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Leaching and Freeze-Thaw Events Contribute to Litter Decomposition - A Review

(Kejadian Larut Lesap dan Beku-Cair Menyumbang kepada Penguraian Sampah - Suatu Ulasan)

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ABSTRACT

Litter decomposition is vital for carbon and nutrient turnover in terrestrial ecosystems, and this process has now been thoroughly demonstrated to be regulated by various mechanisms. The total environment has been continuously changing in recent decades, especially in high-latitude regions; these alterations, however, profoundly contribute to the decomposition process, but a comprehensive recognition has not available. Here we reviewed the empirical observations and current knowledge regarding how hydrological leaching and freeze-thaw events modulate early decomposition of plant litter. Leaching contributes a considerable percentage of mass loss and carbon and nutrient release in early stage of decomposition, but the magnitudes are different between species levels depending on the chemical traits. Frequent freezing and thawing events could positively influence decomposition rate in cold biomes but also hamper soil decomposer and there is no general and predictable pattern has been emerged. Further experiments should be manipulated to estimate how the altered freezing and thawing effect on carbon and nutrient release from plant litter to better understanding the changing environment on litter decomposition.

Keywords: cold biomes; freeze-thaw; leaching; litter decomposition

ABSTRAK

Penguraian sampah adalah penting untuk pusing ganti karbon dan nutrien dalam ekosistem daratan dan proses ini kini telah dibuktikan secara terperinci dikawal oleh pelbagai mekanisme. Persekitaran secara keseluruhan berterusan berubah sejak beberapa dekad kebelakangan ini terutamanya di kawasan berlatitud tinggi; perubahan ini, walau bagaimanapun menyumbang secara mendalam kepada proses penguraian, tetapi tidak terdapat suatu pengiktirafan yang komprehensif. Di sini kami mengkaji cerapan empirik dan pengetahuan semasa tentang bagaimana kejadian hidrologi larut lesap dan beku-cair memodulatkan proses awal pereputan sampah loji. Larut lesap menyumbang kepada peratusan kehilangan jisim dan karbon serta pelepasan nutrien yang agak besar pada peringkat awal pereputan, tetapi magnitud tersebut berbeza antara tahap spesies bergantung kepada sifat kimia. Kekerapan kejadian larut lesap dan beku-cair boleh secara positif mempengaruhi kadar penguraian dalam biom sejuk tetapi juga menghalang tanah diurai serta tidak terdapat pola umum dan boleh diramal yang muncul. Uji kaji susulan harus dimanipulasi untuk menganggarkan bagaimanakah kesan pengubahsuaian larut lesap dan beku-cair ke atas pembebasan karbon dan nutrien dari loji sampah untuk memahami dengan lebih baik persekitaran yang berubah-ubah kepada penguraian sampah.

Kata kunci: Beku-cair; biom sejuk; larut lesap; penguraian sampah

INTRODUCTION

Decomposition of plant litter is one of the most fundamental processes for global carbon budgets, as approximately half of the ecosystem productivity is returned to the soil via litter decay in terrestrial ecosystems (Wardle et al. 2004). Multiple factors are responsible for regulating decomposition rate, but in a given ecosystem, the ambient environment can considerably modulate this process. Alterations of environmental conditions greatly impact on soil decomposer and thereby change the chemical compositions (Aerts 1997; Wardle et al. 2004). This has received increasing interest in the past two decades because many scientists paid their attention to climate warming (Prescott 2010). However, increasing temperature is expected to be amplified in cold biomes (Copper 2014), which are important accumulators of soil organic carbon (Arctic Climate Impact Assessment 2005; Davidson & Janssens 2006) and where litter decomposition is strongly limited by low temperature (Hobbie et al. 2002; Robinson 2002).

Contemporary literatures have mostly focused on the effects of chemical and biological agents on litter decomposition (Preston et al. 2009), while studies investigating physical factors, such as leaching and freeze-thaw events, in litter breakdown were scanty. The amounts of water soluble substances in fresh litter decrease considerably in early stage of decomposition owing to leaching and freeze-thaw cycle was considered to be a significant environmental factors regulating litter decomposition in cold biomes (Zhu et al. 2012). Increasing evidence has demonstrated that freeze-thaw events directly modify carbon release from foliar litter (Wu et al. 2014) and contribute to decomposition rates (Yang et al. 2014). Such results have indicated that changes in freeze-thaw cycles may lead to changes in litter decomposition and elemental cycles in terrestrial ecosystems and the effect of leaching on water soluble substances could also be affected as well because of altered hydrological condition accompanying by soil freezing and thawing. However, there have been only a few studies that investigated the effects of leaching and freeze-thaw events on litter decomposition and the potential mechanisms underlying were still unclear.

