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The Effects of Fire Disturbance on Litter Decomposition and C:N:P Stoichiometry in a *Larix gmelinii* Forest Ecosystem of Boreal China

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Abstract: Fire disturbance can affect the function of the boreal forest ecosystem through litter decomposition and nutrient element return. In this study, we selected the *Larix gmelinii* forest, a typical forest ecosystem in boreal China, to explore the effect of different years (3 years, 9 years, 28 years) after high burn severity fire disturbance on the decomposition rate (*k*) of leaf litter and the Carbon:Nitrogen:Phosphorus (C:N:P) stoichiometry characteristics. Our results indicated that compared with the unburned control stands, the *k* increased by 91%–109% within 9 years after fire disturbance, but 28 years after fire disturbance the decomposition rate of the upper litter decreased by 45% compared with the unburned control stands. After fire disturbance, litter decomposition in boreal forests can be promoted in the short term (e.g., 9 years after a fire) and inhibited in the long term (e.g., 28 years after a fire). Changes in litter nutrient elements caused by the effect of fire disturbance on litter decomposition and on the C, N, and C:N of litter were the main litter stoichiometry factors for litter decomposition 28 years after fire disturbance. The findings of this research characterize the long-term dynamic change of litter decomposition in the boreal forest ecosystem, providing data and theoretical support for further exploring the relationship between fire and litter decomposition.

Keywords: forest fire; high burn severity; nutrient return; long term

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1. Introduction

Fire is becoming increasingly intense in the context of global climate change, which has a substantial and persistent impact on boreal forests [1–3], especially on the decomposition of litter and the cycling of nutrients [4,5]. Litter decomposition shows different change rules under different climate and soil conditions, so it is highly dependent on environment [6,7]. Climate factors such as temperature and humidity have a great impact on litter decomposition. Higher temperatures and humidity are conducive to the activities of decomposers in soil, thus affecting the decomposition of litter [8,9]. At the same time, the changes of soil factors have different effects on litter decomposition, mainly in two aspects: biological factors (soil animals, microorganisms, etc.) and abiotic factors (physical and chemical properties such as soil temperature, humidity, pH value, etc.) in the soil affect litter decomposition [10–13]. Therefore, the relationships between fire, litter stoichiometry, and decomposition become the key to boreal forest ecosystem carbon sequestration and fuel management after fire disturbance [14,15].

The litter decomposition microenvironment (e.g., increasing temperature and reducing water) changes after a fire, which affects the composition of the soil animal community [16] (e.g., decreasing large-scale springtails and increasing small-scale springtails). These interactions between litter fragmentation and soil organisms further promote litter decomposition and carbon (C) and nitrogen (N) mineralization [17–19]. In contrast, inhibition effects include decreased soil N and phosphorus (P) content [20,21]. This chemical imbalance aggravates the nutrient limitation of microbial activity [22], and the subsequent decrease in fungal biomass slows litter decomposition [1]. At the same time, the long-term effects of species invasion on vegetation and decomposers after fire will also affect the litter decomposition rate (k) and the cycling of nutrients [23–29].

There is no uniform regularity in the decomposition and change of litter after a fire; some studies have found that k increased after a fire [30–34]. In contrast, other studies found that litter k slowed after a fire [1]. In terms of stoichiometric changes, studies have shown that the decomposition of litter after a fire will cause high sensitivity to stoichiometric imbalances on local scales [22]. Under nutrient-sufficient conditions, the hydrolysis of C drives the decomposition of litter, microbial N restriction (high litter C:N or low litter N:P) and P restriction (high litter C:P or N:P) appear, and the driving effect of N and P on decomposition is enhanced [35–38]. Frequent fire disturbance reduces the coupling relationship between litter C:N:P stoichiometry, the N:P ratio of microbial biomass, and enzyme activity, and the forest tends toward an N-restricted ecosystem [39].

Although much research has been done on litter decomposition and the nutrient elements of litter [40–43], there is still no conclusion on the change in k and the nutrient return patterns of forest ecosystems in boreal China after disturbance by fire. In this experiment, we selected the *Larix gmelinii* forest, a typical forest ecosystem in boreal China [44], to explore the influence of high burn severity fire disturbance on the decomposition rate (k) of leaf litter and the C, N, and P stoichiometric characteristics. We hypothesized that (1) after high burn severity fire disturbance, k value will accelerate; (2) high burn severity fire disturbance will retard the return of N and P nutrients to forest litter; and (3) the main driving factors affecting litter decomposition in the boreal forest after fire were litter C, N, and C:N. In order to verify the above hypotheses, the objectives of this study were to clarify the long-term variation pattern of litter decomposition in the boreal forest of China after high burn severity fire disturbance, to explore the relationship between litter decomposition and litter C:N:P stoichiometry after fire disturbance, and ultimately to provide data support for the post-fire restoration in boreal forest ecosystems.

2. Materials and Methods

2.1. Site Description

The experimental study was located in the Great Xing'an Mountain area, China (52°09′07″ N, 125°19′55″ E to 52°23′24″ N, 125°114′48″ E; Figure 1). This area is the main forest in northern China, on the southern edge of the Siberian ecosystem. Forest fires also occur frequently [45,46]. The climate of the area is a continental monsoon climate in a cold temperate zone. The atmosphere is humid and rainy in the summer. The annual average temperature is −2.8 °C, the minimum temperature is −52.3 °C, and the frost-free period is 90–110 days. *Larix gmelinii* forest is the top zonal plant community. The dominant woody plants in this area are *Larix gmelinii*, *Betula platyphylla*, and *Populus davidiana*.

To verify the role of fire (regardless of the time since fire disturbance and of both the upper and lower litter layers) in the linear relationship between litter stoichiometry and litter decomposition, we used the k value of various fields and the corresponding annual average stoichiometric value for linear fitting.

