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Soil processes and tree growth at shooting ranges in a boreal forest reflect contamination history and lead-induced changes in soil food webs

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HIGHLIGHTS

- The effects of Pb on a boreal forest ecosystem at shooting ranges were studied.
- Pine needle litter and Pb-containing grass litter decompositions were retarded by Pb.
- Pb-derived changes in the soil food web were reflected in soil functions.
- Tree growth slowed down after starting, but increased after closing the range.
- Decomposition processes recovered after range abandonment

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ABSTRACT

The effects of shooting-derived lead (Pb) on the structure and functioning of a forest ecosystem, and the recovery of the ecosystem after range abandonment were studied at an active shotgun shooting range, an abandoned shooting range where shooting ceased 20 years earlier and an uncontaminated control site. Despite numerous lead-induced changes in the soil food web, soil processes were only weakly related to soil food web composition. However, decomposition of Scots pine (*Pinus sylvestris*) needle litter was retarded at the active shooting range, and microbial activity, microbial biomass and the rate of decomposition of Pb-contaminated grass litter decreased with increasing soil Pb concentrations. Tree (*P. sylvestris*) radial growth was suppressed at the active shooting range right after shooting activities started. In contrast, the growth of pines improved at the abandoned shooting range after the cessation of shooting, despite reduced nitrogen and phosphorus contents of the needles. Higher litter degradation rates and lower Pb concentrations in the topmost soil layer at the abandoned shooting range suggest gradual recovery after range abandonment. Our findings suggest that functions in lead-contaminated coniferous forest ecosystems depend on the successional stage of the forest as well as the time since the contamination source has been eliminated, which affects, e.g., the vertical distribution of the contaminant in the soil. However, despite multiple lead-induced changes throughout the ecosystem, the effects were rather weak, indicating high resistance of coniferous forest ecosystems to this type of stress.

1. Introduction

Lead (Pb) pellets, which are known to be toxic and thus prohibited in waterfowl hunting in Finland and several other countries, are still used at shotgun shooting ranges around the world (Darling and Thomas, 2003; Luo et al., 2014; Rooney et al., 2007; Sorvari et al., 2006). Shotgun pellets can spread over wide areas, and end up in nearby ecosystems, typically in forests in Finland (Sorvari et al., 2006). Even after range abandonment, pellets have usually been left in the soil, where Pb gradually releases from the corroding pellets. When released to the soil, some of the Pb can bioaccumulate (Selonen et al., 2012) and cause toxic effects in the biota (Migliorini et al., 2005; Rantalainen et al., 2006; Salminen et al., 2002; Selonen et al., 2014), or leach through soil and pose risks to groundwater quality (Selonen et al., 2012; Sorvari et al., 2006). However, even though more than 2000 shooting ranges are estimated to exist in Finland alone (Sorvari et al., 2006), little is known about the effects of Pb on ecosystem processes of these contaminated forest ecosystems. Even less is known about long-term changes in these effects after range abandonment.

Lead persists in the environment, and risks to the environment are likely to increase with time as the pellets degrade. In previous studies conducted in the boreal forest zone, we showed that the gradual release of Pb from pellets deep in the humus layer increases Pb concentrations (Selonen et al., 2012) and toxicity of the soil with time, leading to, e.g., reduced abundances of soil biota in the humus layer (Selonen et al., 2014). Since the soil organisms play a crucial role in decomposition

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processes and nutrient cycling in forest ecosystems (Heneghan and Bolger, 1998; Laakso and Setälä, 1999; Setälä, 1995), Pb-induced changes in the soil food web may further impact functions within the entire forest ecosystem. However, it is possible that these negative effects of Pb at the ecosystem level are only temporary in boreal forests. As suggested by Selonen et al. (2012, 2014), low decomposition rates and the lack of soil mixing due to the scarcity of earthworms promote the formation of a less-contaminated topmost soil layer after the cessation of shooting through the accumulation of litter on soil surface (see Selonen et al., 2012). Consequently, soil faunal populations at an abandoned shooting range showed clear signs of recovery in the uppermost soil layer (Selonen et al., 2014). Still, it is not known whether the recovery of soil faunal communities after range abandonment is reflected in the functions of the boreal forest ecosystem.

The aim of this field study conducted at a shotgun shooting range area was to explore how Pb-induced changes in the decomposer food web may influence the rate of decomposition, and whether this is reflected in the growth, foliage nutritional condition and litter production of trees. We also explored whether these effects change with time after range abandonment by comparing ecosystem processes between an active and an abandoned shotgun shooting range locating in the same pine forest stand. We hypothesized that 1) microbial activity and litter decomposition are hampered by Pb contamination, and 2) these changes are associated with an altered soil food web composition. We also hypothesized that 3) tree growth, foliage nutritional status and litter production are impaired by shooting-derived Pb and 4) that these functions reflect the recovery of the forest ecosystem after range abandonment.

2. Material and methods

2.1. Study sites

Three sites were studied at the Hälvälä shooting range area (61°00′N 25°29′E), southern Finland: (1) an active shooting range (new contaminated site [NC]), in a location where shotgun pellets fall from a shooting range that has been active since 1987; (2) an abandoned shooting range (old contaminated site [OC]), with Pb pellets in the soil originating from a shotgun shooting range that was active during 1964–1986; and (3) a control site (Control) without shooting activities in its history (Fig. 1).

