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Lower Contents of Soil Organic Matter, Macro-Nutrients, and Trace Metal Elements in the Longleaf Pine Forests Restored from the Mixed Pine and Hardwood Forests

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Abstract: Restoration of the longleaf pine forest ecosystem is critical for biodiversity. However, the mixed hardwood forests can grow naturally in the same area. There are limited studies comparing soil organic matter and nutrient contents for restoring longleaf pine forests from the mixed hardwood forest areas in the southeastern USA. In this study, a comparison of the contents in soil organic matter, macro-nutrients, trace metal elements, and litterfall amount, was conducted on the 16 forest stands (4 treatments including stand stages × 4 replicants) at William B. Bankhead National Forest in Alabama through the space-replace-time approach. The results indicate that longleaf pine forests have lower contents of soil organic matter, macro-nutrients, most trace metal elements, and litterfall amount than mixed hardwood forests. However, longleaf pine forests have higher soil Ca, Ba, and Pb contents than hardwood forests. Soil Fe content has more correlations with the contents of other metal elements than soil Mn. The results suggest that multiple ecosystem functions, including soil ecology, must be considered in the regional restoration of the longleaf pine ecosystem. Longleaf pine forests with a certain amount of mixed hardwood trees may be a good way to maintain soil organic matter and nutrients.

Keywords: Bankhead National Forest; litter production; soil organic matter; soil nutrients; space-replace-time

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1. Introduction

Longleaf pine (*Pinus palustris* Mill.) forests (LPFs) are among the most ecologically, economically, and culturally valued ecosystems in the southeastern United States [1,2]. Before European settlement, LPFs occupied about 37 million hectares, ranging from eastern Texas to southeastern Virginia [3]. Nowadays, LPFs can only be found in the remaining approximately 1.9 million ha and under fragmented conditions due to decades of timber exploitation, fire suppression, and forest land conversion [4]. Even though longleaf pine timber is still economically valued, LPFs mainly serve as biodiversity refugia because their "savanna" style forest structure and frequent surface fire regimes create valuable habitats for many species [5,6]. LPFs are reported as one of the most biologically diverse ecosystems in the world, as they support 900 plant species, 100 bird species, 36 mammal species, and 170 species of reptiles and amphibians across the range. In addition, included in this community are several endangered species, such as the red-cockaded woodpecker (*Picoides borealis*), gopher tortoise (*Gopherus polyphemus*), black pine snake (*Pituophis melanoleucus*), and a variety of threatened carnivorous plants (*Sarracenia* spp.) [7]. Restoring LPFs has recently become a regional forest management priority. However, the mixed pine and hardwood forests (MPHFs) also grow naturally in the southeastern region.

LPF restoration usually involves clearcutting or removing undesirable woody vegetation and MPHF, replanting longleaf pine seedlings, and maintaining a frequently prescribed fire regime (e.g., 2–5 years) to suppress the growth of hardwood trees [8]. At the same time, forests are required to store more carbon, primarily in soil carbon, to mitigate the increasing atmospheric CO_2 concentration. Replacing hardwood forests with longleaf pine by frequent prescribed burnings can significantly affect the soil organic matter and nutrient storage in forest ecosystems. Thus, comparing the contents of soil organic matter and nutrients in the LPFs and MPHFs is necessary.

Previous studies have indicated that forest conversion could result in the loss of soil organic matter [9], such as tropical forests being transformed into oil palm, rubber, and cacao [10–12]. Similar results occurred in other climate areas when their natural forests were transformed into forest plantations and others [13,14]. It is recognized that the soil's organic carbon stock changes are controlled by numerous (often interacting) factors, including climate, vegetation, parent material, topography, and time. Each factor varies with scales under different environmental settings [15]. However, at a small scale, soil moisture regimes play a vital role in regulating the microbial communities responsible for the decomposition of organic matter [16]. Also, soil mineralogy strongly affects the physical stabilization of carbon on mineral surfaces and makes it vulnerable to losses after land-use change [17,18]. Some trace metal elements may play critical roles in the ecological processes related to soil organic matter formation and nutrient cycling. The availability of manganese (Mn) is found to be negatively associated with carbon storage at humus layers in northern coniferous forests, with exchangeable potassium as an additional predictor [19,20]. The possible explanation for the Mn effect in the humus layer is related to the role of Mn-peroxidase enzymes in fungal-mediated decomposition [21,22].

For longleaf pine forests, despite the carbon flow from tree biomass to the soil in the form of decay products, litterfall, and others, the soils preserve little of recent inputs, which may be rapidly oxidized and lost to the atmosphere from periodic prescribed burnings or maybe washed out of the forest via soil erosion after burning [23]. Soil organic matter can directly affect the formation of soil organic carbon, and most soil organic carbon is concentrated in topsoil [23]. Furthermore, soil carbon accumulation was associated with clay and Fe contents. Under the regular management practices on the LPFs in this region, the mature LPFs would look like woodland (sparse trees) with limited aboveground biomass. The carbon storage capacity of LPFs mainly relies on the soil organic matter. Thus, this study aims to compare the soil organic matter and nutrients in the topsoil of restored LPFs and MPHFs. The specific objectives are to investigate (i) whether there are increased contents of soil organic matter and nutrients (including trace metal elements) in older LPFs than the young ones; (ii) whether LPFs at different stages hold more contents of soil organic matter and nutrients in the topsoil than in the MPHF; (iii) whether LPFs at different stages produce more litterfall amount than in the MPHF; and (iv) whether soil organic matter content is associated with Mn and Fe or other trace metals. The hypotheses are (i) lower soil organic matter content in LPFs than in MPHF and (ii) a negative correlation between soil Mn and soil organic matter contents. The results of this study will be helpful for deciding whether LPFs should be restored from the MPHF, which is important for regional forest planning and management.

