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Research article

Responses of bryophytes to wood-ash recycling are related to their phylogeny and pH ecology

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ABSTRACT

Ash generated by the combustion of solid biofuels is increasingly being returned to the fuel's place of origin (mostly forests). In this way, nutrient depletion and acidification caused by biofuel harvest is counteracted and a waste problem is solved. Concerns about the potential negative effects of ash spreading on forest biodiversity (in particular mosses) have been raised, but little is known. I studied the effects of the application of two types of ash (the most used self-hardened crushed ash including fine particles and a less reactive type, pellets without fine particles) on 28 moss species and 17 liverwort species. In two field experiments, one on transplants of ground-living species and one on wood-inhabiting species *in situ*, I measured the response during the first two months after ash application. Visible damage (discoloration from green to brown) was assessed for all species and the growth response was measured for 24 ground-living species. The responses to crushed ash were clearly related to the species' pH ecology and phylogenetic position. The growth of bryophytes associated with acidic conditions (pooled data from 10 species) or considered as being indifferent to pH (4 species) was negatively affected, whereas there was no effect on the growth of bryophytes of non-acidic habitats (10 species). The connection to phylogeny was even clearer. Most taxa responded negatively, but transplants from the moss order Bryales (4 species) and the family Brachytheciaceae (2 species; order Hypnales) grew better when treated with ash. The genera with the clearest negative responses were *Sphagnum* mosses (5 species), *Tetraphis* mosses (1 species), *Dicranum* mosses (6 species), and *Barbilophozia* liverworts (2 species). The four red-listed wood-inhabiting liverworts studied were not significantly damaged. Concerning ash type, pellets caused smaller effects than crushed ash, both on the positive and negative side. The results show that responses to ash recycling of the bryophyte species included in this study are predictable from their phylogenetic position and/or pH ecology. Further studies are needed to determine the generality of these results and to sort out if phylogeny or current relationship to pH is the primary determinant of the response.

Introduction

Biofuels from trees are increasingly used, mainly for heating purposes, but also for electricity generation and to fuel vehicles. The type of fuel that is most commonly extracted from forest ecosystems is slash (tops and branches) that was previously left after logging. Slash is used as substrate by forest biota such as bryophytes (mosses and liverworts), insects, and fungi (Kruys and Jonsson, 1999; Nordén et al., 2004; Jonsell et al., 2007) and slash removal affects these organisms negatively (Åström et al., 2005; Jonsell, 2007; Nittérus et al., 2007). There are also chemical effects of slash harvest. Slash contains higher concentrations of mineral nutrients than tree stems, and therefore the transportation of these elements out of the forests increases disproportionally with slash harvest. Concerns have been raised that slash harvest will jeopardize the soil nutrient balance and increase problems with acidification (e.g. Stupak et al., 2007; Flueck, 2009). The chemical consequences of slash harvest (except nitrogen loss) could be mitigated by returning to the forest the ashes from heating and power plants that burn biofuels. Another motivation for recycling wood ashes, which is usually less discussed, is that it would solve a growing waste problem. Wood ash recycling has thus become a common practice in the vicinity of ash-producing heating and power plants in north-western Europe (Stupak et al., 2007).

The recycling of wood ash is a new practice, potentially affecting large land areas, and it is therefore important to scientifically assess its environmental effects and to develop policies to environmentally adapt the practice (Levin and Eriksson, 2010). The normal practice in Sweden is to spread the ash mechanically from

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ground vehicles in established stands once per rotation. To spread the ash in its raw form is neither technically nor environmentally feasible. Raw ash is loose and has low density, which makes spreading difficult. It also contains reactive oxides and hydroxides and is highly water soluble, leading to rapidly increased pH and salt concentration in the top soil, which may both negatively impact soil biota (Huhta, 1984; Erland and Söderström, 1991) and directly damage the vegetation (Kellner and Weibull, 1998). To reduce the reactivity and to facilitate effective spreading, wood-ash is usually stabilized by adding water to induce a hardening process before being spread (Aronsson and Ekelund, 2004). The resulting solid product is then mechanically crushed before distribution and therefore frequently termed "crushed ash". A method intended to make the ash even easier to handle and less reactive is to produce pellets by mixing the ash with water and then compress it mechanically.

