaunal and chemical properties of the Brazilian savannah soil restored by integrated systems of green manures with pasture with or without application of limestone and gypsum.

	Bartlett's Test of Sphericity				
Chi-square	8500				
Degree of freedom	325				
p-value	<0.05 *				
	Kaiser–Mayer–Olkin Test				
Index/variable	Principal Component				
	PCI	PCII	PCIII	PCIV	PCV
Eigenvalue	7.83	5.53	3.62	1.78	1.43
Percentage of variance	30.12	21.29	13.93	6.84	5.50
Cumulative percentage of variance	30.12	51.41	65.33	72.17	77.67
	Loading				
Spiders	0.06	−0.25	−0.16	0.13	0.04
Beetles	0.35	0.63 *	0.32	0.40 *	0.20
Adult millipedes	0.24	−0.08	−0.22	0.32	0.41 *
Earthworms	−0.10	0.78 *	0.50 *	0.01	0.06
Adult centipedes	0.32	−0.06	−0.17	−0.06	−0.76 *
Larval stages	0.14	0.09	−0.46 *	−0.14	0.68 *
Eggs	0.16	0.80 *	0.53 *	0.08	0.03
Termites	0.65 *	0.37	0.18	−0.48 *	−0.05
Earwigs	0.16	0.80 *	0.53 *	0.08	0.03
Ants	0.17	0.20	−0.28	−0.21	−0.12
White grubs	0.15	−0.01	−0.52 *	0.55 *	0.06
Stinkbugs	0.27	0.66 *	0.43 *	0.19	−0.02
Crickets	0.01	0.10	−0.16	−0.77 *	0.29
Total of individuals	0.69 *	0.45 *	0.09	−0.42 *	0.03
Total of orders	0.49 *	0.58 *	−0.34	0.24	−0.14
Presin	0.84 *	−0.35	0.12	0.06	0.03
SOM	0.72 *	−0.55 *	0.37	0.01	−0.04
pH	0.47 *	0.43 *	−0.48 *	−0.07	−0.17
K	0.82 *	−0.42 *	0.27	−0.01	0.03
Ca	0.90 *	−0.22	−0.31	0.06	0.01
Mg	0.96 *	−0.18	0.11	0.03	0.04
Potential acidity	−0.02	−0.69 *	0.67 *	0.05	0.05
Al^{3+}	−0.42 *	−0.57 *	0.63 *	−0.01	0.02
SEC	0.96 *	−0.21	−0.07	0.03	0.02
CEC	0.60 *	−0.55 *	0.48 *	−0.02	0.09
Saturation of exchangeable cations	0.95 *	0.01	−0.23	0.04	0.03
	Percentage of Contribution				
Spiders	0.04	1.13	0.71	0.95	0.09
Beetles	1.57	7.07	2.78	9.04	2.87
Adult millipedes	0.75	0.11	1.33	5.90	11.53
Earthworms	0.00	10.94	6.92	0.00	0.23
Adult centipedes	1.33	0.06	0.82	0.21	40.64
Larval stages	0.24	0.13	5.91	1.07	32.36
Eggs	0.32	11.53	7.65	0.39	0.07
Termites	5.35	2.43	2.11	13.13	0.18
Earwigs	0.32	11.53	7.65	0.39	0.07
Ants	0.38	0.71	2.11	2.48	0.93
White grubs	0.28	0.00	7.44	16.92	0.24
Stinkbugs	0.93	7.98	5.08	2.04	0.03
Crickets	0.00	0.18	0.72	33.28	5.91
Total of individuals	6.06	3.72	0.23	9.87	0.05

Table 5. *Cont.*

	Bartlett's Test of Sphericity				
Total of orders	0.49 *	0.58 *	−0.34	0.24	−0.14
Presin	0.84 *	−0.35	0.12	0.06	0.03
SOM	0.72 *	−0.55 *	0.37	0.01	−0.04
pH	0.47 *	0.43 *	−0.48 *	−0.07	−0.17
K	0.82 *	−0.42 *	0.27	−0.01	0.03
Ca	0.90 *	−0.22	−0.31	0.06	0.01
Mg	0.96 *	−0.18	0.11	0.03	0.04
Potential acidity	−0.02	−0.69 *	0.67 *	0.05	0.05
Al^{3+}	−0.42 *	−0.57 *	0.63 *	−0.01	0.02
SEC	0.96 *	−0.21	−0.07	0.03	0.02
CEC	0.60 *	−0.55 *	0.48 *	−0.02	0.09
Saturation of exchangeable cations	0.95 *	0.01	−0.23	0.04	0.03
	Percentage of Contribution				
Spiders	0.04	1.13	0.71	0.95	0.09
Beetles	1.57	7.07	2.78	9.04	2.87
Adult millipedes	0.75	0.11	1.33	5.90	11.53
Earthworms	0.00	10.94	6.92	0.00	0.23
Adult centipedes	1.33	0.06	0.82	0.21	40.64
Larval stages	0.24	0.13	5.91	1.07	32.36
Eggs	0.32	11.53	7.65	0.39	0.07
Termites	5.35	2.43	2.11	13.13	0.18
Earwigs	0.32	11.53	7.65	0.39	0.07
Ants	0.38	0.71	2.11	2.48	0.93
White grubs	0.28	0.00	7.44	16.92	0.24
Stinkbugs	0.93	7.98	5.08	2.04	0.03
Crickets	0.00	0.18	0.72	33.28	5.91
Total of individuals	6.06	3.72	0.23	9.87	0.05
Total of orders	3.11	6.04	3.17	3.25	1.42
Presin	9.01	2.26	0.39	0.24	0.05
SOM	6.69	5.55	3.75	0.01	0.12
pH	2.79	3.33	6.31	0.24	2.12
K	8.59	3.17	1.97	0.00	0.08
Ca	10.28	0.84	2.67	0.20	0.00
Mg	11.84	0.60	0.32	0.06	0.09
Potential acidity	0.01	8.65	12.33	0.14	0.19
Al^{3+}	2.27	5.83	10.88	0.01	0.03
SEC	11.87	0.78	0.13	0.05	0.02
CEC	4.57	5.45	6.29	0.02	0.60
Saturation of exchangeable cations	11.41	0.00	1.51	0.09	0.08
	Chemical neutralization of toxic elements	Diversity of food sources on the soil surface	Biological decomposition of organic matter	Unavailability of aboveground biomass	Predatory activity