2. Material and Methods

2.1. Study Area

The study area is in William B. Bankhead National Forest in Alabama of the USA (Short name Bankhead National Forest) (Figure 1), located in the Southwestern Appalachian zone according to the Alabama physiography. Its coordinates are approximately 34°05′ N

and 87°20′ E (see details in Table 1). Bankhead National Forest comprises approximately 73,654 ha of public land managed by the United States Department of Agriculture (USDA) Forest Service to protect the regional watersheds and streams. About 71,226 ha in this area are currently forested with major forest community types of upland hardwood and mixed pine-hardwood forests broadly classified as about 51 percent southern pines and 49 percent hardwoods [24]. The general soil type in this area is sandy loam soil derived from metamorphic sandstone rock. The taxonomic class of the soil at Bankhead National Forest is coarse-loamy, siliceous, semiactive, and thermic Typic Dystrudepts based on the National Cooperative Soil Survey. The soil pH is mainly acidic and varies from 4.5 to 7.0; other detailed characteristics can be found in [24–26]. The main pine species in this area are loblolly and montane longleaf, and the significant hardwoods are oak and hickory [24]. Topographically, the study stands are in relatively flat areas with an elevation from 200 to 250 m. Based on the recent 10 years of data from the weather station at the Double Spring, the average monthly air temperature ranges from 6 °C to 26 °C, and the annual precipitation is about 1420 mm. The monthly precipitation is about 100–150 mm, and there is slightly more rainfall in winters and springs but less rainfall in the early fall. The summer is hot and humid, and winter is cool and moist in this region. Since LPFs and MPHFs are not at the same location but are within the same region, the space-replace-time idea was used in this study.

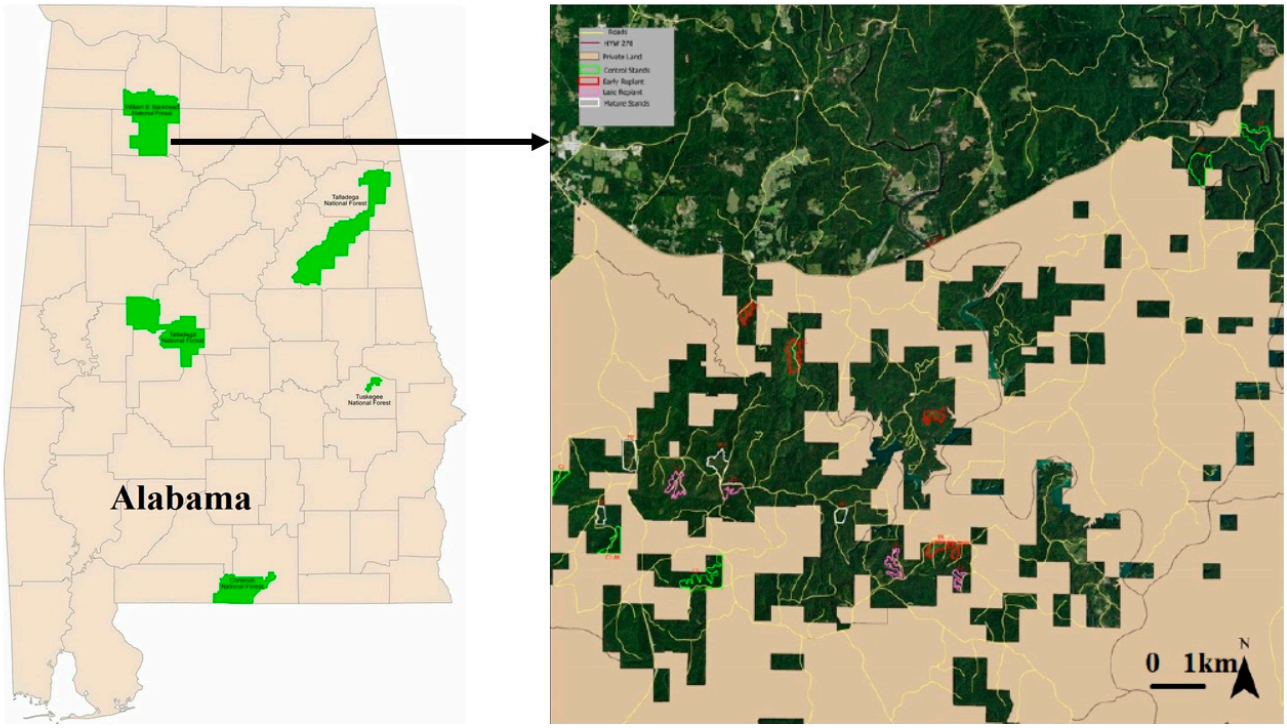


Figure 1. The location of the Bankhead National Forest in Alabama and the layout of study stands. (red line patches: early stage of longleaf pine forest; pink line patches: late stage of longleaf pine forest; white line patches: mature stage of longleaf pine forest; yellow-green line: mixed hardwood forest) (courtesy of Dr. Willian Sutton).

Table 1. The coordinates of each stand in four treatments (C: control, E: early stage of longleaf pine, L: late stage of longleaf pine, M: mature stage of longleaf pine).

Stands	Latitude (N)	Longitude (W)
C1	34°04′56.34″	87°23′56.29″
C2	34°04′10.36″	87°22′15.19″

Table 1. *Cont.*

Stands	Latitude (N)	Longitude (W)
C3	34°09′43.63″	87°14′32.95″
C4	34°10′11.94″	87°13′42.05″
E1	34°07′40.97″	87°21′49.90″
E2	34°07′14.93″	87°21′01.30″
E3	34°06′25.71″	87°18′47.19″
E4	34°04′39.51″	87°18′46.57″
L1	34°05′24.55″	87°22′44.90″
L2	34°05′32.66″	87°21′48.24″
L3	34°04′16.39″	87°19′16.34″
L4	34°04′09.12″	87°18′24.58″
M1	34°04′59.89″	87°24′10.55″
M2	34°05′45.47″	87°23′36.63″
M3	34°05′48.35″	87°22′11.90″
M4	34°05′10.10″	87°20′18.94″

2.2. Treatments

Some areas in the Bankhead National Forest have naturally regenerated montane longleaf pine forests. However, most longleaf pine forests were planted recently in areas where the MPHF grew. In order to compare soil organic matter and nutrients at the topsoil of LPFs at different successional stages, three stages were classified, which include the early stage (forest age $\leq$ 25 years), the late stage (25 years < forest age $\leq$ 75 years), and the mature stage (>75 years). Prescribed burnings were conducted at longleaf pine forests every 3–5 years. Thinning was conducted before LPFs turned into the late or mature stage. At a mature stage, old longleaf pine trees are usually sparse, and the understory has dense seedlings of longleaf pine, shrubs, and herbs. The mature MPHF stands (ages > 75 years) were used for comparison (Figure 2) because MPHF could grow there naturally if there are no management practices for LPFs. The main tree species in the MPHF include loblolly pine (*Pinus taeda* L.), sweetgum (*Liquidambar styraciflua* L.), tulip poplar (*Liriodendron tulipifera* L.), shagbark hickory (*Carya ovata* (Mill.) K. Koch), red oak (*Quercus rubra* L.), black oak (*Quercus velutina* Lam.), white oak (*Quercus alba* L.), American elm (*Ulmus americana* L.), black cherry (*Prunus serotina* Ehrh.), and others. Thus, there are four treatments, including MPHF and three successional stages of LPFs (early, late, and mature). For each treatment, there are four replications. The area of each replication is about 1–3 hectares. Based on a randomized block design, there are 16 stands (4 treatments $\times$ 4 replications). These stands are distributed across the southern part of the Bankhead National Forest (see Figure 1). The detailed coordinate information of these stands is listed in Table 1.