In order to get a general understanding of the roles of leaching and freeze-thaw events on litter decomposition, it would be fundamental for getting a comprehensive mechanism of these physical processes in cold biomes. Hence, we reviewed some empirical observations on the contribution of leaching and freeze-thaw cycles to litter decomposition in cold biomes to provide general insight and highlighted in challenges and opportunities of systematic research in future.

Leaching and Litter Decomposition

At early stage of decomposition, the large amounts of dissolved materials in fresh litter could be leached (Schreeg et al. 2013). This labile leachate could trigger the carbon use efficiency of microorganisms and thereby further promote decomposition (Cotrufo et al. 2015, 2013).

The Effects of Leaching on Mass Loss

As early as in 1878, Müller emphasized that water soluble substances are of great importance for soil formation and these substances derive chiefly from litter during decomposition. Previous investigations have shown a positive correlation between the amount of water soluble substances in the litter and the decomposition rate during the first months and this mainly due to the effect of leaching. It was reported that mass loss from fresh litter was equal to the loss of soluble compounds during the first weeks of *in situ* decomposition (Bernhard-Reversat 1993) and this study emphasized the dependence of early decomposition process on the release of soluble compounds. Nykvist (1963, 1962; 1961a; 1961b, 1959a; 1959b) conducted a series of experiments in laboratory to investigate the factors that may affect the leaching of litter and concluded that: the total amount of water soluble organic and inorganic substances leached from ground litter after one day ranged from 8-25% of the dry mass among six experimented litter types; the amount of water soluble substances was greater when leaching took place under anaerobic conditions than under aerobic; this was due to a greater decomposition rate of water soluble substances under aerobic environment; the pH value raised under aerobic environment, but fallen under anaerobic condition, and this may be related to the formation of aliphatic acids during decomposition; and the influence of temperature on leaching of water soluble substances was greater in oak litter and large amounts were leached from needle litter of pine and spruce at high temperatures. These results indicated that leaching was not only modulated by abiotic factors such as pH value and temperature, but also affected by the functional traits of plant litter, which have been proved to be a predominant factor controlling on litter decomposition within a given ecosystem worldwide (Cornwell et al. 2008; Makkonen et al. 2012).

Many other researchers have also reported the effects of leaching on early stage of litter decomposition (Table 1) and the results were similar to that reported by Nykvist. We can see from Table 1 that mean litter mass loss of foliar litter ranged from 1.5% to 11.4% for one day of leaching and from 6.0% to as much as 47.2% for more than one day of treatment. Generally, leaching is largely completed within the first 24-48 h after immersed in water and the loss up to 30% of the original mass, depending on litter species. However, it is noteworthy that, although the mass loss in the first day may account for a large amount of the whole losing mass, the period of leaching is a prolonged process developing over weeks (France et al. 1997).

The Effects of Leaching on Carbon Release

Dissolved organic matter (DOM) leached from decomposing litter is the most important carrier for the flux of nutrients, eluviation of metals and transport of hydrophobic pollutants. Natural DOM is composed of components that have widely difference in physicochemical properties and may also be consisted of mixtures of labile and refractory to microbial decomposition (Qualls 2005), but the most studied counterparts were dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) in published citations. In a leaching experiment using the needle and fine root of spruce litter, leaching rate of DOC tended to decrease with time for both litter types and was most pronounced for fresh root from mineral soil and senesced needle from litter layer, which had the highest DOC leaching on the first measurement occasion (Hansson et al. 2010). The fraction of carbon leached as DOC decreased with time for all litter types except for the fresh needle litter and almost all litter types stabilized at approximately 20%. Using microcosms, initial carbon mineralization and leaching rates of DOC from litter of eight tree species in CO_2 enrichment conditions were measured by Hagedorn and Machwitz (2007) in a broadleaf forest. Over 11 weeks of leaching, between 2.5% (*Pinus uncinata* and *Fagus sylvatica*) and 15% (*Carpinus betulus*) of litter carbon were leached as DOC, corresponding to 9-36% of the total mass loss. The results suggested that elevated CO_2 decreased lignin degradation but accelerated both carbon mineralization and DOC leaching from the litter and DOC was less biodegradable when its parent litter was incubated under elevated CO_2. Using ^{14}C labeled leaf litter of *Populus fremontii* that had decomposed for one year, the fractions of dissolved organic matters that was extracted in water were, in this order: hydrophilic acid (30.5%), fulvic acid