* significative at 5% (p-value < 0.05).

The first component shows the integrated systems with limestone and gypsum to be positively correlated with the total abundance of macroinvertebrates, termites, Presin, SOM, K, Mg, Ca, SEC, CEC and, obviously, saturation of exchangeable cations. The chemical properties SEC, Mg, SEC/CEC, Ca and Presin had the strongest contributions to interpretable variance of chemical neutralization of toxic elements, followed by the macrofaunal properties, the total of individuals and specific abundance of termites, in that order. The second component was the proof of the native forest microclimate positively correlated with beetles, earthworms, eggs, stinkbugs, total of orders and pH, but negatively correlated with SOM, K, potential acidity, Al^{3+} and CEC. The macrofaunal properties earthworms, earwigs and eggs of arthropods taxonomically unidentified contributed nearly equally to the variance of diversity of food sources on the soil surface, followed by stinkbugs and beetles. The third component had positive loadings with earthworms, earwigs, eggs, Al^{3+} and potential acidity but a negative linear relationship with pH. The potential acidity had the largest percentage of contribution to variance of decomposition of organic matter, followed by Al^{3+} and the macrofaunal properties white grubs, earwigs and earthworms. Crickets and white grubs had positive and negative correlations with the fourth component, respectively; these groups of macroinvertebrates jointly explained the largest portion of variance of unavailability of aboveground biomass. Finally, larval stages of arthropods taxonomically unidentified, adult centipedes and adult millipedes had positive and negative correlations with the fifth component, respectively. Adult millipedes and larval stages jointly explained the largest portion of variance of predatory activity. Globally, potential acidity was the most suppressive chemical factor over the macrofauna in the exposed soil.

The multivariate regression analysis concretely enabled the outcomes of the Pearson product-moment correlation test and the principal component analysis for the taxon–microclimate relationship to fit. Despite the fluctuation in the values of AIC, BIC and Radj2, the regression models described the commendable improvements in soil macrofaunal properties, mainly depending on the neutralization of potential acidity, enhancement of availability of food sources and suitability of microhabitats under integrated systems with regular administration of limestone and gypsum as conditioners (Table 6). The lower the absolute values of AIC and BIC and the higher the value of Radj2, the more reliable and accurate the regression model is to predict how much the integrated systems of green manures and pasture changed the soil to make it chemically and biologically healthier.

Table 6. Parameters and goodness-of-fit of multivariate regression models for the taxon–microclimate relationship.

Variable	Fitted Regression Model †	AIC	BIC	Radj2
White grubs	White grubs (ind m^{-2}) = 0.25 + 0.45 Ca *	108.40	112.30	0.12
Adult centipedes	Adult centipedes (ind m^{-1}) = −0.12 + 0.09 Ca *	27.50	31.38	0.10
Termites	Termites (ind m^{-2}) = 24.09 − 11.48 Ca * − 5.61 K + 20.67 Mg * − 4.75 Al	245.20	252.90	0.32
Total of individuals	Total of individuals = 21.68 * + 8.98 Mg ** − 4.65 Al *	246.90	252.10	0.38
Total of orders	Total of orders = 2.18 − 34.21 SEC + 19.01 Potential acidity *	94.69	99.87	0.46
Soil organic matter	SOM (g dm^{-3}) = 2.78 ** + 0.19 P + 0.01 Ca + 6.55 K **	97.43	103.90	0.82
Spiders	Spiders (ind m^{-2}) = 0.69 ** − 0.30 Stinkbugs *	53.46	57.35	0.07
Termites	Termites (ind m^{-2}) = 18.81 ** + 10.73 Earthworms *	250.10	254.00	0.11
Eggs	Eggs (ind m^{-2}) = −0.01 + 0.19 Earthworms **	−45.63	41.74	0.75
Earwigs	Earwigs (ind m^{-2}) = −0.01 + 0.19 Earthworms **	−45.63	41.74	0.75
Beetles	Beetles (ind m^{-2}) = 0.90 ** + 1.07 Earthworms **	95.64	99.53	0.31
Stinkbugs	Stinkbugs (ind m^{-2}) = 0.08 + 0.54 Earthworms **	−46.10	49.99	0.43
Earwigs	Earwigs (ind m^{-2}) = −0.05 + 0.04 Beetles * + 0.15 Stinkbugs **	37.49	32.31	0.67
Beetles	Beetles (ind m^{-2}) = 0.84 ** + 1.57 Stinkbugs **	89.51	93.40	0.45

AIC: Akaike information criterion; BIC: Bayesian information criterion; Radj2: Adjusted R^2. * significative at 5% (p-value < 0.05); ** significative at 1% (p-value < 0.01).