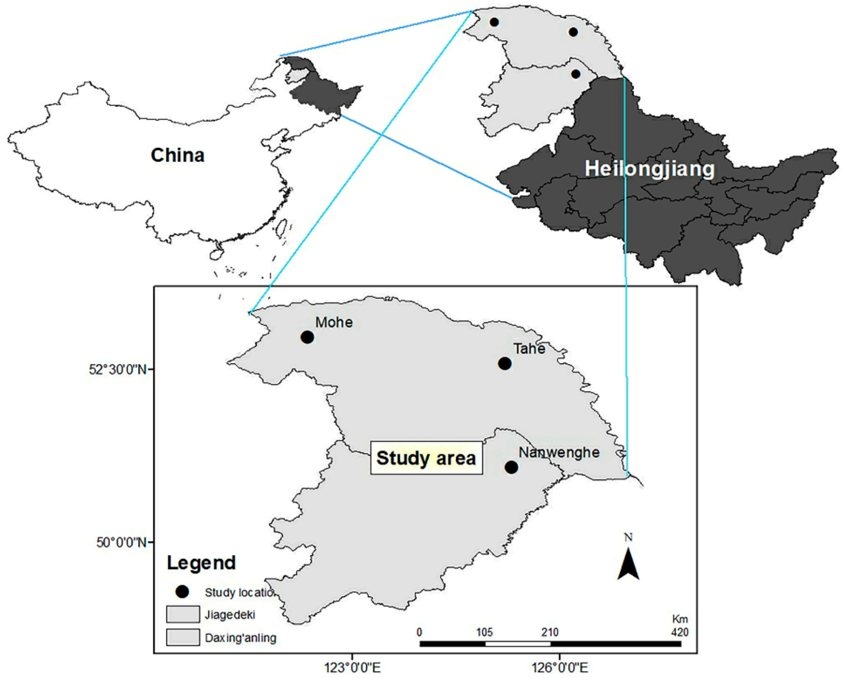

Figure 1. Map of the study region.

2.2. Experimental Design

We selected three sites of Larix gmelinii forest in the Great Xing'an Mountains that had burned in 1987 (Tahe), 2005 (Nanwenghe), and 2012 (Mohe) as the fire disturbance test sites (Figure 1), and we investigated the basic soil data (Table 1). All fire samples were subject to high-severity fire. We selected three replicate stands in the burned area to conduct our investigation, and we selected the nearby unburned area as the control in each burned area. A total of 18 experimental stands were selected in the burned and unburned areas for our study conducted in May 2015. The size of each stand was 400 m^2 (20 m × 20 m), and the distance between stands was more than 200 m to ensure the independence of data acquisition. In each research area, an adjacent unburned forest was selected as the control stand. To show that the difference in the decomposition of litter was caused by fire disturbance rather than litter itself, we placed the same litter bag in the burned and unburned control stands in each area (Figure 2). To consider the response of litter decomposition to environmental changes after fire disturbance, we divided the litter into layers to clarify the mechanism of litter decomposition.

Table 1. Overview of the study area (*n* = 3).

Sample	**3YSF**		**9YSF**		**28YSF**	
	Unburned	**Burned**	**Unburned**	**Burned**	**Unburned**	**Burned**
Dominant species	1 *	1 *,2	1 *,2	1 *,2	1 *,2,3	1 *,2
Mean height(cm)	26.2 ± 2.0	18.1 ± 3.2	14.4 ± 2.3	13.0 ± 1.5	22.0 ± 3.5	14.3 ± 1.6
Average tree height (m)	24.7 ± 1.5	20.1 ± 2.2	17.0 ± 1.3	16.5 ± 0.6	22.5 ± 1.1	16.4 ± 0.8
Canopy density	0.8 ± 0.2	0.7 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.6 ± 0.1
Age (a)	70	45	50	50	60	55
Humus thickness (cm)	9.2 ± 1.2	2.5 ± 0.2	10.5 ± 1.0	6.2 ± 0.6	11.5 ± 2.3	6.3 ± 0.5
Soil TOC ($g{\cdot}kg^{-1}$)	54.26 ± 4.40	74.20 ± 25.31	83.29 ± 26.12	99.25 ± 9.69	140.88 ± 34.53	76.16 ± 32.03
Soil TON ($g{\cdot}kg^{-1}$)	6.94 ± 0.78	7.56 ± 0.74	4.43 ± 1.40	6.75 ± 1.62	9.59 ± 1.02	5.72 ± 0.18
Soil AP ($mg{\cdot}kg^{-1}$)	40.67 ± 4.55	54.35 ± 23.47	57.71 ± 6.29	13.49 ± 2.29	28.66 ± 7.17	26.55 ± 16.47
Soil bulk density ($g{\cdot}cm^{-3}$)	0.82 ± 0.01	0.58 ± 0.08	0.80 ± 0.06	0.61 ± 0.16	0.65 ± 0.27	0.62 ± 0.04

Note: Data are the mean ± standard error *: Dominant species; 1. *Larix gmelinii* Pupr. 2. *Betula platyphylla* Suk. *Populus davidiana* Dode. 3YSF: 3-year postfire, 9YSF: 9-year postfire, 28YSF: 28-year postfire.

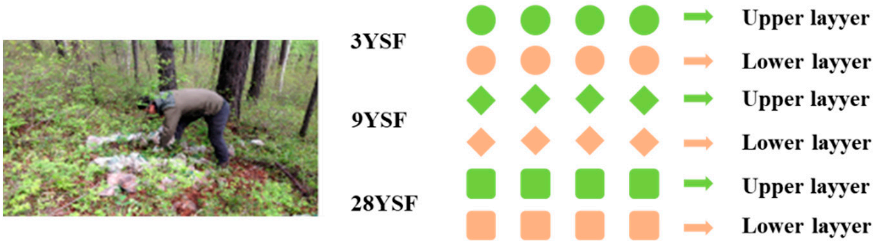

Figure 2. Map of the experimental design. Note: Green: the litter arranged on the upper layer; Orange: the litter arranged on the lower layer. The shape of the litter decomposition bag used was the same for each sample taken at sites representing the same number of years since the fire occurred, indicating that the litter was homogeneous at the beginning of the layout.

2.3. Data Collection

In October 2015, we collected fallen needles in the *Larix gmelinii* forest from various areas and placed 10 g into 15 × 20 cm^2 decomposition bags. The decomposition bags were paired: the upper decomposition bag was placed on the surface of the litter layer, and the lower decomposition bag was placed directly on the soil of forestland with the litter layer removed. A total of 432 bags were placed in the sample areas; 72 bags were placed in each sample area.

