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# Leaf litter decomposition as a bioassessment tool of acidification effects in streams: Evidence from a field study and meta-analysis

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ABSTRACT

Atmospheric acid deposition affects many streams worldwide, leading to decreases in pH and in base cations concentrations and increases in aluminum (Al) concentration. These changes in water chemistry induce profound changes in the diversity, structure and activity of biological communities and in ecosystem processes. However, monitoring programs rely only on chemical and structural indicators to assess stream integrity. Nevertheless, the ability of ecosystems to provide services rely on their functional integrity and thus ecosystem processes should be considered in monitoring programs. We assessed the potential for leaf litter decomposition, a fundamental ecosystem process in forest streams, to be used as a bioassessment tool of acidification effects on stream ecosystem functioning. In a field study in the Vosges Mountains (North-eastern France), using three leaf litter species (*Alnus glutinosa*, *Acer pesudoplatanus* and *Fagus sylvatica*) enclosed in fine and coarse mesh bags and incubated in streams flowing over granite or sandstone bedrock along an acidification gradient, we assessed if the response of litter decomposition to acidification depended on litter species, mesh size, parent lithology and acidification level. In a meta-analysis of 17 primary studies on the effect of acidification on leaf litter decomposition, reporting 67 acidified – reference stream comparisons, we assessed the consistency in the response of litter decomposition to acidification cross studies and the robustness of litter decomposition to be used as a bioassessment tool. Both the field study and meta-analysis revealed an overall strong inhibition (> 60%) of leaf litter decomposition in acidified streams likely resulting from previously well described altered decomposer community structure and activity. No effect of leaf species was found in the field study, while in the meta-analysis inhibition of leaf litter decomposition in acidified streams was stronger for *Fagus* than for *Acer*, *Quercus* and *Liriodendron*. However, differences among leaf species in the meta-analysis might have been confounded by other differences among studies. The response of leaf litter decomposition to acidification was stronger in coarse than in fine mesh bags, indicating strong impairment of detritivore community structure and activity. The magnitude of inhibition also depended on parent lithology, but this is likely related to differences in the degree of acidification. Indeed, the magnitude of the inhibition of leaf litter decomposition increases with increases in $H^+$ in Al concentration. Litter decomposition has the potential to be used as a bioassessment tool of acidification effects in streams since it shows consistent response to acidification across regions and is robust to experimental choices.

## 1. Introduction

Atmospheric acid deposition has drastically affected terrestrial and aquatic ecosystems over large temperate areas of the northern hemisphere (Driscoll et al., 2001) and it is an important emerging problem in Asia (Lu et al., 2010; Liu et al., 2011). The unanimous acknowledgment of the deleterious impacts of atmospheric acid deposition on ecosystems led to the implementation of several national and international rigorous agreements aiming at reducing transboundary air pollution (Likens et al., 2001). Recent decades have indeed witnessed a large decrease in the emission of pollutants and in turn in acid deposition in North America and Europe (Waldner et al., 2014; Lawrence et al., 2015). However, the decrease in acid deposition is not always translated into improved water quality because (i) sulfur compounds accumulated over decades of $SO_2$ atmospheric deposition are still being leached from soils into freshwaters, (ii) there is an increase in $NH_3$ emissions from

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intensification in agriculture and in cattle production, (iii) base cations in catchments in acid-sensitive regions often continue to be depleted, and (iv) there is a decrease in base cations atmospheric deposition (Likens et al., 1996; Alewell et al., 2001; Evans et al., 2001; Liu et al., 2011). Nevertheless, evidence of chemical recovery has been reported for several areas with stream water showing declining concentrations of sulphate ($SO_4$) and aluminum (Al) and increasing pH and acid neutralizing capacity (ANC) (Stoddard et al., 1999; Skjelkvale et al., 2005). But, if signs of chemical recovery have been reported, evidence of biological recovery remains rare (Malcolm et al., 2014a,b) and when it occurs changes in communities (e.g., return of acid sensitive species) appear modest (Monteith et al., 2005). Thus, acidification of freshwaters remains an environmental problem and many ecosystems are still severely affected by water that is chronically or episodically acidic.

