Using soil function evaluation in multi-criteria decision analysis for sustainability appraisal of remediation alternatives

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USING SOIL FUNCTION EVALUATION IN MULTI CRITERIA DECISION ANALYSIS FOR SUSTAINABILITY APPRAISAL OF REMEDIATION ALTERNATIVES

Yevheniya Volchko[a], Jenny Norrman[a], Lars Rosén[a], Magnus Bergknut[bc], Tore Söderqvist[d], Tommy Norberg[e], Sarah Josefsson[f], Karin Wiberg[f], Mats Tysklind[b]

[a]Department of Civil and Environmental Engineering, Chalmers University of Technology, Sven Hultins gata 8, SE-41296, Gothenburg, Sweden
volchko@chalmers.se

[b]Department of Chemistry, Umeå University, SE-901 87 Umeå, Sweden

[c]Envix, SE-906 20, Umeå, Sweden

[d]Enveco Environmental Economics Consultancy Ltd., Måsholmstorget 3, SE-127 48 Skärholmen, Sweden

[e]Mathematical Sciences, Chalmers University of Technology & University of Gothenburg, SE-412 96 Gothenburg, Sweden

[f]Department of Aquatic Sciences and Assessment, Swedish University of Agricultural Sciences, Box 7050 SE-750 07, Uppsala, Sweden

Abstract

Soil functions are critical for ecosystem survival and thus for ecosystems' provision of services to humans. In 2006, the proposed EU Soil Framework Directive introduced ecological, social and economic soil functions to be accounted for in land management practice. Ecological soil functions are a product of the complex interactions between living (biological) and non-living (physical and chemical) soil components. Social and economic soil functions are the benefits humans gain from ecosystems. Once a soil function is utilized by humans, it is usually called an ecosystem service. One of the major threats constraining proper functioning of the soil and thus provision of ecosystem services is soil contamination. Remedial actions typically only address the chemical soil quality. However, emerging regulatory requirements demand a holistic view on soil evaluation in remediation projects. Based on a prototype for sustainability appraisal of remediation alternatives using Multi-Criteria Decision Analysis (MCDA), this paper presents a structured and transparent approach for incorporating the soil function concept into a set of ecological, socio-cultural and economic criteria of the MCDA. The approach suggests using (1) soil quality indicators (SQI – physical, chemical and biological soil properties) for evaluating effects of remediation on soil functions in the ecological domain, and (2) value-related measurements (e.g. attitudes, opinions, and willingness to pay) for exploring the effects on ecosystem services resulting from soil functions in the socio-cultural and economic domains of sustainability. The specific objective of this study is to test applicability of a preliminary minimum data set (MDS) of soil quality indicators for soil function evaluation using a case study site located in Marieberg, northern Sweden. The suggested MDS consists of soil texture, content of coarse material, available water, organic matter content, potentially mineralizable nitrogen, pH, available phosphorus, and contaminant concentration. Although the soil at the Marieberg site is heavily contaminated with dioxins, it provides potentially favourable conditions for soil functioning with some limitations. *Potentially mineralizable nitrogen* indicates limited biological activity in the soil. On the other hand, *content of coarse material*, *pH* and *available water capacity* provide potentially favorable conditions for biological activity. *Available phosphorus* and *content of organic matter* limit soil fertility.

Keywords: remediation, soil functions, soil ecosystem services, sustainability assessment, multi-criteria decision analysis, contaminated sites/soil, soil quality indicators

1. Introduction

1.1. Background

Soil functions are critical for ecosystem survival and thus for ecosystems' provision of services to humans. The components of an ecosystem are dependent on a healthy soil to enable the entire ecosystem to function properly. The close relationship between soil functions and the ecosystem were recognized by scientists in the 1970-s (e.g. Lehmann and Stahr, 2010) and by politicians and decision-makers in more recent years (COM, 2006). In 2006, the proposed EU Soil Framework Directive introduced seven ecological, social and economic soil functions to be accounted for in land management practice. These include (*i*) biomass production, including agriculture and forestry; (*ii*) storing, filtering and transforming nutrients, substances and water; (*iii*) biodiversity pool, such as habitats, species and genes; (*iv*) physical and cultural environment for humans and human activities; (*v*) source of raw materials; (*vi*) acting as carbon pool; (*vii*) archive of geological and archeological heritage (COM, 2006). Being a subset of ecosystem functions, a soil function can be defined asa soil ecosystem service once it is utilized for benefit by humans (Dominati et al., 2010).