We collected nine decomposition bags per sample area per month in May, July, August, and September of 2016. We cleaned, dried, and weighed the litter from the bags. The remaining needles in each pack were crushed with a grinder and passed through a 60-mesh sieve. We digested the sample with the sulfuric acid-hydrogen peroxide method and measured the total C, N, and P contents by spectrophotometry (METASH V5000) and a Multi C/N analyzer (Multi C/N 3000, Analytik Jena, Burladingen, Germany). All litter samples were obtained from the field by the author and brought back to the laboratory for determination, but they were not kept in a publicly available herbarium.

2.4. Data Analysis

Linear model analyses were performed using the statistical analysis software SPSS 16.0 (SPSS Institute, Inc., Chicago, IL, USA). One-way ANOVA was used to compare significant differences in C, N, and P nutrients and *k* after fire disturbance. A two-way ANOVA was used to compare the interactions between fire disturbance, year, and litter layer, followed by least significant differences tests for post hoc comparisons. To refine the relationships between C, N, and P and the decomposition rate after fire disturbance, we used the "ggplot2" package (Dixon 2003) in R4.0.5 software (R core team, 2018) for the linear fitting map. We used the "vegan" package (Dixon 2003) for redundancy analysis (RDA).

2.5. Litter Decomposition Model

The decomposition index model was [47,48]:

$$X_t/X_0 = a \cdot e^{-kt}, \tag{1}$$

where X_0 is the initial weight of the litter, X_t is the weight of the remaining debris after decomposition for a period of time (t), and "a" is the fitting parameter.

The half-life of litter decomposition was calculated as:

$$t_{0.05} = \ln 0.5/(-k), \tag{2}$$

The entire decomposition time (95% decomposition) was calculated as follows:

$$t_{0.95} = \ln 0.05/(-k), \tag{3}$$

where "k" is the litter decomposition coefficient (g/g·a) and "t" is the litter decomposition time expressed in years.

3. Results

3.1. Dynamic Change in Litter Decomposition after Fire Disturbance

After 1 year of decomposition, the residual mass of litter in the upper litter layer was 4.47% lower in the 3-year postfire stands and 7.24% lower in the 9-year postfire stands than in the paired unburned stands ($p > 0.05$), but in the 28-year postfire stands, it was 16.08% significantly higher than that in paired unburned stands ($p < 0.05$, Figure 2).

The quality of litter residue in the fire disturbance years sites was different from those without fire. For 3 years postfire stands, the residual mass of litter arranged in the lower layer was 5.99% higher than that of unburned litter ($p > 0.05$); for 28 years postfire stands, the residual mass of litter arranged in the lower layer was 2.21% lower than that of unburned litter ($p > 0.05$); but, for 9 years postfire stands, the residual mass of litter arranged in the lower layer was 10.19% lower than that of unburned litter ($p < 0.05$, Figure 3).

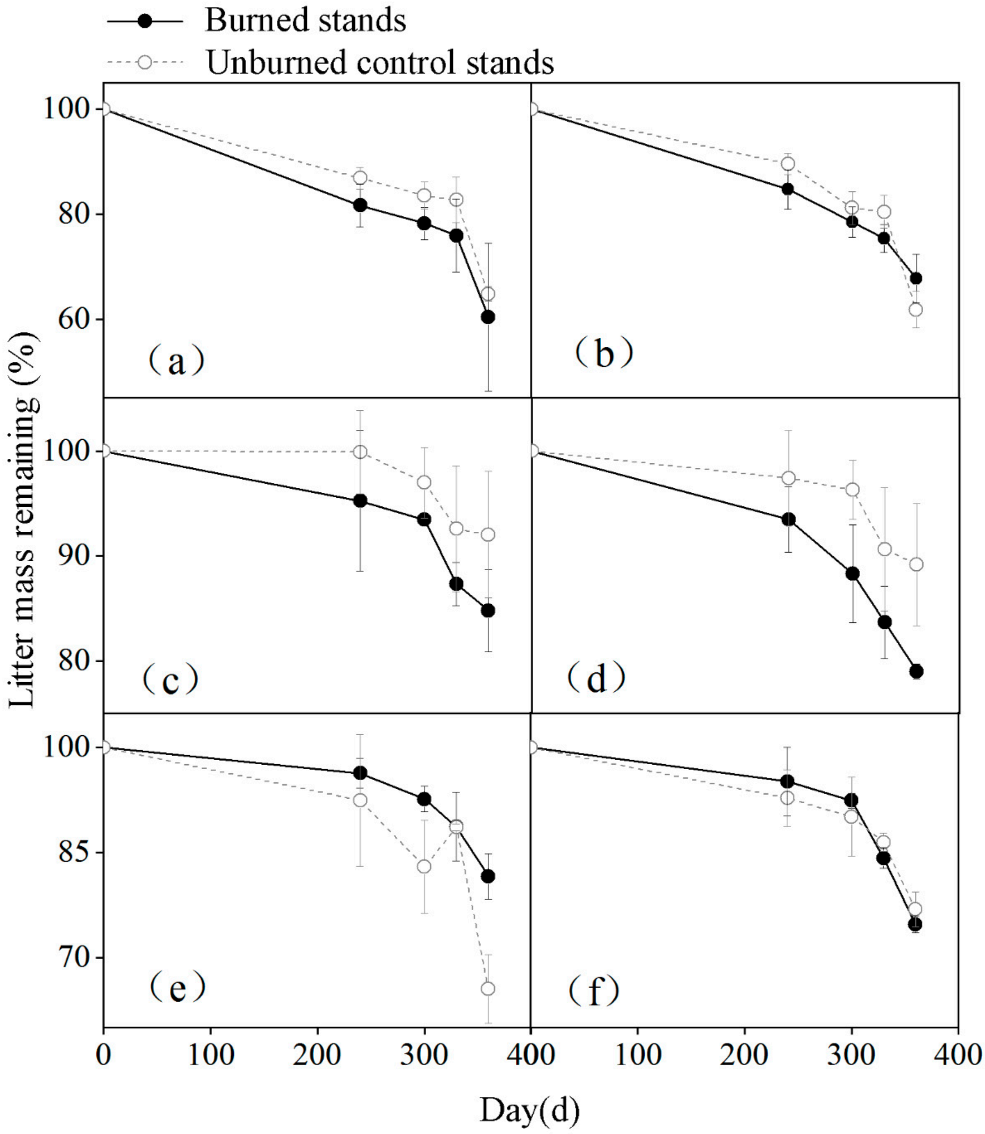

Figure 3. Decomposition of *Larix* leaf litter in bags placed on the soil surface (**left**) and leaf litter surface (**right**) for one year in burned and unburned control stands at different ages after fire disturbance in a *Larix gmelinii* forest ($n = 3$). Note: The data are the mean ± standard error. (**a**,**b**) show the surpluses of litter mass after a three-year fire disturbance. (**c**,**d**) show the surplus of litter mass after a nine-year fire disturbance. (**e**,**f**) show the litter mass surplus after 28 years of fire disturbance. On the left is the upper litter layer, and on the right is the lower litter layer.

