J Arid Land (2018) 10(3): 416–428
https://doi.org/10.1007/s40333-018-0054-6

Science Press Springer-Verlag

Effects of ultraviolet (UV) radiation and litter layer thickness on litter decomposition of two tree species in a semi-arid site of Northeast China

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Abstract: Forests and grasslands in arid and semi-arid regions receive high-intensity ultraviolet (UV) radiation year-round. However, how the UV radiation affects the litter decomposition on the forest floor remains unclear. Here, we conducted a field-based experiment in 2011 in the southeastern Horqin Sandy Land, Northeast China, to investigate the effects of UV radiation, litter layer thickness, and their interaction on the mass loss and chemical properties of decomposing litter from Xiaozhuan poplar (*Populus × xiaozhuanica*) and Mongolian pine (*Pinus sylvestris* var. *mongolica*) plantation trees. We found that UV radiation accelerated the decomposition rates of both the Xiaozhuan poplar litter and Mongolian pine litter. For both species, the thick-layered litter had a lower mass loss than the thin-layered litter. The interaction between UV radiation and litter layer thickness significantly affected the litter mass loss of both tree species. However, the effects of UV radiation on the chemical properties of decomposing litter differed between the two species, which may be attributed to the contrasting initial leaf litter chemical properties and morphology. UV radiation mostly had positive effects on the lignin concentration and lignin/N ratio of Xiaozhuan poplar litter, while it had negative effects on the N concentration of Mongolian pine litter. Moreover, litter layer thickness and its interaction with UV radiation showed mostly positive effects on the N concentration and lignin/N ratio of Xiaozhuan poplar litter and the ratios of C/N and lignin/N of Mongolian pine litter, and mostly negative effects on the C/N ratio of Xiaozhuan poplar litter and the N concentration of Mongolian pine litter. Together, these results reveal the important roles played by UV radiation and litter layer thickness in the process of litter decomposition in this semi-arid region, and highlight how changes in the litter layer thickness can exert strong influences on the photodegradation of litter in tree plantations.

Keywords: lignin; litter decomposition; litter layer thickness; nitrogen; forest plantation; photodegradation; UV radiation

Citation: MAO Bing, ZHAO Lei, ZHAO Qiong, ZENG Dehui. 2018. Effects of ultraviolet (UV) radiation and litter layer thickness on litter decomposition of two tree species in a semi-arid site of Northeast China. Journal of Arid Land, 10(3): 416–428. https://doi.org/10.1007/s40333-018-0054-6

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Received 2017-05-12; revised 2017-12-28; accepted 2018-01-13

1 Introduction

Litter decomposition plays a critical role in the carbon (C) and nutrient cycling of terrestrial ecosystems (Aerts, 1997; Cox et al., 2000; Austin and Ballaré, 2010). Traditional models for how litter decomposition is controlled in terrestrial ecosystems have mainly focused on how litter quality interacts with soil organisms and climate to control the litter decomposition process (Aber and Melillo, 1982; Berg et al., 1993; Coûteaux et al., 1995). Recently, a growing body of evidence suggests that the patterns and mechanisms of litter decomposition in arid and semi-arid ecosystems differ from those in humid regions where microbial degradation dominates (Austin and Vivanco, 2006; Brandt et al., 2010; Smith et al., 2010; Peng et al., 2014; Day et al., 2015). The rate of litter decomposition in arid and semi-arid ecosystems is poorly predicted by temperature and moisture and is actually much faster than predicted from these parameters; this suggests that photodegradation, the breakdown of chemical compounds by solar ultraviolet (UV) radiation, may instead be responsible (Cox et al., 2000; Day et al., 2015). Throop and Archer (2009) highlighted the need for studies that use a manipulative approach to test the effect of UV radiation on litter decomposition in arid and semi-arid ecosystems, where UV radiation is high and biotic drivers may be constrained by water limitations.

UV radiation can have a wide variety of effects on litter decomposition. Studies may be found that report on the positive (Song et al., 2012) and negative (Pancotto et al., 2003, 2005), as well as non-observable effects (Cybulski et al., 2000; Hoorens et al., 2004) of UV radiation on leaf litter decomposition. Differences in the litter chemical properties, abiotic factors (such as moisture, temperature, and soil chemical characteristics) and manipulated UV radiation systems, make it difficult to generalize the variable and even inconsistent results of how UV radiation affects litter decomposition (Caldwell et al., 2007; Zepp et al., 2007; Smith et al., 2010; Uselman et al., 2011; Song et al., 2013a, b).

Changed chemical properties of decomposing litter may be an important factor towards explaining the variation in litter decomposition rates under UV radiation. However, just a few studies have focused on the changes in the litter chemical properties during decomposition, with inconsistent findings (Day et al., 2007; Song et al., 2013b). The nitrogen (N) and lignin concentrations, and the lignin/N and C/N ratios, have been identified as key controllers of the litter decomposition rate (Melillo et al., 1982; Berg et al., 2000; Cornwell et al., 2008). Some studies demonstrated a modest decrease in the lignin concentration during litter decomposition under UV radiation (Rozema et al., 1997; Day et al., 2007; Henry et al., 2008), while others showed no effects of UV radiation on lignin decomposition (Gehrke et al., 1995; Brandt et al., 2007). Recently, Gaxiola and Armesto (2015) showed that C/N and lignin/N ratios were considerably reduced under UV radiation during the decomposition of *Proustia* litter but not that of *Porlieria* litter. Brandt et al. (2007) found that UV exposure altered the chemical properties of decomposing litter at a semi-arid shortgrass steppe site in the Great Plains. Given that differences in biotic and abiotic factors can have large effects on litter decomposition, an important outstanding question is whether the findings observed by Brandt et al. (2007) could extend to other arid and semi-arid ecosystems.