To describe ecological soil functions, soil scientists use soil quality indicators (SQIs) to address the physical, the chemical, and the biological soil elements with an equal degree of importance (e.g. Andrews et al., 2004; Doran and Zeiss, 2000; Schindelbeck et al., 2008). Balanced interconnections of these three soil quality elements are at the core of properly functioning soil. Unfortunately, inherited from the era of industrialization, soil contamination is a widespread threat to proper soil functioning throughout the world. Striving for addressing soil contamination, research and technical development in recent decades has resulted in a wide palette of available remediation techniques to improve chemical soil quality, i.e. reduction of contaminant concentrations and amounts in the soil to tolerable levels guided by intended land uses (e.g. Swedish EPA, 2009). However, when evaluating the sustainability of remediation alternatives, it becomes important to consider the unity of all three soil quality elements (composed of chemical, as well as physical and biological properties) for ensuring that the ecological effects on soil functions are properly taken into account. A Multi Criteria Decision Analysis (MCDA) approach has been suggested by several authors (e.g. CL:AIRE, 2011; Linkov et al., 2006; Rosén et al., 2009, 2013; Sparrevik et al., 2011) to support decision-making on sustainable remediation accounting for both positive and negative effects of available remediation alternatives.

MCDA methods for sustainability appraisal of remediation alternatives can provide a structure for evaluating sustainability considering a set of ecological, socio-cultural and economic criteria.

1.2. Aim and paper outline

This paper presents an approach to soil function evaluation for facilitating input on ecological effects of remediation alternatives in an MCDA framework for sustainability appraisal described by Norrman et al. (2012); Rosén et al. (2009; 2013). First, a brief description of the MCDA framework that forms the point of departure in this study is given in Section 2.1. Further, the paper describes an approach to soil function evaluation within the MCDA framework and presents a preliminary minimum data set (MDS) for soil function evaluation (Section 2.2). Using the suggested MDS, the effects of remediation alternatives on soil functions are evaluated for the site located in Marieberg, northern Sweden (Section 3). The final part of the paper discusses uncertainties associated with soil function evaluation and provides some concluding remarks (Section 4).

2. A Multi Criteria Decision Analysis for sustainability appraisal

2.1 The MCDA framework

The MCDA framework developed by Rosén et al. (2009; 2013) uses the common sustainability model of the three pillars: ecology, economy, and socio-culture. In the economic domain, costs and benefits are measured quantitatively in monetary terms using Cost-Benefit Analysis (CBA) addressing the social profitability criterion (Rosèn et al., 2008). In the ecological and socio-cultural domains however, qualitative scores are assigned to a number of key criteria (Table 1). Each criterion is scored between -2 representing “very negative effect” and +2 representing “very positive effect” relative to a reference alternative. A score of 0 represents “no effect”. Importantly, the effects of remediation alternatives are measured relative to the reference alternative, e.g. when no remedial action is taken.

The MCDA framework is based on a linear additive model (to rank the remediation alternatives) in combination with a non-compensatory method (to identify those alternatives which are regarded as not leading towards sustainability). The score of each criterion are added and integrated, together with the results of the CBA, into a normalized sustainability index. The most sustainable alternative is the one which generates the highest sustainability index.

Uncertainty analysis is an important part of the MCDA model (Norrman et al., 2012; Rosén et al. 2013). The uncertainties in the model are treated with help of a Monte Carlo simulation. Monte Carlo simulation is a technique for calculating uncertainties in the model results by repeatedly picking values from the probability distribution for the uncertain variables in the model (CB, 2010). The assignment of the uncertainty distribution in the MCDA model is suggested to be performed in three steps: (1) selection of distribution type, i.e. selection of whether all types of effects, only positive, or only negative effects are possible for the specific criterion; (2) estimation of the most likely effect using the scale presented above; and (3) assigning the uncertainty level of the estimation of the most likely effect (Rosén et al., 2013). The three-step procedure results in a probability distribution representing the uncertainty of the scoring of criteria in the ecological and the social domains of the MCDA. Lognormal distributions are assigned to the cost and benefit items in the economic domain of the MCDA. Further, a Monte Carlo simulation is performed to calculate a probability distribution for the normalized sustainability index.

2.2 Soil function evaluation within the MCDA framework

To comply with the proposed EU Soil Framework Directive, the MCDA framework by Rosèn et al. (2009; 2013) aims to include soil function evaluation in the decision process. For integrating the soil function evaluation into sustainability appraisal of remediation alternatives, it is important to make a distinction between the ecological soil functions and the soil ecosystem services. The latter are related to the socio-economic effects. The effects of remediation on soil ecosystem services (*iv*) *physical and cultural environment for humans and human activities* (including recreation, aspiration services), and (*vii*) *archive of geological and archeological heritage* are addressed in the socio-cultural domain of the MCDA model. These soil ecosystem services correspond to and are to some extent covered by *Local environmental quality and amenity* and *Cultural heritage* criteria respectively (Table 1). The soil abilities to serve as a *(v) source of raw materials* and to act as a *(vi) carbon pool* can be monetized and addressed in the economic domain of the MCDA model. *(i) Biomass production including agriculture and forestry* is not considered relevant in soil remediation projects. The effects on ecosystem services resulting from changes in soil quality are suggested to be evaluated using value-related measurements. These measurements can be expressed in: (1) community-based values which reflect attitudes, preferences, and intentions associated with a soil ecosystem service; (2) economic values revealed by market data (if any) about a soil ecosystem service, or the willingness to pay (WTP) for the service provided by the end use of the soil (SAB, 2009).