Figure 2. The stand conditions for four treatments ((**a**): The old mixed pine and hardwood forest; (**b**): the early stage of longleaf pine forest; (**c**): the late stage of longleaf pine forest; (**d**): the mature stage of longleaf pine forest) (courtesy of Dr. Willian Sutton).

2.3. Soil Sample Analysis

After removing the surface litter layer, five soil samples were randomly collected in the topsoil (0–20 cm) through a soil probe at each forest stand. Since the soil probe is skinny, it needs multiple points to collect sufficient mixed soil for one sample. These soil samples were stored in sealed plastic bags at a low temperature. There was a total of 80 samples (16 × 5). Each soil sample was dried and homogenized by passing through a <2 mm sieve, and roots, twigs, and green vegetation were removed by hand before all samples were sent for soil testing at the soil laboratory. The soil test included soil organic matter (%), total nitrogen (%), potassium (K, ppm), phosphorus (P, ppm), magnesium (Mg, ppm), calcium (Ca, ppm), aluminum (Al, ppm), arsenic (As, ppm), boron (B, ppm), barium (Ba, ppm), cadmium (Cd, ppm), chromium (Cr, ppm), copper (Cu, ppm), iron (Fe, ppm), manganese (Mn, ppm), molybdenum (Mo, ppm), sodium (Na, ppm), nickel (Ni, ppm), lead (Pb, ppm), and zinc (Zn, ppm). Total nitrogen and organic matter in soil samples were analyzed by thermal combustion, and the concentrations of metal elements were analyzed using a modified method of ICP digestion based on the EPA [27].

2.4. Litter Production

Due to access difficulty, litter production from three stands of each treatment was collected from September to December 2023. Five plastic buckets with a diameter of 20 cm were randomly placed in each stand. These buckets have holes and stones at the bottom so they can stay over there, and water will not accumulate inside. The collected litter (e.g., dead leaves, needles, and others) was dried and weighed. The average dry weight of the five collected samples was used to represent litter production at each stand.

2.5. Statistical Methods

One-way ANOVA was conducted to test the difference in soil organic, nutrients, metal elements, and litter production between the four treatments. The average values of the four stands within the same treatment were used to represent this treatment. Pearson correlation was conducted between soil organic matter and nutrients or litter production at the treatment and all soil sample levels. SAS software 10.3 (Cary, NC, USA) was used for the analysis (ANOVA and correlation). The statistical test was considered significant at $p < 0.05$.

3. Results

3.1. Comparison of the Contents of Soil Organic Matter and Nutrients in LPFs and MPHF

The soil organic matter content was the highest at the MPHF (Figure 3) and the lowest at the late stage of LPF. The soil organic matter content was similar at the early and mature stages of LPF. Soil nitrogen content was the lowest at the early stage of LPF (Figure 3) and the highest at the mature stage of LPF. The soil P and K concentrations reached the highest at the MPHF (Figure 3), and they decreased during the LPF's successional stages. The soil Mn concentration was the highest at the MPHF and the lowest at the late successional stage of the LPF (Figure 3). The soil Ca concentration was the highest at the mature LPF and the lowest at the MPHF. Other metal elements, such as Al, As, B, Cd, Cr, Cu, Fe, Mn, Na, Ni, and Zn, were highest in the MPHF. However, Pb content was the highest at the late successional stage of the LPF (Figure 3). Mg content was the highest at the early stage of the LPF. Restoring LPF on the MPHF leads to the loss of soil organic matter, soil nutrients, and most metal elements. However, some metal elements, such as Ca, Ba, and Pb, increased after LPF restoration.