Environmental quality assessment of streams is generally based on community (e.g., benthic macroinvertebrates, diatoms and fish) structural variables (Birk et al., 2012; O'Brien et al., 2016). However, community structure and ecosystem function are not always closely coupled and several proposals have been made for the incorporation of ecosystem processes in bioassessment programs (Gessner and Chauvet, 2002; Young et al., 2008).

Leaf litter decomposition is a fundamental ecosystem process in forest headwater streams, since primary production is limited by shading and leaf litter of terrestrial origin constitutes the main source of energy and carbon for aquatic communities (Wallace et al., 1997). The rate at which litter decomposes depends on litter intrinsic characteristics, microbial (mainly aquatic hyphomycetes) and invertebrate consumer (i.e., shredders) activity, and environmental conditions (Webster and Benfield, 1986). Generally, soft litter with high nutrient concentration (i.e., high quality litter) decomposes faster than more recalcitrant litter since microbial colonization is faster and microbial activities are higher in the former than in the latter substrate (Gessner and Chauvet, 1994; Gulis et al., 2006). Leaf litter decomposition is also stimulated in the presence of shredders and increases with increases in their density (Taylor and Chauvet, 2014). Changes in environmental conditions can affect litter mass loss directly, and indirectly by altering community structure and activity of microbial and invertebrate decomposers (Webster and Benfield, 1986).

Stream acidification, and associated increase in monomeric Al concentration and decrease in base cations concentrations, generally inhibits leaf litter decomposition rates (Dangles and Guérold, 1998, 2001a,b; Dangles et al., 2004; Baudoin et al., 2008; Simon et al., 2009; Cornut et al., 2012). This is achieved via inhibition of microbial activities (Griffith et al., 1995; Dangles et al., 2004; Simon et al., 2009), reduction of microbial biomass (Griffith and Perry, 1994; Meegan et al., 1996; Dangles et al., 2004), and reduction of aquatic hyphomycete species richness (Baudoin et al., 2008; Cornut et al., 2012). Also, there is disappearance of acid-sensitive detritivores such as gammarids, sericostomatids and limnephilids that are also large and/or efficient shredders, and reduction of shredder biomass (Meegan et al., 1996; Dangles and Guérold, 1998, 2001a,b; Dangles et al., 2004; Simon et al., 2009). Thus, leaf litter decomposition is particularly interesting as a potential bioassessment tool for addressing acidification effects on stream functioning since it is a key ecosystem process, which has been widely studied and whose response to acidification can be predicted a priori (Dangles et al., 2004; Young et al., 2008; Simon et al., 2009).

In this study, we assessed the potential for leaf litter decomposition to be used as a bioassessment tool to detect acidification effects on stream ecosystem functioning. By performing a field experiment where three leaf litter species were enclosed in fine and coarse mesh bags and incubated in streams flowing over granite or sandstone bedrock along an acidification gradient, we assessed if the response of leaf litter decomposition to acidification depended on litter species, mesh size, parent lithology and acidification level. By performing a meta-analysis of primary studies on the effects of acidification on leaf litter decomposition, we assessed the consistency in the response of leaf litter decomposition to acidification across studies and the robustness with which leaf litter decomposition may be used as a bioassessment tool. We expected a strong inhibition of leaf litter decomposition with increased acidification (i.e., decrease in pH or increase in $H^+$ concentration) and Al concentration (Dangles et al., 2004; Simon et al., 2009; Cornut et al., 2012; Clivot et al., 2014). This inhibition should be especially strong for soft leaf litter with high nutrient concentration, since microbial activities and shredder contribution to litter mass loss are generally higher in this litter than in more recalcitrant litter (Hieber and Gessner, 2002; Gulis et al., 2006). Since some highly efficient detritivores are acid-sensitive species (Meegan et al., 1996; Dangles and Guérold, 1998, 2001a,b), the inhibition of leaf litter decomposition with acidification should be especially strong for litter incubated in coarse mesh bags.