The ecological soil functions are related to the internal functioning of a soil system. The effects of remediation alternatives on such ecological soil functions as (*ii*) *storing, filtering and transforming nutrients, substances and water*, and (*iii*) *biodiversity pool such as habitats, species and genes* are to some extent addressed by the *Soil* criterion of the MCDA model (Table 1). Together with conventional risk assessment methods, soil quality indicators (SQIs), i.e. physical, chemical and biological soil properties, are used for evaluation of the effects of remediation alternatives on soil functions. A suggested minimum data set (MDS) for ecological soil function evaluation is presented in Table 2. The MDS was identified based on a literature review, primarily considering the works by Bone et al. (2010); Brown et al. (2005), Craul and Craul (2006), Doni et al. (2012), Epelde et al. (2008a,b; 2009; 2010a,b), Gugino et al. (2009), Jelnsic et al. (2013), Lehmann et al. (2008), Pazos et al. (2012); Schindelbeck et al. (2008), and van Herwijen et al. (2007). The suggested MDS is identified by compiling SQIs that are (1) suggested by three or more literature sources in the studies exploring the effects on ecological soil functions in remediation projects, and (2) consistent with the MDSs for the purposes other than agricultural productivity of land (Bone et al., 2010; Craul and Craul, 2006; Lehmann et al., 2008; Schindelbeck et al., 2008).

3. Marieberg case study: Evaluation of the effects on ecological soil functions

The former Marieberg saw mill site is situated in northern Sweden (Aberg et al. 2010) and covers an area of approximately 1500 m x 150 m. Chlorophenol (CP) based wood preservatives was used for more than two decades until closure of the activities in 1970. The CP formulations were contaminated with polychlorinated-*p*-dibenzodioxins and dibenzofurans (PCDD/Fs). The CP formulations were contaminated with polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs, commonly called 'dioxins'). These compounds are highly persistent organic pollutants, which tend to partition to particles rather than being dissolved and mobilized by water (Persson et al., 2008). As a result, the site is still heavily polluted with PCDD/Fs from many different activities (Aberg et al. 2010). The site includes areas that were used for sawing, impregnation, indoor storage, indoor drying, and an outdoor timber yard. Inside and just outside the area, there are residential houses, pastures for dairy cows, a farm, a hostel, and a camping area. In a previous risk assessment study of the site (Aberg et al. 2010), human exposure to PCDD/Fs through a broad spectrum of exposure pathways was assessed. Soil, air, groundwater, raspberries, carrots, potatoes, grass, milk, and eggs were analyzed for the content of PCDD/Fs, and the results showed that most exposure media were clearly elevated as compared to national reference samples. The calculated exposure levels showed that a number of site-specific exposure routes can be of importance for people residing this area. Thus, despite low mobility of PCDD/Fs, these contaminants can be transferred from the polluted soil to other environmental media and into humans.

3.1 Remediation alternatives

Three remediation alternatives are considered within this study (Table 3).

3.2 Soil sampling and analysis

Soil was randomly sampled to a depth of 0.5 m, covering the entire saw mill area. In total, 18 samples were collected. The samples were handled according to ISO 10381-6 and sent to certified laboratories for analysis of the concentrations of the 2,3,7,8- substituted CDD/Fs (using the isotope dilution method, with isotopically labelled standards for all 17 2,3,7,8-CDD/F congeners), and of the suggested SQIs, i.e. *particle size distribution* (ISO 3310-2),*organic matter content* (SS-EN 12879), *potentially mineralizable nitrogen* (Standard Methods 18th ed., 4500 NH_3-B), *pH* (ISO 10390), and *available phosphorus* (AL-P, Egner et al., 1960 and SS 02 8310). *Available water capacity* was determined as a function of a FAO (Food and Agriculture Organization of the United Nations) soil texture class, organic matter content and bulk density (Lehmann et al., 2008).

3.3 Evaluation of the effects on ecological soil functions

The evaluation of the effects on ecological soil functions is performed in a separate module. The output of this module provides input to the MCDA framework addressing the effects of remediation alternatives on soil functions. The procedure for evaluation of the effects on soil functions includes the three steps described below.

Step 1. Soil classification (into one of five classes) for a reference remediation alternative according to the methodology suggested by Gugino et al. (2009), Idowu et al. (2008), Schindelbeck et al. (2008), Volchko (2013). This methodology implies scoring of each SQI in the MDS in the interval [0; 1] where the scores of [1; 0.71], [0.7; 0.31], [0.3; 0] represent soils of good, medium and poor qualities, respectively. Thereafter the scores are integrated into a total index using the arithmetic mean values of the scores. The total index forms a basis for soil classification into five soil classes: very good, good, medium, poor, and very poor (Gugino et al., 2009; Volchko, 2013). *Soil texture* and *contaminant concentration* are not scored. However, *soil texture* is used to determine the *available water capacity* as well as the scores for *potentially mineralizable nitrogen* and *available phosphorus*. Contaminant concentration is used to evaluate the ecotoxicological risk and not included in the soil function index.

