

Life Cycle Assessment of Remediation Alternatives for Dredged Sediments

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The Life Cycle Assessment (LCA) is an ISO standardized and widely used methodology for environmental assessment of products, processes and services, by identifying, quantifying and evaluating all the resources consumed and all the emissions and wastes released. The LCA methodology enables adequate comparison between different remediation options and can be used as a decision-making tool for the authorities.

In this study, LCA was used to compare, in terms of their associated environmental burdens, two scenarios for managing the contaminated dredged sediments of the seabed of the Livorno Port area. The compared options were: (i) confined longshore disposal, i.e. placement of dredged material in a confined disposal facility; (ii) phytoremediation treatment, by an association of salt-tolerant shrub and grass species, aimed at turning the polluted sediment an agronomic substrate (techno-soil). The results of the life cycle impact assessment underline that the potential impacts of the two compared options involve different environmental problems. Indeed, for phytoremediation the most significant impacts are related to energy and resources consumption, while for the confined disposal is related to loads in the marine ecotoxicity categories. Therefore, phytoremediation can be considered a promising alternative solution for the management and valorization of contaminated dredged sediments.

1. Introduction

In Europe, 100 - 200 Mm³ are dredged yearly to clean and maintain the depth of navigational waterways (evaluation of the SedNet - European Sediment Network). Due to human activities during the last decades, marine sediments have been contaminated with various organic and inorganic contaminants (metals, polyaromatic hydrocarbons, mineral oil). Currently, dredged sediments with low contamination are mostly placed in confined disposal facilities where the risks related to the contamination of the contained material are carefully assessed and controlled. Phytoremediation is proposed as a low cost, safe and sustainable alternative for treating the contaminated material and reusing it in the terrestrial environment. This technique involves the use of plants to remove, contain, inactivate or destroy harmful environmental pollutants from soils or sediments.

Selection of sediment management alternatives for contaminated dredging sediments is often based on human and ecological risk assessment (HERA) framework (Bridges et al., 2006). Whereas HERA is suitable for assessing whether the contaminated sediments constitute an unacceptable human and environmental risk, it does not address environmental consequences associated with implementing remediation process. Assessment of environmental effects over the whole life cycle (i.e. Life Cycle Assessment, LCA) could help in selecting the most appropriate option to manage dredged sediment. The LCA is an ISO standardized and widely used methodology, the aim of which is to evaluate the environmental burdens of a product/process over its entire life cycle by the modelling and calculation of the resources used and the emissions produced. During the early years of LCA, the methodology was mostly applied to products (Gillani et al., 2013), but recent literature suggests that it also has potential as an analysis tool for chemical processes (Castiello et al., 2008) and in process design (Mayumi et al., 2010) for

comparison and selection of options (Wibul et al., 2012). Thus, LCA enables adequate comparison between different remediation options and can be used in planning sediment dredging and treatment, for marketing purposes or as a decision-making tool for the authorities. Even though LCA has been developed and applied in multiple environmental management cases, applications to contaminated sediments are rare.

In this study, the LCA was used to compare two scenarios for managing the sediments dredged from the Livorno Port in terms of their associated environmental burdens. The compared options were: (i) confined long shore disposal, i.e. placement of dredged material in a confined disposal facility; (ii) phytoremediation treatment, by an association of salt-tolerant shrub and grass species, aimed at turning the polluted sediment an agronomic substrate (techno-soil).

2. Methods

This study was performed using a methodological framework based on the International Organization for Standardization (ISO) recommendations (UNI EN ISO 14040 and 14044). According to the ISO 14044, LCA methodology consists of four phases: goal and scope definition, inventory analysis, impact assessment and interpretation. In the goal and scope definition are defined the objectives of the study, the functional unit (i.e. the reference unit to which the inputs and outputs are related), the boundaries of the system (i.e. the extension of the study), and the impact assessment methodologies. The inventory analysis involves data collection for all the activities in the studied system: raw materials (including energy carriers), products, and solid waste and emissions. This step includes calculation of the amount of resource use and pollutant emission of the system in relation to the functional unit. The impact assessment phase assigns the inventory results to impact categories and quantifies the system potential contribution to different environmental impacts.