Under all treatments with different burning years, the *k* value of needle leaf litter was less than 0.41. In different years postfire, the effects of fire vs. no fire on the *k* value were different. In 9-year postfire stands, the decomposition rate of the upper litter increased by 91% ($p < 0.05$) compared with that of the unburned control stands, and it decreased by 45% ($p < 0.05$) compared with that of the 28-year postfire stands. Samples taken from the 9-years postfire stands, showed a decomposition rate of the lower litter having increased by 109% ($p < 0.05$) compared to that of the unburned control stands (Table 2).

Table 2. Fitting rate of coniferous litter decomposition ($n = 3$).

Post-Fire Disturbance Ages	Treat	Fitting Equation	*k* Value	R Square	Years Until Half Decomposition (a)	Time of 95% Decomposition (a)
3	BU	$y = 1.0278e^{-0.405x}$	0.405	0.7899	1.78	7.46
	BL	$y = 1.0204e^{-0.35x}$	0.35	0.9136	2.04	8.62
	UU	$y = 1.0302e^{-0.324x}$	0.324	0.674	2.23	9.34
	UL	$y = 1.0441e^{-0.366x}$	0.366	0.6579	2.01	8.30
9	BU	$y = 1.0156e^{-0.147x}$	0.147	0.7582	4.82	20.48
	BL	$y = 1.0209e^{-0.211x}$	0.211	0.8174	3.38	14.30
	UU	$y = 1.0135e^{-0.077x}$	0.077	0.5771	9.18	39.08
	UL	$y = 1.013e^{-0.101x}$	0.101	0.674	6.99	29.79
28	BU	$y = 1.0223e^{-0.163x}$	0.163	0.6687	4.39	18.51
	BL	$y = 1.0342e^{-0.226x}$	0.226	0.6014	3.22	13.40
	UU	$y = 1.0391e^{-0.297x}$	0.297	0.5343	2.46	10.22
	UL	$y = 1.0222e^{-0.207x}$	0.207	0.7124	3.45	14.58

Note: BU: burned upper litter layer, BL: burned lower litter layer, UU: unburned upper litter layer, UL: unburned lower litter layer.

3.2. Litter C, N, and P Contents and Stoichiometric Ratios

In the 3-year postfire stands, the average annual C content of the lower litter layer was 1.3% lower than that of the paired unburned stands ($p < 0.05$), and the middle yearly C:N ratio of the lower litter layer was 87.7% higher than that of the paired unburned sample areas ($p < 0.05$). In the 9-year postfire stands, the average annual N content of the lower litter layer was 19.6% less than that in paired unburned stands ($p < 0.05$). In the 28-year postfire disturbance stands, the average annual C content of the upper litter layer was significantly lower than that in the paired unburned stands ($p < 0.05$). All other changes in C, N, and P and their proportion in the litter were not significant ($p > 0.05$) (Figure 4).

3.3. Litter Stoichiometry and Decomposition Rate

In the unburned sample stand, the effect of litter N, P, C:N ratio, C:P ratio, and *k* value was greater than that in the burned stands ($p < 0.05$, Figure 5, Table A3); at the same time, there was no significant linear relationship between C and *k* value, N:P ratio, and *k* value in the burned and unburned control stands ($p > 0.05$). With increasing *k* values, the contents of N and *k* decreased gradually; in contrast, the C:N ratio and the C:P ratio increased gradually with increasing *k* values. Based on this, we concluded that the *k* value of litter was higher under the condition of fire disturbance. In the case of a large *k* value, the lower the return efficiency of N and P; at the same time, the change rate of the C:N ratio increased. The faster the litter decomposes, the higher the change rate of the C:N ratio.

