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Leaf litter decomposition dynamics of *Pinus taiwanensis* and *Quercus variabilis* associated with various elevations

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ABSTRACT:

Leaf litter decomposition is an important process of carbon cycle in forest ecosystems. In this study, the decomposition dynamics of oak (*Quercus variabilis* Blume) and pine (*Pinus taiwanensis*) leaves in Northern Taiwan was investigated using the litterbag method, the effects of elevation and buried type on leaf decomposition were determined. In the laboratory, the impacts of incubation temperature, soil moisture and type on leaf decomposition were simultaneously tested. Results showed that soil basic physicochemical properties differed from the selected three sites with different elevations High temperature and low soil moisture could result in a high decomposition rate of oak and pine leaves. In field, oak and pine leaves decomposed 60-80% after one year and had a half decomposition life from two to seven months. Results also indicated that oak leaf decomposed faster than pine leaf and both leaves decomposed quickly buried in the soil and at the low elevation sites. Nutrients released from the leaves during the decomposition varied with time and tree species. Overall, both environmental condition and species control the plant litter decomposition process that influences further the carbon storage and nutrient cycling of forest ecosystems.

Keywords:

Leaf litter, Decomposition, Elevation, Oak, Pine.

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INTRODUCTION

Leaf litter decomposition is an important process of carbon cycle, and is crucial for nutrient cycling and carbon storage of forest ecosystems. The soil carbon pool is estimated as 1500 pg that is two times of atmospheric carbon. Most soil carbon is preserved in forest ecosystems. Therefore, the carbon cycling in forest ecosystem is important to influence forest productivity and atmospheric carbon exchange. Leaf litter decomposition was a focused topic around the world. Usually, leaf decomposition is controlled by temperature, moisture, quality and decomposer organisms and its rate varied with these factors (Hill *et al*., 1988; Walse *et al*., 1998; Seastedt *et al*., 2001; Gonzalez and Seastedt 2001). Mixing of leaf litter types could have a significant impact on nutrient cycling in forests (Gartner and Cardon, 2006).

Decomposition rate of year-old deciduous forest -leaf litter was found to be a linear function of log (water potential, 20-40%) and to approach a maximum near 40°C (Moore, 1986). Dry weight could lose significantly at relative humidity and moisture content values of 32 and 5% in a *Eucalyptus* leaf litter decomposition experiment (Nagy and Macauley, 1982). Moisture variation influenced the decay process of needle litter of Stone pine rather than litter quality (Virzo *et al*., 1993). But the influence of temperature and moisture conditions on leaf litter decomposition varied with temperature and moisture regimes (Orsborne and Macauley, 1988; Albers *et al*., 2004; Taylor *et al*., 2017). Litter decomposition has been widely studied in mineral soil sites and under controlled laboratory conditions. Most of the variation in decomposition rates can be explained by litter quality, temperature and soil moisture (Berg *et al*., 1993; Walse *et al*., 1998; Jia *et al*., 2016). The properties of soil can influence decomposition of leaf litter indirectly through their influence on the characteristics of the leaf litter entering the ecosystem (Carreiro *et al*., 1999; Berg *et al*., 2003; Sundqvist *et al*., 2011). Related soil properties have been shown to be important for single species decay, with leaf litter decay often faster on more nutrient-rich sites (Prescott, 1996; Greggio *et al*., 2008). Obviously, when leaf litter incorporated with soils, its decomposition is closely related to the soil properties. However, not all litter types respond similarly to soil nutrients (Vesterdal, 1999).

Many landscape decomposition studies have evaluated surface litter decomposition rates using litter bags, but few have measured decomposition rates of litter buried with soils. Because soil temperature generally decreases with elevation, decomposition is expected to occur much slower and over a shorter season at higher altitudes. But the soil moisture is not always similar to temperature associated with elevation. Because of the co-relationships among soil properties, temperature, moisture regimes and site elevation, leaf litter decomposition associated with elevation can be complicated and few studies have been done (Withington and Sanford, 2007). Therefore, the objectives of this study were to determine leaf litter decomposition rates buried with or without soils with respect to site elevation and test the effects of temperature and moisture in the laboratory.