2.1 System description

Currently, the slightly contaminated sediments that are being dredged from the port of Livorno are placed into large confined disposal facilities built along the coast by bounding sea stretches with rip-rap and by sealing their inner part with waterproof liner. Phytoremediation is a low cost, ecologically sound and sustainable reclamation alternative to the current solution. A pilot project plant was set up to test the efficiency of a phytoremediation technique applied to contaminated marine sediments dredged from the port of Livorno. The technique involved the use of plants (the salt-tolerant shrub species *Tamarix gallica* and *Spartium junceum*, associated to the salt-tolerant grass *Paspalum vaginatum*) in order to recreate an active ecosystem in which plants, micro- and macroorganisms could interact with each other through the rhizosphere, for the adsorption, extraction and/or degradation of conservative and degradable pollutants. Furthermore, the plants microbiologically activated the sediment, through the creation of a bio-microsystem in which plants and microorganisms could interact and give to the sediment the connotation of a biologically activated agronomic soil (techno-soil). The tested phytoremediation technique emerged as a promising treatment option for an operational re-use of dredged marine sediments for agricultural purposes. The techno-soil obtained could represent an alternative and suitable option for the final destination of a great amount of the dredged sediments from rivers and harbor docks. On the basis of the pilot experiment, a full-scale phytoremediation plant was designed on top of one of the existing confined disposal facilities, with the aim of treating the contained sediments and moving them to terrestrial destinations in order to free room within the facility for newly dredged sediments instead of building new disposal facilities to receive them.

2.2 Goal definition and functional unit

The main objective of this LCA was to compare the environmental potential impacts of two options for managing the contaminated dredged sediment. A contained longshore disposal, i.e. placement of dredged material into a confined disposal facility to be purposely built along the shore, was compared to a phytoremediation treatment by salt-tolerant shrub and grass species aimed at remediating the polluted sediments and turning them into a land-usable agronomic substrate (techno-soil). The scope is to include all important activities of each scenario, i.e. covering raw materials acquisition, materials production and use stage. These results would also allow the proposal of some optimization processes to reduce the environmental load of the phytoremediation treatment.

Based on recommendations for a life-cycle framework for the assessment of site remediation (Diamond et al., 1999), the functional unit was set equal to remediation, during a two year period, of 56,250 m³ of contaminated sediment dredged from the seabed of the Porto of Livorno.

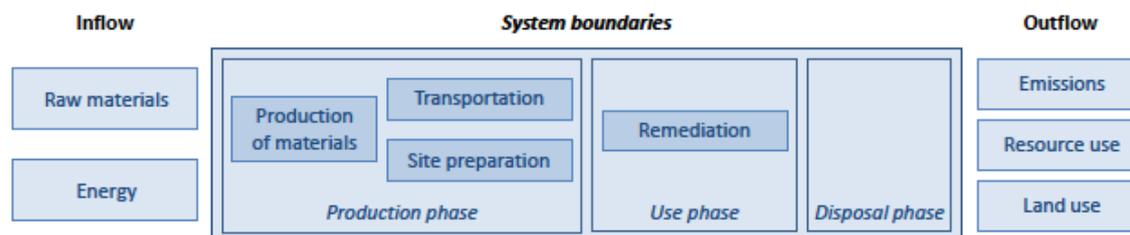


Figure 1: Life cycle flow diagram

2.3 Inventory analysis

The environmental load was calculated in relation to the functional unit, and the inventory results are evaluated and distributed into the life cycle stages, shown in Figure 1. Each life cycle stage (for instance, site preparation) is composed of one or several processes, which can be material production or equipment operation.