Furthermore, most studies to date have focused on the effects of UV radiation on litter decomposition under a fixed litter layer thickness, rarely investigated the responses of litter decomposition to UV radiation under different quantities of litter (Henry et al., 2008). Because UV radiation is usually first absorbed by the upper layer of leaf litter, the influence of UV radiation may be limited to just this surface layer, which could translate into differences in the decomposition rate between the thin-layered and thick-layered litter (i.e., different litter quantities). However, the effects on litter mass loss, nutrient release, and C compound decay from changes in the litter layer thickness when exposed to UV radiation remain unclear (Henry et al., 2008).

Mongolian pine (*Pinus sylvestris* var. *mongolica*) and Xiaozhuan poplar (*Populus* × *xiaozhuanica*) have been widely planted to control wind-induced desertification in the Horqin Sandy Land, Northeast China, since the late 1960s (Zeng et al., 2009). In a previous study, we had found that the litter of Xiaozhuan poplar (a broad-leaved tree species) differed from that of Mongolian pine (a coniferous species) in their initial leaf chemical properties (Zhao et al., 2013). Moreover, the Horqin Sandy Land is characterized not only by nutrient-poor soil that limits plant growth (Chen et al., 2006) but also by solar radiation that has increased by about 4.17% from 2010 to 2015 (unpublished data of the Daqinggou Ecological Station, Institute of Applied Ecology, Chinese Academy of Sciences). Considering the important role of litter decomposition in the C and nutrient cycling of terrestrial ecosystems (Hättenschwiler et al., 2005), it is necessary to assess the independent and joint influence of UV radiation and litter layer thickness on litter decomposition of Mongolian pine and Xiaozhuan poplar. In this study, we carried out a 6-month field-based experiment investigating the decomposition of Mongolian pine and Xiaozhuan poplar litter to test the following hypotheses: (1) UV radiation would stimulate the litter mass loss of both tree species by changing the N release and lignin decomposition of their leaves; and (2) litter layer thickness would diminish the positive effects of UV radiation on the decomposition of litter from Mongolian pine and Xiaozhuan poplar plantations.

2 Materials and methods

2.1 Study area

This study was carried out at the Daqinggou Ecological Station (42°58′N, 122°21′E; 260 m a.s.l.), geographically located in the southeastern Horqin Sandy Land, Northeast China. This area is in a semi-arid region characterized by a temperate climate. The average annual precipitation is 450 mm, annual average temperature is 6.4°C, average monthly maximum temperature is 23.8°C in July and average monthly minimum temperature is –12.5°C in January.

2.2 Experimental design

To assess how UV radiation or litter layer thickness, or their interaction, may affect litter decomposition, we used two contrasting tree species, Mongolian pine, and Xiaozhuan poplar, in our experiment (Table 1). Naturally-senesced leaf litter of Mongolian pine and Xiaozhuan poplar was respectively collected from an 11-year-old Mongolian pine plantation and a 20-year-old Xiaozhuan poplar plantation in late October 2010 by a nylon net (2-mm mesh). The freshly fallen litter sample was weighed and divided into two sub-samples per species. One was used to analyze the initial leaf chemical properties after oven-drying the litter at 65°C to constant mass, and the other sub-sample was used for an incubation experiment after air-drying the litter for 1 week to minimize the effects of litter moisture on litter decomposition.

Table 1 Initial leaf litter chemical properties of Mongolian pine and Xiaozhuan poplar

Species	C concentration (mg/g)	N concentration (mg/g)	C/N ratio	Lignin concentration (mg/g)	Lignin/N ratio
Xiaozhuan poplar	446.4±6.2^{a}	10.5±0.3^{b}	42.4±1.6^{a}	273.7±14.8^{a}	26.0±1.6^{a}
Mongolian pine	550.5±7.3^{b}	3.6±0.1^{a}	152.6±3.1^{b}	306.0±6.9^{b}	84.8±1.3^{b}

Note: Mean±SE. Different lowercase letters in the same column indicate statistical difference between the two species at $P<0.05$ level.

In the incubation experiment, we applied 6 treatments (2 levels of UV radiation×3 levels of litter layer thickness) for each species with destructive harvests performed 3 times (after 2, 4, and 6 months of incubation). Acrylic boxes (10 cm×10 cm×6 cm) and polycarbonate boxes (10 cm×10 cm×6 cm) were used to produce the UV pass and UV block treatment levels, respectively. Each box had no bottom and was perforated around the four sides to let air in and circulate. We used a 2-mm nylon mesh to close the bottom of the boxes, which allowed the free access of soil fauna. To generate the 3 levels of litter layer thickness, we evenly placed a quantity of 1, 2, and 4 g of leaf litter (corresponding to 100, 200, and 400 g/m^2) of each species into three boxes (i.e., on the top of the nylon mesh). For each species, 18 boxes (6 treatments×3 harvests) were randomly positioned in each of 4 plots (i.e., four replications; 72 total number of boxes used per species) in an abandoned cropland at the Daqinggou Ecological Station in early May 2011. In each plot (3 m×3 m), all the aboveground vegetation was removed to minimize shading and plant–microbe competition.