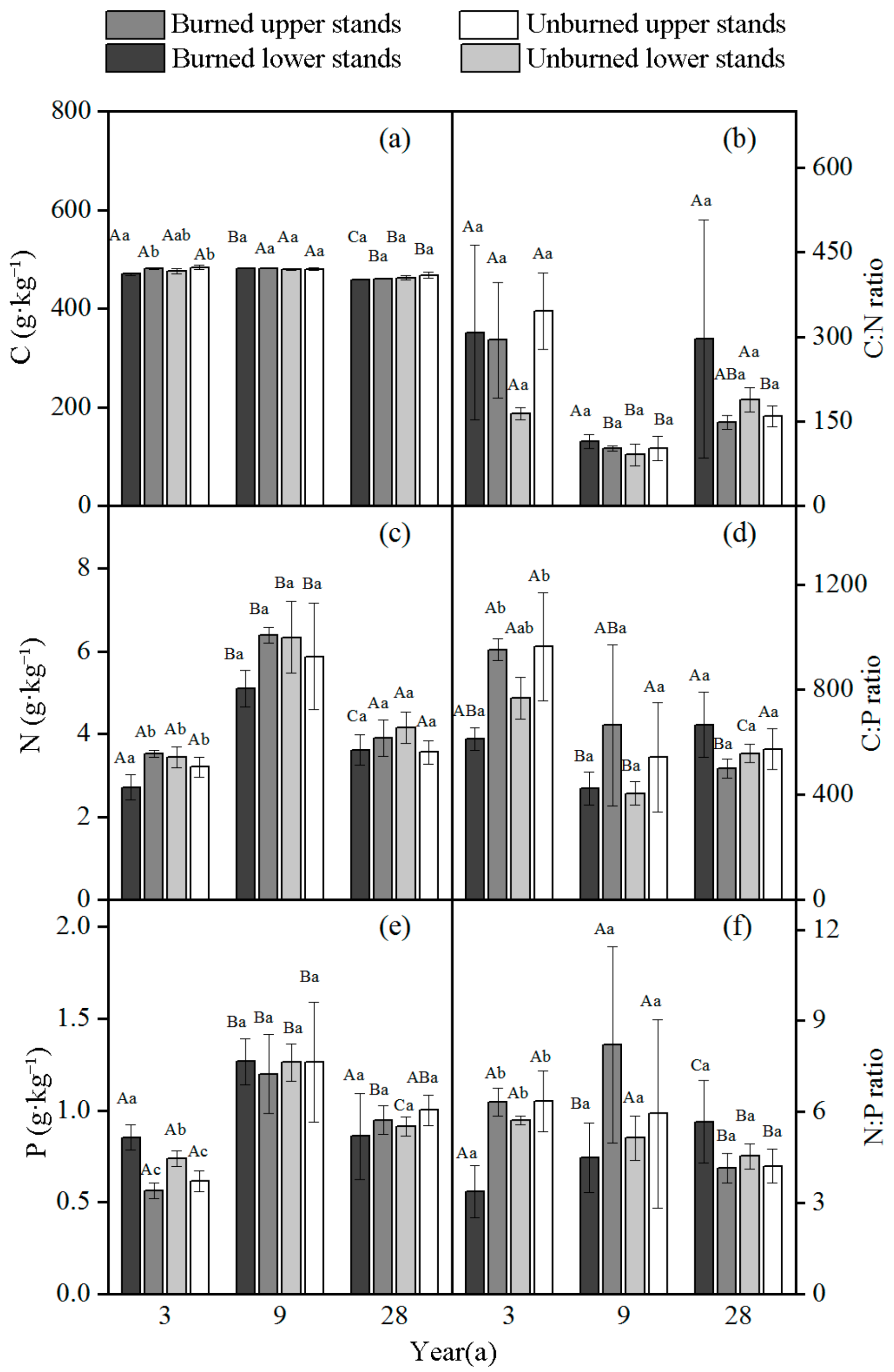

Figure 4. Carbon (C), nitrogen (N), and phosphorous (P) contents and stoichiometric ratios of leaf litter in stands of different years after fire disturbance in the *Larix gmelinii* forest (*n* = 3). Note: The data are the average annual value ± standard error. Capital letters represent differences between groups, and small letters represent differences within groups. (**a**) indicates the change of C concentration of litter in different layers under different burning years; (**b**) indicates the change of C:N of litter in different layers under different burning years; (**c**) indicates the change of N concentration of litter in different layers under different burning years; (**d**) indicates the change of C:P of litter in different layers under different burning years; (**e**) Indicates the change of P concentration in different layers of litter under different burning years; (**f**) indicates the change of N:P in different layers of litter under different burning years.

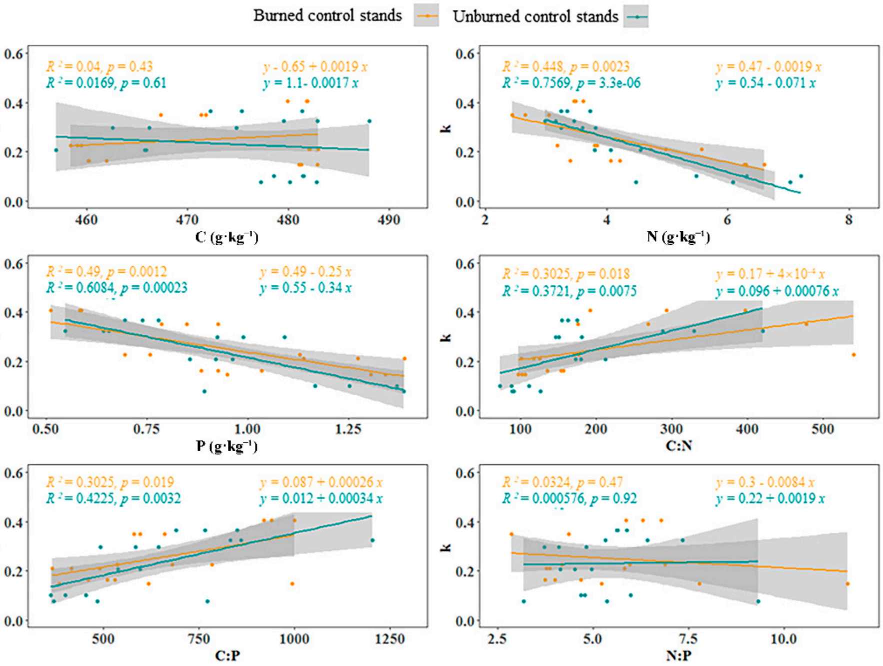

Figure 5. Linear relationships between C, N, P, and their ratios and the litter decomposition rate (k) (n = 3). **Note:** The grey area is the 95% confidence interval.

The redundancy analysis (RDA) examined the multivariate relationships of C, N, and P and their ratios with the k values. In the unburned stands, the two main RDA axes (RDA1 and RDA2) accounted for 71.33% and 27.82% of the variation, respectively. In the burned stands, RDA1 and RDA2 accounted for 62.84% and 36.38%, respectively. The C:N and C:P ratios were positively associated with k, while the N and the P contents were negatively associated with k. In burned stands, the C:N ratio appeared more associated with k (Figure 6). To further clarify the relationship between fire, k, and litter elements, we built a mixed effect model. The results showed that P and N:P ratio-driven litter decomposition changed to C:N and N:P ratio-driven litter decomposition after fire disturbance (Figure 6).

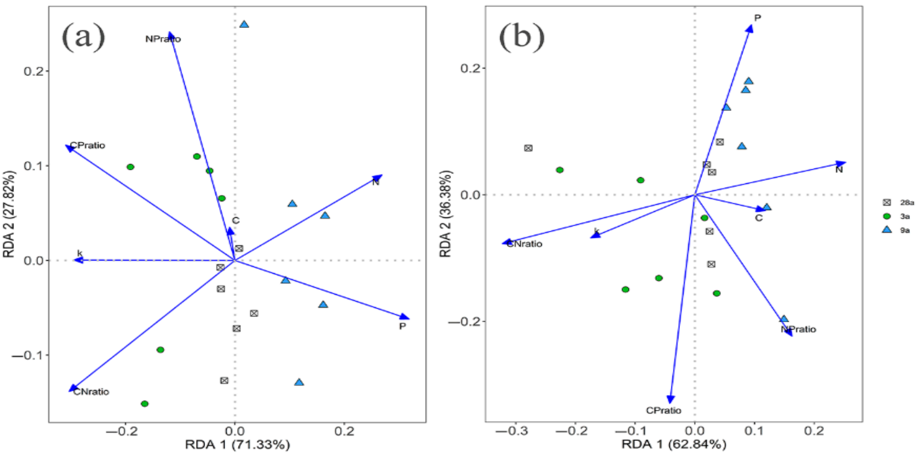

Figure 6. Redundancy analysis of leaf litter nutrients and stoichiometry and k values in burned and unburned control (**a**) and burned (**b**) stands of three different years postfire (n = 3).

