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Research article

Selection of native plants with phytoremediation potential for highly contaminated Mediterranean soil restoration: Tools for a non-destructive and integrative approach

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ABSTRACT

The aim of this study was to develop an effective and non-destructive method for the selection of native Mediterranean plants with phytoremediation potential based on their spontaneous recovery capacities. The study site consisted in a mixed contaminated soils (As, Cu, Pb, Sb, Zn) in the vicinity of a former lead smelting factory abandoned since 1925 in the Calanques National Park (Marseille, southeastern France).

We developed an integrated characterization approach that takes into account topsoil metal(loid)s (MM) contamination, plant community composition and structure and mesologic parameters without using destructive methods. From a statistical selection of significant environmental descriptors, plant communities were described and interpreted as the result of spontaneous recovery under multiple stresses and local conditions (both natural and anthropogenic). We collected phytoecological and MM topsoil data using field monitoring and geographic information system (GIS) on a pollution hotspot where natural plant communities occur.

The results of the multivariate analysis performed between species and descriptors indicated that a century of MM pollution pressure produced a significant correlation with plant community dynamics in terms of composition, diversity and structure, leading to the co-occurrence of different plant succession stages. Thus, these successions seemed linked to the variability of anthropogenic disturbance regimes within the study site.

We recorded high topsoil contamination heterogeneity at the scale both of the plot and of the whole study area that suggested a heterogeneous MM distribution pattern dependent on the source of contaminants and site environmental variability. We identified 4 spontaneous plant communities co-occurring through a MM contamination gradient that could be used later from degraded to reference communities to define ecological restoration target combined to phytoremediation applications with respect to local conditions. Our results suggested that some of the native plant species such as *Coronilla juncea* and *Globularia alypum* might be tolerant to high mixed MM soil concentrations and they could thus be used for phytostabilization purposes in polluted Mediterranean areas in regard to their life-traits.

Our non-destructive methodology led both to the selection of tolerant native plant species and communities and identification of highly polluted priority intervention areas through the study site where phytostabilization should be implemented. Furthermore, by analyzing succession dynamics linked to contamination patterns throughout the area and spontaneous recovery of native tolerant vegetation, our methodology opens up broad perspectives and research fields for ecological restoration for Mediterranean protected and contaminated areas based on ecosystem trajectories and new approaches for the integrative management of polluted soils.

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1. Introduction

Metals and metalloids (MM) have been spread worldwide by human activities, contaminating industrial, urban and natural soils in the vicinity of metallurgical industry areas (Alkorta et al., 2004; Khan et al., 2008; Wuana and Okieimen, 2011). Such soils with high levels of MM increase the physico-chemical pressure on the environment that often leads to sparse vegetation and extensive surface areas of bare soil. Wind and water erosion is consequently more extensive on these soils that can be transformed into sources of pollution for surrounding environments (Affholder et al., 2014; Testiati et al., 2013; Wong, 2003), increasing the risks of pollution exposure. As an alternative to conventional soil reclamation techniques such as excavation or containment, phytotechnologies and more specifically phytostabilization applied to soil diffuse pollution are sustainable and environmental-friendly techniques (Ali et al., 2013) that can be used as ecological engineering methods to restore polluted ecosystems (Li, 2006; Marchiol et al., 2013; Suchkova et al., 2014). For natural contaminated soils in particular, located within protected areas where conventional techniques could not be applied without extensive or total destruction of ecosystems, phytotechnologies using local plant species represent an integrative, ecological and sustainable solution for pollution control. For this purpose, it is important to investigate the vegetation that grows spontaneously at these sites in order to select native plant species adapted to local conditions, that can be used simultaneously for phytoremediation and ecological rehabilitation purposes (to decrease soil erosion, increase biodiversity and/or functionality and/or naturalness). According to Baker et al. (2010) the tertiary metal and metalloid contaminated sites, which correspond to naturally non-metal-enriched environments that have been contaminated by industrial emissions, host tertiary plant communities able to tolerate MM toxicity selected from the local non-contaminated habitats. These plant species can also be described as pseudo-metallophytes according to their capacity to establish and grow in both non-contaminated and MM contaminated environments (Favas et al., 2014; Tordoff et al., 2000). Furthermore, in the Mediterranean semi-arid context, local plant species are able to tolerate strong water stress. These adaptations are particularly required for the ecological rehabilitation of MM polluted areas (Frérot et al., 2006; Mendez and Maier, 2008; Moreno-Jiménez et al., 2011). Moreover, within the context of protected or sensitive habitats, it is important to avoid disturbances linked to the introduction of exotic or invasive plant species in a natural environment such as those routinely used in phytoremediation projects such as *Miscanthus sp.* (Mench et al., 2009; Nsanganwimana et al., 2014). Screening the local spontaneous plant communities is thus necessary in order to understand the interactions between species, environment and disturbances through the expression of different ecological functionalities (Disante et al., 2010; Párraga-Aguado et al., 2013). These parameters are then determinant for the success of restoration projects for polluted areas.