According to the meteorological data collected at the Daqinggou Ecological Station, solar radiation was always lower in the spring and autumn than in the summer. Therefore, we evaluated the influence of UV radiation on litter decomposition for a single growing season, and retrieved the litter boxes after 2, 4, and 6 months of incubation.

We used an illuminometer (LM8000; Lutron Electronic Enterprise Co., Ltd.) and a UV radiometer (UV 340A; Lutron Electronic Enterprise Co., Ltd.) to check and confirm the light transmittance and UV radiation removal in the two types of boxes (acrylic boxes and polycarbonate boxes), respectively. The solar radiation and UV radiation in the boxes were monitored monthly at an interval of 2 h from 08:00 to 18:00 LST during the period from May to October. Under cloudless conditions, the illuminometer and UV radiometer probes were respectively placed inside the acrylic and polycarbonate boxes (15 arylic boxes and 15 polycarbonate boxes, respectively). Simultaneously, the ambient environment (control) was likewise also monitored to compare the light transmittance and UV radiation removal between the box incubators and the ambient environment. On average, the acrylic box, used as the litter incubator for the UV pass treatment, had an 87% light transmittance and a 68% UV radiation relative to the ambient UV radiation level, from May to October. For the UV block treatment, the polycarbonate box had a 76% light transmittance and a <1% UV radiation relative to the ambient UV radiation level (Fig. 1).

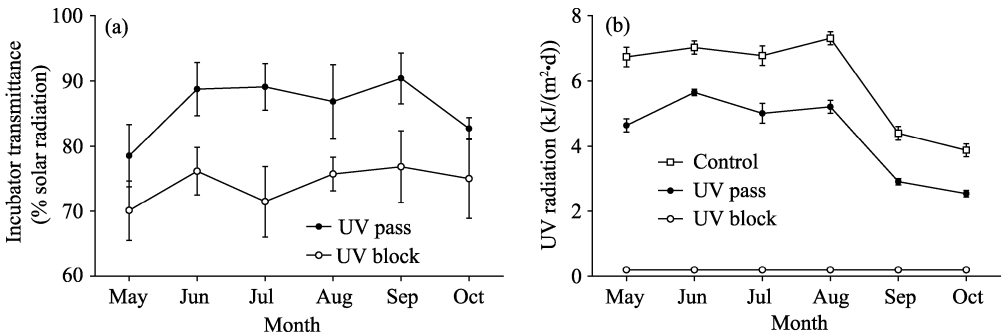

Fig. 1 Incubator transmittance (a) and UV (ultraviolet) radiation (b) of two kinds of litter incubators (UV pass and UV block) from May to October. The control represents the ambient UV radiation level. Bars mean standard errors.

2.3 Chemical analyses and data analyses

After the brushing away of any adhering soil particles, the litter in each litter box was oven-dried at 65°C to a constant mass and weighed. Then, the litter was milled and its total C concentration was determined using the $K_2Cr_2O_7$–H_2SO_4 wet oxidation method of Walkley and Black (Nelson and Sommers, 1996). Total N concentration of litter was determined with a continuous-flow autoanalyzer (AutoAnalyzer III, Bran+Luebbe GmbH, Hamburg, Germany) after the litter samples were digested by the Kjeldahl method (Bremner, 1996). We measured the lignin concentration using a modified acetyl bromide method (Iiyama and Wallis, 1990).

The differences of initial leaf litter chemical properties between the two species were determined by the *t*-test. For each species, a three-way analysis of variance (ANOVA) was used to test the effects of incubation month, litter layer thickness, and UV radiation on the mass loss and chemical properties of litter. Furthermore, a two-way ANOVA was used to test the interactive effects of UV radiation and tree species on the mass loss and chemical properties of litter. All statistical analyses were performed with the SPSS 16.0 software package for Windows. The significance level for the statistical tests was set at 0.05 ($P<0.05$) in this study. In addition, the effect sizes of UV radiation on the litter mass loss and chemical properties of the two species under the three litter layer treatment levels (100, 200, and 400 g/m^2) for different incubation periods (2, 4, and 6 months) were calculated as the natural logarithm of the response ratio (*RR*; Eq. 1):

$$\ln RR = \ln \frac{X_{\text{pass}}}{X_{\text{block}}}, \tag{1}$$

where X_{pass} and X_{block} denote the litter mass loss (or whichever chemical property) under the UV pass and UV block treatments, respectively.

3 Results

3.1 Effects of UV radiation and litter layer thickness on the mass loss of litter

UV radiation had a significant positive effect on the mass loss of Xiaozhuan poplar litter and Mongolian pine litter under all treatments (Tables 2 and 3), except for the mass loss of Xiaozhuan poplar litter under the 400 g/m^2 thickness level after 2 months of incubation (Table 2). Meanwhile, according to the ANOVA results, there was a significant interactive effect of UV radiation and tree species on the mass loss of litter (P=0.027).

