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Long-term effects of biomass removal on soil mesofaunal communities in northeastern Ontario (Canada) jack pine (*Pinus banksiana*) stands

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ABSTRACT

In North American boreal forests, woody biomass is increasingly becoming an attractive bioenergy feedstock as it represents a more renewable, and low carbon alternative to fossil fuel. However, concerns over the ecological sustainability of an intensification of biomass harvesting over the long term remain. We assessed the effects of a gradient of biomass removal established 20 years ago in five jack pine (*Pinus banksiana*) stands across northeastern Ontario on the taxonomic and functional structure of ground-dwelling Collembola and Oribatida communities. Essential to soil functioning, these two major taxa of mesofauna are dependent on microhabitats and food supply such as fungi provided by woody debris. Three treatments were considered including stem-only harvesting, whole-tree harvesting (stem, tops and branches removed), and blading (whole-tree harvesting plus removal of stump and forest floor). Adjacent uncut mature (± 90 year-old) stands were considered as reference state conditions (*i.e.* the endpoint of stand development following stand replacing disturbance). Soil mesofauna were collected and environmental variables measured across all treatments. We identified species of both taxa and measured a suite of functional response traits such as body length and reproduction strategy. Compared to mature uncut forests, soil mesofaunal communities remained modified 20 years after biomass harvesting, notably in the most intense practice (blading). Treatment effects were more evident in Oribatida communities both taxonomically (lower density, biomass, species diversity and shifted composition) and functionally (lower diversity and modified trait composition resulting from fewer surface-dwelling, fast-dispersing and micro-detritivorous species) than in Collembola communities. This taxa-specific response may reflect generally shorter lifespans, higher reproduction rates and faster dispersal of Collembola than Oribatida. Incomplete recovery of mesofauna was consistent with persistent modifications of soil environmental conditions in harvested plots, notably after blading. Modifications included a reduced organic cover (ground vegetation, mosses and woody debris) as well as lower organic soil thickness and moisture, which likely resulted in fewer suitable microhabitats for many species. Using complementary taxonomic and trait-based approaches to highlight the underlying mechanisms of mesofaunal responses, our study revealed that recovery is incomplete within 20 years after intensive biomass removal in these boreal conifer-dominated stands, and is likely linked to stand development and associated processes. As a result, longer-term monitoring will be required to track mesofaunal community recovery through these later developmental stages.

1. Introduction

There is increasing interest in the use of woody biomass from North American boreal forests to provide a feedstock for bioenergy production in response to socioeconomic (*e.g.* declining markets for traditional wood products, energy requirements of northern communities) and environmental issues, primarily climate change (Paré et al., 2011; Puddister et al., 2011; Lemprière et al., 2013). Intensification of biomass removal beyond stem-only harvesting, which includes operational whole-tree harvesting (stem, tops and branches of merchantable trees plus unmerchantable trees) as well as stump removal, has negative consequences on the soil in the short term (less than five years) such as nutrient depletion, more exposed mineral horizons, reduced moisture and modified biota (Fleming et al., 2006; Walmsley and Godbold, 2010; Thiffault et al., 2011; Rousseau et al., 2018). However, a more comprehensive assessment of the longer-term consequences of these

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practices is required to provide information that supports sustainable forest management (Berch et al., 2011; Stupak et al., 2011).

Long-term experiments are necessary to assess boreal forest dynamics in response to harvesting (Berch et al., 2011; Thiffault et al., 2011; Venier et al., 2014) along the different stages of stand development (Chen and Popadiouk, 2002). In the 1990s, the Long-Term Soil Productivity (LTSP) program was launched in order to monitor the effects of biomass removal on soil nutrient cycling and tree productivity of forests over the long term with more than 100 experimental sites established across North America (Powers, 2006). The LTSP design includes a very intensive biomass removal including site preparation by blading *i.e.* whole-tree harvesting plus stump and forest floor removal. There have been clear and persistent effects beyond 15 years, especially after blading, such as a loss of nutrients in soils (Hazlett et al., 2014), lower respiration rates (Webster et al., 2010) and modified microbial communities (Hartmann et al., 2012). In comparison, whole-tree harvesting effects on these processes were more similar to those observed after stem-only harvest (Webster et al., 2010; Hazlett et al., 2014 but see Thiffault et al., 2011). However, little work has been conducted to examine long-term effects on soil mesofauna biodiversity.

Springtails (Collembola) and oribatid mites (Oribatida), two dominant mesofauna taxa, have been identified as potentially good indicators of forest integrity due to their highly abundant and diverse communities in the soil and their roles in ecological processes such as litter decay (Petersen and Luxton, 1982; Neher et al., 2012) or physical microaggregation (Maab et al., 2015). These communities are also dependent on downed woody debris for suitable microhabitats including a stable microclimate and food supply (Snider, 1996; Malmström, 2012a; Siira-Pietikäinen et al., 2008). The few existing long-term studies in the boreal forest have shown that the taxonomic structure of communities for these two taxa generally remained modified with lower density, species diversity and altered species composition 5 (Berch et al., 2007), 10 (Addison, 2006), and 17 years (Bengtsson et al., 1997) after intensive practices of whole-tree harvesting and blading, when compared to stem-only harvesting. A previous short-term study (2 years post-harvest) in Ontario jack pine forests showed similar responses (Rousseau et al., 2018). Collectively, these persistent modifications were possibly due to a lower availability of nutrients that may modify food resources. Additionally, changed microclimate due to desiccation of woody debris and forest floor removal, may have reduced suitable microhabitats.