The regression models assisted us in drafting the following insights on the taxon–microclimate relationship:

If the Ca content increases marginally, the visual count of white grubs would increase by 0.25 individuals per area unit. Therefore, the addition of Ca to the soil by applying limestone and gypsum combined with the decomposition of agricultural residues would be beneficial for the growth and development of young Coleoptera.

If the Ca content increases marginally, the visual count of adult centipedes would increase by 0.09 units. Therefore, microclimates richer in Ca would be more suitable for adult Dermaptera than those poorer in this macronutrient, whose major sources are certainly limestone and gypsum.

If the Al^{+3} content increases and the Mg content increases, both marginally, the visual count of termites would increase by about 25.4 individuals per area unit. The administration of gypsum or chemical calcium sulphate ($CaSO_4.2H_20$) would boost the population density of termites by complexing aluminum, thus protecting them from eventual adversities of this element, which was the most toxic physical property for both the floral and faunal components of the soil,

If the contents of P, K and Ca increase marginally, the soil organic carbon content would increase by 6.75 g dm^{-3}. Thus, the improvement in the availability of macronutrients from the conditioners and the degradation of mulching by genera of N-fixing plants throughout the years would concentrate organic matter. It is important to have technologies that protect the storage of organic carbon in the soil, considering its quick decomposition in tropical climates due the humidity and high temperatures.

If the number of earthworms increases marginally, the quantities of termites and beetles would both increase by about 10.75 and 1.1 units, respectively. Any change in soil structure caused by Haplotaxida would be beneficial for Isoptera and Coleoptera and even for earthworms at very low specific abundance.

4. Discussion

The soil bulk density and its total porosity, as well as the contents of Presin, SOM, K, Ca and Mg of exposed soil, in the field experiment were predictably out of the critical ranges described in the literature [34]. The integrated systems with and without the administration of limestone and gypsum greatly improved the physical and chemical properties of the site under investigation. After 17 years of hard experimentation, Presin content was significantly higher in successions of *Cajanus* sp., *Stizolobium* sp. and *U. decumbens* than in exposed soil. Symbiotic relations between the genera of N-fixing plants and plant growth-promoting microorganisms, such as endophytic and free-living bacteria and arbuscular mycorrhizal fungi, as well as the biological decomposition of agricultural residues by macro- and mesoinvertebrates were probably factors that positively influenced the availability of phosphorus in the depths of 0.00–0.10, 0.10–0.20 and 0.20–0.40 m. Additionally, increased contents of K, Ca, Mg and SOM, as well as increased SEC, CEC and saturation of exchangeable cations, could be the result of gradual reactions of the soil conditioners with H^+ and Al^{3+}, thus neutralizing their potential adverse impacts on the dynamics of organic and inorganic elements for the growth and development of faunal and floral components.

The soil pH for the treatments used for restoration had similar behavior, differing in the Brazilian savannah's superficial layer (the soils are naturally acidic). The similar pH in the superficial layer was due to the contribution of *U. decumbens* in the addition of organic matter in all experimental plots. Similar results were found by Franchini et al. [35]. They report that the presence of certain plant materials is capable of enhancing the effect of liming, mobilizing the so-called front alkaline. These organic compounds have the ability to complex and mobilize Ca and Mg, raise the pH and neutralize Al. Similar results were verified by Fonseca et al. [36]. The pH increase in their study with the phytomass decomposition of green manure may explain the increase in pH, mainly due to the contribution of organic matter. Raij et al. [37] reported that the contents of Presin and SOM in tropical soils in Brazil typically range from 13 to 30 mg dm^{-3} and from 16 to 30 mg dm^{-3}, respectively. The results of this work for the contents of Presin and SOM were lower than the ones reported in the literature. Despite the substantial improvement of chemical properties in the Brazilian savannah site, the integrated systems were not efficient enough when it came to Presin and SOM. Considering the macrofaunal patterns reported in the literature, the relatively low total count of macroinvertebrates was probably due to an unsatisfactory availability of Presin and SOM. Chemical properties certainly had a crucial influence on the time–space distribution and ecological features of macroorganisms dwelling through the depths of 0.00–0.05, 0.00–0.10 and 0.10–0.20 m. Therefore, one could expect the macrofauna to reach a great total count in microclimates where suitable food sources are available. Organic matter and nutrients are vital to meet the global energy demand for the food web of macroinvertebrates, regardless of climate [38–41].

The soil-dwelling macrofauna of the Brazilian savannah site consisted mostly of termites; beetles, white grubs and ants made up the other relevant smaller insect orders. These macroinvertebrates were more sensitive to edaphoclimatic changes during the process of restoring the degraded soil than termites, beetles, white grubs and ants. The macrofauna taxonomy was indeed dependent on the availability and quality of food sources and weather conditions, varying drastically with the microclimate, period of sampling and soil depth.

