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Heavy metal distribution in a sediment phytoremediation system at pilot scale

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ABSTRACT

The continuous stream of polluted sediments, dredged from harbors and water bodies in order to maintain the navigation, is a common practice, but the fate of these sediments is an issue recognized worldwide. This pilot case study evaluated the application of phytoremediation as sustainable management strategy for the decontamination of polluted dredged marine sediments.

The treatments were based on the use of different plant species (*Paspalum vaginatum* Sw.; *P. vaginatum* Sw. + *Spartium junceum* L.; and *P. vaginatum* Sw. + *Tamarix gallica* L.) and organic matter (compost). The synergic action of plants and compost in removing both heavy metals (Cd, Ni, Zn, Pb, and Cu) and total petroleum hydrocarbons, and in recovering the nutritive and biological sediment properties were evaluated. In addition to the detection of total metal removal efficiency, the chemical distribution of metals in the sediment phases (exchangeable, manganese and iron oxides, organic matter, and residual minerals) was also measured in order to make a more realistic estimation of the phytoremediation efficiency for the sediment decontamination. Finally, a complete picture of the metal flux was obtained by investigating the metal mass-balance in the treated sediments. The results of metal content in the sediment phases showed that metal distribution was not uniform and each metal predominated in different fractions; the bioavailability of metals in the initial and treated sediments at 0–20 cm in the decreasing order was: Cd > Zn > Cu > Pb > Ni. The higher proportion of Ni and Pb in the residual phase can be the reason of the lower translocation of these metals in the plant tissues. On the other hand, Cd, Zn, and Cu were the metals most easily translocated in plant tissues, both aboveground and roots, confirming their higher bioavailability for the plants.

The results of mass balance indicated that, at the end of the experimentation, a high content of metals were still found in the sediment. The greatest contribution in metal containment was attributed to a phytostabilization process at rhizosphere level followed by gravel and sand absorption. The capacity of rhizophere to precipitate heavy metals, could be considered as an alternative option for reducing the metal availability and, consequently, the toxicity in contaminated sediments.

1. Introduction

A large amount of sediments is dredged every year from ports and waterways in order to maintain adequate depths for ship navigation, but the fate of these sediments is an issue worldwide recognized. Usually, dredged sediments are disposed in specific facilities and may cause environmental problems due to their contamination by metals and organic compounds. Marine sediments, especially in coastal and estuarine regions in the vicinity of urban and harbor areas, are, in fact, becoming increasingly polluted with heavy metals (Loring and Rantala, 1992; Szefer et al., 1995).

Phytoremediation, which involves plants and their associated microorganisms to stabilize or reduce contamination, is a low-cost and environmental friendly technology of soil restoration, targeting phytoextraction, phytodegradation, or phytostabilization of contaminants (Schwitzguébel et al., 2009). The three different plant-based technologies of phytoremediation, each having a different mechanism of action for remediating polluted matrices generally include: (1) phytoextraction, in which plants absorb metals from soil and sediment and translocate them to harvestable shoots where they accumulate (2) phytodegradation, utilizing plants to degrade organic contaminants from soil and sediment; and (3) phytostabilization, where plants stabilize, rather than remove contaminants by plant root metal retention.

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Compared to physico-chemical and engineering techniques, phytoremediation represents an attractive alternative for low or medium polluted matrices decontamination which, in addition, results in increased ecosystem fertility by promoting restoration and biodiversity (Mench et al., 2010; Vangronsveld et al., 2009). However, phytoremediation is still regarded as an emerging technology that has to prove its sustainability for dredged sediment treatment (Bert et al., 2009; Doni et al., 2013).

The proper selection of plants is crucial for phytoremediation success on contaminated sediments due to specific traits and conditions of sediments (e.g., moisture, flooding, elevated organic matter, clay, and salinity); in view of this, the selection of potential plants to be used in sediments reclamation should not be based solely on plant metal uptake capacity, but also on the basis of their ecological adaptability (Antoniadis and Alloway, 2001; Moreno et al., 2002).

King et al. (2006) reported cases of failed phytoremediation application to canal sediments due to low metal uptake and high mortality of various tree species, such as poplars, willows, and alders. However, Vervaeke et al. (2003) showed that hydraulically raised dredged sediment can be successfully planted with willow species.

In some previous experiments, organic residues and liming materials were added to sediment in order to attenuate the phytotoxic effect (Adriano et al., 2004; Brown et al., 2005). Similarly, several authors reported that the application of inorganic fertilizer in combination with compost was effective in providing nutrients and organic matter for plant growth in degraded sites or metal-rich substrates (De Coninck and Karam, 2008).

