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Phytoremediation of dredged marine sediment: Monitoring of chemical and biochemical processes contributing to sediment reclamation

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ABSTRACT

In this study, a pilot phytoremediation experiment was performed to treat about 80 m^3 of silty saline sediments contaminated by heavy metals and organic compounds. After preliminary mixing with a sandy soil and green compost application, three different plant treatments [*Paspalum vaginatum* (P); *P. vaginatum* + *Spartium junceum* (P + S); *P. vaginatum* + *Tamarix gallica* (P + T)] were compared to each other and to an unplanted control (C) in order to evaluate the plant efficiency in remediating and ameliorating agronomical and functional sediment properties. The experiment was monitored for one year after planting by taking sediment samples at two depths and performing several chemical and biochemical analyses. After one year, the increase in hydrolytic enzyme and dehydrogenase activities indicated the stimulation of sediment functionality. Additionally, the availability of energy sources derived from organic matter application and plant-root activity promoted the formation of a stable organic matter fraction. Finally, P + S and P + T were also effective in decontaminating polluted marine sediments from both organic (total petroleum hydrocarbons, TPH) and inorganic (heavy metal) pollutants.

1. Introduction

In marine environments, harbours worldwide have a long history of acting as sinks for contaminants produced by navigation and by surrounding industrial and urban settlements (Taylor et al., 2004). Dredging of sediments from such harbours is necessary to prevent flooding and allow shipping traffic efficiency, but also for remediation purposes where the risk to the environment and health might be high.

The European policy encourages valorization of dredged sediments, and this will be a technological challenge in the near future (SedNet, 2013). Physical, chemical, and thermal decontamination treatments are in most cases not economically sustainable, due to the large quantity of sediments produced that must be treated every year with high specific costs (Meers et al., 2005). In this context, phytoremediation has a high chance of acceptance by the general public, since it can be cost-effective, socially acceptable, and feasible to provide a natural management option (Doni et al., 2012a; Ghosh and Singh, 2005; Glick, 2010). Additionally, phytoremediation has the potential to turn lightly polluted sediments into a matrix with characteristics approaching those of a natural soil (Bianchi et al., 2011, 2010a). Such a matrix, originated from a waste material (as dredged sediments are) by technogenic soil-forming processes, can be defined as a techno-soil (Lehmann and Stahr, 2007).

The effectiveness of soil phytoremediation has been demonstrated for many classes of pollutants, such as oil hydrocarbons, polycyclic aromatic hydrocarbons, pesticides, chlorinated solvents, and heavy metals (Doni et al., 2012b; Gerhardt et al., 2009; Macci et al., 2012; Padmavathiamma and Li, 2007; Vamerali et al., 2010). Conversely, phytoremediation of dredged sediments is still considered an emerging technology that needs further studies to demonstrate its level of effectiveness (Doni et al., 2012a). An additional problem is related to the selection of potential plants to be used in sediment reclamation. Indeed, peculiar properties of dredged sediments, such as salinity and fine texture, limit the selection to plants which combine very high ecological adaptability with the capability to uptake metal and/or absorb or remove organic pollutant.

King et al. (2006) reported cases of failed phytoremediation application to canal sediments due to high mortality of various tree

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species such as poplars, willows, and alders. In some reported experiments, the application of organic residues and liming materials (Ye et al., 1999) or lime-stabilized biosolids attenuated the phytotoxic effect of sediments (Adriano et al., 2004), allowing an active vegetation cover to be established (Brown et al., 2005). In a mesoscale phytoremediation study on marine sediment (Bianchi et al., 2010b), performed with a combination of a grass species (*Paspalum vaginatum*) and a shrub species (*Tamarix gallica*), a preliminary bio-physical conditioning of sediments was necessary to allow vegetation to be properly established. It was carried out by mixing sediment with a sandy soil and by applying green compost in order to create an environment suitable for plant growth and heavy metal uptake. Nine months after planting, all plants were observed to be healthy, and the organic and inorganic contaminations were both significantly reduced, demonstrating the success of such a sediment remediation procedure. In a later mesoscale phytoremediation experiment, the effectiveness of two shrub species (*T. gallica* and *Spartium junceum*), in association with the grass *P. vaginatum*, in reducing organic and inorganic contamination of slightly polluted brackish dredged sediments was confirmed (Doni et al., 2012a).

On the basis of the results of those mesoscale experiments, in the present work a pilot scale phytoremediation experiment was set up to treat dredged marine sediments with a high silt–clay fraction, high salinity, and moderate contamination by heavy metals and organic compounds. Four different treatments were selected: (1) control (unplanted); (2) *P. vaginatum* (P treatment); (3) *P. vaginatum* + *S. junceum* (P + S treatment); and (4) *P. vaginatum* + *T. gallica* (P + T treatment). The experiment aims at decontaminating dredged sediments and at the same time ameliorating their chemical, physical, and biochemical properties in order to turn them into a matrix with characteristics approaching those of a natural soil.