On the Mediterranean coast of Marseille, south-eastern France, the former lead smelting factory of Escalette, which ceased activity in 1925, is a brownfield to date still left unreclaimed. Its activities strongly contributed to the mixed contamination of the surrounding area (Affholder et al., 2014; Testiati et al., 2013), which is located within the first French peri-urban National Park, founded in 2012. The particularity of this site is that within the same brownfield are included urban and natural areas combining major anthropogenic disturbances (urban and industrial pollution, trampling, erosion) and biodiversity-richness, and consequently it is the focus of major conservation issues (Affre et al., 2015). At this site, recent studies have shown the capacity of certain native plants to grow spontaneously on highly contaminated soils and their phytostabilization potential (Affholder et al., 2013, 2014; Laffont-Schwob et al., 2011; Testiati et al., 2013). These observations correspond indeed to one century of spontaneous recovery of the tolerant native plant communities after high industrial disturbances (Laffont-Schwob et al., 2016). Previous results have also highlighted MM pollution hotspots in the vicinity of the brownfield (Rabier et al., 2014), including some occurring in particular in natural areas as the result of slag and atmospheric deposits or ashes from former industrial structures such as the horizontal chimney (Affholder et al., 2013; Testiati et al., 2013). Accordingly, there is a need for more extensive screening of local plants in relation with the diversity of spontaneous plant communities, adapted to local heterogeneous environmental conditions, which may be able to persist on the land or be resilient for future phytoremediation applications.

In this study, we focused on the area which was under the influence of the smelter horizontal chimney, where both high mixed contamination and spontaneous native vegetation occur, in order to perform a precise and georeferenced characterization of this particular ecosystem. Our aim was to assess changes in vegetation structure and/or composition caused by contaminants and other mesologic parameters to highlight the most MM-tolerant native plant species throughout heterogeneous environment. We developed a protocol without using destructive methods, in conformity with the regulations regarding this protected area that consisted in X-ray fluorescence field equipment for soil MM analysis, coupled with phytoecological monitoring relative to plant distribution and cover and discriminant environmental parameters. We thus developed an integrative methodology not based on plant MM uptake but on plant distribution and assemblages, habitat characterization and life-traits. The aim was to characterize plant communities in a context of MM heavy contamination in order to identify tolerant native plants that can be used to optimize the phytostabilization potential of the vegetation (improvement of soil quality by C and N soil input, creation of habitats for microorganisms, erosion control, MM chelation) and to favor restoration of contaminated protected areas while limiting future pollution dispersion.

2. Materials and methods

2.1. Site description

The Escalette former lead smelting factory area (WGS84 coordinates: N = 43.22578°, E = 5.35059°), located on the south coast of Marseille, south-east France (Fig. 1), is a territory combining housing, brownfield, slag heaps and natural Mediterranean landscapes. The factory, which was in operation from 1851 to 1925, has to date not been reclaimed. Since 1925, MM pollution of the site and its surroundings has been directly and indirectly caused by the slag deposits in the vicinity and by dispersion of contaminants from the polluted buildings, chimney ashes and dumps by weathering and bioalteration processes (Testiati et al., 2013). The factory structure is characterized by a horizontal chimney, built along a ridge over approximately 300 m, culminating at an altitude of 140 m (Fig. 1). The horizontal smelter chimney area is one of the most contaminated sites in the area, with high As, Cu, Pb, Sb and Zn mixed-pollution (Affholder et al., 2014) due to ash deposits along the chimney flue and their dispersion into the vegetation and soils located nearby. However, from a phytomorphological point of view, this area seems very similar to the Calanques natural landscapes, characterized by a mosaic of spontaneous plant communities that constitute calcareous xero-thermophilous shrublands (Mediterranean matorral), grasslands and stands of Aleppo pine (interactive Escalette map.kml).