Marchão et al. [34] carried out a scientific study on the ecological aspects of macroinvertebrates under integrated crop–livestock systems in the Brazilian savannah. The authors found 194 morphospecies of macroinvertebrates belonging to 30 groups, orders or families, including mostly Coleoptera, Diplopoda, Formicidae, Isoptera and Oligochaeta. They asserted that conventional and integrated fields of soybean yielded exactly 105 and 102 morphospecies, respectively, while the permanent pastures had only 37 morphospecies, probably due to uncontrollable and unpredictable conditions for growth, development and reproduction. The authors still reported a total of about 4790 ind m^{-2} for native vegetation and 980 ind m^{-2} for integrated systems, which had lower species diversity and abundancy. Complementarily, the most predominant groups of macroinvertebrates were Isoptera and Formicidae, with significant values of specific abundance of roughly 4340 and 245 ind m^{-2}, respectively; Formicidae was the most substantial family with 60 morphospecies of Myrmicinae, Formicinae and Panerinae, which are subfamilies naturally occurring in forests and grasslands. Lammel et al. [42] conducted a scientific study on the microbiological and macrofaunal properties of conventional and organic systems of coffee crop. The authors reported that integration of coffee crop with *U. decumbens* and Arachis pintoi had macrofauna which heterogeneously consisted of Coleoptera, Hymenoptera, Isoptera, Mollusca and Oligochaeta. Contextually, a scientific study was performed on the spatial profile of macroinvertebrates and on soil properties [43]. The authors reported that the macrofauna of riparian forest mostly consisted of Aranae, Coleoptera, Dermaptera, Diptera, Haplotaxida, Hymenoptera and Mollusca, all of which jointly yielded a total abundance of 43.1 ind m^{-2}. They still stated that natural forests were richer in macroinvertebrates when compared to agroecosystems and artificial woodlands, which is in line with the results of this work, as the native forest was the most receptive microhabitat for the coexistence of Aranae, Coleoptera, Dermaptera, Diplopoda, Isoptera, Haplotaxida, Hemiptera, Hymenoptera and Orthoptera.

According to Sithole et al. [7], who performed a scientific study on the impacts of conservationist agriculture on soil properties and productive yield of corn crop (*Zea mays* L.), Aranae, Chilopoda and Gastropoda made up the macrofauna under a conventional system, whereas Coleoptera, Diplopoda and Isoptera composed the macrofauna under a no-tillage system, with a total abundance ranging from as low as 30 to upwards of 40 ind m^{-2}. The authors pointed out that plant material remaining on the soil surface improved the patterns of macrofauna by not only controlling the temperature and relative humidity but also by releasing food sources and offering worthy microhabitats for growth, development and reproduction. From the perspective of Suárez et al. [44], who performed a scientific study on the soil macrofaunal properties under land uses in the Colombian Amazon, Isoptera and Hymenoptera were predominant over other groups of macroinvertebrates, including mostly Aranae, Chilopoda, Diplura and Pseudoscorpionida. Out of all 7854 individuals, 2937 and 2241 were termites and ants, respectively, which is consistent with the predominance of termites over other macroorganisms in this study. The authors identified 21 taxonomic groups, which is inconsistent with the results of this study. A study on the effects of the preparation and management of agricultural systems for the production of corn crop on the chemical and physical properties of the soil macrofauna has been conducted [31]. The authors asserted that Aranae, Carabidae, Chilopoda, Enicocephalidae, Latridiidae, Lumbricidae, Scarabaeidae and Staphylinidae composed the highly heterogenous macrofauna of no-tillage and conventional systems, with or without the removal of plant material.

Wang et al. [45] performed a scientific study on the responses of macroinvertebrates to water stress in agroforest systems. The authors found macrofauna of 218 individuals belonging to 13 genera, 5 orders and 11 families; *Drawida* sp. and *Eisenia* sp. were the genera of earthworms with the highest percentages of 48.2 and 21.1% of the total samples from co-cropping systems of *Glycine max*, *Capsicum annuum* and *Zanthoxylum bungeanum*. They emphasized the physicochemical composition of plant material and relative humidity of the soil as relevant factors determining the composition of the food web of macroinvertebrates. Plant tissues of lower carbon to nitrogen ratio benefited the macroinvertebrates; in contrast, plant alkaloids offered potential risks to macroorganisms, especially earthworms, eggs and larval stages of arthropods. Velasquez and Lavelle [30] carried out a scientific study on macroinvertebrates as bioindicators of ecosystem services in agricultural landscapes. The authors reported that soil-dwelling macrofauna mostly consisted of Isoptera and Oligochaeta, with significant values of specific abundance of 1461 and 408 ind m^{-2}, respectively; other relevant groups were Coleoptera and Myriapoda, with lower values of specific abundance of 263 and 256 ind m^{-2}, respectively. They pointed out that the pastures improved the macrofaunal properties by cooling down the microclimate by shading, thus biologically preventing the macroinvertebrates from potential body dehydration due to high temperatures. It is worth citing this reference in this work in order to better understand how the morphological architecture and physiology of the pasture species *U. decumbens* could have assisted the integrated systems to restore macrofaunal properties of the Brazilian savannah site, mostly with regard to beetles and white grubs.

