


## Review article

# Modelling the environmental implications of phytoremediation in urban settings: A review of the integration of life cycle assessment and ecosystem services approaches

Lidia Favaretto <sup>a</sup>, Benedetto Rugani <sup>b,c,\*</sup> , Carlo Calfapietra <sup>b,c</sup>, Massimo Labra <sup>a</sup>, Werther Guidi Nissim <sup>a</sup>

<sup>a</sup> Department of Biotechnology and Biosciences, University of Milano-Bicocca, Piazza Della Scienza 2, Milan I-20126, Italy

<sup>b</sup> Research Institute on Terrestrial Ecosystems (IRET), National Research Council of Italy (CNR), Via G. Marconi 2, Porano TR 05010, Italy

<sup>c</sup> National Biodiversity Future Centre (NBFC), Piazza Marina 61, Palermo 90133, Italy

## ARTICLE INFO

Handling Editor: Dr Cecil Konijnendijk van den Bosch

## Keywords:

Brownfields redevelopment  
Environmental sustainability  
LCA  
Nature-based Solutions  
Phytomanagement  
Phytotechnologies  
Urban greening

## ABSTRACT

Gentle Remediation Options (GRO) such as phytoremediation are gaining particular attention as a sustainable approach for remediating contaminated land and for the redevelopment of critical areas such as urban brownfields. Beyond soil remediation, these solutions can offer multiple benefits in the form of Ecosystem Services (ES), helping mitigate other important urban issues such as the heat island effect or air pollution. The balance between impacts and benefits can be quantitatively assessed combining industrial ecology tools like Life Cycle Assessment (LCA) with the ES evaluation, but the integration of these approaches remains limited. This review focuses on phytoremediation solutions for urban settings and aims to understand how LCA is applied in this specific field, highlighting potential gaps in the integration with the ES evaluation. A systematic literature search resulted in the analysis of 13 studies published between 2010 and 2024. The results show that LCA is a useful tool in the quantitative assessments of this GRO, but efforts should be made to broaden the types of ES considered in the analysis. Moreover, a phytomanagement perspective should be applied, considering the post-remediation effects on the overall impacts-benefits estimation and thus providing decision-makers with a comprehensive tool for sustainable planning.

## 1. Introduction

Sustainable urban development is crucial to preserving cities as vital centers of human activities. In 2008, the global urban inhabitants outnumbered the rural and, by 2050, it is expected that two-thirds of the population will be living in cities (United Nations, 2019). Parallel to this trend, many industrial sites that were once part of the urban center are now abandoned, or due to urban sprawl some former industrial areas are no longer suburban and have been incorporated into the inner-city structure (Wang et al., 2020). The result is a heterogeneous mixture of derelict land, which is often neglected for reuse or redevelopment due to doubts concerning possible environmental contamination of the sites (Norrman et al., 2016; EPA, 2022). To be differentiated from “greenfields” (i.e. land that has not been previously developed), these areas

have been defined as “brownfields” (Adams et al., 2010, January).

The presence of contaminants in urban soils poses risks to human health as they can be leached into water reserves or cause direct damage through the inhalation of dust, dermal contact and ingestion (Akram et al., 2018; Al-Swadi et al., 2022; Kicińska and Wikar, 2024; Lemming et al., 2010; Petruzzelli et al., 2010; EPA, 2011). Brownfields regeneration encompasses not only environmental considerations, but also social and economic ones; in other words, a meticulous sustainable approach is necessary (Bielinskas et al., 2018; Laprise et al., 2018).

So far, the remediation activities have been hindered by many factors, such as high costs, intricate bureaucratic systems, and uncertainty in the results (Green, 2018). Furthermore, traditional remediation technologies, such as dig and haul or chemical treatments, can result in loss of land functionality and cause secondary pollution (e.g., emission

\* Corresponding author at: Research Institute on Terrestrial Ecosystems (IRET), National Research Council of Italy (CNR), Via G. Marconi 2, Porano TR 05010, Italy.

E-mail addresses: [l.favaretto@campus.unimib.it](mailto:l.favaretto@campus.unimib.it) (L. Favaretto), [benedetto.rugani@cnr.it](mailto:benedetto.rugani@cnr.it) (B. Rugani), [carlo.calfapietra@cnr.it](mailto:carlo.calfapietra@cnr.it) (C. Calfapietra), [massimo.labra@unimib.it](mailto:massimo.labra@unimib.it) (M. Labra), [werther.guidinissim@unimib.it](mailto:werther.guidinissim@unimib.it) (W. Guidi Nissim).

<https://doi.org/10.1016/j.ufug.2025.128788>

Received 22 October 2024; Received in revised form 10 March 2025; Accepted 17 March 2025

Available online 19 March 2025

1618-8667/© 2025 The Author(s).

<http://creativecommons.org/licenses/by/4.0/>.