## 2. Material and methods

### 2.1. Field study

#### 2.1.1. Streams

Eight 1st–2nd order streams were used in the field experiment, all located in the Vosges Mountains, North-eastern France, a region which has received high atmospheric acid deposition in the past (Party et al., 1995; Probst et al., 1999). Soils in the region vary between acid brown and podzolic, and are underlain by quartz enriched (thus weathering-resistant) granite or sandstone bedrock (Party et al., 1995). Due to small-scale differences in the mineral composition of the bedrock, nearby streams may have quite different pH, ANC, total Al and base cations concentrations (Dangles et al., 2004). Four nearby streams were selected along an acidification gradient on both granite and sandstone bedrock (Table 1) to evaluate how the magnitude of acidification effect on litter decomposition may depend on parent lithology and acidifica-

**Table 1**
Location and water characteristics (mean ± SD, n = 10) of the study streams during the litter decomposition experiment (December 18, 2008–February 26, 2009). Within each parent lithology (granite or sandstone), streams are ordered by increasing acidity with the first stream being a reference (circumneutral). ANC, acid neutralizing capacity.

| Parent lithology and stream name | Stream acronym | Latitude (N) | Longitude (E) | Elevation (m asl) | Conductivity (μS $cm^{-1}$) | pH | ANC (μeq $L^{-1}$) | Total Al (μg $L^{-1}$) | $Ca^{2+}$ (mg $L^{-1}$) | $NO_3^-$ (mg $L^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| Granite bedrock | | | | | | | | | | |
| Tihay | TH | 47°58′50.9″ | 6°52′32.6″ | 667 | 46.4 ± 4.7 | 6.65 ± 0.10 | 102 ± 23 | 53 ± 41 | 2.29 ± 0.34 | 2.83 ± 0.36 |
| Grand-Clos | GC | 47°58′46.3″ | 6°52′33.4″ | 647 | 16.9 ± 0.8 | 5.99 ± 0.09 | 21 ± 4 | 88 ± 27 | 0.85 ± 0.08 | 0.98 ± 0.16 |
| Longfoigneux | LF | 47°57′57.5″ | 6°51′53.3″ | 620 | 15.7 ± 0.6 | 5.49 ± 0.17 | 5 ± 3 | 128 ± 23 | 0.67 ± 0.08 | 0.78 ± 0.12 |
| Wassongoutte | WA | 47°58′27.0″ | 6°53′12.8″ | 668 | 14.2 ± 0.8 | 5.11 ± 0.17 | −3 ± 3 | 188 ± 160 | 0.42 ± 0.08 | 0.84 ± 0.14 |
| Sandstone bedrock | | | | | | | | | | |
| La Maix | LM | 48°27′58.9″ | 7°03′17.3″ | 387 | 80.5 ± 5.9 | 7.33 ± 0.09 | 523 ± 51 | 61 ± 77 | 7.05 ± 0.59 | 3.29 ± 0.13 |
| Ravines | RV | 48°25′14.8″ | 6°56′39.3″ | 382 | 35.4 ± 0.9 | 5.21 ± 0.11 | 0 ± 2 | 107 ± 42 | 1.75 ± 0.09 | 2.88 ± 0.11 |
| Gentil Sapin | GS | 48°27′03.7″ | 7°03′58.3″ | 536 | 30.6 ± 2.0 | 4.57 ± 0.14 | −22 ± 10 | 413 ± 175 | 1.16 ± 0.19 | 4.45 ± 0.66 |
| Basse des Escaliers | BE | 48°27′58.9″ | 7°05′46.2″ | 740 | 30.8 ± 1.9 | 4.39 ± 0.09 | −35 ± 7 | 571 ± 107 | 0.76 ± 0.05 | 2.67 ± 0.40 |