2. Materials and methods

2.1. Experimental layout

Polluted marine sediments were dredged from the sea bottom of the port of Livorno (Central Italy, 43°33′25″ N, 10°17′39″ E), and were mixed with a sandy soil (calculated as 30% by volume) to ameliorate their particle size composition. In December 2009, the sediments were placed in a sealed basin (20 m length, 5 m width, and 1.3 m depth) purposely built on the ground in the proximity of the dredging area. The usable volume of the facility for sediment treatment was about 110 m^3. To prevent the leachate from draining into the ground and to ensure the correct inflow–outflow water balance, the treatment basin had been lined with a composite low/high density polyethylene membrane (LDPE–HDPE) of 0.45 mm thickness, covered with a protective geotextile. A 30 cm draining layer made up of gravel and sand was hand laid on the bottom of the facility before filling it with the soil–sediments mixture. The facility was designed to treat about 80 m^3 of sediments, previously mixed with 24 m^3 of soil. A dose of 4 kg m^{-2} of compost was uniformly added on the top of the soil–sediment mixture and was incorporated into the top 20 cm layer of sediment by soft harrowing in order to favour the initial plant adaptation and growth. The weather conditions (evapotranspiration, temperature and rainfall) of the experimental site have been reported in Fig. 1. The main characteristics of the sediment, soil, compost, and soil–sediment mixture used for the experimentation are shown in Table 1. In May 2010, four areas of about 5 m × 5 m each were marked out in the facility and planted as follows: (1) *P. vaginatum* (P treatment); (2) control (unplanted); (3) *P. vaginatum* + *S. junceum* (P + S treatment); and (4) *P. vaginatum* + *T. gallica* (P + T treatment) (Fig. 2).

Table 1
Main characteristics of sediment, soil, compost and soil-sediment mixture used for the experimentation.

	Sediment	Soil	Compost	Mix soil–sediment
Clay (%)	38.0	4.6	–	18.8
Silt (%)	46.5	26.2	–	25.0
Sand (%)	15.4	69.2	–	56.2
pH	7.78	7.99	6.92	7.1
E.C. (dS m^{-1})	2.01	0.310	3.69	1.9
TOC (%)	1.20	0.075	45.1	0.860
TN (%)	0.119	0	1.49	0.078
TEC (%)	–	–	5.9	–
FAs (%)	–	–	3.4	–
HAs (%)	–	–	2.5	–
TP (mg P kg^{-1})	640	197	2015	536
Cd (mg Cd kg^{-1})	1.55	–	1.44	1.43
Cu (mg Cu kg^{-1})	65	–	80.7	52.0
Zn (mg Zn kg^{-1})	278	–	258	256
Ni (mg Ni kg^{-1})	84	–	21.7	63.0
Pb (mg Pb kg^{-1})	83	–	35.5	64.0
Cr (mg Cr kg^{-1})	60	–	30.0	37.0
TPH (mg TPH kg^{-1})	1566	–	–	1430

E.C.: Electrical Conductivity; TOC: Total Organic Carbon; TN: Total Nitrogen; TEC: Total Extractable Carbon; FAs: Fulvic Acids; HAs: Humic Acids; TP: Total Phosphorus; TPH: total petroleum hydrocarbons.

The sealed basin had a drainage system that consisted of four submerged pumps located in the centre of each of the four areas. The leachate derived from each area was directly pumped into a drain well and collected separately.

The pilot system was monitored by performing sediment samplings two weeks (June 2010, T0), six months (December 2010, T1), and one year (June 2011, T2) after the experiment was set up.

Each sediment sample was prepared by mixing three subsamples and then homogenized, sieved (2 mm) and split in two

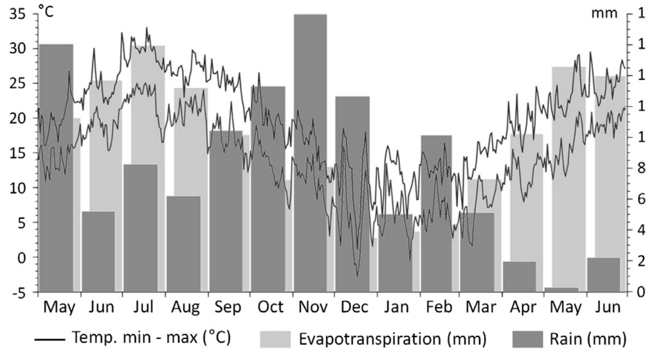

Fig. 1. Weather conditions (evapotranspiration, temperature and rainfall) of the experimental site for the entire period of the experimentation.

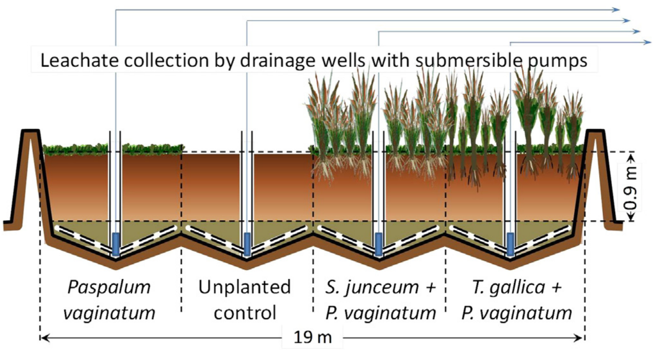

Fig. 2. Plan-view of the experimental set up.