Step 2. Evaluation of the effects of available remediation alternatives on soil functions relative to the reference alternative using a suggested matrix of the effects on soil functions (Fig. 1). The effects are scored between -2 representing "very negative effect" and +2 representing "very positive effect" relative to a reference alternative. A score of 0 represents "no effect".

Step 3. Uncertainty and sensitivity analyses of the resulting scores.

3.4 Results

The studied soils at the case study site were sands and sandy loams according to a FAO taxonomy triangle. The evaluated SQIs for *Reference Alternative* are compiled in Table 4. Using the methodology for soil classification by Gugino et al. (2009), a mean index of 0.58 corresponding to soil class 3 and a medium soil function performance was computed for the analyzed soil samples. The mean score for potentially mineralizable nitrogen of 0.02 indicates limited biological activity in the soil. On the other hand, the mean scores for content of coarse material, pH and available water capacity were 0.85, 0.74 and 0.9 respectively, providing potentially favorable conditions for biological activity. The scores for available phosphorus and content of organic matter were 0.52 and 0.41 respectively thus limiting e.g. soil fertility.

A preliminary correlation analysis indicates dependencies between concentration of dioxins and organic matter content. A strong correlation between surface soil organic matter and organic pollutants has also been reported in other studies (e.g. Bergknut et al., 2010; Meijer et al., 2002; Meijer et al., 2003), but for sites contaminated directly from industrial activities rather than from atmospheric deposition, this correlation is expected to be less pronounced.

The effects of remediation alternatives on soil functions (i.e. assigned scores) were evaluated relative to the reference alternative using a suggested matrix of the effects (Fig. 1). The remediation alternative *Conservation of the site as* "*Environmental Risk Area*", which does not include any remedial action, will generate no effect, i.e. a score of 0. Depending on the soil class of the refilling material, the alternatives *Excavation* and *Excavation of Hot Spots* will generate different effects on soil functions and accordingly different scores (Table 5). Obviously, the quality of the selected refilling material becomes a crucial factor for the future soil functioning.

3.5. Uncertainty analysis for soil classification at the Marieberg site

The soil classification was based on scoring of the SQIs in the suggested MDS and integrated into a soil function index that corresponds to one of five soil classes. Lognormal distributions were used to represent the uncertainties in the SQIs. First, the measured value (assigned as the mode) of the SQI was transformed into the mean on the lognormal scale. Further, the 95^{th} percentile was computed representing the upper uncertainty level in the measurement of the SQI reported by the laboratory. For example, the uncertainties in the measurements of *pH*, *organic matter content*, and *potentially mineralizable nitrogen* were ±0.2 units, ±15%, ±20% respectively. The lognormal distributions were assigned using a location of 0, the computed mean on the lognormal scale and the computed 95^{th} percentile. Thereafter, a Monte Carlo Simulation (performed with the Oracle Crystal Ball© add-in software) was run to analyze the uncertainties in the resulting soil class for *Reference Alternative*. The simulation results showed that with almost 100% certainty, the simulated total soil function index corresponds to soil class 3, representing medium soil function performance (Fig. 2).

Using Oracle Crystal Ball©, a sensitivity analysis was done to investigate the contribution from each input variable, i.e. SQIs, to the total uncertainty (Fig. 3). *Available phosphorus* and *pH* in soils were the most sensitive input variables in the model that contribute most to the total uncertainty.

4. Discussion and concluding remarks

This paper shows the important distinction between soil functions and the soil ecosystem services (Section 2.2). The ecological soil functions are related to the internal functioning of a soil system, i.e. what the soil does in its natural state. The soil ecosystem services are related to the benefits humans gain from ecosystems. Further, in accordance with emerging regulatory requirements on soil protection, this work shows how effects on soil functions can be included in sustainability appraisal of remediation alternatives. This paper only addresses ecological effects, but in a full sustainability appraisal, the effects on soil ecosystem services also have to be taken into consideration. Such effects have to be addressed in the socio-cultural and economic domains, e.g. by evaluating the impact of these effects on *Local environmental quality and amenity, Cultural heritage* and *Social profitability*, using CBA (Table 1). To meet emerging regulatory requirements on soil protection, the MCDA for sustainability appraisal of remediation alternatives suggests using (1) physical, chemical, and biological soil quality indicators (SQIs) for addressing the effects on ecological soil functions in the ecological domain, and (2) value-related measurements for addressing the effects on soil ecosystem services in the socio-cultural and the economic domains of the MCDA. The suggested MDS of SQIs consists of soil texture, content of coarse material, available water, organic matter content, potentially mineralizable nitrogen, pH, available phosphorus, and contaminant concentration (Table 2). This study shows how these SQIs can be practically used in sustainability appraisal of remediation alternatives. Contaminant concentration is not included into the soil function index. This particular SQI is a key factor of ecotoxicological risk. Therefore, the results of ecological soil function evaluation, described in this paper, and ecotoxicological risk assessment are combined in the MCDA model addressing the *Soil* criterion.