4. Discussion

4.1. Effect of Fire Disturbance on k

Our results showed that the k value did not continue to accelerate after disturbance by fire (Figure 3, Tables 2 and A1). This result was different from the initial increase of *k* value [30–32] and the decrease after fire disturbance [1,49–52] as well as the research results that there is no change in the early stage 15 years after fire disturbance, and it was suppressed in the later stage [53] (Table A2). For boreal forest ecosystems, sunlight and rain become important regulatory factors in the upper litter layer in the short term after fire disturbance [54]. The *k* value seems to increase due to the enhancement of photodegradation and the increase in black carbon [30–32]. With more time since the fire [8], the external water environment also affects nutrient element limitation [55]. Fire disturbance causes deeper soil water infiltration [56]. This will lead to the downward transfer of the soluble components in litter and soil, thus influencing litter decomposition by affecting microorganisms and enzymes. Warm and humid sites promote enzyme activity [9], fungal biomass, microorganism abundance, levels of chitinase, and arthropods all increase, while vegetation (notable shrub) cover increases. These changes weaken the promoting effect of fire on decomposition, and the increase in *k* slows until a decrease appears [1,23,57,58]. In the long term, high-severity wildfire disturbance changes the properties of litter with the germination of shrubs and grass, the accumulation of refractory substances, and the increase in decomposition pressures, resulting in slower decomposition rates [8,18,57,59]. The lower decomposition rate will further promote the occurrence of fire pairs, which means that litter decomposition driven by fire is more efficient than that driven by microorganisms [56].

However, this study also found that the upper and the lower litter layers had different responses to fire disturbance. The litter microenvironment plays a critical role in boreal forest ecosystem decomposition [60,61]. After fire disturbance, and an increase in vegetation and shrub cover, the upper litter layer decomposition rate decreases significantly [32]. Whereas after the fire, the lower litter layer decomposition increases significantly [18,33,58,62]. Fire changes the microenvironment and then affects the litter decomposition process [39,63–67].

The transformation of fungi and microorganisms in the microenvironment plays an important role in the decomposition of litter [6,10,68]. After fire disturbance, the potential activity of decomposers is reduced, which will reduce the decomposition of a variety of organic compounds [11]. Fungi have an impact on the activity of soil animals and microorganisms [69]. After fire disturbance, the temperature increases, the pH value and moisture content of the soil changes, and the living habitat of soil animals are affected, resulting in a reduction in the activity of soil animals and microorganisms to inhibit the decomposition of litter [70]. Additionally, extracellular enzyme activity is an essential indicator of litter decomposition in complex microenvironments after fire disturbance [33,71,72]. The decrease in extracellular enzyme activity explains why litter rate decomposition decreases after a fire [33,71].

4.2. Effect of Fire Disturbance on C, N, and P Stoichiometry

Our results showed that litter C and N returned faster in burned stands than in the unburned control stands, confirming the hypothesis that the return of litter nutrients to the boreal forest will be accelerated after severe fire disturbance (Figure 4, Table A1). Due to the decrease in soil-available N and P after fire disturbance, microorganisms have a more robust demand for litter, which further leads to the acceleration of a lower litter layer N return [63]. Fire disturbance decouples N and P cycling, and unaffected decomposers control their C:N ratio by adjusting C and P turnover time and N mineralization rates, resulting in the disproportionate return of litter nutrient elements and a short transition to an N-restricted ecosystem [39,73]. In contrast to our results, Yang [34] found that the litter N and P contents in boreal forest ecosystems increased with the time since fire; the results showed a decrease after 4 to 14 years and then a return to the unburned level 40 years after a fire. This result was probably due to the different types and amounts of microorganisms and bacteria affecting litter nutrient return. During decomposition after a fire, the upper litter layer's coverage increases the relative abundance of mycorrhizal fungi, gram-positive bacteria, and gram-negative bacteria in the lower litter layer [32,74,75].

Fungi tend to assimilate relatively simple substrates, whereas gram-positive bacteria show a preference for more complex substrates, which means that the upper litter layer has a certain inferiority in nutrient return, especially in the process of microbial recovery after a fire [76–79].

Additionally, this study showed that the interaction between fire and the litter layer had a significant effect on the N:P ratio in the short term (Table A1), consistent with previous results. For example, the litter N:P ratio is affected by the time since burning, and it returns closer to the control level with increasing time [34]. Fire disturbance can accelerate litter P release in the upper layer, and the effect of fire disturbance on litter P is greater than that of N, especially in P-poor soil with alternating dry and wet seasons, which further affects the N:P ratio [80,81]. However, some studies have also shown that fire disturbance can weaken the return rate of litter N and P to the soil, which may be affected by fire frequency [82]. Therefore, fire disturbance generally accelerates the nutrient release of litter, and it regulates the litter N:P ratio.

4.3. The Relationship between Litter Nutrient Elements and Decomposition Rate

The "ecological stoichiometry hypothesis" believes that element migration occurs and that it is an important cause that affects decomposition [35], litter decomposition and nutrient changes co-occur, so their relationship is key to understanding the nutrient cycling processes of forest ecosystems [83]. Our results showed that litter P and N:P ratio-driven litter decomposition changed to C, N, and N:P ratio-driven litter decomposition after fire disturbance (Figures 5 and 6). We do not deny that decomposers are the most vital driving force of decomposition. Using the litter element itself as a driving factor to analyze litter changes makes the decomposition problem more accessible and more intuitive [57]. However, current research shows no consistent conclusion on which element is the most critical factor driving decomposition [35,84].