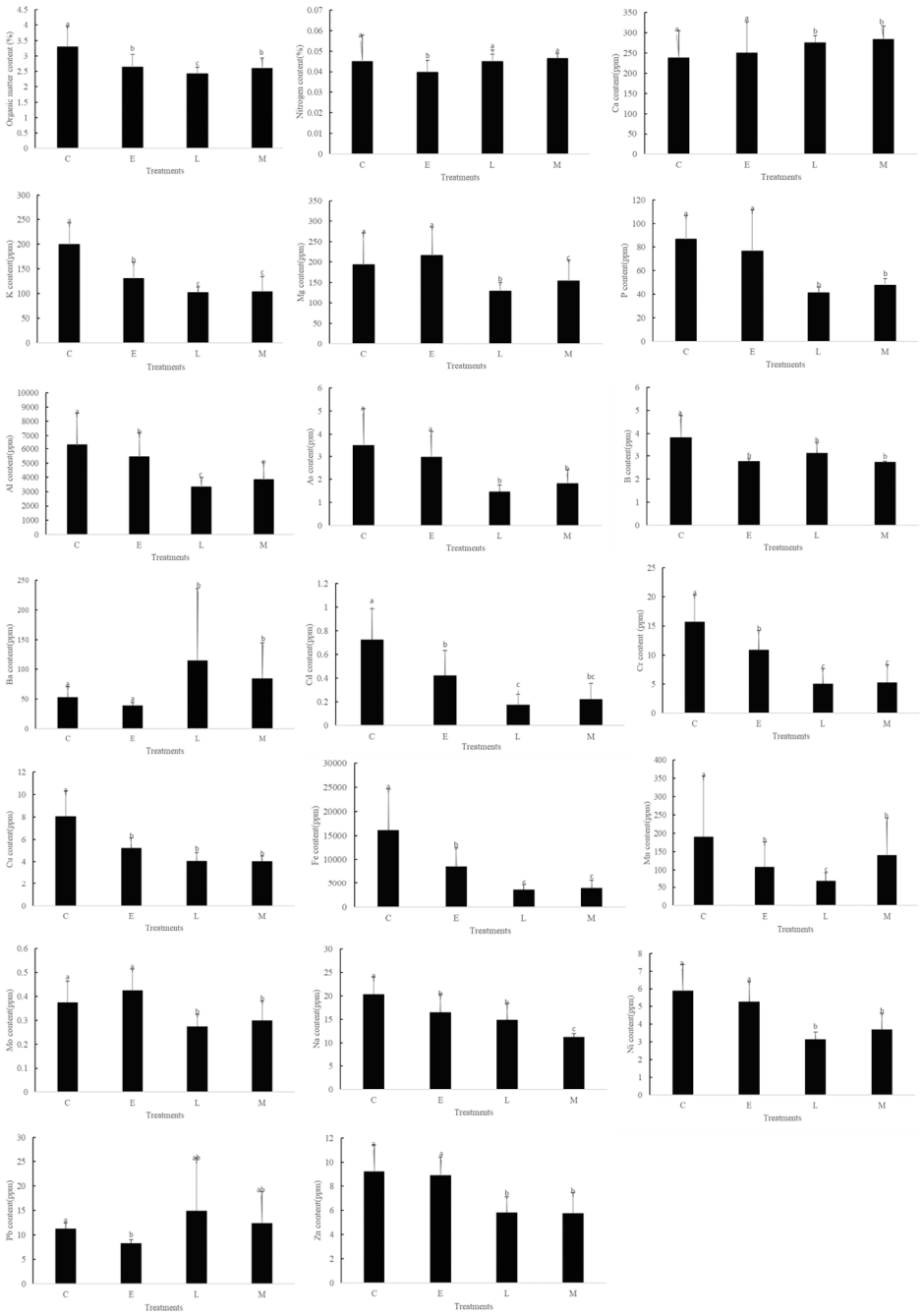


Figure 3. Comparison of the contents in soil organic matter, macro-nutrients, and trace metal elements at the mixed pine and hardwood forest and three stages of longleaf pine forest. (C: The old mixed pine and hardwood forest; E: the early stage of longleaf pine forest; L: the late stage of longleaf pine forest; M: the mature stage of longleaf pine forest. Different letters above error bars mean statistically different).

3.2. Correlations Among Soil Organic Matter, Macro-Nutrients, and Trace Metal Elements at the Treatment Level

At the treatment level, the soil organic matter content was positively correlated with most soil metal elements ($p < 0.05$) (Figure 4), including K, P, Al, As, Ni, B, Cr, Cd, Fe, Cu, Mn, Na, and Zn. It was negatively correlated with soil Ca content (Figure 5). However, the soil organic matter content was not significantly correlated with that of soil N, Mo, Ba, and Pb ($p > 0.05$). The soil N content was significantly correlated with the soil Mg, Mo, and Pb ($p < 0.05$) (Table 2). However, it was not correlated with other metal elements ($p > 0.05$), including Ca, K, P, Al, As, B, Ba, Cd, Cr, Cu, Fe, Mn, Ni, and Zn. The soil Mn

content was significantly correlated with Fe, K, P, Al, As, Cd, Cr, Cu, and Ni ($p < 0.05$) (Table 2), and it was not correlated with Ca, Mg, B, Ba, Mo, Na, Pb, and Zn. The soil Fe content was significantly correlated with that of more metal elements ($p < 0.05$), such as Ca, K, P, Al, As, B, Cd, Cr, Cu, Na, Ni, Mn, and Zn, and it was not correlated with that of Mg, Pb, Mo, and Ba ($p > 0.05$) (Table 2).