In Sweden, excavation is the most common remediation technology (van Hees, 2008). The material used for refilling can vary from the crushed rock to glacial till. Since the effects of remediation alternatives on soil functions, i.e. scores, strongly depend on the soil quality class of the refilling material, the resulting scores presented in Table 5 are associated with large uncertainties. Thus, it is reasonable to assign probability distributions for the scores instead of point values, in accordance with the assessment of criteria in the MCDA (Norrman et al., 2012; Rosén et al., 2013). The assignment of the uncertainty distribution in the MCDA model is suggested to be performed in three steps: (1)

selection of distribution type, i.e. selection of whether all types of effects, only positive, or only negative effects are possible for the specific criterion; (2) estimation of the most likely effect; and (3) assigning the uncertainty level of the estimation of the most likely effect. For example, if the soil of class 3 (medium soil function performance) will be substituted with a refilling material of poor quality then no positive scores are possible. Instead, there is a negative effect on the soil functions with a low level of uncertainty. On the other hand, if the same soil will be substituted with a refilling material of good quality, no negative scores are possible, and there is a positive effect on the soil functions with a low level of uncertainty. Further, if nothing is known about the refilling material, then all scores are possible, and e.g. the most likely effect on soil functions is positive with a medium level of uncertainty, or the most likely effect on soil functions is very positive with a high level of uncertainty. Thus, the effects of soil excavation on ecological soil functions strongly depend on the type of refilling material. Together with conventional risk assessment methods, the effects on ecological soil functions (i.e. the effects on physical, chemical and biological soil properties) of the refilling material should be thoroughly considered in remediation projects in order to meet emerging regulatory requirements on soil protection.

Remediation is usually aimed at reducing risks of negative impact on human health and the environment posed by contaminants in the soil. The level of risk reduction is typically linked to the intended land use, i.e. reduction of contaminant concentrations and amounts in the soil to tolerable levels guided by the end use of the site. For example, chemical soil quality requirements for the sensitive land uses such as residential and green areas are stricter than for the less sensitive land uses such as industrial areas, parking spaces and roads. The end use of the site will, however, also have a direct impact on the targeted soil functions and in turn on the resulting soil ecosystem services. For this reason, identification of the end use of the site (i.e. land use scenarios) should be done early in the sustainability assessment. Once land uses and a corresponding set of soil functions and services are identified, the suggested SQIs and relevant value-related measurements can be used to evaluate effects associated with available remediation alternatives. The suggested MDS of SQIs is therefore particularly relevant to the future green areas within a remediation site.

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References

Aberg A, Tysklind M, Nilsson T, MacLeod M, Hanberg A, Andersson R et al. Exposure assessment at a PCDD/F contaminated site in Sweden - field measurements of exposure media and blood serum analysis. Environmental Science and Pollution Research 2010; 17 (1): 26-39.

Andrews SS, Karlen DL, Cambardella C A. The soil management assessment framework: a quantitative soil quality evaluation method. Soil Sci. Soc. Am. J. 2004; 68: 1945-62.

Bergknut M, Laudon H, Wiberg K. Dioxins, PCBs and HCB in soil and peat profiles from a pristine boreal catchment. Environ. Pollut. 2010; 158(7): 2518-25.

Bone J, Head M, Barraclough D, Archer M, Scheib C, Flight D, Voulvoulis N. Soil quality assessment under emerging regulatory requirements. Environment International 2010; 36: 609-22.

Brinkhoff P. Multi-Criteria Analysis for Assessing Sustainability of Remediation Actions: Applications in Contaminated Land Development. A Literature Review. Report No 2011:14, ISSN 1652-9162. Gothenburg: Chalmers Reproservice; 2011.

Brown S, Sprenger M, Maxemchuk A, Compton H. Ecosystem Function in Alluvial Tailings after Biosolids and Lime Addition. J Environ Qual 2005; 34:139-48.

CL:AIRE. A framework for Assessing the Sustainability of Soil and Groundwater Remediation. London: CL:AIRE; 2010.

CL:AIRE. Annex 1: The SuRF-UK Indicator Set for Sustainable Remediation Assessment. London: CL:AIRE; 2011.

CB. Crystal Ball User's Guide, 11.1.2. Oracle USA, Inc., 500 Oracle Parkway, Redwood City, CA 94065; 2010.

COM. Proposal for a Directive of the European Parliament and of the Council establishing a framework for the protection of soil and amending Directive 2004/35/EC. Brussels, Belgium; 2006.

Craul TA, Craul PJ. Soil Design Protocols for Landscape Architects and Contractors. New Jersey: John Wiley and Sons; 2006.

de Groot RS, Wilson MA, Boumans RMJ. A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecological Economics 2002; 41: 393-408.

Doni S, Macci C, Peruzzi E, Arenella M, Ceccanti B, Masciandaro G. In situ phytoremediation of a soil historically contaminated by metals, hydrocarbons and polychlorobiphenyls. J Environ Monit 2012; 14: 1383-90.