The aggregated data collected for modeling the systems were derived from the design calculations realized for the installations of the sediment aquatic disposal and from the pilot plant used to test the phytoremediation technique. Raw materials input used for SimaPro models of phytoremediation treatment are listed in Table 1. The needed equipment, diesel and electricity quantities were calculated in relation to treatment time for each scenario. Inventory data for the background system (production of plastics, electricity, lorry transport, etc.) were based on average technology data from the Ecoinvent 2.2. database. The main assumptions used in this LCI elaboration were the following: all transportation to and from the site was included (distances varied depending of the supplier); a time horizon of 20 y was assumed; a product avoided credit was added to the phytoremediation system, since since techno-soil and wood are produced from the sediment treatment, which avoid the use of virgin soil and wood as energy source.

2.4 Impact assessment method

The two options were developed and analyzed with SimaPro 7.3 software (Pré Consultants). To conduct an LCIA (Life Cycle Impact Assessment), it is necessary to select an impact assessment methodology which regroups the different characterization models for each impact category. These characterization models allow the calculation of characterization factors which express the measured substance's strength relative to a reference substance.

Among the different methods available in the software, the ReCiPe endpoints and midpoints (hierarchist version) methods were used. The ReCiPe impact model employs USES-LCA which is at present the only readily available impact assessment method that includes a marine release compartment and was therefore selected for this study. Besides, an endpoint method was used for the impact assessment in order to achieve maximal agreement with the comparative and management-oriented objectives of the study. Endpoint indicators describe the integrated damage of the components from the inventory, in contrast to midpoint indicators which address effects only. For global warming, a typical midpoint indicator would be the effect of radiative forcing (global warming potential), whereas the end point approach would assess the human and environmental damage based on radiative effects. Use of endpoint indicators facilitates the interpretation of results for management purposes and allows integration of results to a single score indicator. ReCiPe uses three main damage categories: human health, ecosystems and resources. Human health includes climate change, ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation, and ionising radiation (expressed in disability adjusted life years, DALY). Ecosystems includes climate change, terrestrial acidification, freshwater and marine eutrophication, terrestrial, freshwater and marine ecotoxicity, agricultural and urban land occupation, and natural land transformation (expressed in species·y). Resources include metal depletion and fossil depletion, expressed in \$.

3. Results and discussion

Figure 2 shows the results of a contribution analysis performed to reveal the most important contributing activities for the phytoremediation system. The transportation of materials constitutes a considerable impact, followed by the activities related to sediment dredging and plant cultivation. Shrub plants cultivation has its highest impacts in fertilizer and harvesting.

Table 2 lists the parameter values obtained from the life cycle impact assessment of two remediation options, which are used to calculate the disadvantage factors in Table 3. The disadvantage factors are calculated by dividing the higher value by the lower value, in order to highlight how many times a

remediation technique causes more environmental burdens compared to the other one (Volkwein et al., 1999). The results show that the potential environmental loads for the two studied scenarios are similar for all impact categories except for the land occupation and transformation and the marine ecotoxicity category. This is due to the different use of the area occupied by the phytoremediation plant and by the confined disposal facility: the first one contributes to biodiversity through the transformation of land for short-cycle forest, the second one is conversely similar to a dump site.

Table 1: Raw materials input of phytoremediation.

Process	Amount	Unit
Concrete, normal, at plant	2,071	t
Steel, low alloyed, at plant	312.2	t
Wire drawing, steel	27.7	t
Gravel, crushed, at mine	50,962	t
Sand, at mine	24,000	t
Waterproofing membrane ^a	577	m ²
Chromium steel 18/8, at plant	9.2	t
Polyethylene, HDPE, granulate, at plant	44.1	t
Soil, unspecified, in ground	31,875	t
Ammonium nitrate phosphate, as N, at regional storehouse	11.3	t

^a Process created for this study

The remarkable difference in the Marine ecotoxicity category is related to the presence of stored sediment contaminated by metals and hydrocarbons in the case of the confined disposal option. The small difference in the other impact categories point out that the net environmental consequences of remediation process are not always positive. This is consistent with LCA studies on contaminated soil (Suer et al., 2004) and indicates that the costs to the environment and human health in the form of increased greenhouse gas emissions, particle emissions, use of limited resources, etc. may often outweigh the gain obtained by remediation. In particular, Climate change and Fossil depletion categories are affected by energy consumption that turns out to be higher for phytoremediation process as a result of transportation of materials and cultivation activities.

