Ecotoxicology and Environmental Safety 113 (2015) 183–190

Contents lists available at ScienceDirect

Ecotoxicology and Environmental Safety

journal homepage: www.elsevier.com/locate/ecoenv

Earthworm populations of highly metal-contaminated soils restored by fly ash-aided phytostabilisation

Fabien Grumiaux [a,b,*], Sylvain Demuynck [a], Céline Pernin [a], Alain Leprêtre [a]

[a] Université Lille Nord de France, Laboratoire Génie Civil et géo-Environnement (LGCgE) – Lille1, Bât. SN3, 59655 Villeneuve d'Ascq Cedex, France
[b] Université Lille Nord de France, Ecole Supérieure du Professorat et de l'Education (ESPE), site d'Arras, 7 bis rue Raoul François, BP 30927, F-62022 Arras Cedex, France

A R T I C L E I N F O

Article history:
Received 3 July 2014
Received in revised form
26 November 2014
Accepted 2 December 2014
Available online 11 December 2014

Keywords:
Earthworms
Contaminated soil
Trace metals
Phytostabilisation
Fly ashes

A B S T R A C T

Highly metal contaminated soils found in the North of France are the result of intense industrial past. These soils are now unfit for the cultivation of agricultural products for human consumption. Solutions have to be found to improve the quality of these soils, and especially to reduce the availability of trace elements (TEs). Phytostabilisation and ash-aided phytostabilisation applied since 2000 to an experimental site located near a former metallurgical site (Metaleurop-Nord) was shown previously as efficacious in reducing TEs mobility in soils. The aim of the study was to check whether this ten years trial had influenced earthworm communities. This experimental site was compared to plots located in the surroundings and differing by the use of soils. Main results are that: (1) whatever the use of soils, earthworm communities are composed of few species with moderate abundance in comparison with communities found in similar habitats outside the TEs-contaminated area, (2) the highest abundance and specific richness (4–5 species) were observed in afforested plots with various tree species, (3) ash amendments in afforested plots did not increase the species richness and modified the communities favoring anecic worms but disfavoring epigeic ones. These findings raised the questions of when and how to perform the addition of ashes firstly, to avoid negative effects on soil fauna and secondly, to keep positive effects on metal immobilization.

1. Introduction

Since the 19th century, industrial activities generated a great number of uncontrolled hazardous sites and large areas contaminated by trace elements (TEs) in many European countries such as Netherlands (Ma et al., 1983) and United Kingdom (Spurgeon and Hopkin, 1996). This is also the case of the former coal-mining region in the North of France especially around smelters at Noyelles-Godault, Auby and Mortagne du Nord. At Noyelles-Godault, Metaleurop-Nord, a major Pb plant in Europe for about 100 years generated significant amounts of emitted metal containing smoke until its closedown in 2003. According to the Regional Board for Industry, Research and the Environment (DRIRE, 2003), Metaleurop's annual atmospheric emissions in 2002 were still about 1 t of Cd, 17 t of Pb and 32 t of Zn. This industrial activity resulted in a considerable contamination of the surrounding soils for 7 km to the N-NW by 5 km to the N-NE (Frangi and Richard, 1997). This contamination concerned agricultural (Sterckeman et al., 2000, 2002), urban (Douay et al., 2008a) and forest habitat top soils (Douay et al., 2009). The contamination occured mainly in the upper 20–30 cm of the soil but traces of Cd and Zn were found at about 2 m deep (Sterckeman et al., 2000). Due to the large contaminated surface (approximately 35 km^2 around the smelter) low-cost and ecologically sustainable remediation methods had to be developed to reduce impacts on human and environmental health. Indeed, the contamination of soils by TEs have not only effects on herbaceous plants and trees (Pruvot et al., 2006; Bidar et al., 2007; Douay et al., 2008b) but also on human health (de Burbure et al., 2006). Among the methods available, phytostabilisation may be used to reduce the mobility, ecotoxicity and dispersion of TEs through the ecosystem (Vangronsveld et al., 2009). Mineral amendments such as fly ashes (FAs) are known to help phytostabilisation of TEs-contaminated soils (Vangronsveld et al., 2009). FAs, industrial by-products originated from combustion processes, are interesting because of their large availability and low-cost. Pandey and Singh (2010) reviewed recently the interests of FAs in soil systems and indicated the possibility of FAs addition