TABLE 1. Mass loss of some foliar litters attributed by leaching

Species	Mass loss (%)		References
	1 day	>1 day	
Annona senegalensis	6.5	15.7	Ibrahima et al. 2007
Acacia mangium	--	27.9	Yang et al. 2012
Berzelia lanuginosa	11.4	14.7	Raubenheimer & Day 1991
Betula papyrifera	--	15.7	France et al. 1997
Castanea sativa	6.0	13.8	Ibrahima et al. 1995
Cistus monspeliensis	3.5	11.2	Ibrahima et al. 1995
Eucalyptus urophylla	--	47.2	Yang et al. 2012
Elegia thyrsifera	2.5	8.5	Raubenheimer & Day 1991
Fagus sylvatica	3.1	6.5	Ibrahima et al. 1995
Lophira lanceolata	2.3	9.8	Ibrahima et al. 2007
Nothofagus solandri var. *cliffortioides*	1.5	7.3	McCammon 1980
Populus tremuloides	--	12.4	France et al. 1997
Picea mariana	--	15.1	France et al. 1997
Pinus banksiana	--	5.7	France et al. 1997
Pinus massoniana	--	30.8	Yang et al. 2012
Pinus halepensis	2.9	8.0	Ibrahima et al. 1995
Quercus pubescens	4.8	11.7	Ibrahima et al. 1995
Quercus coccifera	4.8	12.4	Ibrahima et al. 1995
Quercus ilex	3.9	13.8	Ibrahima et al. 1995
Quercus robur	--	6.0	Tietema & Wessel 1994
Syzygium guineense var. *guineense*	4.4	14.1	Ibrahima et al. 2007
Syzygium guineense var. *macrocarpum*	3.1	11.7	Ibrahima et al. 2007
Vitellaria paradoxa	8.6	14.2	Ibrahima et al. 2007
Vitex doniana	9.1	15.5	Ibrahima et al. 2007
Vitex madiensis	15.0	19.0	Ibrahima et al. 2007
Ximenia americana	18.8	34.0	Ibrahima et al. 2007

(33.8%), humic acid (39.0%), unfractionated DOC (43.5%), unseparated hydrophilic acid and neutral phenolic (63.3%), glucose (66.4%) and hydrophilic neutral (70.2%) (Qualls 2005).

THE EFFECTS OF LEACHING ON NUTRIENT RELEASE

Nutrient leaching from freshly senesced litter could provide essential materials available for plant and microbial uptake, such as orthophosphate, inorganic and organic nitrogen (Sinsabaugh et al. 2002). It was reported that grazed pastures lost large amounts of nitrogen as DON through leaching and these amounts were estimated to be 4-120 kg N ha^{-1} $year^{-1}$ in some New Zealand pasture soils (Ghani et al. 2010). In a laboratory study, the concentration of DON in the leachates declined to less than 1 mg N L^{-1} within 7-14 days of incubation; this consistent with the observation that extractable DON in water ranged between 2 and 63 mg N L^{-1} (Ghani et al. 2013). Within the first 21 days of incubation, DON concentration was decreased to near zero without any significant change in the concentration of NO_3^- or NH_4^+, indicating that microbes could utilized organic nitrogen preferentially. Phosphorus leached from both fresh and aged leaves was mostly free of orthophosphate and therefore was readily available (Baldwin 1999). Hafner et al. (2005) measured the concentrations of DOC, DON, NH_4^+, NO_3^-, dissolved organic sulfur, SO_4^{2-}, Cl^-, Al, Ca, K, Mg, Na and P of through fall and leachates of litter and coarse woody debris *in situ* at a young mixed lowland forest in New York. Their results suggested that concentrations of DOC were much higher in coarse woody debris leachate (15 mM) than in through fall (0.7 mM) or litter leachate (1.6 mM). Concentrations of some elements correlated with DOC concentrations, highlighting the possibility of elemental complexation reaction with DOM. At microsite scale, the fluxes of DOC from coarse woody debris were higher relative to through fall and litter leachate. Including DOC, some solute concentrations through fall showed positive correlations to mean air temperature and fewer showed positive correlations in litter leachate, while negative correlations were observed to precipitation. These results suggested that both biological and hydrologic factors controlling leaching.

Collectively, the solubility of different elements during leaching varied markedly. On average 100% of total potassium, 35% of total phosphorus, 28% of total sodium, 5% of total nitrogen, 4% of total calcium and 3% of total carbon could be soluble (Schreeg et al. 2013). Elemental solubility was linked within a species: when a species ranked high in the soluble fraction of one element, it also ranked high in the solubility of other elements. Overall nutrient-specific patterns of solubility from freshly senesced litter emphasized that litter elements cannot be treated equally in conceptual models of decomposition.