Table 2 Natural logarithm (ln) response ratio of mass loss and chemical properties of Xiaozhuan poplar litter and Mongolian pine litter under UV radiation at three litter layer thickness levels (100, 200, and 400 g/m^2) after 2, 4, and 6 months of incubation

Variables	Incubation time (months)	Natural logarithm (ln) response ratio					
		Xiaozhuan poplar litter			Mongolian pine litter		
		100 g/m^2	200 g/m^2	400 g/m^2	100 g/m^2	200 g/m^2	400 g/m^2
Mass loss	2	0.214	0.203	–0.159	0.087	0.095	0.949*
	4	0.458*	0.143	0.173*	0.711*	0.031	0.470*
	6	0.631*	0.073	0.070	0.157	0.070	0.272
N concentration	2	–0.108*	0.035	0.008	–0.214*	–0.156*	–0.029
	4	0.006	0.005	0.009	0.209*	–0.071	0.021
	6	–0.074*	0.060*	0.056*	0.003	–0.034	0.043*
C/N ratio	2	0.110	0.007	0.025	0.219*	0.156*	0.026
	4	–0.031	–0.001	–0.012	–0.182	0.054	–0.013
	6	0.071	–0.073	–0.076	0.028	0.029	–0.075
Lignin concentration	2	0.008	0.020	0.016	–0.004	–0.015	–0.011
	4	0.046*	0.060*	0.039	–0.027	–0.017	–0.027
	6	0.039*	0.020	–0.002	–0.027	–0.013	–0.029
Lignin/N ratio	2	0.117*	–0.015	0.009	0.211*	0.140*	0.017
	4	0.040	0.055	0.031	–0.236*	0.051	–0.049
	6	0.114*	–0.040	–0.059*	–0.029	0.019	–0.072*

Note: * indicates statistical difference between UV pass and UV block treatments at P<0.05 level.

Table 3 ANOVA effects of incubation month, litter layer thickness, and UV radiation on the mass loss of Xiaozhuan poplar litter and Mongolian pine litter

Sources of variation	Xiaozhuan poplar litter			Mongolian pine litter		
	df	*F*	*P*	*df*	*F*	*P*
Month	2	56.9	<0.001	2	140.4	<0.001
Thickness	2	11.4	<0.001	2	19.0	<0.001
UV	1	2.9	0.001	1	19.8	<0.001
Month×Thickness	4	1.3	0.274	4	1.8	0.134
Month×UV	2	0.7	0.496	2	4.3	0.019
Thickness×UV	2	5.1	0.009	2	3.3	0.044
Month×Thickness×UV	4	1.5	0.209	4	2.1	0.098
Residual	71			71		

Note: Month, incubation month; Thickness, litter layer thickness; UV, UV radiation.

Litter layer thickness had a highly significant negative effect on the mass loss of both Xiaozhuan poplar litter and Mongolian pine litter (Table 3). Generally, the litter mass loss under the UV pass and UV block treatments was lower at the 400 g/m^2 litter layer thickness level than at the 100 and 200 g/m^2 litter layer thickness levels (Fig. 2). Furthermore, the interaction of UV radiation and litter layer thickness also had a significant effect on the mass loss of Xiaozhuan poplar litter and Mongolian pine litter (Table 3).

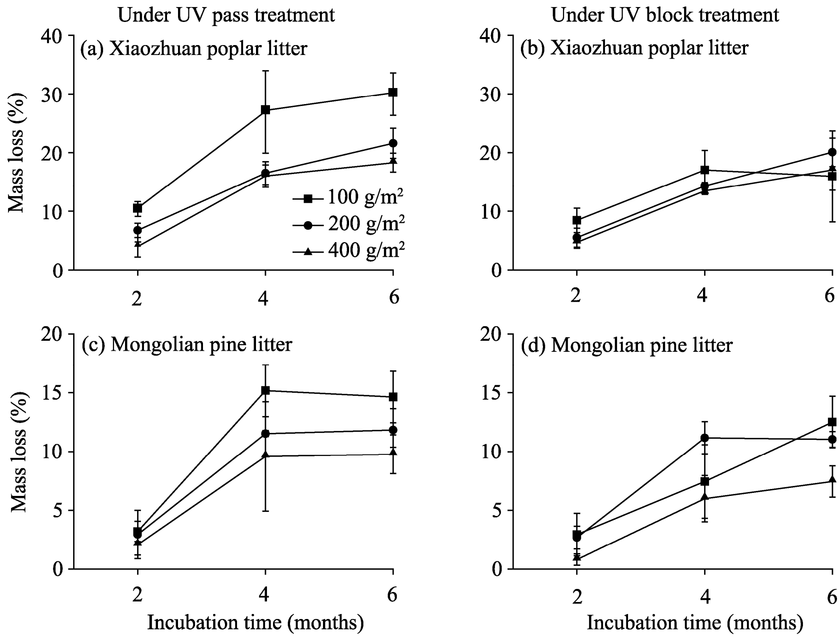

Fig. 2 Mass loss of Xiaozhuan poplar litter (a and b) and Mongolian pine litter (c and d) at three litter layer thickness levels (100, 200, and 400 g/m^2) under the UV pass and UV block treatments throughout the incubation months. Bars mean standard errors.