MATERIALS AND METHODS

Site description

Three oak (*Quercus variabilis* Blume) pine (*Pinus taiwanensis*) mixed forest sites were selected at different elevations of 1400 (A), 1600 (B) and 1800 m (C), respectively, in the montane area of northern Fujian, China (approximately 27°56'N and 117°55'E). Oak and pine are common tree species in the study area. The climate belongs to subtropical monsoon, the annual rainfall is 1700 mm and mean temperature is 13.2°C. Soils are inceptisols derived from slate parent material. The topography is steep and mainly covered with oak and pine forests. Variation of oak-pine ratio was observed along the altitude. Much more pines were observed with the increasing elevation. In each site, sur-

Table 1. Physiochemical properties of soil at study sites

S. No	Site	pH	TC (%)	TN (%)	C/N	CEC (cmol/kg)	Exchangeable cation (cmol/kg)				Clay	Texture
							K	Na	Ca	Mg	%	
1	A (1400 m)	4.85	5.51	0.31	17.41	18.5	0.51	0.38	0.80	0.42	34.0	SCL
2	B (1600 m)	4.70	5.62	0.27	19.26	21.6	0.37	0.14	1.18	0.20	32.0	SCL
3	C (1800 m)	5.00	3.53	0.26	13.61	30.5	1.25	0.19	8.48	0.75	16.0	SCL

SCL: Sandy Clay Loam

face soils (0-10 cm) were collected for physicochemical analysis and prepared for laboratory experiments.

Leaf litter collection and litterbag experiment

Freshly senesced leaves of oak and pine were collected from the top surface of litter layer at the same site. Leaves were mixed and weighed by 100 g for each litterbag in October 2016. Litterbags were constructed by nylon-fiber with 1 mm mesh window-screen. At each site, 24 litterbags were placed at the soil surface and fixed with thread to tree-trunks. Another 24 litterbags were buried five cm below the soil surface. Every three months, six replicates of buried and unburied litterbags were harvested. Each harvested litterbag was brushed clear of external soil and litter, placed in a paper bag, and over-dried at 65°C. After reaching constant mass, litterbags were cut open and leaves from each layer were weighed. Mass loss in each layer was determined as the difference between known initial dry weigh and final dry weight of leaves. The litter decomposition rate was expressed and the percentage of the lost mass to the initial dry weight were also expressed.

Leaf decomposition experiment in the laboratory

Effect of temperature

Pine and oak leaves gathered from the fields were cut into approximately 1 cm size in the laboratory. 1 g of litter debris was mixed with 10 g soil into a glass conical flask of 125 mL. The soil moisture was wetted to the content of field water capacity. In each flask, a little bottle contained 10 mL 0.1 N KOH solution was tied above the soil surface to absorb released CO_2. A total of 40 flasks were deployed to investigate the effect of temperature on leaf litter decomposition with soils. Three sites and three temperatures (5, 15 and 25°C, respectively) cross treatments were dealt in an incubation box with sealed lid and without light. Blank and control treatment of soils were simultaneously conducted. Three replicates were conducted and every month the released CO_2 was determined. The incubation lasted for six months. Absorbed CO_2 in the KOH solution was titrated by 0.1 NH_4Cl and calculated.

Effect of soil moisture

One gram of treated leaves of oak and pine was also incorporated with 10 g soil. The soil moisture was wetted and kept at 20 and 40% in the incubation. The incubation temperature was 15°C that is close to the field yearly mean temperature. A three-site, two-moisture and three-replicate treatment was conducted to investigate the effect of soil water content on leaf litter decomposition. Blank and control treatment of soils were also simultaneously conducted. The incubation method was same as that in the temperature effect in-

Table 2. Distribution of organic carbon functional group of the study soils (%)

S. No	Site	Alkyl-C	N-alkyl-C	O-alkyl-C	Acetal-C	Aromatic-C	Phenolic-C	Carboxyl-C
1	A	17.9	11.7	18.6	9.3	22.6	10.3	9.5
2	B	22.6	11.5	18.5	9.6	20.1	9.4	8.3
3	C	19.1	10.4	15.3	10.8	22.6	11.2	10.6