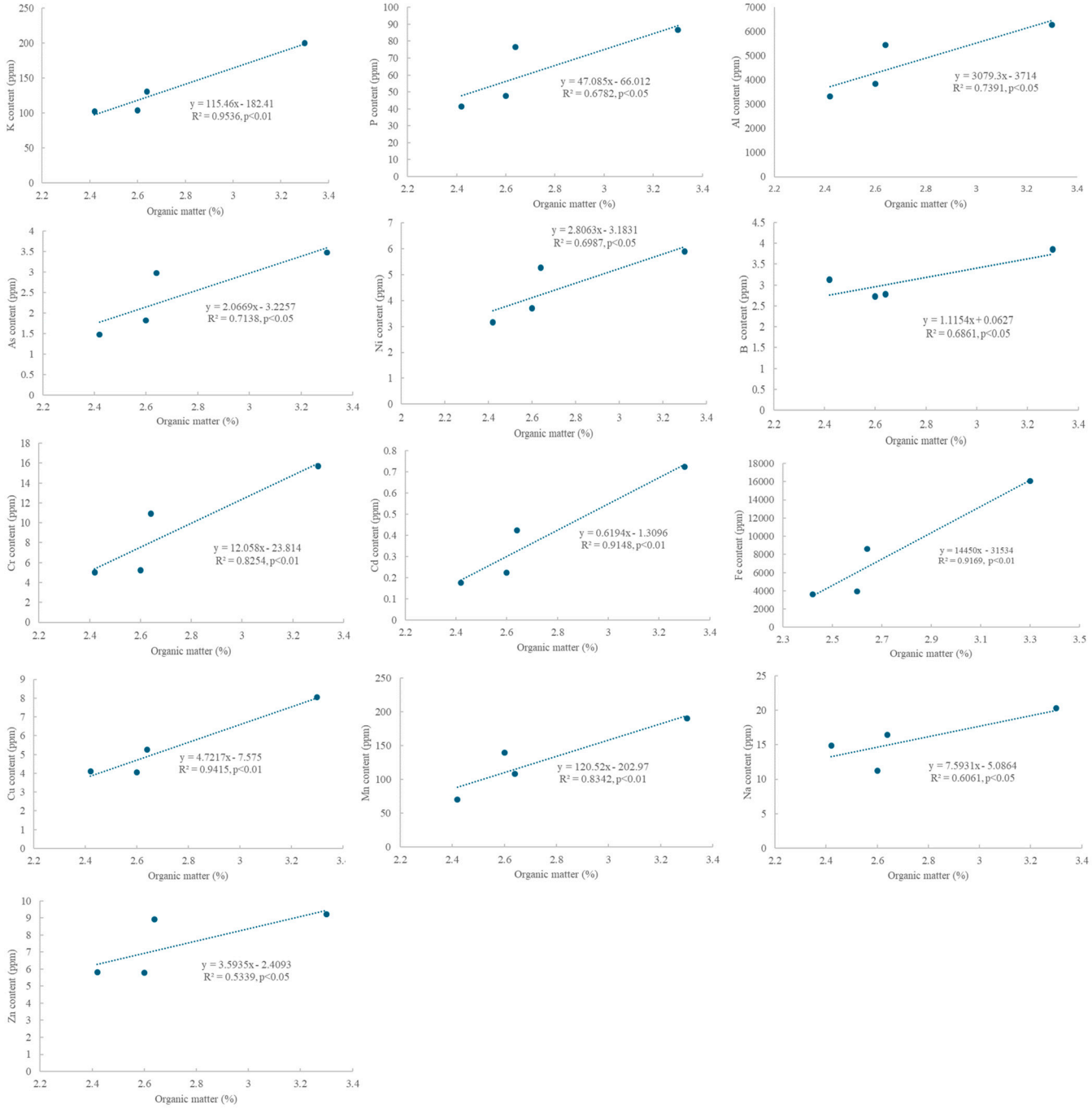


Figure 4. The positive correlation between the soil organic matter content and different elements on the treatment level.

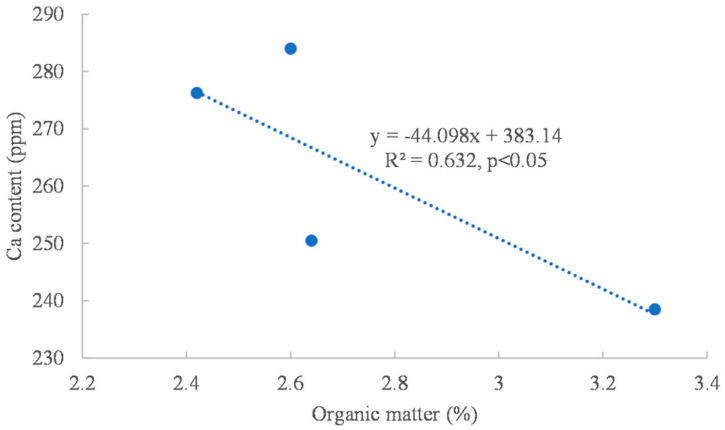


Figure 5. The negative correlation between soil organic matter and soil Ca contents.

Table 2. The correlation between the contents of soil N, Mn, and Fe with other metal elements (* indicates statistical significance).

Soil Metal Elements	N	Mn	Fe
Ca	Y = 3629.5x + 102.86 R^2 = 0.2575, $p > 0.05$	Y = −0.2318x + 291.81 R^2 = 0.3041, $p > 0.05$	Y = −0.0034x + 290.03 R^2 = 0.8754, $p < 0.01$ *
K	Y = −1067.7x + 180.87 R^2 = 0.0048, $p > 0.05$	Y = 0.7257x + 41.612 R^2 = 0.6559, $p < 0.05$ *	Y = 0.0078x + 71.245 R^2 = 0.9867, $p < 0.01$ *
Mg	Y = −9621.9x + 595.78 R^2 = 0.531, $p < 0.05$ *	Y = 0.3568x + 127.66 R^2 = 0.2164, $p > 0.05$	Y = −0.0046x + 136.13 R^2 = 0.4669, $p > 0.05$
P	Y = −3625.9x + 222.29 R^2 = 0.2363, $p > 0.05$	Y = 0.2933x + 25.68 R^2 = 0.4581, $p < 0.05$ *	Y= 0.0035x + 34.608 R^2 = 0.8648, $p < 0.01$ *
Al	Y = −197333x + 13393 R^2 = 0.1783, $p > 0.05$	Y = 19.794x + 2204.7 R^2 = 0.5317, $p < 0.05$ *	Y = 0.2245x + 2914.3 R^2 = 0.8947, $p < 0.01$ *
As	Y = −142.86x + 8.7139 R^2 = 0.2004, $p > 0.05$	Y = 0.0132x + 0.7571 R^2 = 0.5073, $p < 0.05$ *	Y = 0.0002x + 1.2124 R^2 = 0.8794, $p < 0.01$ *
B	Y = 45.095x + 1.1376 R^2 = 0.0659, $p > 0.05$	Y = 0.0061x + 2.3437 R^2 = 0.3562, $p > 0.05$	Y = 0.000007x + 2.54 R^2 = 0.6455, $p < 0.05$ *
Ba	Y = 7405x − 252.51 R^2 = 0.4184, $p > 0.05$	Y = −0.3682x + 119.67 R^2 = 0.3065, $p > 0.05$	Y = −0.0041x + 105.55 R^2 = 0.4881, $p > 0.05$
Cd	Y = −17.003x + 1.1345 R^2 = 0.0405, $p > 0.05$	Y = 0.004x − 0.1152 R^2 = 0.6478, $p < 0.05$ *	Y = 0.00004x + 0.0425 R^2 = 0.9951, $p < 0.01$ *
Cr	Y = −567.09x + 34.138 R^2 = 0.1073, $p > 0.05$	Y = 0.0732x − 0.0845 R^2 = 0.529, $p < 0.05$ *	Y = 0.0009x + 2.2249 R^2 = 0.9755, $p < 0.01$ *
Cu	Y = −54.838x + 7.7717 R^2 = 0.0075, $p > 0.05$	Y = 0.0293x + 1.6378 R^2 = 0.6296, $p < 0.05$ *	Y = 0.0003x + 2.7792 R^2 = 0.9883, $p < 0.01$ *
Fe	Y = −351921x + 23519 R^2 = 0.032, $p > 0.05$	Y = 89.858x − 3376.2 R^2 = 0.6173, $p < 0.05$ *	
Mn	Y = 4529.5x − 71.743 R^2 = 0.0692, $p > 0.05$		Y = 0.0069x + 71.891 R^2 = 0.6173, $p < 0.05$ *
Mo	Y = −18.734x + 1.1668 R^2 = 0.6462, $p < 0.05$ *	Y = 0.0005x + 0.2813 R^2 = 0.1312, $p > 0.05$	Y = 0.000008x + 0.2817 R^2 = 0.4234, $p > 0.05$
Na	Y = −411.27x + 33.787 R^2 = 0.1045, $p > 0.05$	Y = 0.0341x + 11.377 R^2 = 0.2131, $p > 0.05$	Y = 0.0006x + 11.006 R^2 = 0.8187, $p < 0.05$ *
Ni	Y = −200.21x + 13.302 R^2 = 0.2089, $p > 0.05$	Y = 0.0181x + 2.2007 R^2 = 0.507, $p < 0.05$ *	Y = 0.0002x + 2.8416 R^2 = 0.8621, $p < 0.01$ *
Pb	Y = 719.22x − 19.866 R^2 = 0.5998, $p < 0.05$ *	Y = −0.0181x + 14.04 R^2 = 0.1131, $p > 0.05$	Y = −0.0002x + 13.566 R^2 = 0.233, $p > 0.05$
Zn	Y = −394.03x + 24.748 R^2 = 0.3771, $p > 0.05$	Y = 0.02x + 4.866 R^2 = 0.2893, $p > 0.05$	Y = 0.0003x + 5.1184 R^2 = 0.7794, $p < 0.05$ *