3.2 Effects of UV radiation and litter layer thickness on the chemical properties of litter

UV radiation did not significantly influence the N concentration and C/N ratio in the Xiaozhuan poplar litter (Table 4). In contrast, UV radiation significantly influenced the N concentration and C/N ratio in the Mongolian pine litter. Meanwhile, litter layer thickness and its interaction with UV radiation significantly affected the N concentration and C/N ratio in the litter of both species. According to the ANOVA results, there was significant interactive effects of UV radiation and tree species on the N concentration and C/N ratio (P=0.008 and P=0.011, respectively).

UV radiation significantly decreased the N concentration of Mongolian pine litter at the 200 g/m^2 litter layer thickness level at 2 months of incubation. Litter layer thickness had significant effects on the N concentration and C/N ratio of both Xiaozhuan poplar litter and Mongolian pine litter (Table 4). For the Xiaozhuan poplar litter, the N concentration under the UV block and UV pass treatments was lower at the 400 g/m^2 litter layer thickness level than at the 100 and 200 g/m^2 litter layer thickness levels (Figs. 3a and b). For the Mongolian pine litter, under the UV block treatment, the N concentration was lower at the 400 g/m^2 litter layer thickness level than at the other two litter layer thickness levels at 4 and 6 months of incubation; while under the UV pass treatment, this differential thickness effect was evident throughout the incubation months (Figs. 3c and d). Finally, the 400 g/m^2 litter layer thickness level of Mongolian pine litter under the UV block and UV pass treatments had a higher C/N ratio than did the other two litter layer thickness levels (Figs. 3g and h).

Meanwhile, UV radiation significantly affected the lignin concentration and lignin/N ratio of Xiaozhuan poplar litter (Table 5). The interactive effects of litter layer thickness and UV radiation significantly affected the lignin/N ratio of both Xiaozhuan poplar litter and Mongolian pine litter.

Table 4 ANOVA effects of incubation month, litter layer thickness, and UV radiation on the N concentration and C/N ratio of Xiaozhuan poplar litter and Mongolian pine litter

Chemical property	Sources of variation	Xiaozhuan poplar litter			Mongolian pine litter		
		df	*F*	*P*	*df*	*F*	*P*
N concentration	Month	2	576.2	<0.001	2	99.1	<0.001
	Thickness	2	143.8	<0.001	2	88.3	<0.001
	UV	1	0.3	0.572	1	12.2	0.001
	Month×Thickness	4	26.7	<0.001	4	13.6	<0.001
	Month×UV	2	4.6	0.015	2	50.9	<0.001
	Thickness×UV	2	34.2	<0.001	2	16.4	<0.001
	Month×Thickness×UV	4	8.8	<0.001	4	20.0	<0.001
	Residual	71			71		
C/N ratio	Month	2	530.4	<0.001	2	47.5	<0.001
	Thickness	2	159.9	<0.001	2	70.0	<0.001
	UV	1	0.0	0.964	1	10.4	0.002
	Month×Thickness	4	15.5	<0.001	4	11.4	<0.001
	Month×UV	2	19.9	<0.001	2	43.6	<0.001
	Thickness×UV	2	22.3	<0.001	2	12.3	<0.001
	Month×Thickness×UV	4	11.7	<0.001	4	16.4	<0.001
	Residual	71			71		

Note: Month, incubation month; Thickness, litter layer thickness; UV, UV radiation.

Table 5 ANOVA effects of incubation month, litter layer thickness, and UV radiation on the lignin concentration and lignin/N ratio of Xiaozhuan poplar litter and Mongolian pine litter

Chemical property	Sources of variation	Xiaozhuan poplar litter			Mongolian pine litter		
		df	*F*	*P*	*df*	*F*	*P*
Lignin concentration	Month	2	56.9	<0.001	2	30.0	<0.001
	Thickness	2	3.9	0.025	2	4.8	0.012
	UV	1	75.0	<0.001	1	0.1	0.774
	Month×Thickness	4	1.7	0.170	4	7.1	<0.001
	Month×UV	2	5.2	0.009	2	0.7	0.497
	Thickness×UV	2	2.7	0.077	2	2.1	0.133
	Month×Thickness×UV	4	1.6	0.193	4	1.4	0.254
	Residual	71			71		
Lignin/N ratio	Month	2	36.8	<0.001	2	71.5	<0.001
	Thickness	2	12.7	<0.001	2	32.2	<0.001
	UV	1	51.8	<0.001	1	4.3	0.043
	Month×Thickness	4	2.4	0.063	4	12.9	<0.001
	Month×UV	2	2.1	0.135	2	20.8	<0.001
	Thickness×UV	2	4.9	0.011	2	5.7	0.006
	Month×Thickness×UV	4	3.6	0.012	4	7.9	<0.001
	Residual	71			71		

Note: Month, incubation month; Thickness, litter layer thickness; UV, UV radiation.