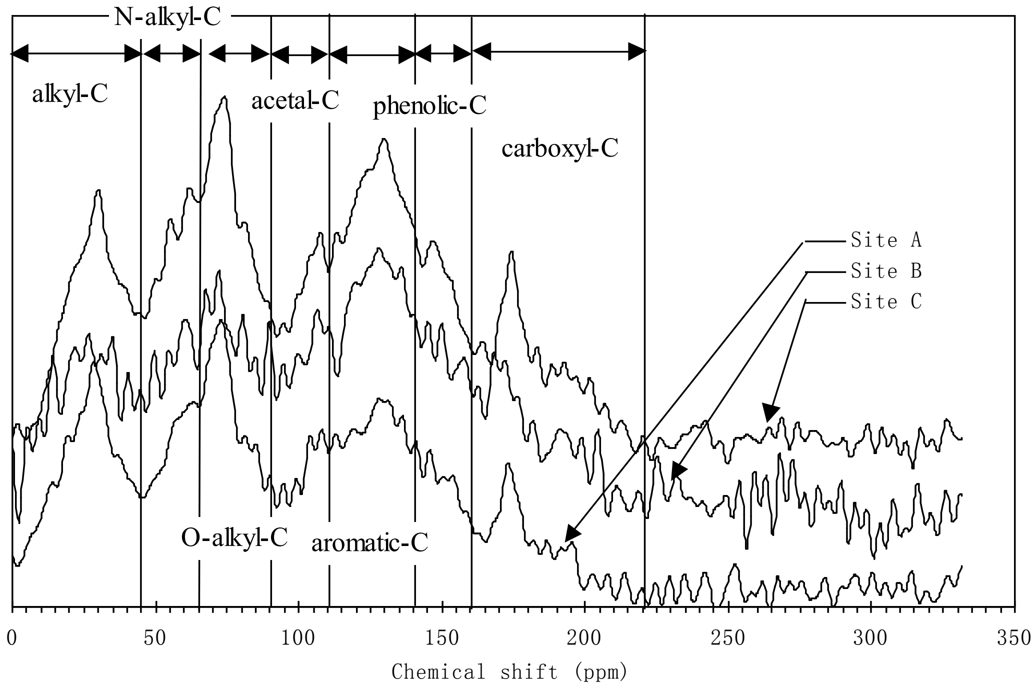


Figure 1. CPMAS ^{13}C NMR Spectra of study soils

vestigation. CO_2 release was determined every month for total six times.

Soil measurements

Soil samples were air-dried and ground to pass a 2 mm sieve. Water content in air-dried soil sample was measured the oven-dry method and soil water retention capacity was also determined (Gardner and Hartge, 1986). Soil texture was determined by the method of precipitation (Gee and Bauder, 1986). Soil pH was determined by a cation electrode. Total carbon and nitrogen concentration was determined by a CNH analyzer (Elemental Analyzer, EA 1110). The cation exchangeable capacity (CEC) was measured by 1 M NH_4AcO (Thomas, 1982).

Plant measurements

Total carbon and nitrogen concentration was also determined by a CNH analyzer. Acid non-soluble lignin was extracted by 72% H_2SO_4 and measured (Ding, 1999). Potassium, sodium, calcium, magnesium and phosphorus concentration in the leaf litter was digested by HNO_3-$HClO_4$ and measured by AAS (HITACHI 180-30 AAS).

CPMAS ^{13}C-NMR determination

CPMAS ^{13}C NMR spectroscopy (Bruker MSL-200 NMR) was used to examine the organic functional groups of ground leaves and soils. The NMR spectra were divided into the following chemical shift regions: alkyl-C (0-45 ppm), N-alkyl-C (46-65 ppm), O-alkyl (65-90 ppm), acetal-C (90-110 ppm), aromatic-C (110-140 ppm), phenolic-C (140-160 ppm) and carboxyl-C (160-200 ppm) (Preston *et al*., 1990; Oades, 1995). The relative content of each 'C' group could be measured as the percentage of total area. The phenolic 'C' contents were calculated from O-substituted aromatic

Table 3. Initial concentrations of chemicals at the leaf litter of pine and oak

S. No	Leaf	C (%)	N (%)	K (%)	Na ($g.kg^{-1}$)	Ca ($g.kg^{-1}$)	Mg ($g.kg^{-1}$)	P ($g.kg^{-1}$)	Lignin (%)
1	Pine	49.5	1.6	2.31	0.47	5.65	5.50	0.04	55.5
2	Oak	47.1	2.3	1.95	0.57	6.80	5.87	0.05	50.0

Table 4. Distribution of organic carbon functional group of initial leaves

S. No	Leaf	Alkyl-C	N-alkyl-C	O-alkyl-C	Acetal-C	Aromatic-C	Phenolic-C	Carboxyl-C
1	Pine	17.7	13.4	37.9	11.6	8.9	5.9	4.7
2	Oak	18.8	13.7	35.9	10.2	9.5	4.6	7.2

'C' (Baldock *et al*., 1992).