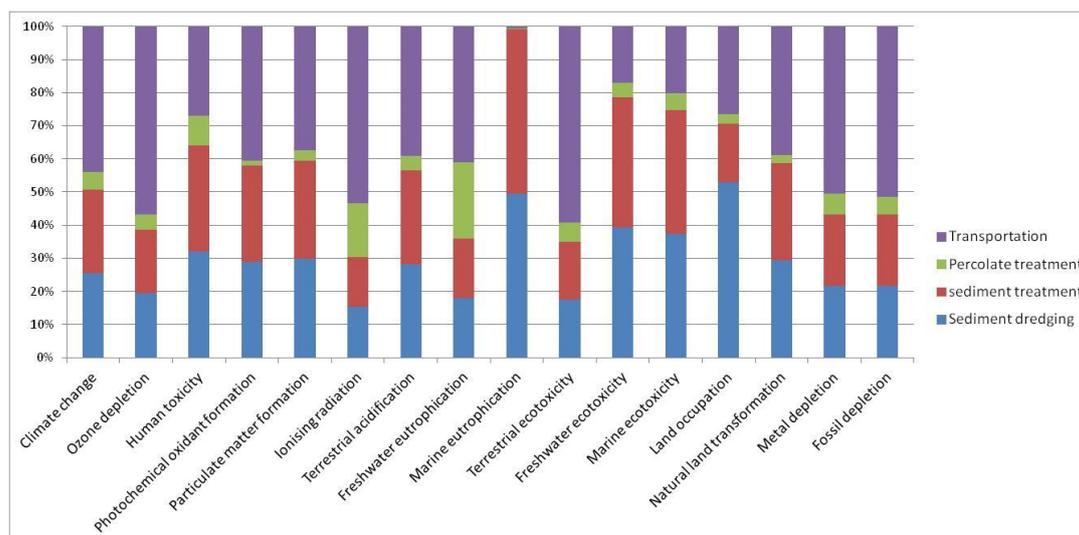


Figure 2: Contribution of subsystems of the phytoremediation technique to each impact category.

Table 2: Midpoints results per impact categories.

Impact Category	Unit	Confined disposal	Phytoremediation
Climate change	kg CO ₂ eq	9.12	1.19
Ozone depletion	kg CFC-11 eq	$1.39 \cdot 10^{-6}$	$1.65 \cdot 10^{-6}$
Photochemical oxidant formation	kg NMVOC	$9.84 \cdot 10^{-2}$	$1.09 \cdot 10^{-1}$
Particulate matter formation	kg PM10 eq	$3.04 \cdot 10^{-2}$	$3.09 \cdot 10^{-2}$
Terrestrial acidification	kg SO ₂ eq	$8.00 \cdot 10^{-2}$	$6.90 \cdot 10^{-2}$
Freshwater eutrophication	kg P eq	$1.30 \cdot 10^{-3}$	$1.31 \cdot 10^{-3}$
Marine eutrophication	kg N eq	$2.18 \cdot 10^{-1}$	$1.91 \cdot 10^{-1}$
Land occupation	m ²	5.28	$1.25 \cdot 10^{-1}$
Natural land transformation	m ²	$2.61 \cdot 10^{-1}$	$4.50 \cdot 10^{-3}$
Metal depletion	kg Fe eq	$7.17 \cdot 10^{-1}$	$6.14 \cdot 10^{-1}$
Fossil depletion	kg oil eq	4.48	4.17
Human toxicity	kg 1.4-DB eq	2.64	2.05
Terrestrial ecotoxicity	kg 1.4-DB eq	$1.13 \cdot 10^{-3}$	$1.51 \cdot 10^{-3}$
Freshwater ecotoxicity	kg 1.4-DB eq	$3.38 \cdot 10^{-3}$	$5.78 \cdot 10^{-2}$
Marine ecotoxicity	kg 1.4-DB eq	13.9	$5.86 \cdot 10^{-2}$