The plants *Tamarix gallica* L. and *Spartium junceum* L. have shown an extensive capability of adaptation to adverse environmental conditions. These plants have been able to colonize marginal areas and contaminated soil (Moreno-Jimenez et al., 2011; Muzzi and Fabbri, 2007). In addition, in two mesoscale phytoremediation studies on marine and brackish dredged sediments, *T. gallica* L. and *S. junceum* L. in combination with *Paspalum vaginatum* Sw. were effective in decontaminating polluted sediments from both organic and inorganic pollutants (Bianchi et al., 2010; Doni et al., 2013). Nevertheless, in both these studies, the preliminary bio-physical conditioning of sediments by mixing the sediment with a sandy soil and by applying green compost have been necessary in order to obtain the proper establishment of plants.

The purpose of this paper is to approach the phytoremediation for the decontamination of dredged marine sediments. The efficiency of different plant species in association with compost for phytoremediating contaminated sediments was investigated at pilot scale experiment. The plants *T. gallica* L. and *S. junceum* L. in combination with the grass *P. vaginatum* Sw. were selected on the basis of the previous results at mesoscale level. In order to obtain a better insight of the expected period of time for sediment decontamination, the heavy metal content in the different compartments of the system (sediment, leachate, draining layer, rhizosphere, and plant tissues) and the mass balance were calculated.

2. Materials and methods

2.1. Experimental layout

Polluted marine sediments were dredged from the port of Livorno (Center of Italy, 43°33′25″N, 10°17′39″E). These sediments were mixed with a sandy soil (calculated as 30% in volume) to improve the particle size composition. The construction of the facility (19 m length, 5 m width, 1.3 m depth, and volume 110 m^3) was performed on December 2009 in the Livorno's harbour area (Fig. 1). The treatment basin was lined with a low and high density polyethylene composite (LDPE–HDPE) waterproof membrane to prevent the leachate from draining into the ground and ensure the correct inflow–outflow water balance. A 30 cm draining layer made of gravel (32.7 t, $8 < d_{50} < 20$ mm) and sand (20.3 t, $1 < d_{50}$

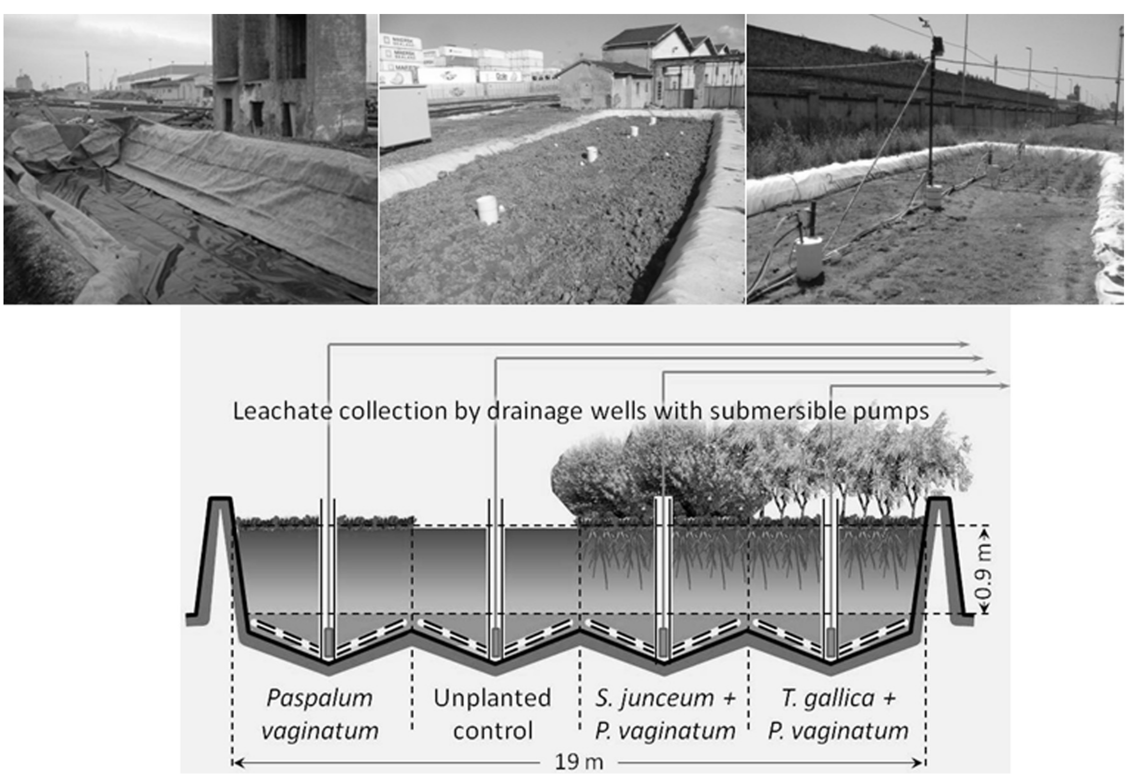

Fig. 1. Plan view of the facility.