* Corresponding author at: Université Lille Nord de France, Laboratoire Génie Civil et géo-Environnement (LGCgE) – Lille1, Bât. SN3, 59655 Villeneuve d'Ascq Cedex, France. Fax: +33 3 20436732. .
E-mail address: fabien.grumiaux@univ-lille1.fr (F. Grumiaux).

http://dx.doi.org/10.1016/j.ecoenv.2014.12.004
0147-6513/

in degraded soil for improving nutritional and physico-chemical properties. Among positive effects on soils, FAs can increase the levels of pH, particle density, porosity and water holding capacity (Pandey et al., 2009a). Thus, FAs can be used as an economic fertilizer and soil amendment in small-scale/large-scale cultivation of plants that have ornamental, floricultural, horticultural and forestry potential (Pandey et al., 2009b). FAs are also usefull to enrich soil productivity and crop yields for dry tropical nutrient poor soils (Singh et al., 2011; Singh and Pandey, 2013). However, because FAs can contain toxic inorganic compounds as TEs, their addition to uncontaminated soils can provoke accumulation or translocation of these TEs in plants (Pandey et al., 2009a). Regarding their use as amendments in TEs contaminated soils, FAs represent an effective, cost-effective, eco-friendly management option for reclamation of these soils (*in* Pandey and Singh, 2010). FAs can play significant role in TEs immobilization in soils. Kumpiene et al. (2007) demonstrated that ashes amendment reduced the leaching by 91.1 percent for copper and by 87.1 percent for lead in a Pb- and Cu-contaminated landfilled soil.

In 1999, a pilot study started in a former agricultural field located nearby the former smelter Metaleurop Nord. This project consisted in testing the growth of five trees species with or without the use of silico-alumineous FAs (Sodeline®, FA1) and sulfo-calcic FAs (Soproline®, FA2) as amendments to reclaim soils with high levels of Pb, Cd and Zn. In the experimental site, after eight years of fly ash-aided phytostabilisation, Lopareva-Pohu et al. (2011a) showed that soil pH had decreased on the whole site while organic carbon content increased. The observed change of these parameters influencing TEs mobility was explained by afforestation. Over time, concentrations of 0.01 M $CaCl_2$-extractable metals increased and were correlated with the soil pH decrease. In the amended soils with FA1 and FA2, extractable Cd and Zn concentrations were about 10-fold lower than in the non-amended soil. The results indicated that the two FAs buffered natural soil acidification due to vegetation development, limited trace element mobility and thus could limit their bioavailability (Lopareva-Pohu et al., 2011a). Fly ash amendments strongly decreased TEs availability to three of the five trees species (*Alnus glutinosa*, *Acer pseudoplatanus* and *Robinia pseudoacacia*) and their translocation to aboveground parts (Pourrut et al., 2011). Similar results were obtained for both FAs on herbaceous species under laboratory conditions (Lopareva-Pohu et al., 2011b).