Dominati E., Patterson M, Mackay A. A framework for classifying and quantifying the natural capital and ecosystem services of soil. Ecological economics, 2010; 69:1858-68.

Doran JW, Zeiss MR. Soil health and sustainability: managing the biotic component of soil quality. Appl Soil Ecol 2000; 15:3-11.
Egner H, Riehm H, Domingo WR. Untersuchungen über die chemische Bodenanalyse als Grundlage für die Beurteilung desNahrstoffzustandes der Boden, II: Chemische Extractionsmetoden zu Phosphor und Kaliumbestimmung. Kunliga Lantbrukshügskolans Annaler 1960; 26: 199-215.
Epelde L, Hernάndez-Allica J, Becerril JM, Blanco F, Garbisu C. Effects of chelates on plants and soil microbial community: Comparison of EDTA and EDDS for lead phytoextraction. Science of The Total Environment 2008a; 401(1-3): 21-8.
Epelde L, Becerril JM, Hernάndez-Allica J, Barrutia O, Garbisu C. Functional diversity as indicator of the recovery of soil health derived from Thlaspi caerulescens growth and metal phytoextraction. Applied Soil Ecology 2008b; 39(3): 299-310.
Epelde L, Becerril JM, Mijangos I, Garbisu C. Evaluation of the efficiency of a phytostabilization process with biological indicators of soil health. Journal of Environmental Quality 2009; 38(5): 2041-9.
Epelde L, Becerril JM, Kowalchuk GA, Deng Y, Zhiu J, Garbisu C. Impact of Metal Pollution and *Thlaspi caerulescens* Growth on Soil Microbial Communities. Applied and Environmental Microbiology 2010a; 76 (23): 7843-53.
Epelde L, Becerril JM, Barrutia O, Gonza lez-Oreja JA, Garbisu, C. Interactions between plant and rhizosphere microbial communities in a metalliferous soil. Environmental Pollution 2010; 158: 1576-83.
Fanger G, Jones C, Jonsson K, Elander P, Pyyny M. Marieberg f.d. sågverk – Huvudstudie om markföroreningar m.m. Huvudstudierapport: miljöteknisk del. Kemikata Konsult Ab, Envipro Miljöteknik; 2007.
Gugino BK, Idowu OJ, Schindelbeck RR, van Es HM, Wolfe DW., Moebius-Clune BN et al. Cornell Soil Health Assessment Training Manual. 2nd ed. Ithaca: Cornell Digital Print Services; 2009.
Idowu OJ, van Es HM, Abawi GS, Wolfe DW, Ball JI, Gugino B K et al. Farmer-oriented assessment of soil quality using field, laboratory, and VNIR spectroscopy methods. Plant Soil 2008; 307: 243-53.
ISO 3310-2 Test sieves – Technical requirements and testing – Part 2: Test sieves of perforated metal plate. International Standard Organization; 1999.
ISO 10381-6 Soil quality – Sampling. Guidance on the collection, handling and storage of soil for the assessment of aerobic microbial processes in the laboratory. International Organization for Standardization, 1993.
ISO 10390 Soil quality – Determination of pH. International standard organization; 2005.
Jelusic M, Grcman H, Vodnik D, Suhadolc M, Lestan D. Functioning of metal contaminated garden soil after remediation. Environmental pollution 2013; 174: 63-70.
Lehmann A, David S, Stahr K. TUSEC – A manual for the evaluation of Natural Soils and Anthropogenic Urban Soils. Bilingual edition. Stuttgart: Hohenheimer Bodenkundliche Hefte; 2008.

Lehmann A, Stahr K. The potential of soil functions and planner-oriented soil evaluation to achieve sustainable land use. Journal of Soils Sediments 2010; 10: 1092–1102.

Linkov I, Satterstrom FK, Kiker G, Batchelor C, Bridges T, Ferguson E. From comparative risk assessment to multi-criteria decision analysis and adaptive management: Recent developments and applications. Environmental Risk Management 2006; 32: 1072-93.

Linkov I, Sahay S, Kiker G, Bridges T, Saeger TP. Multi-criteria decision analysis: A framework for managing contaminated sediments. In: Levner E, Linkov I, Proth JM. Strategic Management of Marine Ecosystems. Amsterdam: Kluwer, 2004.

Meijer SN, Ockenden WA, Sweetman A, Breivik K, Grimalt JO, Jones KC. Global distribution and budget of PCBs and HCB in background surface soils: Implications or sources and environmental processes. Environ Sci Technol 2003; 37:667-72.

Meijer SN, Steinnes E, Ockenden WA, Jones KC. Influence of environmental variables on the spatial distribution of PCBs in Norwegian and UK soils: Implications for global cycling. Environ Sci Technol 2002; 36:2146-53.

Mendoza GA, Martins H. Multi-criteria decision analysis in natural resource management: A critical review of methods and new modelling paradigms. Forest Ecology and Management 2006; 230: 1–22.

Norrman J, Volchko Y, Rosén L, Brinkhoff P, Norin M, Söderqvist T et al. Development of a tool for evaluating the sustainability of remediation alternatives. Proceedings of the 16th Nordic Geotechnical Meeting. Copenhagen, May 9-12, 2012. Vol. 2/2, dgf-Bulletin 27, 793-800.