3.3. Correlations Among the Contents in Soil Organic Matter, Macro-Nutrients, and Trace Metal Elements Across All Samples

Across all soil samples, soil organic matter content was only significantly correlated with soil N content ($p < 0.05$) (Figure 6), and it was not correlated with the contents of other elements ($p > 0.05$). Soil N or Mn contents were not correlated with others. The soil Fe content was significantly correlated with the content of soil K, P, Al, As, Cu, Mg, Cd, Cr, and Zn, respectively ($p < 0.05$) (Figure 7).

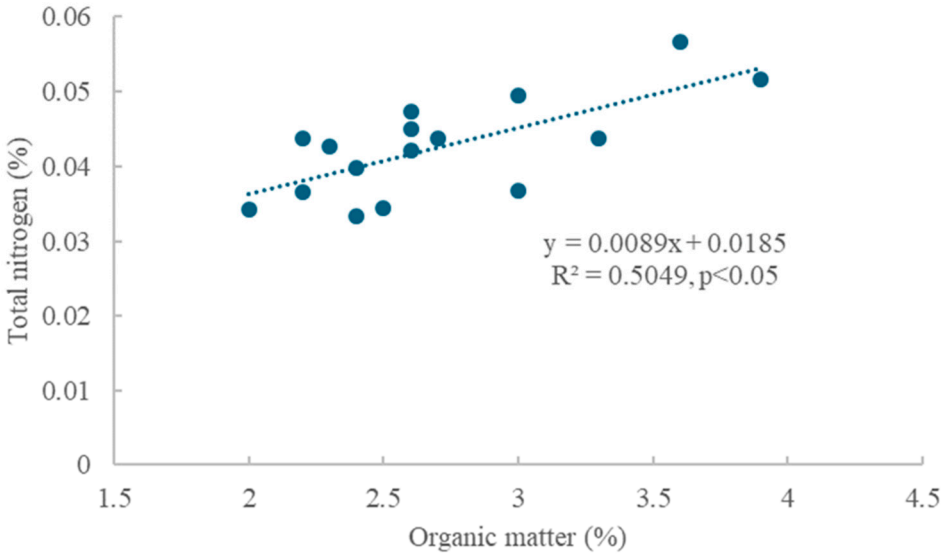


Figure 6. The correlation between soil organic matter and soil N contents across all soil samples.

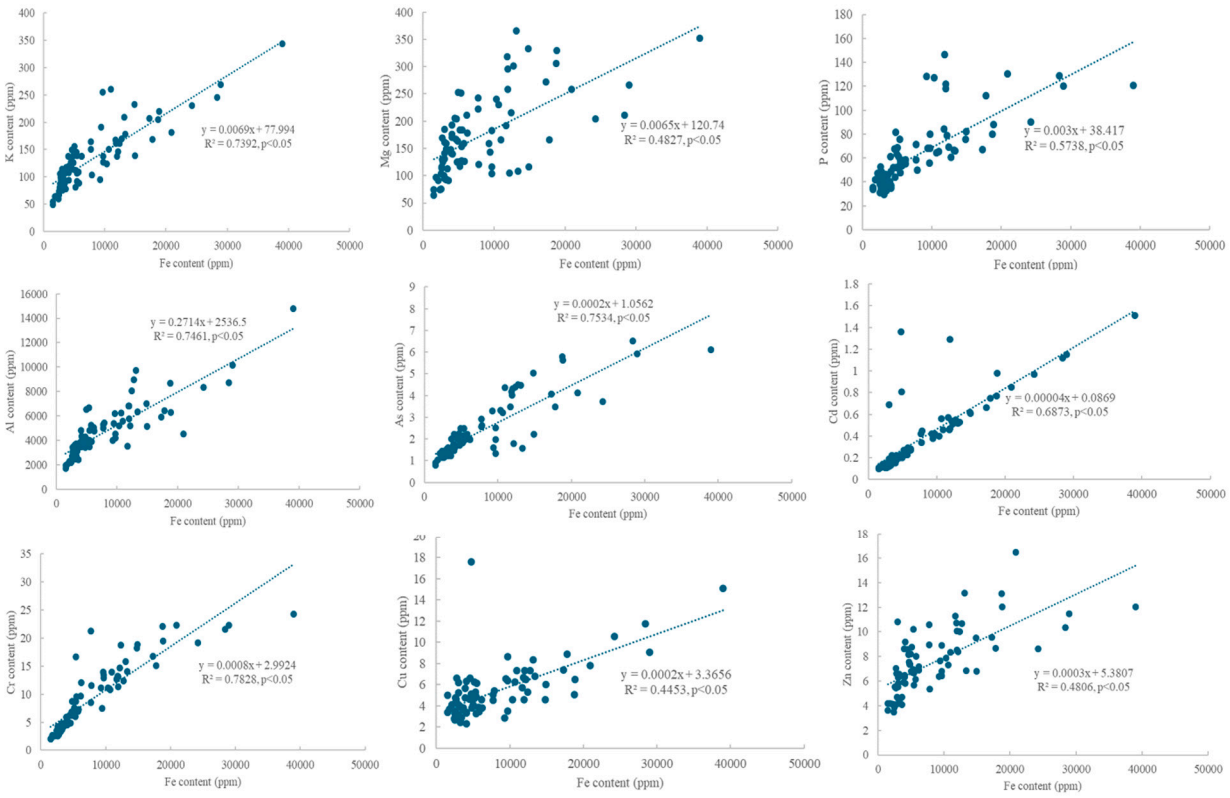


Figure 7. Correlations between the contents of soil Fe and other soil metal elements.