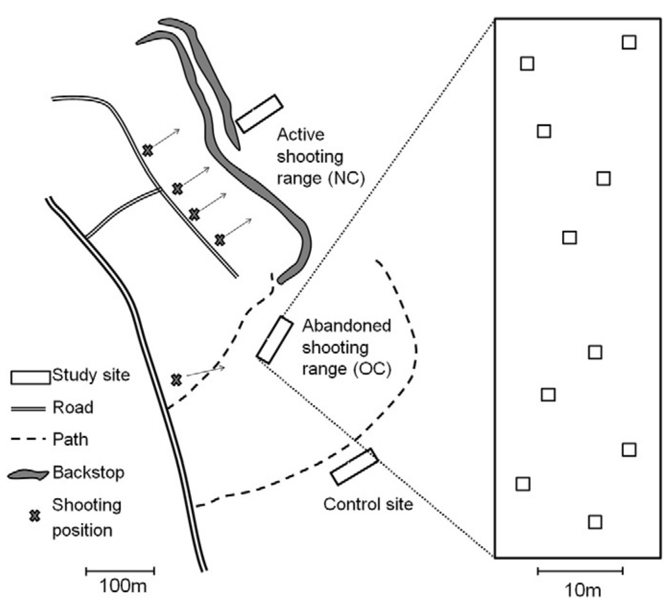

Fig. 1. Map of the shotgun shooting range area in Hälvälä, southern Finland, where three study sites were established: a control site and two active (new contaminated [NC]) and abandoned (old contaminated [OC]) shooting range sites. At each site, ten study plots were established, as illustrated on the right (Selonen et al., 2012).

The study sites were located 200–500 m apart (Fig. 1) in the same forest stand, which regenerated naturally in the 1980s with Scots pine (*Pinus sylvestris*) as the dominant tree species. Shrubs *Vaccinium vitis-idaea* and *Vaccinium myrtillus* and grasses *Deschampsia flexuosa* and *Calamagrostis arundinacea* are the dominant species in the field layer and mosses *Pleurozium schreberi* and *Dicranum* sp. in the bottom layer (Rantalainen et al., 2006). Soil at the sites is stony moraine with a mor-type organic soil layer, which can be divided into an upper 3–6 cm thick litter (L) and fermentation (F) layer and a lower, approximately 1 cm thick, humus (H) layer with well-decomposed, homogeneous structure.

Pb pellet loads were equal at the two contaminated sites, reaching up to 4000 g m^{-2} at the most contaminated plots at the two sites (Selonen et al., 2012), but shooting activity occurred 20 years earlier at the OC than at the NC. Thus, due to gradual litter accumulation and gravity, Pb pellets are located deeper in the organic soil horizon at the OC than at the NC. Consequently, total Pb concentrations in the F layer at the OC are lower (on average 12,000 mg kg^{-1}) than at the NC (23,000 mg kg^{-1}), measured after removal of the pellets. However, deeper in the soil (H layer), total Pb concentrations are generally higher at the OC (28,000 mg kg^{-1}) than at the NC (19,000 mg kg^{-1}) due to the gradual release of Pb from the pellets (Selonen et al., 2012).

2.2. Soil sampling

At each site ten study plots, 1.5 m × 1.5 m in size, were randomly established a few metres apart so that plots at the two contaminated sites are spread along a Pb concentration gradient reflecting increasing distance from the shooting position (Fig. 1). The organic soil horizon was sampled at two locations per plot in May 2005 (Spring I), October 2005 (Autumn) and May 2006 (Spring II), except in Spring II when only one location at five plots was sampled at the Control. At each location, a sample for the measurement of basal respiration and substrate induced respiration (SIR) and for the analysis of soil Pb concentrations was taken with a 22 cm^2 steel auger. In addition, samples for soil characteristics and extraction for soil fauna (see Selonen et al., 2014) and phospholipid fatty acids (PLFA; to estimate soil fungal and bacterial biomass) were taken, but only data from the Spring II sampling event are dealt with here. The samples for the analysis of soil Pb and soil fauna were divided into two layers: upper F layer and lower H layer, whilst samples for PLFA, protozoans (Protozoa) and soil characteristics were taken only from H layer.

2.3. Soil properties

Soil pH, soil organic matter (SOM) content, moisture and nutrients (NO_3^-, NH_4^+ and PO_4^{3-}) were analysed from the H layer at each sampling location. Soil pH was measured in 0.01 M $CaCl_2$, nitrate (NO_3^-) and ammonium (NH_4^+) in 1 M KCl and phosphate (PO_4^{3-}) in distilled H_2O. Soil moisture was analysed after drying the samples at 105 °C for 24 h and SOM after ignition at 550 °C for 4 h. The study sites were similar in terms of SOM (53 ± 11% [mean ± sd]), soil moisture (53 ± 5%), ammonium (NH_4^+; 92 ± 23 mg kg^{-1}) and phosphate (PO_4^{3-}; 25 ± 15 mg kg^{-1}) concentrations. Soil pH (4.1 ± 0.3; all sites combined) was highest at the OC, being 0.6 units higher than in the NC and 0.9 units higher than in the Control. Nitrate (NO_3^-) concentrations at the Control (0.06 ± 0.06 mg kg^{-1}) were lower than at the NC (5.5 ± 2.3 mg kg^{-1}) and at the OC (6.2 ± 3.1 mg kg^{-1}). In addition, three fractions of Pb — total Pb (tot-Pb), H_2O extractable Pb (H_2O-Pb) and 0.01 M $CaCl_2$ extractable Pb ($CaCl_2$-Pb), the latter two being estimates of biologically available Pb, were measured after the removal of pellets from the soil samples (Houba et al., 1996; Smit et al., 1997; Suomen standardisoimisliitto, 1980). For a detailed description of the methods and results related to Pb, see Selonen et al. (2012).