Pazos M, Plaza A, Martin M, Lobo MC. The impact of electrokinetic treatment on a loamy-sand soil properties. Chemical Engineering Journal 2012; 183:231-7.

Persson Y, Shchukarev A, Öberg L, Tysklind M. Dioxins, chlorophenols and other chlorinated organic pollutants in colloidal and water fractions of groundwater from a contaminated sawmill site. Environm. Sci. Pollut. Res. 2008; 15(6): 463-71.

Postle M, Fenn T, Grosso A, Steeds J. Cost-benefit analysis for remediation of land contamination. R & D Technical Report P316. Bristol: UK Environment Agency; 1999.

Rosén L, Söderqvist T, Back PE, Soutukorva Å, Brodd P, Grahn L. Cost-benefit analysis for prioritizing of remediation alternatives. Method development and examples. (*In Swedish:* Kostnadsnyttoanalys som verktyg för prioritering av efterbehandlingsinsatser. Metodutveckling och exempel på tillämpning.) Sustainable Remediation Programme. Report 5836. Stockholm: Swedish Environmental Protection Agency; 2008.

Rosén L, Söderqvist T, Back PE, Soutukorva Å, Brodd P, Grahn L. Mulicriteria analysis (MCA) for sustainable remediation at contaminated sites. Method development and examples. (*In Swedish*: Multikriterieanalys (MKA) för hållbar efterbehandling av förorenade områden. Metodutveckling och exempel.) Sustainable Remediation Programme, Report 5891. Stockholm: Swedish Environmental Protection Agency; 2009.

Rosén L, Back PE, Norrman J, Söderqvist T, Brinkhoff P, Volchko Y et al. SCORE: Multi-Criteria Analysis (MCA) for Sustainability Appraisal of Remedial Alternatives. Proceedings of the

Second International Symposium on Bioremediation and Sustainable Environmental Technologies. Jacksonville, Florida, USA, June 10-13, 2013.
SAB: Valuing the Protection of Ecological Systems and Services: A report of the EPA Science Advisory Board. Washington. EPA-SAB-09-012, May 2009.
Schindelbeck R, van Es HM, Abawi GS, Wolfe DW, Whitlow TL, Gugino BK et al. Comprehensive assessment of soil quality for landscape and urban management. Landscape and Urban Planning 2008; 88: 73-80.
Sparrevik M, Barton DN, Bates M E, Linkov I. Use of stochastic multi-criteria decision analysis to support sustainable management of contaminated sediments. Environmental Science & Technology 2011; 46: 1326-34.
SS 02 8310 P-AL method. (*In Swedish*: P-AL metoden). Swedish Standards Institute; 1993.
SS-EN 12879 Slam characterization – Loss on ignition. (*In Swedish:* Karaktärisering av slam - Bestämning av torrsubstansförlust vid upphettning.) Swedish Standards Institute.
Standard Methods: For the Examination of Water and Wastewater, 18th ed. 1992.
Swedish EPA. Guideline values for contaminated land: Model description and a guide. (*In Swedish:* Riktvärden för förorenad mark: Modellbeskrivning och vägledning.) Report 5976. Stockholm: Naturvordsvärket; 2009.
van Hees PAW, Elgh-Dalgren K, Engwall M, von Kronhelm T. Re-cycling of remediated soil in Sweden: An environmental advantage? Resources, Conservation and Recycling 2008; 52: 1349-61.
van Herwijnen R, Al-Tabbaa A, Hutchings TR, Moffat AJ, Ouki SK, Johns ML. The Impact of Waste Compost-Based Soil Amendments on the Leaching Behavior of a Heavy Metal Contaminated Soil. Environmental engineering science 2007; 24 (7): 897-904.
Volchko Y. SF Box – A tool for evaluating ecological soil functions in remediation projects. Report 2013:1, ISSN 1652-9162. Gothenburg: Chalmers Reproservice; 2013.

Table
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Table 1
Key criteria of the updated MCDA framework by Rosén et al. (2013).

Environmental domain	Socio-cultural domain	Economic domain
• Soil • Flora and fauna • Groundwater • Surface water • Sediment • Air • Non-renewable natural resources • Non-recyclable waste	• Local environmental quality and amenity • Cultural heritage • Equity • Health and safety • Local participation • Local acceptance	• Social profitability

Table

Table 2

A suggested minimum data set for evaluation of the ecological soil functions in remediation projects.

Soil Quality Indicators (SQIs)
Soil texture
Content of coarse material
Available water capacity
Organic matter content
Potentially mineralizable nitrogen
pH
Available phosphorus

Table

Table 3
Remediation alternatives at the Marieberg site.