3.4. Comparison of Litter Production Between LPFs and MPHF

Forest litter production was the highest at the MPHF and the lowest at the early and late stages of LPF (Figure 8). At the treatment level, litter production was significantly correlated with the soil organic matter, K, B, Cu, and Mn contents ($p < 0.05$) (Figure 9).

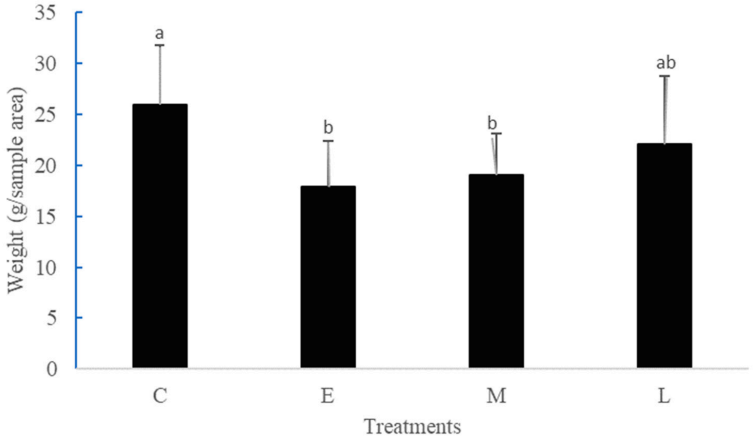


Figure 8. Comparison of litter production at the mixed pine and hardwood forest and three stages of longleaf pine forest (C: The old mixed pine and hardwood forest; E: the early stage of longleaf pine forest; L: the late stage of longleaf pine forest; M: the mature stage of longleaf pine forest. Different letters above error bars mean statistically different).

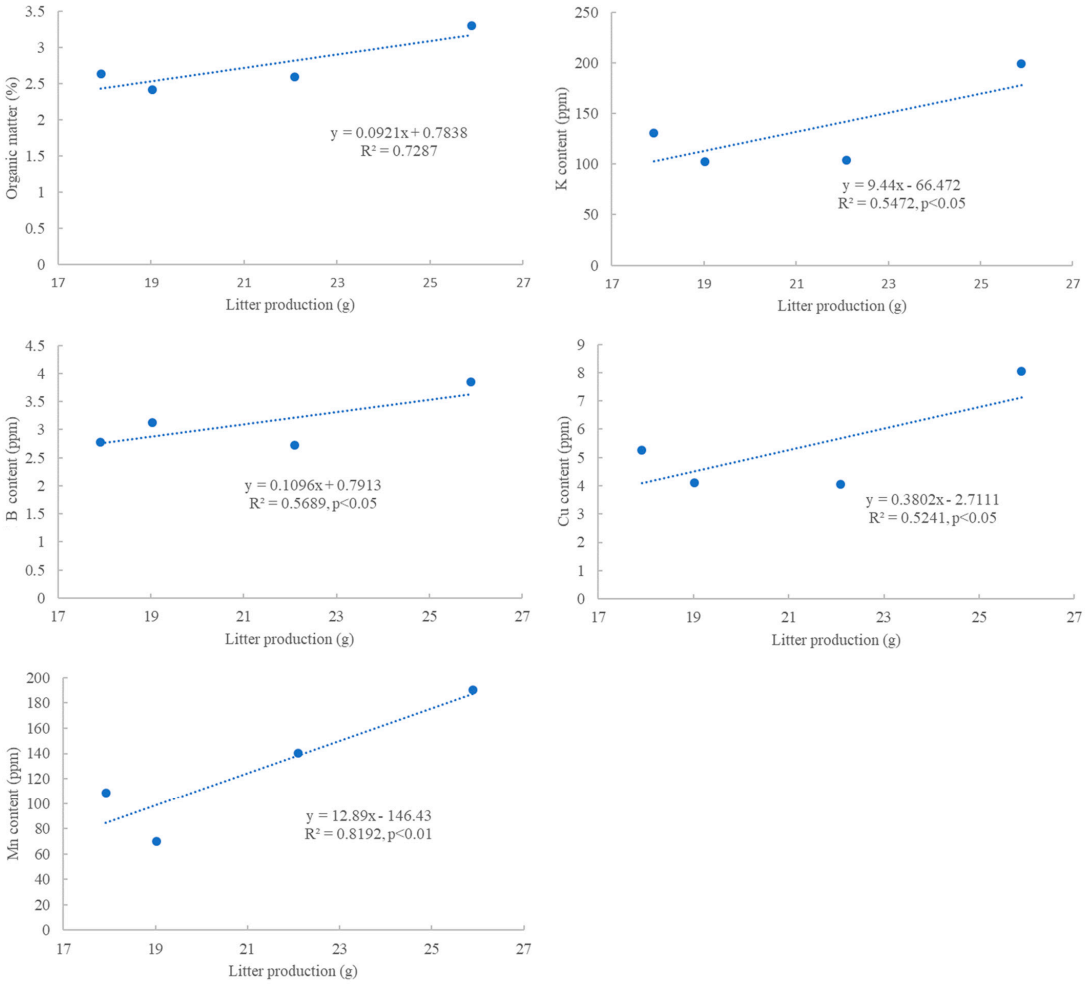


Figure 9. Correlation between litter production and the soil organic matter, K, B, Cu, and Mn contents on the treatment level.

4. Discussion

This study used the space-replace-time approach to compare soil organic matter and nutrients at the MPHF and different successional stages of LPF. This method was usually used to study slow ecological processes in static spatial data sets. This practice is problematic since ecological processes occur in time, especially in nonstationary environments [28]. Since restoring longleaf pine forests takes a long time, monitoring the soil's organic matter and nutrients for such a long time is not practical across a region. In addition, four stands, as replications to represent each treatment in this region, had limited spatial variations. It is reasonable to evaluate the contents of soil organic matter and nutrients based on the aboveground forest types and successional stages.