RESULTS

Soil characteristics of study sites

Soil pH ranged from 4.70 to 5.0 among the three sites, and total carbon decreased with increasing pH Table 1. Total soil nitrogen concentration was similar with total carbon. Cation Exchangeable Capacity (CEC) was highest in the site 'C' with higher elevation, and also were potassium, sodium, calcium and magnesium concentrations. Soil texture was sandy clay and loam of all three sites and the percentage of sand was over 50%.

According to the results of CPMAS ^{13}C NMR, main organic carbon functional groups were identified Figure 1 and the relative content of different functional group was calculated Table 2. The ^{13}C NMR spectra of soils from the three sites differed slightly among the signals in various chemical shifts. Such a result could be confirmed from the distribution of organic carbon functional group. This indicated a little difference that was present in the soil organic carbon from the different study sites.

Nutrient content and organic carbon composition of leaf litter

The initial nutrient concentrations of pine and oak leaves differed slightly, but the lignin content and C/N ratio were higher in the pine leaves than oak leaves Table 3. It was identified by ^{13}C NMR that O-alkyl-C was the main part of organic carbon functional group in the pine and oak leaves Table 4. Compared with the distribution of organic carbon functional group in soils, the part of aromatic C was much lower and O-alkyl-C was higher in the leaves.

Leaf litter decomposition dynamics and nutrient release

Leaf mass decreased with increasing time in all decomposition treatments. The relationship between mass loss and time could be expressed by the first order exponential decay equation. The equation was expressed as:

$$Y = A \exp(-t/b) + Y_0$$

where 'Y' is the mass residue of leaves (%); 'A' is the parameter for decomposable mass of leaves (%); 'Y_0' is the recalcitrant part for decomposition (%); and '*b'* is the parameter for the decomposition rate. The leaf litter

Table 5. Exponential model simulation parameters of pine and oak leaves decomposition dynamics

Parameter	Pine						Oak					
	Site A		Site B		Site C		Site A		Site B		Site C	
	B	Un	B	Un	B	Un	B	Un	B	Un	B	Un
A	66.9	64.4	80.6	67.9	81.1	67.7	77.3	70.2	90.7	71.2	76.9	70.5
b	3.51	4.61	2.49	2.29	5.71	5.25	3.03	2.52	3.22	2.49	3.92	4.23
Y_0	32.3	34.5	18.9	31.8	19.3	32.8	22.0	29.4	8.63	18.9	22.9	29.7
R^2	0.975	0.980	0.985	0.987	0.998	0.994	0.983	0.987	0.989	0.971	0.999	0.998
DT_{50}(mo)	4.67	6.57	2.37	3.02	5.55	7.19	3.08	3.09	2.53	2.06	4.09	5.27

B: buried, Un: unburied, DT_{50}: Half decomposition life (month)

Table 6. Nutrient concentration variations of oak and pine leaves after one-year decomposition

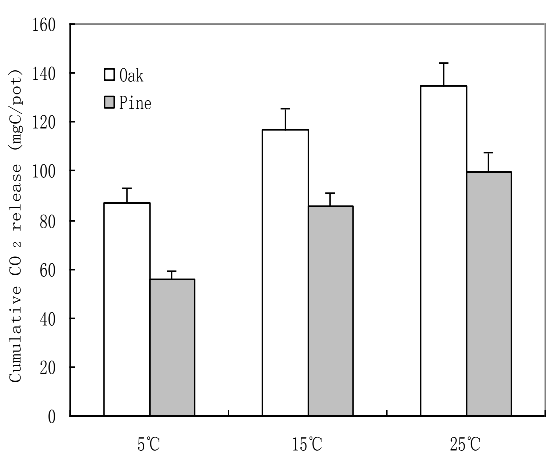
	Nutrient	C (%)	N (%)	P ($g.kg^{-1}$)	K ($g.kg^{-1}$)	Ca ($g.kg^{-1}$)	Mg ($g.kg^{-1}$)	Na ($g.kg^{-1}$)
Oak	Initial conc.	47.1	2.30	0.049	1.95	6.80	5.87	0.57
	Final conc.	46.0	2.52	0.017	3.82	9.15	2.90	0.52
	Removed (%)	69.5	65.8	89.2	38.8	58.0	84.6	71.5
Pine	Initial conc.	49.5	1.60	0.037	2.31	5.65	5.50	0.47
	Final conc.	48.2	1.70	0.011	3.13	4.6	2.00	0.44
	Removed (%)	56.4	51.8	91.6	36.6	64.7	88.1	58.4