Some studies believe that the demand for microorganisms in a specific environment determines the relationship between elements and the decomposition rate [85]. Due to the order of microorganisms for N, the litter decomposition of high-N leaves is faster, while a low N content will inhibit litter decomposition [39,63,86]. Fire disturbance changed the preference of microorganisms for N and P, causing litter nitrogen to replace P to drive decomposition [22]. In this regard, Saura [87] proposed that rainwater interception under drought conditions reduces the N decomposition of litter, which explains the reduction in litter N to a certain extent. Some scholars think that there is a similar "Alfred ratio" in the microbial N and P contents. When the N:P ratio is more than 16, it is limited by P; when the N:P ratio is less than 14, it is limited by N, and when the N:P ratio is between 14 and 16, it is limited by both N and P [88]. However, some scholars believe that the loss of litter quality is mainly driven by the loss of C [22] because the loss of litter quality and C content have the same pattern [41]. The soluble C content of litter is linearly correlated with microbial activity, thus affecting the k [19]. Additionally, both the C:N ratio and the C:P ratio are closely related to the litter k value [89]. Chacón [90] suggested that litter P content and C:N ratio can be used to predict litter mass surplus or loss.

Fire disturbance increases the limitations of N and P in boreal forests through soil-available N, and it makes this demand more urgent [22,28,39,91,92]. The change in litter-driving elements after a fire is consistent with the shift in dominant microbial populations [93]. The abundance of bacteria is generally higher under N restriction, while P restriction is more suitable for fungal survival [94]. P and N:P ratio-driven litter decomposition changed to C:N and N:P ratio-driven litter decomposition after fire disturbance (Figure 4). The effects of soil conditions and invertebrates on decomposition also increase after fire disturbance, which may be related to the higher C:N and lower C:P ratios at higher decomposition rates [95,96].

At the same time, relevant studies show that the frequency and the severity of fire interference determines its impact on ecosystem processes [8], and the litter coverage after fire is lower than that without fire [97]. High-frequency fire has an inhibitory effect on litter decomposition [96]. High-frequency fire leads to an increase in the temperature of litter itself, a decrease in water content, and a decrease in the effectiveness of soil N and P. The decomposition rate of litter produced at frequent combustion sites slows down and reduces the N cycle in the region, but the C:N ratio of litter increases with increasing fire frequency [51,96]. The implementation of reasonable prescribed burning measures is conducive to litter decomposition. Ficken [95] found that the k value of planned fires once every three years was higher than that of yearly planned fires and no fires. Prescribed burning greatly reduces the accumulation of litter, promotes litter decomposition, and reduces the frequency of fire [98].

As an important ecological factor, fire disturbance should not be ignored in understanding nutrient cycling processes in boreal forests [22]. Future research should explore how the inflection point of the k value changes with time after combustion, the impact of postfire environmental changes on litter decomposition, and the impact of postfire products such as black carbon and ash on litter decomposition. Further consideration of the vertical plant-litter-soil pathways should reveal the migration patterns of C, N, and P through the forest ecosystem and help to clarify the role of fire disturbance in the stoichiometric change in forest litter nutrients [39].

5. Conclusions

Fire disturbance can affect the function of the boreal forest ecosystem through litter decomposition and nutrient element return. Fire disturbance promotes litter decomposition and nutrient cycling in the short term. However, over longer time scales as forests recover, the promotion turns into inhibition, which is inconsistent with the first and the second hypotheses. Changes in litter nutrient elements caused by the effect of fire disturbance on litter decomposition, C, N, and C:N of litter were the main litter stoichiometry factors for litter decomposition 28 years after fire disturbance, which is consistent with our third hypothesis. Our results indicated that the role of fire disturbance on litter decomposition and nutrient cycling should not be ignored in the boreal forest of China. After twenty-eight years, fire still functions as an inhibitory effect on litter decomposition in the boreal forest. Based on this, our research provides a data supplement for the dynamic change of litter decomposition in different years after fire, which can explore the driving factors of fire disturbance on the rate of litter decomposition and the stoichiometry of C, N, and P in the boreal forest ecosystem of China, and it can characterize the long-term dynamic change of litter decomposition in the boreal forest ecosystem, providing theoretical support for further exploring the relationship between fire and litter decomposition.

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Appendix A

Table A1. Stoichiometry and two-way ANOVA of C, N and P in different layers of litter under the same burning age.

Disturbance Years	Litter Layer	Control	C Content (g·kg^{-1})	N Content (g·kg^{-1})	P Content (g·kg^{-1})	C:N Ratio	C:P Ratio	N:P Ratio	*k*
3	Upper	Burned	481.20 ± 0.63	3.52 ± 0.04	0.56 ± 0.02	294.14 ± 58.93	953.10 ± 23.89	6.31 ± 0.26	0.41 ± 0.14
		Unburned	483.49 ± 2.48	3.20 ± 0.14	0.61 ± 0.03	345.68 ± 39.12	964.61 ± 119.56	6.36 ± 0.58	0.33 ± 0.04
	Lower	Burned	470.17 ± 1.41	2.71 ± 0.18	0.85 ± 0.04	307.63 ± 89.41	611.93 ± 24.53	3.36 ± 0.50	0.35 ± 0.47
		Unburned	476.32 ± 2.67	3.44 ± 0.15	0.74 ± 0.02	163.93 ± 5.98	767.97 ± 46.17	5.71 ± 0.08	0.37 ± 0.03
	p value	B	0.06558	0.17984	0.352155	0.443	0.24216	0.01837 *	0.472
		L	0.00176 **	0.07107	0.000174 ***	0.179	0.00366 **	0.00217 **	0.875
		L * B	0.35831	0.00489 **	0.026756 *	0.126	0.3077	0.02184 *	0.267
9	Upper	Burned	481.74 ± 0.57	6.39 ± 0.11	1.20 ± 0.12	101.90 ± 2.62	664.55 ± 177.81	8.21 ± 1.87	0.15 ± 0.03
		Unburned	480.06 ± 1.60	5.87 ± 0.74	1.26 ± 0.19	102.22 ± 12.08	541.92 ± 119.68	5.94 ± 1.79	0.08 ± 0.06
	Lower	Burned	482.35 ± 0.29	5.09 ± 0.25	1.27 ± 0.07	114.75 ± 7.17	423.69 ± 35.80	4.48 ± 0.66	0.21 ± 0.01
		Unburned	480.52 ± 0.98	6.33 ± 0.50	1.26 ± 0.06	90.89 ± 11.36	405.20 ± 26.32	5.14 ± 0.42	0.10 ± 0.06
	p value	B	0.114	0.4612	0.812	0.233	0.537	0.568	0.013 *
		L	0.602	0.3939	0.785	0.936	0.123	0.132	0.138
		L * B	0.943	0.0953	0.789	0.222	0.647	0.312	0.495
28	Upper	Burned	460.79 ± 0.61	3.89 ± 0.25	0.95 ± 0.04	148.42 ± 6.74	499.60 ± 20.30	4.13 ± 0.28	0.14 ± 0.03
		Unburned	467.87 ± 3.63	3.55 ± 0.16	1.00 ± 0.05	159.28 ± 10.77	573.33 ± 44.55	4.21 ± 0.33	0.30 ± 0.05
	Lower	Burned	459.01 ± 0.30	3.61 ± 0.21	0.86 ± 0.14	296.33 ± 122.06	666.45 ± 71.82	5.67 ± 0.79	0.23 ± 0.00
		Unburned	462.86 ± 2.96	4.14 ± 0.22	0.91 ± 0.03	188.32 ± 12.18	557.22 ± 19.46	4.53 ± 0.23	0.22 ± 0.02
	p value	B	0.0497 *	0.6649	0.51	0.454	0.701	0.2855	0.002 *
		L	0.1891	0.4967	0.284	0.189	0.129	0.0798	0.833
		L * B	0.5129	0.0765	0.999	0.363	0.074	0.2283	0.002 *