Webster et al. [32] performed a scientific study on macrofauna as a bioindicator of soil functioning in agroecosystems. The authors recorded an impressive 20 orders and 60 families of macroinvertebrates in pastures. Coleoptera, Hymenoptera, Isoptera and Oligochaeta were the most predominant groups; ants, earthworms, beetles and termites accounted for 37.8, 16.8, 15.4 and 12.4% of the total macrofauna, respectively. They still reported that pastures under degradation caused the earthworms to have a lower specific abundance of 27.3 ind m^{-2}, as compared to managed pastures with 56.9 ind m^{-2}, which is inconsistent with the results of this work. In the particular case of this study, Haplotaxida practically did not exist in integrated systems of green manures with *U. decumbens*, regardless of the application of limestone and agricultural gypsum. Globally, despite dissimilarities in diversity, richness, evenness and total abundance, orders and classes of macroinvertebrates reported through this work were relatively in agreement with the taxonomic aspects of the macrofauna reported in the literature. The taxonomic aspects of macrofauna vary drastically with land use, management practices and weather conditions as well as with other biotic and abiotic factors influencing the growth, development and reproduction of macroinvertebrates [46–48].

The long-term integrated systems of green manures with tropical pasture with or without the application of limestone and agricultural gypsum proved to be technically viable to recover soil macrofaunal properties of formerly degraded sites by earthworks and dam foundations. Irrespective of period of sampling and soil depth, the succession of *Stizolobium* sp. with *U. decumbens* with the application of soil conditioners had an insignificant count of macroinvertebrates and, consequently, a lower total abundance. Yet, this integrated system provided the macrofauna of the recovered site of Brazilian savannah with the most balanced indexes of diversity, dominance and evenness. Hence, *Stizolobium* sp. was simultaneously the most suitable N-fixing plant for the growth, development and reproduction of Aranae, Coleoptera, Dermaptera, Diplopoda, Hymenoptera, Isoptera, and eggs and larval stages of arthropods taxonomically unidentified under subsequent cultivation of *U. decumbens.* The next most ecologically suitable integrated system was the succession of *Cajanus* sp., *Canavalia* sp. and *U. decumbens* with limestone. In fact, the greater the availability of sources of organic and mineral elements released from the crop plants and soil conditioners during the process of recovery, the more appropriate the indexes of Shannon, Simpson and Pielou. The higher the diversity and evenness and the lower the dominance, the more versatility and advantages the macrofauna can provide for plant growth and development, such as improvement in the mechanical resistance of soil to penetration, formation and stabilization of biogenic aggregates, infiltration and retention of water, gaseous exchanges, cycling of nutrients, decomposition of organic matter and the controlling of temperature. In addition to availability, the quality of plant material was another relevant factor determining the patterns of soil-dwelling macrofauna. The C:N ratio may have influenced the decomposition of organic matter, making it readily assimilable for spiders, beetles, white grubs, adult millipedes, earwigs, adult centipedes, ants and termites, thus satisfying their respective energy demands. Further scientific studies on how physicochemical composition of plant material of the genera of green fertilizers *Cajanus* sp., *Canavalia* sp. and *Stizolobium* sp. influences the time–space distribution, diversity, dominance, evenness and total abundance of macrofauna of the Brazilian savannah are, therefore, necessary to validate the hypothesis.

In the winter, after 17 years of implementation of the research and monitoring of the properties of the soil under study, the exposed soil, interestingly, had the highest indexes of dominance and evenness, exclusively due to the inexpressive presence of termites making up the greatest insect order, Isoptera. Such a finding is of high importance to documenting how devastating the installation of a hydroelectric power plant is when it comes to the diversity and richness of the Brazilian savannah macrofauna and how termites are impressively resilient to the biologically, chemically and physically degraded soil by mechanical forces. In the summer, after 17 years of implementation of the research and monitoring of the properties of the soil under study, the total absence of macrofauna, including termites, in exposed soil meant that the anthropogenically degraded microclimate became much more sensitive to internal and external biotic and abiotic factors, suppressing the macrofauna. The noticeable scarcity of macroinvertebrates in the exposed soil was probably due to the continuously rising temperature, the low relative humidity of the soil and the low availability of food sources because of the low density of native vegetation in the process of natural recovery. Vegetation is evidently highly important in restoring and protecting the soil biota against stressing weather agents. Technically and ecologically, the more adequate indexes of diversity, dominance and evenness of macroinvertebrates dwelling through the depths of 0.00–0.05, 0.05–0.10 and 0.10–0.20 m in integrated systems and native forest proved how relevant the flora, either natural or artificial, was in the recovery of the macrofaunal properties of the heavily degraded Brazilian savannah site in the beginning of the field experiment that was conducted for 17 years. Effectively, the soil under mechanical degradation by earthworks and dam foundations was the harshest microclimate for the food web of macroinvertebrates. Increased contents of H^+ and Al^{3+} and decreased contents of SOM, Presin, K, Ca, Mg, in combination with heightened apparent density and microporosity, predictably declined the growth, development and reproduction of macroinvertebrates. Therefore, the macrofauna was dependent on the physical and chemical properties of the soil.