Does Temperature Count in Leaching?

Temperature is one of the most important environmental factors affecting litter decomposition and its effect would be more distinct in cold biomes. In a laboratory leaching experiment, temperature was proven to be an important factor affecting DOC leaching obviously after 1-36 days of incubation (Andersson & Nilsson 2001; Andersson et al. 2000), indicating that temperature must be taken into consideration while assessing the effect of leaching on litter decomposition. However, literature about this was rare and the available data were not all-inclusive. What the contribution of leaching to litter decomposition across different temperatures looks like and how to compare the leaching contribution visually across a range of temperatures, will be interesting questions for scientists.

Freeze-Thaw Events and Decomposition

Increasing evidence has indicated that decomposition rate during freeze-thaw season accounted for a large proportion (Christenson et al. 2010; Wu et al. 2010) and the altered spatial and temporal patterns of soil freezing conditions have significant implications for nutrient cycling in cold biomes. Freeze-thaw events could alter chemical compositions, nutrient availability and transportation in soils by various mechanisms and generally promote mineralization (Deluca et al. 1992), thus litter decomposition may be affected by a complex range of chemical, biological and physical factors induced by freeze-thaw.

The Roles of Freeze-Thaw Events on Litter Decomposition

Soil freeze-thaw event is an alternately process of freezing and thawing in topsoil as a consequence of temperature fluctuation, accompanying by other physical processes such as cryoturbation and leaching (Henry 2007). The main effect of freeze-thaw cycle was the influence on soil physical characteristics. The volumetric change in ice water conversion (expansion and contraction) could damage soil aggregate structure with the occurrence of leaching of snowmelt during this process. Alternate freezing and thawing can change the physical structures of litter, increase litter infiltration rate and decrease the stability of soil aggregates. The magnitude depends on temperature, soil moisture, soil aggregates and frequency of freeze-thaw cycles (Edwards et al. 2007). Moreover, high water content and continuous freeze-thaw cycles during early spring could show a greater destructive impact on macromolecular substances in leaf litter (Austin & Ballaré 2010). In addition, the changes of chemical compounds in litter during wintertime inevitably affect the subsequent decomposition in growing season. However, most of the current studies reporting freeze-thaw events were carried out in agricultural or forested soil; little research was manipulated on litter decomposition. Due to methods limitation and low activity of soil organisms, measurements of litter decomposition in cold biomes during winter and early spring were limited (Uchida et al. 2005).

The Effects of Freeze-Thaw Events on Mass Loss

In the past, it was generally assumed that litter decomposition during winter could be ignored (Campbell et al. 2005). However, in the last decade, an increasing numbers of studies reported that microbial activity, which is crucial to litter decomposition, does not cease in winter (Robinson 2001; Schimel & Mikan 2005). Significant mass loss and nutrient release from litter during winter in low temperature forests and other cold biomes have been reported (Hobbie & Chapin 1996; Melillo et al. 1982). Simulated laboratory experiments have indicated that frequent freeze-thaw cycles show considerable effect on the physical structure of litter and therefore on decomposition rate (Freppaz et al. 2007; Taylor & Parkinson 1988). Our previous studies conducted litterbags during freeze-thaw season in subalpine forests region (Wu et al. 2010; Zhu et al. 2012) have suggested that decomposition rates during this period contributed significantly to the first year of decomposition that about 18% and 20% of mass lost from fir (*Abies faxoniana*) and birch (*Betula albosinensis*) litter, respectively. Mass loss and nutrient release during freeze-thaw season were attributed to physical destruction, hydraulic leaching and the related microbial activity.

The Effects of Freeze-Thaw Events on Soil Decomposer

The effect of freeze-thaw events on soil fauna and microorganism could also have great influences on litter decomposition rate. Sjursen et al. (2005) reported that there was no conclusive evidence that recurring freeze-thaw events had a negative effect on soil fauna community and such treatment even seemed to stimulate the abundance of Acaridida. Yanai et al. (2004) investigated the effects of soil freeze-thaw cycles on soil microbial biomass and found that freeze-thaw cycles led to a significant 6% of increase in chitin decomposition and a 7% of decrease in rice decomposition, indicating that the partial sterilization associated with the soil freeze-thaw cycles might disturb soil microbial functions. Freeze-thaw cycles, in seasonally snow covered soils, were likely to have a selective effect on the microbial biomass (Freppaz et al. 2007). Freezing and thawing resulted in a change of ammonification and release of DON, which represent an important influence upon nitrogen cycling in cold biomes (Figure 1). Xia et al. (2012) quantified the contribution of soil fauna to the decomposition of birch leaf litter in a subalpine forest during freeze-thaw season using different mesh sizes (0.02, 0.125, 1 and 3 mm) of litterbags. Over the freeze-thaw season, about 11.8%, 13.2%, 15.4% and 19.5% of the mass losses were detected in the litterbags with 0.02, 0.125, 1 and 3 mm mesh sizes, respectively. The total contribution of soil fauna to litter decomposition accounted for 39.5%