The interactive effects of UV radiation and tree species also significantly affected the lignin concentration and lignin/N ratio in the litter of both species ($P<0.001$ and $P=0.001$, respectively). Furthermore, litter layer thickness showed significant effects on the lignin concentration and lignin/N ratio of both Xiaozhuan poplar litter and Mongolian pine litter. For the litter of two species, the 400 g/m^2 litter layer thickness level had a higher lignin concentration than did the other two litter layer thickness levels, under both the UV block and UV pass treatments, during the whole incubation period, except for the lignin concentration of Mongolian pine litter at 2 months of incubation under the UV pass treatment (Figs. 4a–d). Specifically, for the Xiaozhuan poplar litter, the 400 g/m^2 litter layer thickness level under the UV pass treatment had a lower lignin/N ratio than did the 200 g/m^2 litter layer thickness level, whereas this difference was insignificant under the UV block treatment at 4 months of incubation (Figs. 4e and f). Concerning the Mongolian pine litter, under the UV pass treatment, the 400 g/m^2 litter layer thickness level had a lower lignin/N ratio than did the 100 g/m^2 litter layer thickness level, whereas under the UV block treatment, it had a higher lignin/N ratio than did the other two litter layer thickness levels after 2 months of incubation (Figs. 4g and h).

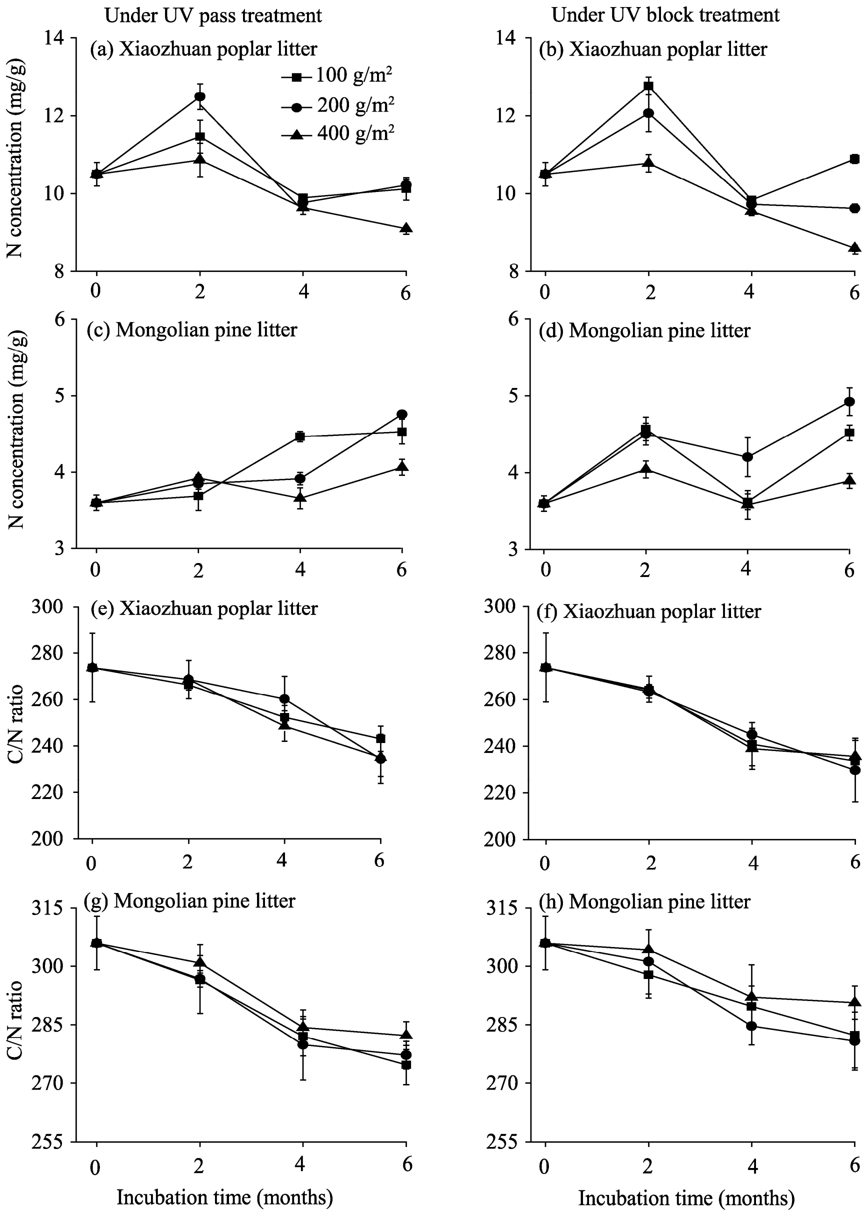

Fig. 3 N concentration and C/N ratio of Xiaozhuan poplar litter and Mongolian pine litter at three litter layer thickness levels (100, 200, and 400 g/m^2) under the UV pass and UV block treatments throughout the incubation months. Bars mean standard errors.