The previous considerations emerge from the summarised damage categories, shown in Figure 4. Indeed, the potential effects on human health (which includes the climate change category) are higher for the phytoremediation option. These results of the life cycle assessment at endpoints level highlight that the resources used for phytoremediation are not compensated for by gains from toxicity source reduction. This indicates that the amount of energy and resources to remediate contaminated sediments result in higher environmental footprint in comparison to the disposal into confined aquatic facilities. On the other hand, the potential damage on ecosystems and resources results higher for confined disposal in relation to loads in the marine ecotoxicity and land occupation categories.

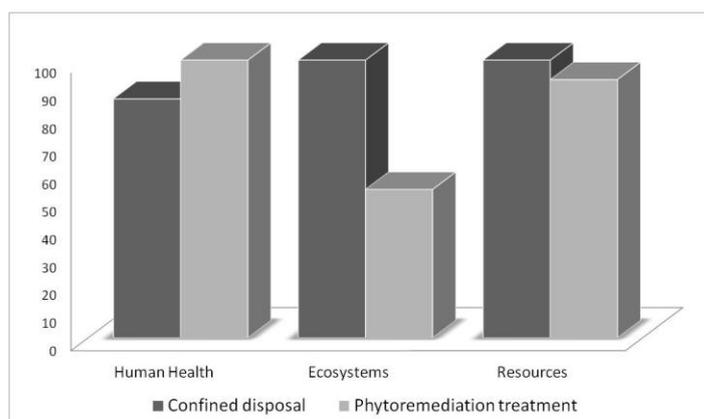


Figure 4: Comparison of the environmental impact associated with the two options at endpoints level.

4. Conclusions

A comparison of the environmental performance of two managing options for dredged sediments was carried out. The results of the life cycle impact assessment underline that the potential impacts of the two options (i.e. confined aquatic disposal versus phytoremediation treatment) involve different environmental problems: the amount of energy and resources to remediate contaminated sediments results in higher environmental footprint in comparison to the disposal into confined facilities. On the other hand, the potential damage on ecosystems and resources turns out to be higher for confined disposal.

Besides, LCA methodology allows identifying of the hot-spots in the life cycle, i.e. which activities cause the greatest environmental impact. For phytoremediation treatment, the analysis suggests that attention should be paid to the on-site operation of mechanical equipments: reduction of the operation time of these facilities, that implies reduction of energy and fossil fuel consumption, could reduce the global impact of the phytoremediation. This study also showed that sustainable sediment management can only be achieved by a holistic approach toward the assessment of remedial alternatives and LCA may be a valuable tool for assessing the potential environmental burdens of sediment remediation system. From the obtained results, phytoremediation can be considered a promising alternative solution for the disposal and valorization of contaminated dredged sediments.

Table 3: Disadvantage factors per impact categories.

Impact Category	Confined disposal	Phytoremediation
Climate change	1.0	1.3
Ozone depletion	1.0	1.2
Photochemical oxidant formation	1.0	1.1
Particulate matter formation	1.0	1.0
Terrestrial acidification	1.2	1.0
Freshwater eutrophication	1.0	1.0
Marine eutrophication	1.1	1.0
Land occupation	42.2	1.0
Natural land transformation	57.9	1.0
Metal depletion	1.2	1.0
Fossil depletion	1.1	1.0
Human toxicity	1.3	1.0
Terrestrial ecotoxicity	1.0	1.3
Freshwater ecotoxicity	1.0	1.7
Marine ecotoxicity	237.1	1.0

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