In the summer, after 17 years of implementation of the research and monitoring of the properties of the soil under study, the macrofauna increased to a higher density at the depths of 0.05–0.10 and 0.10–0.20 m. The high temperature and low relative humidity of the soil probably forced the macroinvertebrates to migrate from the top to deeper depths, where microhabitats were theoretically milder for the growth, development and reproduction of spiders, beetles, white grubs, adult millipedes, earwigs, adult centipedes, stinkbugs, earthworms, ants, termites, crickets, eggs and larval stages of arthropods taxonomically unidentified. The spatial distribution of the macrofauna was evidently dependent on the floral composition of the integrated system's physical and chemical properties of the substrate and on the weather agents. The rainfall, temperature, solar irradiance, relative humidity of the air, habits of dispersion and colonization top the list of the most relevant biotic and abiotic factors ubiquitously influencing the time–space profile of macroinvertebrates, as pointed by Marchão et al. [34]. The authors stated that savannah forest, pastures, conventional fields of soybean and integrated crop–livestock systems had a greater number of macroinvertebrates in the first 0.30 m; Coleoptera and Oligochaeta, with percentages of

85% and 75% of the total macrofauna, respectively, appeared to be more predominant at a depth of 0.00–0.10 m, beneath on forestry litterfall, whereas Diptera and Formicidae were present at higher abundance at a depth of 0.10–0.30 m, mostly in co-cultivation of legumes with pasture. Soil depth determines the spatial distribution of macrofauna because of the availability of food sources and gaseous exchanges through the pores. In a compacted soil, low oxygen flow often makes the macrofauna decline [44,49,50]. In sites heavily degraded by pedoclimatic or anthropogenic forces, macroinvertebrates commonly concentrate in deeper depths as a function of their adaptive mechanisms to stressing agents, such as high temperature and low moisture [45,51–53]. The escaping behavior of the macroinvertebrates was, therefore, a reliable bioindicator of macrofauna stressed by mechanical compaction and depletion of chemical properties, such as Presin and SOM.

According to Rampelotto et al. [54], who conducted a scientific study on the changes in abundance, diversity and structure of soil biota in the Brazilian savannah, dissimilarities in patterns of macrofauna under natural and artificial environments are normal. The authors asserted that the land uses (sugarcane field, pasture and forest) determined different trophic relations and behavior habits of bioturbators, reorganizers and weathering agents of clay minerals due to the particularities in the availability and quality of food sources as well as the physical and chemical properties of the substrate. Franco et al. [55] performed a scientific study on the association between soil structure and the abundance of macroinvertebrates under economic exploitations. The authors pointed out that 58% of the total macrofauna in pastures were termites, which is in line with the predominance of termites over other groups of macroinvertebrates reported in this work. They still stated that termites were the greatest soil engineering bioagents at performing foraging, tunneling and nesting; these habits provide the soil functioning with a wide range of ecological services, such as cycling of nutrients, decomposition of organic matter, formation and stabilization of biogenic aggregates, improvement of hydraulic flow and gaseous exchanges. These references are worth citing in this work to evidence how particular ecological aspects of integrated systems, exposed soil, and forest could have influenced in such exclusive ways the macrofauna of the Brazilian savannah and how the predominance of termites could have assisted the biosystems in rehabilitating the soil health. The genera of N-fixing plants, *Cajanus* sp., *Canavalia* sp. and *Stizolobium* sp., the species of pasture, *U. decumbens*, and termites were apparently complementary—the tropical crop plants offered worthy conditions for the food and reproduction habits of termites, while termites positively changed the microclimates, making them biologically, physically and chemically suitable for plant growth and development. The habits of termites may have assisted with the process of soil recovery in which green fertilizers and tropical pasture growing in harsh environments are used. Winter and summer pastures are biosystems technically effective at mitigating the degradation of soil biological, chemical and physical properties [56–61].

Kamau et al. [1] performed a scientific study on the effects of dominant tree species and gradient soil degradation on macrofauna. The authors reported a total abundance of 14 to 389 ind m^{-2} for earthworms, 82 ind m^{-2} for termites and 8 ind m-2 for spiders in artificial forestry systems of *Z. gilletii*, *Eucalyptus grandis* and *Croton megalocarpus*. They incisively asserted that the time of cultivation, availability and quality of plant materials, and soil chemical properties, mostly including total carbon and total N, were the most important factors influencing the trophic relationships, intensity, quality and regularity of ecological functions of macroinvertebrates. In the particular case of this work, the native forest was replete with termites, with a moderate number of beetles, earthworms and ants, which is inconsistent with the ecological features of the macrofauna reported in the literature. Effectively, the macrofauna is dependent on the forest ecosystem. In the Brazilian savannah, soils are naturally more acidic, richer in Al^{3+} and poorer in SOM and mineral elements. Such chemical properties could explain the inferiority of earthworms in relation to termites and beetles. Annelids are often more sensitive to the quality of substrate due to their more fragile body structure. Mechanization, pesticides and fertilizers pose risks to earthworms, termites, beetles, spiders, crickets and millipedes [1,62,63].