Many studies have been published on the effects of ash application on forest productivity, ground and surface water quality, soil biology, and plant cover (for a review see Aronsson and Ekelund, 2004), whereas the effects on biodiversity is poorly known. Visible damage (discoloration mainly from green to brown) on moss leaves and stems has been observed to be particularly pronounced, and I therefore chose to focus on these organisms and the previously unstudied liverworts in my study. Loose ash and crushed hardened ash cause severe visible leaf damage to mosses (Kellner and Weibull, 1998; Jacobson and Gustafsson, 2001; Ozolincius et al., 2007). There is some variation in tolerance among the few abundant moss species that has been studied. In a field experiment in a 70-year-old pine stand, Kellner and Weibull (1998) showed high visible damage in crushed ash and loose ash treatments for *Dicranum polysetum*, slightly less for *Ptilium crista-castrensis*, still less for *Hylocomium splendens*, and least for *Pleurozium schreberi*. They also found a reduction in cover of *D. polysetum* and *P. crista-castrensis* combined with an increase in *P. schreberi* when ash was spread on existing established vegetation including these species, and this effect remained three years after ash treatment. Plots with only *P. schreberi* and *H. splendens* showed no such change in dominance. The same rank order among *D. polysetum*, *H. splendens*, and *P. schreberi* for tolerance to application of crushed ash was shown in a five-year experiment, conducted on established vegetation in a 50-year-old pine stand and reported by Jacobson and Gustafsson (2001). In their experiment, ash pellets did not produce any visible damage to the three moss species.

With the exception of four abundant mosses, bryophyte responses to ash application is thus still unknown, and direct measurements of effects on growth has never been reported. Furthermore, previous studies have been conducted in only one stand each, hampering generalizations of the results. For liverworts, a group including many red-listed wood-inhabiting species, there are no published studies on effects of ash application on individual species.

The primary goal of this study was to experimentally assess the variation in response (both visible damage and growth) to crushed ash application among a significant fraction of the bryophyte species and higher taxa occurring in boreal forests (Table 1). The variation was analyzed in relation to the phylogenetic affinities of the species and their relationships to ambient pH. A secondary goal was to test the hypothesis that responses to crushed ash (including fine particles) are more pronounced than the responses to ash pellets (with small particles removed). To achieve these goals I designed two field experiments. One experiment was conducted in seven spruce stands and included transplants of ground-living species and the other was conducted in three spruce stands and included *in situ* patches of wood-inhabiting species, a focal group in forest bryophyte conservation.

Table 1
List of the 45 species och bryophytes (mosses and liverworts) included in the two field experiments, one using transplants of ground-living bryophytes and one *in situ* experiment on wood-inhabiting bryophytes.

Ground experiment	Wood experiment
Mosses	**Mosses**
Sphagnopsida	***Tetraphidopsida***
Sphagnum angustifolium	Tetraphis pellucida
Sphagnum capillifolium	
Sphagnum centrale	***Bryopsida***
Sphagnum girgensohnii	Dicranum fuscescens
Sphagnum russowii	
	Liverworts
Polytrichopsida	***Jungermanniopsida***
Polytrichastrum formosum/longisteum	*Order Ptilidiales*
Polytrichum commune	Ptilidium pulcherrimum
	Order Jungermanniales
Bryopsida	Anastrophyllum hellerianum
Order Dicranales	Blepharostoma trichophyllum
Dicranum drummondii	Barbilophozia attenuata
Dicranum flexicaule	Calypogeia suecica
Dicranum majus	Calypogeia integristipula
Dicranum polysetum	Cephalozia leucantha
Dicranum scoparium	Cephalozia lunulifolia
Order Bryales	Lophocolea heterophylla
Mnium stellare	Lophozia ascendens
Plagiomnium cuspidatum	Lophozia ciliata
Plagiomnium ellipticum	Lophozia longidens
Rhodobryum roseum	Lophozia longiflora
Order Hypnales	Lophozia ventricosa ssp. silvicola
Climacium dendroides	
Cirriphyllum piliferum	
Hylocomiastrum pyrenaicum	
Hylocomiastrum umbratum	
Hylocomium splendens	
Pleurozium schreberi	
Ptilium crista-castrensis	
Rhytidiadelphus subpinnatus	
Rhytidiadelphus triquetrus	
Sciuro-hypnum oedipodium	
Liverworts	
Jungermanniopsida	
Barbilophozia lycopodioides	
Lophocolea heterophylla	
Lophozia obtusa	
Plagiochila asplenoides	

Materials and methods

Study sites

The study was conducted in the middle boreal zone (Ahti et al., 1968) in the southernmost part of the province of Ångermanland in central Sweden. The growing season in this area is approximately 150 days; mean monthly temperatures for May, June, July, August, and September are 7, 13, 15, 14, and 9 °C, respectively. Mean monthly precipitation for these months are 35, 40, 60, 70, and 70 mm, respectively (Raab and Vedin, 1995).

For the experiment on transplants of ground-living bryophytes I selected seven mature spruce-dominated stands in relatively productive sites with mesic to moist ground. In Sweden, these are typical stands from which forest fuels are harvested in association with clear-cutting (Egnell, 2009), and should thus also be the target for ash recycling. The experimental sites were located in parts of the stand having few boulders and stones, to allow preparation of homogenous experimental plots. The stands were situated 62°45′ to 63°08′ N, 17°27′ to 17°54′ E, and 125–255 m a.s.l. (average 174). Distances among the seven stands ranged from 0.5 to 46 km. The diameter at breast height was measured for all trees within 10 m of each of the study plots. Maximum diameter of