The soil organic matter content decreased by about 19% after the LPF replaced MPHF. This result confirmed the first hypothesis. The soil organic matter content continuously declined in LPF before the mature stage. The decrease of soil organic matter content should be related to the frequent burnings in LPF. The slight increase of soil organic matter content at the mature stage may be due to the increase of understory vegetation. Burnings lead to very little contents of organic matter on the ground and low soil N [29]. In fact, longleaf pine trees like to live on acidic and infertile sandy soils with low organic matter [30]. Burnings of accumulated organic materials result in soil C and N losses via volatilization. The soil organic matter fraction change was related to dehydrogenation, de-oxygenation, and decarboxylation under repeated burnings [25]. However, the ash, which consists of soil C and N, is considered to leach into the mineral soil [26]. The increase of soil N content is very limited in this study. Without prescribed burnings or with a longer burning interval, more woody debris accumulation, and hardwood tree establishment, it may have led to higher organic matter inputs. However, the development of hardwood trees at the LPF stands may affect the growth of longleaf pine because longleaf pine is a shade-intolerant species. Thus, restoring LPF from the MPHF will decrease soil organic matter (or carbon) content and increase air pollution due to prescribed burning [31].

The restoration of LPF on the MPHF also led to the loss of soil macro-nutrients (N, P, K). At least 10% of N, 30% of K, and 12% of P contents disappeared. This decline may be the direct effect of logging and prescribed burning and the indirect effect of soil erosion and leaching due to rainfall [32–34]. However, it depends on the severity of rainfall just after prescribed burnings. Losses in forest floor N and organic matter increased with the frequency of burning [35]. However, some early studies found increased N content in topsoil after burning [30,36] or no significant change in soil N and P contents [37]. Although multiple prescribed burnings were conducted on these longleaf pine stands, the result in this study indicated that the contents of soil nutrients in LPF changed with its successional stages (e.g., early stage, late stage, or mature stage). Overall, compared with the MPHF, the contents of soil macro-nutrients declined in the LPF.

Most soil metal elements had lower contents in the LPF than in MPHF, except for Ca, Ba, and Pb. The increase in soil Pb content might be related to the prescribed burning process, including applying gasoline for ignition [38]. The high availability of soil Ca content can affect tree species growth and forest dynamics [39], while high soil Ba content could be toxic to plants [40]. If a large amount of these elements were washed into a water body, the water quality would be degraded. However, a previous study found no change in Ca and Mg concentrations after the initial burning and thinning in the nearby mixed hardwood forest ecosystem [30]. Significant changes in the contents of magnesium, calcium, and sodium were also found over the pre-burn to post-burn and green-up time frame [32]. Trace metal elements in forest soil are mainly from litter decomposition through biogeochemical cycling. The function of metal elements is critical for forest ecosystems. The formation of stable soil organic matter is related to the microbial residues associated with

mineral surfaces [41]. Also, B plays a role in cell wall constituents and is highly required for plant reproductive structure [42]. The B concentrations in wood and bark are relatively high, and in two *Pinus sylvestris* stands, the proportion of B in stem wood and bark could reach 30% and 56% [43]. The difference in B content between forest ecosystems may indicate differences in physiological function, such as water use [44]. When B enters the root system, it is strictly transported in the xylem with the occurrence of transpiration [45]. B deficiency makes trees more susceptible to frost damage, such as the dieback of apical buds and wood deformation in tree stems [46]. Thus, tree growth and physiological processes can affect metal elements in soil. This study also found that soil Mn and Fe contents significantly correlated with the contents of soil organic matter and other metal elements, which does not support the second hypothesis. The soil Fe content has more correlations with others than Mn. This result means that Fe has a high co-occurrence with other trace metal elements for absorbing or binding. Fe-bound organic carbon (OC-Fe), an essential component of mineral-associated organic carbon, plays a crucial role in the accumulation and preservation of soil organic carbon through the formation of Fe–organic complexes [47,48]. However, soil Ca content has a negative correlation with that of Mn and Fe. The partial reason is that Ca is used to help longleaf pine interfere with disruption in photosynthetic reactions, phenolic biochemistry, or Mg function [44]. The information on metal elements in different pools (e.g., soil and foliar) must be integrated to fully understand forest growth and nutrient use. Further research on the biogeochemical processes of metal elements is needed in the LPF and MPHF. The major way to lose trace metal elements in forest soil may be leaching, harvesting, and burning. Thus, the current management approach (e.g., logging and burning) in longleaf pine restoration may cause a loss in soil metal elements, especially when the young longleaf pine forest was restored from the original hardwood forest area in several years (e.g., 3–5 years). Although there might be variability in nutrient changes from location to location, we should not continue to manage LPF ecosystems without improving soil fertility over the long term [49,50]. This long-term ecological process and the longleaf pine ecosystem restoration on soil organic matter and nutrient loss need considerable study [51].

At the treatment level, the soil organic matter content was positively correlated with litterfall and most soil metal elements. Litter production in LPFs increased by about 11% to 15% from the early stage to the late stage or from the late stage to the mature stage. This result is understandable because old longleaf pine trees produce more litter than young ones. The MPHF had produced 13% more litterfall amount than the mature LPF. Though the tree ages, density, and environment could affect litter production, this study's litter production of longleaf pine is about 50% more than was reported in South Carolina [52]. Generally, it is better to measure litter production for multiple years because of the high inter-annual variation in litter production. Litter production and accumulation contribute to organic formation, carbon sequestration, and soil fertility buildup. Based on personal observation in the study area, the fallen leaves were decomposed within several months, while needles may last longer. Hardwood leaf litter was also reported to contain high nitrogen content and facilitate decomposition [53].

5. Conclusions

Restoring longleaf pine forests through burning and harvesting hardwood tree species is important for this ecosystem. However, after comparing the contents of soil organic matter, macro-nutrients (e.g., N, P, K), and trace metal elements in the topsoil between the MPHF and LPF at three successional stages restored from hardwood forests in the Bankhead National Forest through the space-replace-time approach, the results indicated that the contents of soil organic matter, macro-nutrient, most trace metal elements, and

litterfall amount were the highest at the MPHF. This pattern could significantly affect the capacity of soil carbon and nutrient storage in the LPFs, although further detailed research on the processes should be conducted across the LPF range. It is unclear whether this is a general phenomenon across LPFs. Also, did periodic prescribed burnings and logging lead to this condition? The result of this study may have implications for the current policy and practices of longleaf pine forest restoration in mixed pine and hardwood forest areas. For most areas, it is hard to find large patches of hardwood forests within the longleaf pine historical range. A complete evaluation of the forest's multiple functions from different perspectives, including soil ecology, should be considered before ecological restoration. Longleaf pine forests mixed with patches of hardwood trees may be a good approach to maintaining soil organic matter and nutrients.

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