Removed %=(initial DW ´ conc.-final DW ´ conc.)/(initial DW ´ conc.)´100

decomposition of pine and oak in the field with or without bury treatment was fitted and calculated Table 5. According to R^2 values (ranged from 0.975 to 0.999), the fit of leaf decomposition was better using the first order exponential decay equation.

Results showed that the half decomposition life (DT_{50}) of pine leaves ranged from 2.37 to 7.19 months, while ranged from 2.06 to 5.27 of oak leaves. DT_{50} of pine leaves was longer than that of oak leaves. The potential decomposable part (A) of pine leaves ranged from 64.4 to 81.1% that was also lower than that of oak leaves. However, the decomposition rate of leaves showed no significant difference. It also showed that leaves buried with soils could decompose quickly than that unburied. Additionally, compared with the lower elevation sites A and B, the leaf litter decomposition rate was lower in the higher elevation site C, suggesting the temperature and soil moisture condition had a significant effect on leaf litter decay. However, the potential decomposable part of leaf litter showed no significant difference among the three sites.

After one year decomposition on the surface, nutrient loss with mass loss in the pine and oak leaves were calculated Table 6. However, the lost nutrients varied with different elements. Phosphorus lost was about 90% after one year decomposition from the leaves, while potassium was lost only about 37%. Except for phosphorus and magnesium, other element concentration changed a little before and after one year decomposition. Related to the mass loss, the nutrient re-



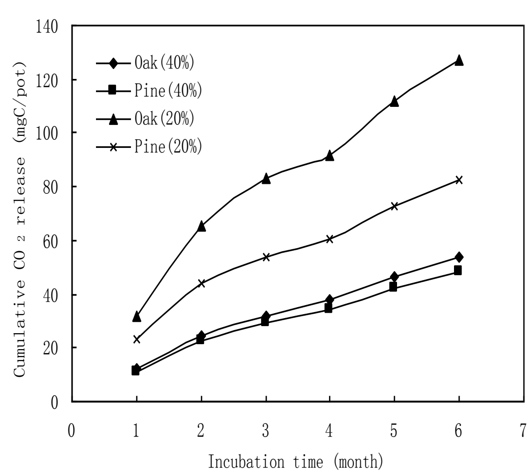


Figure 2. Effects of soil temperature (right) and moisture (left) on leaf litter decomposition

moved from the decomposition was higher in the oak leaves than that in the pine leaves. And the removed rate varied with different elements. According to the removed rate, nutrient release during the decomposition showed such an order: P>Mg>Na>C>N>Ca>K (oak) and P>Mg>Ca>Na>C>N>K (pine).

Effects of temperature and moisture on litter decomposition

The effect of temperature on leaf litter decomposition was significant that CO_2 release rate increased with increasing temperature (Figure 2). CO_2 released from the oak leaves were more than that from the pine leaves, indicating that oak leaves decomposed rapidly than pine leaves. Soil moisture also had a significant effect on leaf litter decomposition (Figure 2). The leaves decomposition rate was quick under the moisture of 20% rather than 40%. Under the moisture of 40%, the decomposition rate of pine and oak leaves had no significant difference. But when the moisture is reduced to 20%, the decomposition rate of pine and oak leaves increased greatly and it was much higher in oak leaves than that of pine leaves. During the six months incubation period, CO_2 release was increasing.

DISCUSSION

Leaf litter fall accounts for the most important proportion to soil organic carbon pools in forest ecosystems (Waring and Schlesinger, 1985; Crow *et al*., 2009). Leaf litter decomposition is therefore playing an important role in carbon cycling and storage in forest ecosystems. This study examined the effects of site elevation associated with different temperature and soil moisture on leaf litter decomposition. The species, litter quality, temperature and moisture are all related to site elevation that certainly influences the leaf litter decomposition. We tested a pine (*Pinus taiwanensis*) and oak (*Quercus variabilis* Blume) species in leaf decomposition. The pine is a kind of conifer while the oak belongs to broadleaf tree, they have different temperature adaptability. In the study site, oak generally grows under the elevation of 1800 m, but pine almost grows without the elevation limitation. The characteristics of pine and oak leaf have significant differences in lignin and nitrogen concentration Table 3.