4 Discussion

Consistent with our first prediction, UV radiation stimulated the mass loss of Xiaozhuan poplar

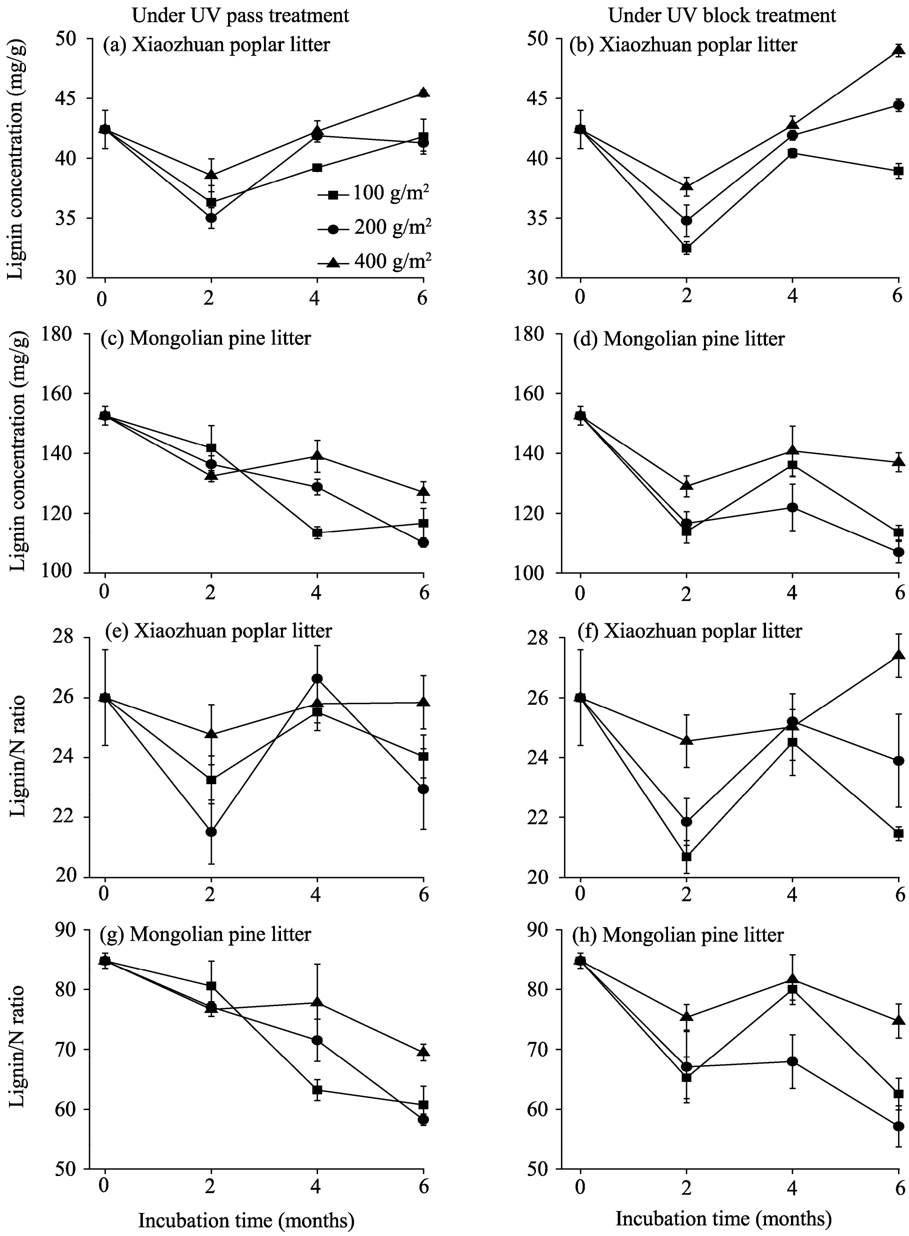

Fig. 4 Lignin concentration and lignin/N ratio of Xiaozhuan poplar litter and Mongolian pine litter under three litter layer thickness levels (100, 200, and 400 g/m^2) under the UV pass and UV block treatments throughout the incubation months. Bars mean standard errors.

litter and Mongolian pine litter, similar to some previous reports (Austin and Vivanco, 2006; Day et al., 2007; Foereid et al., 2010). Several prior studies identified lignin as the main organic compound lost from litter exposed to UV radiation (Gehrke et al., 1995; Rozema et al., 1997; Lanzalunga and Bietti, 2000; Pancotto et al., 2005). UV radiation significantly decelerated the lignin decomposition rate of Xiaozhuan poplar litter in our study, similar to the results of Day et al. (2007) and Henry et al. (2008), while it had an insignificant effect on the lignin decomposition rate of Mongolian pine litter (Brandt et al., 2007). Such species differences in response to UV radiation between the Xiaozhuan poplar litter and Mongolian pine litter may be due to their leaf area and initial litter chemical properties. The broad-leaved species (Xiaozhuan poplar) possesses a larger area for UV absorption than does the coniferous species (Mongolian pine); hence, we may well expect higher effects of UV radiation on Xiaozhuan poplar litter than on Mongolian pine litter just on the basis of differences in their leaf area (Gaxiola and Armesto, 2015). Furthermore, the quality of Xiaozhuan poplar litter was greater than that of Mongolian pine litter (i.e., low lignin concentration and lignin/N ratio for the Xiaozhuan poplar litter versus high lignin concentration and lignin/N ratio for the Mongolian pine litter; Table 1). Species with a higher-quality litter could be more sensitive to UV radiation than species with a lower-quality litter (Gallo et al., 2009). Meanwhile, in addition to lignin, cellulose and hemicellulose are also susceptible to breakdown by solar exposure, so that the photodegradation of these compounds could also contribute to C losses (Brandt et al., 2010; King et al., 2012). Several studies found that the concentrations of cellulose and hemicellulose were notably decreased when litter was exposed to UV radiation whereas the lignin concentration was negligibly affected (Brandt et al., 2007; Gaxiola and Armesto, 2015). Further chemical analyses for cellulose and hemicellulose are thus required to fully evaluate the extent to which C compounds may account for the positive effects of UV radiation on the decomposition of Mongolian pine litter.