According to Melman et al. [31], the production of corn crop under a no-tillage system with preservation of plant material on the soil surface caused the macrofauna to increase its total abundance of 637 ind m^{-2} and body biomass of earthworms of 50.4 g m^{-2}, compared to conventional systems, with and without the removal of straw, which were 218 ind m^{-2} and 7.7 g m^{-2}, respectively. The authors attributed the results to improved structure, infiltration and retention of water, pH, electric conductivity, availability of organic carbon, total N and Presin. They complementarily argued that crop plants growing in symbiosis with plant-growth-promoting microbes, such as N-fixing bacteria and arbuscular mycorrhizal fungi, were often less responsive to earthworms. Considering the reference, a relatively lower count of earthworms under integrated systems consisting of genera of green fertilizers with tropical pasture with or without the application of limestone and gypsum was probably due to effective symbiotic relationships between *Cajanus* sp., *Canavalia* sp. and *Stizolobium* sp., and diazotrophic bacteria naturally existing in the soil.

The positive linear associations between stinkbugs, termites, earthworms, beetles and earwigs probably meant that these macroinvertebrates did not spend a substantial portion of energy on competing interspecifically for ecological niches and food sources. In particular, stinkbugs, beetles and earwigs were typical components of aboveground macrofauna, while the earthworms and termites were underground macroinvertebrates predominantly existing in the drilosphere and termitosphere, respectively. Foraging, tunneling and nesting habits by termites and earthworms may have positively influenced the stinkbugs and earwigs by indirectly increasing the availability of food sources, as well as by conditioning of the microclimate. Therefore, the greater the count of Coleoptera, Haplotaxida and Isoptera, the greater the count of Dermaptera and Hemiptera. The negative correlation between spiders and stinkbugs meant that Aranae was the natural enemy of Hemiptera. Therefore, the higher the predatory pressure of spiders on stinkbugs, the smaller the insect group of Hemiptera. This finding is of high importance to the development of biological control. The positive correlation between termites and the total of individuals was solely due to the predominance of Isoptera over other orders or classes of macroinvertebrates.

The negative correlation between the total of orders and potential acidity meant that the higher the cumulative content of H^+ and Al^{3+}, the lesser the spatial presence of Aranae, Coleoptera, Dermaptera, Diplopoda, Haplotaxida, Hemiptera, Hymenoptera, Isoptera and Orthoptera. This linear association proved that the exposed soil was indeed the harshest microclimate for the growth, development and reproduction of spiders, beetles, white grubs, adult millipedes, earwigs, adult centipedes, earthworms, ants, termites and crickets because of its high potential acidity. The higher SOM content and greater count of macroinvertebrates in integrated systems with nutritional supplementation of limestone and gypsum was in line with the correlations between macronutrients, organic matter and macrofauna. We confidently advocate the use of limestone and gypsum as the most affordable management practice to help the genera of N-fixing plants *Cajanus* sp., *Canavalia* sp. and *Stizolobium* sp. and the species of pasture *U. decumbens* to mitigate situations of soil degradation in the Brazilian savannah.

In line with the patterns recognized through the Pearson correlation test, the primary component referring to the chemical neutralization of toxic elements proved that the limestone and gypsum are technically effective in assisting integrated systems of green fertilizers with pasture to restore chemical and macrofaunal properties of sites formerly degraded by earthworks and dam foundations. The soil conditioners offered key benefits to the successions, including, but not limited to, the amendment of potential acidity by neutralizing H^+ and Al^{3+}, improvement of availability of minerals readily assimilable by crop plants, such as Ca, Mg and S, as well as hypothetical acceleration of decomposition of native organic matter and agricultural residues remaining on the soil surface after harvesting at the flowering stage. A high density of macroinvertebrates, specially termites, great availability of Presin, K, Ca, Mg and SOM and high SEC/CEC ratio were the most sensitive and reliable indicators of chemically balanced soil. The secondary component correlated positively with the total of the taxonomic orders but negatively with the potential acidity and SOM content, which meant the more diverse the sources of organic and mineral elements on the soil surface, the more heterogeneous the food web of macroinvertebrates dwelling in the soil beneath the litterfall. The ternary component described the earthworms and larval stages of arthropods taxonomically unidentified, as well as pH and potential acidity, as the most important biological and chemical indicators as to the degree of decomposition of SOM in the aluminum-rich, naturally acidic soil of the Brazilian savannah. With significant loadings between eigenvectors and PCIII, it is possible to point out that the more acidic the soil beneath the litterfall, the more intensive the natural decomposition of organic matter by earthworms, as well as the smaller the count of white grubs and larval arthropods. Macroinvertebrates in the beginning of the cycle of life are much more sensitive to acidic substrates than those at older stages. The quaternary component figured out that crickets and termites were the most sensitive and most reliable bioindicators of the unavailability of aboveground biomass. Thus, the lower the productive yield of biomass of integrated systems of green fertilizers and *U. decumbens*, the smaller the count of crickets and termites; in the particular case of termites, the unavailability of aboveground biomass may affect their habits of foraging and nesting. The quintenary component was in line with our expectation of adult millipedes to be natural predators of larval stages of arthropods taxonomically unidentified.