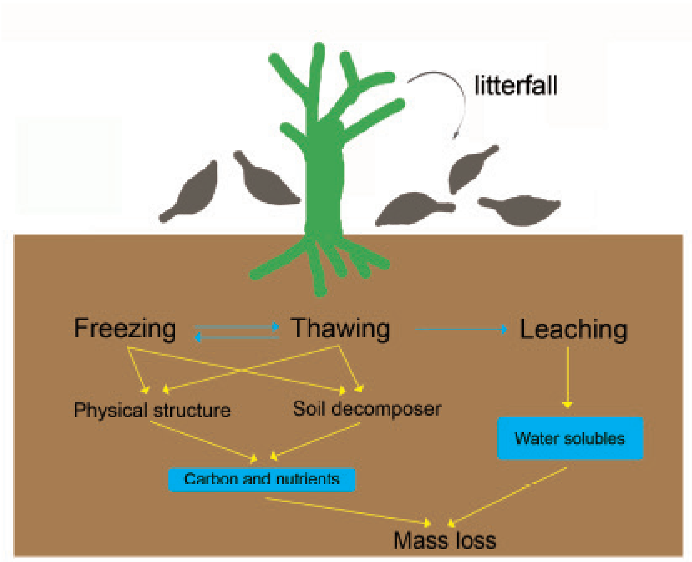

FIGURE 1. A diagram explaining leaching and freeze-thaw events affecting litter decomposition

of the mass loss and showed the order of micro- < meso- < macro-fauna. Moreover, the highest contribution of micro-fauna (7.9%), meso-fauna (11.9%) and macro-fauna (22.7%) occurred at the onset of freezing stage, deep frozen stage and thawing stage, respectively. All these results demonstrated that soil fauna play an important role in litter decomposition during freeze-thaw season.

THE EFFECTS OF FREEZE-THAW EVENTS ACCOMPANIED WITH OTHER FACTORS

A study has suggested that most of mass in fresh litter during cold season loss in autumn before the onset of winter and the decomposition during the 'true' wintertime is almost non-existent (Bokhorst et al. 2010). Both the repeated warming and freezing treatments in their laboratory incubation and the simulated winter warming in field had no effect on total mass loss. So they suggested that freeze-thaw events do not affect fresh litter decomposition. However, according to our previous investigations and the available literatures, we propose that freeze-thaw cycles do affect litter decomposition significantly and the potential mechanisms can be summarized as follows: biological decomposition might be responsible for a majority of mass loss and release of carbon and nutrient during the cold season, as microbial activity did not completely cease in the frozen period (Brooks et al. 1997); Thawing events, accompanied with the increase of moisture and temperature during the early spring, can increase microbial activity and the concomitant leaching can induce great release of nutrients (Lemma et al. 2007); and freezing may have a destructive effect on the physical structure of litter, breaking down the recalcitrant components such as resin and 'lignin' in litter (Groffman et al. 2001) and consequently promote mass loss and nutrient release.

POTENTIAL PROBLEMS IN STUDYING FREEZE-THAW CYCLES ON LITTER DECOMPOSITION

Physical disruptions, such as frequent freezing and thawing, did not generate feedbacks during litter decomposition. Freeze-thaw events were likely to affect litter decomposition through mechanical disruption and thus expose new surfaces on where enzymes could act. Physical disruption may even be more important to formation of soil organic matter because a mixture could promote the aggregation of organic and mineral materials. Thus studies on freeze-thaw events effect on litter decomposition should not be restricted to fresh litter only. Another problem was about how to quantify the freeze-thaw cycle. Some inappropriate methods may result in misleading quantification of the frequency of freeze-thaw cycles and made it hard to establish a causal connection between litter decomposition and effects of freeze-thaw events. Accompanying with the alternate freezing and thawing, the amount of water available for leaching seems to be important for the release of water soluble substances. How to distinguish such confounding factors and the effect of freeze-thaw itself is of great importance. Controlled experiments may be useful in further investigations.

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