Note: *, **, *** represents $p < 0.05$, $p < 0.01$, $p < 0.001$, respectively.

Table A2. Stoichiometric characteristics and two-way ANOVA of C, N and P in different layers of litter burned and unburned under different burning years.

Control	Litter Layer		C Content (g·kg^{-1})	N Content (g·kg^{-1})	P Content (g·kg^{-1})	C:N Ratio	C:P Ratio	N:P Ratio	*k*
Burned	Upper	3	481.20 ± 0.63	3.52 ± 0.04	0.56 ± 0.02	294.14 ± 58.93	953.10 ± 23.89	6.31 ± 0.26	0.41 ± 0.14
		9	481.74 ± 0.57	6.39 ± 0.11	1.20 ± 0.12	101.90 ± 2.62	664.55 ± 177.81	8.21 ± 1.87	0.15 ± 0.03
		28	460.79 ± 0.61	3.89 ± 0.25	0.95 ± 0.04	148.42 ± 6.74	499.60 ± 20.30	4.13 ± 0.28	0.14 ± 0.03
	Lower	3	470.17 ± 1.41	2.71 ± 0.18	0.85 ± 0.04	307.63 ± 89.41	611.93 ± 24.53	3.36 ± 0.50	0.35 ± 0.47
		9	482.35 ± 0.29	5.09 ± 0.25	1.27 ± 0.07	114.75 ± 7.17	423.69 ± 35.80	4.48 ± 0.66	0.21 ± 0.01
		28	459.01 ± 0.30	3.61 ± 0.21	0.86 ± 0.14	296.33 ± 122.06	666.45 ± 71.82	5.67 ± 0.79	0.23 ± 0.00
	p value	Y	0.0000401 ***	0.838	0.778	0.767	0.1453	0.6739	0.000 ***
		L	0.163	0.217	0.505	0.39	0.0931.	0.0522	0.343
		L * Y	0.35	0.626	0.297	0.362	0.0126 *	0.0179 *	0.141
Unburned	Upper	3	483.49 ± 2.48	3.20 ± 0.14	0.61 ± 0.03	345.68 ± 39.12	964.61 ± 119.56	6.36 ± 0.58	0.33 ± 0.04
		9	480.06 ± 1.60	5.87 ± 0.74	1.26 ± 0.19	102.22 ± 12.08	541.92 ± 119.68	5.94 ± 1.79	0.08 ± 0.06
		28	467.87 ± 3.63	3.55 ± 0.16	1.00 ± 0.05	159.28 ± 10.77	573.33 ± 44.55	4.21 ± 0.33	0.30 ± 0.05
	Lower	3	476.32 ± 2.67	3.44 ± 0.15	0.74 ± 0.02	163.93 ± 5.98	767.97 ± 46.17	5.71 ± 0.08	0.37 ± 0.03
		9	480.52 ± 0.98	6.33 ± 0.50	1.26 ± 0.06	90.89 ± 11.36	405.20 ± 26.32	5.14 ± 0.42	0.10 ± 0.06
		28	462.86 ± 2.96	4.14 ± 0.22	0.91 ± 0.03	188.32 ± 12.18	557.22 ± 19.46	4.53 ± 0.23	0.22 ± 0.02
	p value	Y	0.0000429 ***	0.71	0.496	0.435	0.0987.	0.0391 *	0.000 ***
		L	0.112	0.551	0.936	0.184	0.2448	0.5468	0.968
		L * Y	0.983	0.856	0.581	0.081	0.4492	0.4554	0.098

Note: *, *** represents $p < 0.05$, $p < 0.001$, respectively.

Table A3. Linear Fit of Decomposition Rate *k* and Litter CNP.

Fitting Element	Control	Picture Number	Linear Equation	R Square	*p* Value
C	Burned	a	y = 467.37 + 20.67x	0.03937	0.430
	Unburned	b	y = 477.42 − 9.74x	0.01695	0.607
N	Burned	c	y = 6.39 − 8.72x	0.45138	0.002
	Unburned	d	y = 6.85 − 10.62x	0.75055	0.000
P	Burned	e	y = 1.43 − 1.94x	0.49177	0.001
	Unburned	f	y = 1.42 − 1.99x	0.64738	0.000
C:Nratio	Burned	g	y = 21.79 + 753.95x	0.30394	0.018
	Unburned	h	y = 63.97 + 485.78x	0.36926	0.007
C:Pratio	Burned	i	y = 345.12 + 1164.22x	0.29938	0.019
	Unburned	j	y = 348.82 + 1251.7x	0.42756	0.003
N:Pratio	Burned	k	y = 6.34 − 3.92x	0.03296	0.471
	Unburned	l	y = 5.25 + 0.3x	0.00058	0.924

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