Moreover, we found that UV radiation significantly altered the N concentration and ratios of C/N and lignin/N during litter decomposition, though the effects of UV radiation on the chemical properties depended on the tree species. This result is consistent with those from Brandt et al. (2007) and Gaxiola and Armesto (2015). The differential effects of UV radiation on the changes in the chemical properties of litter could arise from interspecific differences (such as leaf morphology and initial leaf litter chemical properties) and the complexities of C compound decomposition and nutrient release of litter under UV radiation (Cybulski et al., 2000; Newsham et al., 2001; Song et al., 2013b, 2014). Xiaozhuan poplar litter had higher initial nutrient concentrations and lower initial lignin concentrations than did Mongolian pine litter. Thus, Xiaozhuan poplar litter is expected to be more conducive to the activity of soil macrofauna and microbes compared to Mongolian pine litter. Unequal activity of soil macrofauna and microbes between species could have contributed to their different responses to the effects of UV radiation in terms of the chemical properties of their leaf litter (Killham, 1994; Peterson et al., 1997; Pancotto et al., 2003). Furthermore, the marked differences in leaf surface area and shape between Xiaozhuan poplar litter and Mongolian pine litter could potentially alter the impact of UV radiation on the leaching process, thereby influencing how the litter chemical properties are changed (Song et al., 2013b). Thus, contrasting initial chemical properties and morphology of leaf litter likely represent two important factors contributing towards UV radiation effects on the chemical properties of decomposing litter of tree species.

Changes in the litter layer thickness, which are mainly determined by climate, soil parent materials, and tree species composition and distributions, may affect the cycling of C and N, because the litter layer provides habitats and substrates for earthworms, arthropods, fungi, and microorganisms (Sayer, 2006; Zepp et al., 2007). We found that litter layer thickness modulated the effects of UV radiation on the mass loss of both Xiaozhuan poplar litter and Mongolian pine litter. Moreover, litter layer thickness also modulated the effects of UV radiation on the N concentration and ratios of C/N and lignin/N of Xiaozhuan poplar litter and Mongolian pine litter. Hence, change to the litter layer thickness likely represents an important factor affecting litter decomposition under conditions of high-intensity UV radiation (Henry et al., 2008; Gallo et al., 2009).

Furthermore, we found that the mass loss of litter was significantly decreased with increasing thickness of litter layer (i.e., the highest mass loss of litter at the 400 g/m^2 litter layer thickness level), indicating that high rates of annual litter deposition would inhibit the process of litter photodegradation. Therefore, future changes in the litter layer thickness appear to have more important implications for litter UV exposure than do increases in the UV radiation intensity entering Earth's atmosphere (Henry et al., 2008). Moreover, the elevated atmospheric CO_2, N deposition, and air temperature may result in a greater overall litter production (Sayer, 2006). To better manage the litter layer in tree plantations, so as to improve soil quality and nutrient cycling, we now need to study how litter layer thickness affects the litter decomposition process in concert with other climate factors, such as elevated atmospheric CO_2 and/or elevated N deposition.

Sustaining an adequate nutrient availability for plant growth and controlling the cycling of nutrient elements through living communities are the core principles upon which ecosystem management is based (Schimel and Bennett, 2004; Vitousek, 2004). Prior studies suggested that N deficiency is one of the major factors limiting ecosystem productivity in the Horqin Sandy Land (Chen et al., 2006). In our study, we found that by increasing the litter layer thickness, the N concentration of Xiaozhuan poplar litter decreased but that of Mongolian pine litter increased, during the incubation period. Meanwhile, we also found that the mass loss of Xiaozhuan poplar litter was faster than that of Mongolian pine litter. This result suggests that a greater thickness of litter layer was conducive to N release and decomposition of Xiaozhuan poplar litter but not so for Mongolian pine litter. Litter layer thickness in forests, but especially in monospecific plantations, depends on tree species, stand density, and canopy coverage (Hennessey et al., 1992; Adu-Bredu et al., 1997). For promoting soil N availability in our study region, we recommend that the stand density of Mongolian pine (typically at a spacing of 2 m×5 m or more) should be reduced via thinning.

5 Conclusions

This study contributes to our understanding of the effects of UV radiation, litter layer thickness, and their interaction on the mass loss and chemical properties of Xiaozhuan poplar litter and Mongolian pine litter in plantations. Our data revealed that UV radiation and litter layer thickness are two important drivers of litter decomposition in the Horqin Sandy Land, and further highlighted that changes in the litter layer thickness can exert strong influences on the photodegradation of litter. The effects of UV radiation on the changed chemical properties of decomposing litter depended on tree species identity, largely due to the contrasting initial chemical properties and morphology of leaf litter. Furthermore, litter layer thickness significantly modulated UV radiation and affected the mass loss and chemical properties of decomposing litter of Xiaozhuan poplar and Mongolian pine trees.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (31270668, 41373038), the National Basic Research Program of China (2012CB416902) and the China Postdoctoral Science Foundation (2016M601342). We thank two anonymous reviewers for their valuable comments and suggestions. Special thanks are extended to LI Jingshi and AI Guiyan for their laboratory analyses.

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