Franco et al. [55] carried out a scientific study on the relation between the visual structure of the soil status and the abundance of soil engineering invertebrates depending on different land uses. The authors reported a positive correlation between the total abundance and visual evaluation scoring as well as a negative correlation between Oligochaeta and Isoptera. Such linear features proved that the less structurally consistent the soil is, the higher the count of termites and the total abundance of macroinvertebrates, as well as the smaller the number of samples of earthworms in disturbed substrate. In this study, Oligochaeta and Isoptera contrasted each other in terms of spatial representativeness, proving that earthworms and termites were bioindicators of ecologically constant microclimates as well as their reestablishment, respectively.

According to Kamau et al. [1], earthworms correlated positively with P and K and negatively with lignin content in mulching; adult centipedes correlated positively with the ratios of C:N, C:P:lignin:N and polyphenols:N and negatively with N, P, Ca and Mg; termites correlated positively with Mg and negatively with N and P; earthworms and adult centipedes positively correlated with the physicochemical quality of root tissues, while the beetles, adult millipedes, ants and spiders did not correlate with physical and chemical properties of the aboveground biomass and root system.

When analyzing the reference systematically, the predominance of termites over other groups of macroinvertebrates dwelling through the depths of 0.00–0.05, 0.05–0.10 and 0.10–0.20 m in integrated systems of green fertilizers with tropical pasture, with application of limestone and agricultural gypsum, was probably due to the release of Mg and Ca from the soil conditioners rather than due to the mineralization of N-rich agricultural residues of *Cajanus* sp., *Canavalia* sp. and *Stizolobium* sp. Fitting multiple regression models such as the ones relating termites to chemical properties of the soil could support this analytical inference.

From the perspective of [7], adult centipedes prefer C-rich plant materials, while earthworms prefer lower ratios of C:P, C:K and lignin:N. The physicochemical quality of the root system of *U. decumbens*, which hypothetically is rich in C, may, therefore, be more suitable for the food habits of adult centipedes, thus supporting the predominance of Diplopoda over Haplotaxida in integrated systems. Additionally, specific abundance of the species of earthworms, Drawida sp. and Eisenia sp., positively correlates with N-$NH4^+$; the authors also emphasize that ammonium makes the soil acidic and increases the count of earthworms. The relatively higher density of Haplotaxida in the native forest reported in this work, compared to exposed soil and integrated systems, was probably due to the higher availability of N-$NH4^+$ from litterfall decomposition, as the earthworms and pH did not correlate with each other.

According to Webster et al. [32], patterns of macrofauna had significantly positive correlations with clay content and yield of mulching and negative correlations with percentage of exposed soil. The authors apprised the higher degree of compaction and the lower organic matter content as physical and chemical factors suppressing the macroinvertebrates in exposed soil. Therefore, the substantially low total abundance reported through these works for macroinvertebrates in exposed soil was not only due to high Al^{3+} content but also due to high apparent density, low macroporosity and low SOM content in the anthropogenically degraded site of the Brazilian savannah at the beginning of the experiment. These stress factors commonly reduce infiltration and retention of water as well as gaseous exchanges through the pores. Furthermore, the negative correlation between the macrofauna and the percentage of exposed soil reported in the literature is paramount to realizing how beneficial plant cover is in the process of recovering soil macrofauna and its chemical properties. The availability and quality of food sources, temperature of the soil and oxygenation are factors which influence the ecological characteristics of macrofauna, as reported in the scientific study by Abail and Whalen [41] on the dynamics of earthworm populations.

In this study, Aranae did not distinguish adequately restored soil from degraded soil, since spiders were present in integrated systems of green fertilizers with tropical pasture, exposed soil and native forest, despite their lower density, as compared to termites, beetles and ants. The most desirable characteristic for a bioindicator is being a generalist; other relevant characteristics include prediction accuracy and cost-effectiveness. Velasquez and Lavelle [30] argued that the Oligochaeta and Isoptera associated with old-growth forest, also termed as primary forest, and Coleoptera associated with fallow and pasture, thus corresponding very well with the results of this study for beetles and white grubs as well as for earthworms at higher densities in the presence of *U. decumbens* and native forest, respectively. The authors still described the Myriapoda as an order of detritivore macroinvertebrates in tight association with perennial crops and that Formicidae are associated with preserved, explored or burnt forestry systems. In line with the reference, ants did not perform as a bioindicator of neither the exposed soil nor the biologically restored soil in this work. Ants were also not reliable to study and assess the process of restoring degraded soil in the Brazilian savannah. For this purpose, the use of termites is confidently recommended. The next most suitable options would be beetles and white grubs, as the Coleoptera and integrated systems of green fertilizers with *U. decumbens* were strongly associated with each other.

5. Conclusions

The long-term integration of the genera of green fertilizers *Cajanus* sp., *Canavalia* sp. and *Stizolobium* sp. with the species of pasture *Urochloa decumbens* is an inexpensive, environmentally friendly strategy for the restoration of the macrofaunal properties of a Brazilian savannah site following anthropogenic degradation due to mechanical forces of earthworks and dam foundations after the installation of a hydroelectric power plant.

The integrated systems, with and without the administration of limestone and gypsum, improved the soil chemical properties of the site under investigation.

The macrofauna was a good indicator of soil recovery.

After 17 years of the effects of these treatments for soil restoration, the soil macrofauna is either similar to or even better than the natural soil conditions.

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