Remediation alternative	**Comment**
Reference Alternative	No remedial action taken.
Excavation	The alternative assumes replacement of the contaminated soil with a clean soil. This alternative has been decided on by the authorities and will be executed in 2013/2014.
Excavation of Hot Spots	The alternative assumes replacement of the heavily contaminated soil in the hot spots with a clean soil. This alternative has been discussed by the authorities but was in the specific case not chosen mainly due to concerns connected with future land use.
Conservation of the site as "Environmental Risk Area"	The alternative prohibits access to the area by fences and assumes no remedial action. This alternative is a part of the presented research project. The alternative is possible within current legislation and is therefore of interest, especially concerning the effects on soil functions and the socio-cultural domain.

Table
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Table 4
Basic statistics for the analyzed soil quality indicators at the Marieberg site.

	Sum PCDD/F 17, [pg/g]	AW,[%]	CM,[%]	OM,[%]	pH	NH4-N, [mg/kg]	AL-P, [mg/kg]
No	18	18	18	18	18	18	16*
Mean	31 000	22	13	2.8	6.6	190	34
Std	46 000	1.5	6.5	2.2	0.7	25	10
Min	210	21	2	0.6	5.6	140	20
Max	160 000	25	21	7	8.2	230	59
CV	1.6	0.1	0.5	0.8	0.1	0.1	0.3

No: number of soil samples. Std: standard deviation. Max: maximum. Min: minimum. CV: coefficient of variation.
CM: content of coarse material (ø>2 mm). AW: available water capacity. OM: organic matter content.
NH_4-N: potentially mineralizable nitrogen. AL-P: available phosphorus. PCDD/F: dioxins.
*The AL-P (available phosphorus) results for two soil samples textured sands are missing due to a mistake by the lab.

Table 5
Possible scoring of the effects on soil performance after remediation at the Marieberg site as a function of the refilling material.

	Soil class of refilling material				
	1	**2**	**3**	**4**	**5**
Remediation alternatives	”Very good”	”Good”	”Medium”	“Poor”	”Very poor”
Excavation	+2	+1	0	-1	-2
Excavation of Hot Spots	+2	+1	0	-1	-2

+2: very positive effect. +1: positive effect. 0: no effect. -1: negative effect. -2: very negative effect.

Reference Soil Class	Soil Class after Remediation				
	1*	**2***	**3***	**4***	**5***
1	0	-1	-2	-2	-2
2	+1	0	-1	-2	-2
3	+2	+1	0	-1	-2
4	+2	+2	+1	0	-1
5	+2	+2	+2	+1	0

Fig. 1. A suggested matrix of the effects on soil functions.

Soil Quality Classes:

1	Very good
2	Good
3	Medium
4	Poor
5	Very poor

Effects on Soil Functions:

+2	Very positive
+1	Positive
0	No effect
-1	Negative
-2	Very negative

Figure
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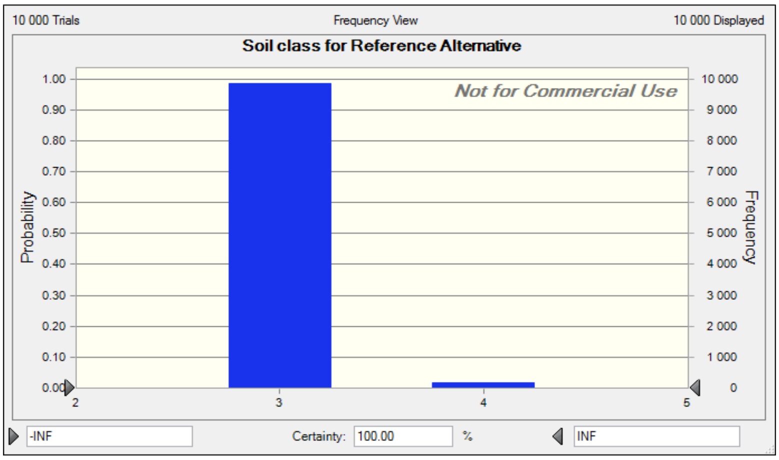

Fig. 2. Soil classes for *Reference Alternative* at the Marieberg site.

Figure

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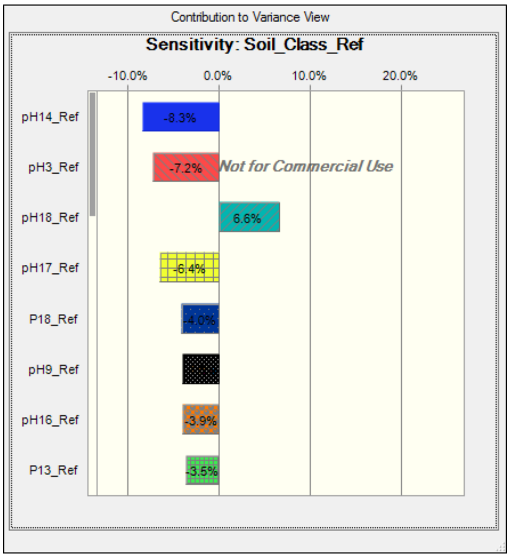

Fig. 3. Sensitivity chart for *Reference Alternative* showing the contribution of the input SQIs to the total uncertainty in the resulting soil class.