To assess such potential mechanisms associated with forest disturbance, functional response traits, *i.e.* morphological, physiological, life-history or behavioural features of species which are sensitive to environmental changes (Pey et al., 2014), can be a useful and complementary tool. The functional structure of soil Collembola and Oribatida communities can be altered through forest disturbances such as fire (Malmström, 2012b) and drought (Lindo et al., 2012) or changes in forest leaf litter composition such as plantations (Vanderwalle et al., 2010; Mori et al., 2015). For example, following fire that changes the physical structure and microclimate of organic horizons, Collembola communities show fewer surface-dwelling species that are generally larger, more pigmented and sexually reproducing (Malmström, 2012b). In response to intense biomass removal two years after harvesting, Rousseau et al. (unpublished results) found that the functional diversity of Oribatida communities decreased due to fewer surface-dwelling and mostly micro-detritivorous species. Shifts in trait composition were less marked for Collembola communities due to a potentially faster recovery linked to their life history traits (shorter lifespan, higher reproductive rate) and faster dispersal than Oribatida (Petersen, 2002; Gergócs and Hufnagel, 2009; Åström and Bengtsson, 2011). Generally, Collembola communities recover (*i.e.*, no more difference between communities from undisturbed and disturbed areas in their taxonomic and functional structure) more rapidly than those of Oribatida to soil disturbance associated with forest management activities (Battigelli et al., 2004; Addison, 2006; Berch et al., 2007) or drought (Lindberg and Bengtsson, 2006).

To our knowledge, to date, no long-term study has considered both Collembola and Oribatida species-level responses to biomass removal. In the present study, we assessed the effects of a gradient of biomass removal implemented at five experimental sites of the LTSP network in northeastern Ontario jack pine stands 20 years after establishment on soil Collembola and Oribatida communities. The gradient from least to most intensive disturbance included uncut mature stands as reference state conditions, stem-only harvesting, whole-tree harvesting, and whole-tree harvesting with stump plus forest floor removal (blading). The structure of Collembola and Oribatida communities was characterized using taxonomic and trait-based approaches while soil environmental conditions were also measured to help interpret their respective responses. Our first hypothesis was that compared to uncut mature stands, there would be an overall lack of recovery of community structure of both taxa after biomass harvesting, but that Oribatida communities would show a stronger response to removal treatments, both taxonomically and functionally, compared to Collembola communities. Our second hypothesis was that the degree of recovery would be a function of the intensity of biomass removal such that communities will have recovered less in the more intense removal treatments.

2. Materials and methods

2.1. Study sites and experimental design

Our study used five sites of the LTSP network situated in the boreal forest of northeastern Ontario (Fig. 1): Superior 1,3 (combined sites), Superior 2, Nimitz, Eddy 3 and Wells (see Tenhagen et al. (1996), Hazlett et al. (2014) and Table S7 (Supplementary material) for specific conditions of each site). Controls at these sites are fire-origin stands dominated by jack pine ranging in age from 77 to 102 years in 2013 (year of sampling). The understory species are dominated by *Vaccinium angustifolium*, *Cornus canadensis* and *Pleurozium schreberi*. Sites have an annual mean temperature of 2.3 °C, an annual mean total precipitation of 882 mm and a growing season of approximately 90 frost-free days (early June to September). Soils are sandy humo-ferric podzols with nearly 6 cm organic horizon (humifibrimor) soil depth across all sites. In 1993, each site was clear-cut, except for an uncut portion of the mature stand that was maintained as a reference state condition. Three replicate plots (30 × 30 m) were randomly assigned to each of the following biomass removal treatments operationally applied (from lowest to highest degree of biomass removal intensity): (1) "tree-length" = stem-only harvesting (stems cut, delimbed and topped at stump), (2) "full-tree" = whole-tree harvesting (stem, top and branches of all merchantable trees plus unmerchantable trees removed to roadside), and (3) "bladed" = whole-tree harvesting followed by blading (complete forest floor removal including stumps, ground woody debris, organic soil horizons and usually the upper 5 cm of mineral soil using a bulldozer). Stem-only and whole-tree harvesting practices are accepted and operational in boreal forests in Ontario while whole-tree harvesting followed by blading is currently not permitted on public land (OMNRF, 2015). This very intensive practice was considered here to maximize biogeochemical and hydrological disturbance experimentally rather than to simulate actual operational harvesting. All plots were separated from each other by at least 20 m to reduce edge effects. Soon after harvest, all stem-only and whole-tree harvested plots were disc trenched and subsequently all harvested plots were planted with jack pine, the following spring (1994). Three "control" treatment plots (30 × 30 m) were also established in the adjacent area of uncut mature forest of each site as reference state conditions. Even though these plots were spatially clustered in the uncut area rather than dispersed among harvested plots, we considered that each site had a randomized experimental design.

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