Earthworms have a prominent role in soil functioning (Darwin, 1881). They are known to be bio-indicators for evaluating the effects of soil contamination by trace metals and pesticides, but also for instance the effects of agricultural practices and acid rain (Ghilarov, 1978; Bouché, 1972; Eijsackers, 1983; Paoletti et al., 1991). Grumiaux et al. (2007) tested the intrinsic toxicity of FA1 and FA2 under laboratory-controlled conditions using the earthworm *Eisenia andrei*. Although, a high mortality (between 60 and 100 percent) was registered in the worms exposed to a freshly ash amended artificial soil, probably due to a rise of soil pH value (from 6 to 8.9 and to 9.5 for FA1 and FA2 respectively). The survival was not significantly affected when worms were exposed to 8 weeks old artificial soil treated with fly ashes which pH stabilized around 8. However, both ashes were still responsible for detrimental effects on worm growth rates (decrease of about 20 percent for the both FAs) and cocoons productions (decrease of 43 and 89 percent for FA1 and FA2 respectively). The sulfo-calcic fly ash FA2 was shown to fully reduce cocoon hatching. Regarding the soil of the experimental site, the acute toxicity of 2 years-old FAs-treated soils to *E. andrei* was significantly lower than those of the untreated soil (Grumiaux et al., 2010). In addition, mortality was 3.6–5-fold lower for worms exposed to FAs amended soil, so 2 years ash-treatment of these contaminated soils decreased their toxicity. However, reproductive parameters appeared more affected in the worms exposed to the soil treated with sulfo-calcic ashes (FA2) than in those exposed to the untreated metal-contaminated soil. Thus, adding such immobilising agents could negatively affect earthworm populations. This was reinforced by the observation of that experimentally exposed *Eisenia fetida* to FA1 or FA2 amended soils avoided (avoidance rate > 70 percent) these soils significantly (Demuynck et al., 2014).

At present, still nothing is known in this experimental site about soil fauna, and particularly about earthworms. Previous results obtained under laboratory conditions with experimental exposures of biological models (Grumiaux et al., 2007, 2010, Demuynck et al., 2014) revealed contrasting physiological effects. In one hand, ash addition should reduce TEs bioaccumulation and reduce worm mortality but in another hand it should alter reproductive output and growth, and modify worm behavior. These findings suggest a possible impact on field earthworm population. So, the aim of the present study was to check whether a ten years trial of fly ash-aided phytostabilisation on highly metal contaminated soils of an experimental site influenced *in situ* earthworm communities. The study included the comparison of this site with plots located in the surroundings and differing by the use of soils.

2. Materials and methods

2.1. Plots

The experimental site is described in details in previous works (Bidar et al., 2007; Lopareva-Pohu et al., 2011a). The site (50°26′N, 3°01′E) is located at Evin-Malmaison, 600 m northeast of Metaleurop-Nord (Noyelles-Godault, North of France) downwind of dominating wind directions (Fig. 1). The experimental site was set up in 1999 on a former agricultural field of about 10,000 m^2, which had been cultivated with maize and wheat. It was divided in 2000 into 3 plots of about 3000 m^2. The first one (R) was not amended. The two other plots (F1 and F2) were amended respectively with silico-aluminous fly ashes (Sodeline®, FA1) and sulfo-calcic fly ashes (Soproline®, FA2) at a rate of 23.3 kg/m^2 then plowed up to a 25- to 30-cm soil depth where the most part of the TEs contamination occurred. These two fly ashes (Table 1), provided from Surschiste Ldt (Mazingarbe, France) were previously described (Lopareva-Pohu et al., 2011a). They were produced by fluidised-bed combustion of bituminous coal (Carling thermal power plant) and lignite (Gardanne thermal power plant) respectively. The experimental site (R, F1 and F2) was planted in 2000 with various tree species (*R. pseudoacacia* L., *A. glutinosa* L., *Quercus robur* L., *A. pseudoplatanus* L. and *Salix alba* L.) and sown with an herbaceous mixture (*Festuca ovina* L., *Lolium perenne* L., *Bromus catharticus* Vahl and *Trifolium repens* L.).

Three additional plots located in the surroundings of the experimental site and representing different soil uses were also considered in the study to determine the influence of ground covers on earthworm communities. A plot (MV) which had been cultivated with maize and wheat until 2009 was considered as the absolute reference (i.e., agricultural soil without fly ash-aided phytostabilisation and earthworm communities negatively impacted by plowing and TEs contamination). A plot (BS) which is a meadow since 1999, located in the South of the experimental site and an ash tree wood (FO), located in the West have been also sampled. Characteristics of soils are given in Table 2. According to Lopareva-Pohu et al. (2011a), the soil of the experimental site is a silt-loamy redoxic neoluvisol (clay contents, 13–21 percent; silts 55–62 percent; sands 22–26 percent) with a neutral pH, developed from loess. It lies on a truncated paleoneoluvisol developed from clay. During winter, the groundwater level reaches 60 cm in