The composition discrepancy may be responsible for the different decomposition rate of pine and oak leaf. Such a result was consistent with the reports of Fioretto *et al*. (1998). However, the decomposition rates of oak and pine leaves varied with temperature, moisture and soil buried. Undoubtedly, the external factors also played an important role in the decomposition process. In addition to the composition of leaves, oak and pine showed no significant difference.

The effect of placement of litterbags on leaf litter decomposition was significant in site A and C. The leaf litter decomposition rate was higher in the buried soils than unburied treatments. But in site B, the case was not so. As shown in Table 1 and 2, the soil physicochemical properties of site C were much different with those of site A and B, suggesting that these soil characteristics and temperature may not result in the great difference between site A, C and B. Therefore, the soil moisture may control the leaf decomposition rate in the study site. Within a small region, the rainfall was uniform in site A, B and C. So the difference of soil moisture may result from the soil water retention capacity. As measured, the air-dried soils from site A, B and C had water contents of 6.7, 15.3 and 10.7%, respectively. Soil from site B had the highest water content even when samples were air-dried, suggesting it had the highest water retention potential in the field. Possibly this was the main reason resulted in high decomposition rate when leaf litter was buried with soils. The results were consistent with those of the reported buried substrate done by Withington and Sanford (2007). Former studies showed that nutrient-rich soil will be benefited to litter decomposition (Swift *et al*., 1979; Prescott, 1996; Hobbie *et al*., 2000; Hoorens *et al*., 2003). However, soils from A and B had the similar characteristics that did not respond similarly to the decomposition rate, suggesting that soil properties showed complicate effect on leaf litter decomposition and this needs further study.

The effect of temperature on leaf litter decomposition can be expected (Moore, 1986; Orsborne and Macauley, 1988; Moore *et al*., 1999). Calculated from the results, when the temperature was 5°C, Q_{10} of pine and oak leaves were 1.54 and 1.79. When the temperature was increased to 15°C, Q_{10} of them became 1.15 and 1.16. This indicated that oak leaf can decay rapidly than pine leaf under the low temperature (<15°C), but not under the high temperature condition in the early decomposition stage (six months). Our results showed that the effect of lower soil moisture was significant on leaf decomposition, but no significant effect was observed when the moisture increased to 40% (Figure 2).

Usually, decomposition rates were positively correlated with substrate moisture content (Moore 1986; Orsborne and Macauley, 1988). Soil microbial activity controls the leaf litter decomposition in the incubation, suggesting 20% moisture was more favorable for decomposition than 40%. One possible explanation of such a phenomenon was that O_2 was lacking in the incubation under high moisture content. The decomposition rates exhibit a curvilinear relationship with soil temperature and soil moisture (Seastedt *et al*., 2001, Withington and Sanford, 2007), but water availability appears to be the primary factor that controls decomposition rate of buried substrates (Withington and Sanford, 2007).

CONCLUSION

In the high elevation site, pH value and base cation contents were higher than the lower sites, but low organic carbon content was observed. Soil organic carbon functional groups in all sites were similar and dominated by aromatic-C and O-alkyl-C identified by CPMAS ^{13}C NMR. In the leaf composition, oak leaf had higher nitrogen and low lignin content than those of the pine. Both leaves of oak and pine comprised mainly of O-alkyl-C. Oak and pine leaf litter decomposed 60-80% after one year and had a half decomposition life from two to seven months. Soil temperature and moisture control the leaf litter decomposition of pine and oak, as well as soils in this study.

However, the relationship between leaf litter decay and site elevation was not correlated. Variations of soil properties and moisture may be responsible for the variations. Results also indicated that oak leaf decomposed faster than pine leaf, additionally leaves decomposed quickly when buried in the soil and in the low elevation site. Nutrients released from the leaves during the decomposition varied with time and tree species. Temperature and moisture could exert an effect on leaf litter decomposition but the extent of influence varied with soil and leaf species. Laboratory incubation results showed that high temperature and low soil moisture could result in high decomposition rate of oak and pine leaves. Leaf litter decomposition with respect to site elevation was complicated that merits further study for the better understanding of soil carbon storage of forest ecosystems.

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