Published by Elsevier GmbH. This is an open access article under the CC BY license

of greenhouse gases, SO<sub>x</sub>, NO<sub>x</sub>, VOCs) (Hou et al., 2023). A valid alternative is the deployment of Gentle Remediation Options (GRO), which are extensive low cost (mostly plant based) technologies defined as risk management strategies that also provide a net gain, or at least no gross reduction, in soil function (Cundy et al., 2013). GRO are Nature-based Solutions (NbS) that deploy plants, fungi, bacteria and soil amendments to extract, degrade or stabilize contaminants (e.g., heavy metals, hydrocarbons) (Cundy et al., 2015; Drenning et al., 2022). Among GRO, phytoremediation relies on the contaminant removal or immobilization performances of plants (Song et al., 2019; Wang et al., 2021). It is possible to divide phytoremediation into categories based on the strategies adopted by plants for dealing with xenobiotics: phytoextraction, phytostabilisation, phytodegradation, and rhizodegradation (Meagher, 2000; Peuke and Rennenberg, 2005). Despite the many proven environmental and economic benefits (Asante-Badu et al., 2020; Cristaldi et al., 2017; Farraji et al., 2016; Fermeiglia and Perišić, 2023a), phytoremediation is still far from being adopted on a large scale, mainly due to constraints such as variable yields of plants living on harsh soil conditions (Schwitzguébel, 2017; Seth, 2012), long operational time and high dependence on site-specific conditions (Fernández-Braña et al., 2023; Moreira et al., 2021; Schwitzguébel, 2017). Moreover, the investments in phytoremediation projects are often hindered by high uncertainty in the results and discrepancies between the short-term budget strategies and the long remediation time (Gerhardt et al., 2017). To better promote this kind of solutions and to ensure the maximum delivery of benefits, there should be a shift from the concept of phytoremediation to that of phytomanagement, applying costs-benefits analysis and considering all aspects of remediation on different time scales (Moreira et al., 2021).

Fundamental benefits that need to be clearly assessed in phytomanagement are the various services that a restored natural land could provide to humankind. Healthy environments can offer benefits that have been defined as “Ecosystem Services” (ES) by the Millennium Ecosystem Assessment (M.E.A., 2005). The evaluation of ES such as reducing greenhouse gas emissions through carbon uptake, managing and improving water flow and quality, restoring soil ecosystems, and supplying raw materials for bioenergy generation is essential for a comprehensive analysis of green remediation options (GRO) like phytoremediation.

The application of industrial ecology tools such as Life Cycle Assessment (LCA) can help account for the environmental impacts of production processes on ecosystems (Larrey-Lassalle et al., 2022). This provides a quantitative basis for defining the benefits and costs of GRO throughout the lifetime of a remediation project, as well as illustrating different scenarios under changing climate conditions (Chan and Satterfield, 2020; Roman et al., 2021). LCA is an ISO standardized method that quantifies the environmental impacts of human activities with a systematic approach, from raw materials and resource extraction and processing, to production, use phase and end-of-life (ISO14044:2006). Research on LCA has shown that the sustainable handling of contaminated sites can lead to positive environmental and socioeconomic outcomes (Khan et al., 2023; Kuykendall and McMullan, 2014; O'Connor et al., 2019; Vigil et al., 2015).

Many recent studies have highlighted the importance of integrating LCA and ES accounting frameworks to comprehensively address environmental costs and benefits, as well as quantify direct and indirect interactions between human activities and the environment (Alshehri et al., 2023; Babí Almenar et al., 2023; Lee and Bakshi, 2023; Rugani et al., 2019). However, the integration of these two academic fields is still facing several methodological challenges, and efforts are being made to address these gaps in different ways. Some researchers emphasize that LCA could enhance the evaluation of ES supply changes by considering the ecosystem transformations caused by inventory flows (Blanco et al., 2018; Bruel et al., 2016). They acknowledge that this approach is complex, as it requires precise expression of relationships between different elements and may be data-intensive to develop

models for multiple ES simultaneously (Bruel et al., 2016). Additionally, information on some ES may be either unavailable or qualitative in nature (Blanco et al., 2018). Another common observation is that LCA and ES operate at different temporal and spatial scales, with LCA assuming homogeneity over time and space, while ES are dynamically variable and location-specific (Othoniel et al., 2016; Rugani et al., 2019). This issue is deeply linked with the assessment of process chains' impacts on biodiversity, where the advances in ES accounting still face challenges in the integration with LCA. For instance, the consistency of using methods operating across different scales and boundaries or the heterogeneity of data still hinder the integration of LCA metrics into decision-making processes (Crenna et al., 2020). Furthermore, LCA has traditionally focused on the negative impacts of product flows on ES, neglecting potential benefits in some cases (Hardaker et al., 2022). Recent studies suggest developing impact categories already included in LCA, such as land use and land occupation, to better address the dynamic and spatial explicit interaction of ES with anthropogenic drivers (VanderWilde and Newell, 2021).

Starting from these considerations about LCA and ES integration, and recognizing the importance of a holistic approach in the evaluation of GRO, this review aims to examine how these challenges have been addressed in the assessment of the impacts and benefits generated by phytoremediation projects. The review seeks to answer the following questions:

- 1) How and to what extent is LCA integrated into the environmental sustainability analysis of phytoremediation of brownfields?
- 2) How are the concepts of ES systematically incorporated into the LCA of phytoremediation?
- 3) Is post-remediation management included in the assessment?

## 2. Methodology

A systematic review of the literature on LCA and ES accounting was conducted with a focus on phytoremediation projects. Because the assessment of ES encompasses both non-monetary and monetary sources of value, not only the cases where an economic valuation of ES is carried out (as in Alshehri et al., 2023) were considered. Many studies did not involve any monetary calculations related to ES, even though these values were still accounted for in the flows. For example, the inclusion of biomass valorization in the system could be viewed as a provisioning ES provided by phytoremediation interventions.

The literature collection took place in May 2024 using the Scopus platform. The search string combined the concepts of brownfields and bioenergy with phytoremediation and LCA, excluding any references to wastewater since the primary focus was on remediating brownfield land only. The search string used was as follows:

( TITLE-ABS-KEY ( "brownfield\*" OR "wasteland" OR "marginal land" OR "polluted land" OR "abandoned land" OR "vacant lot\*" OR "informal green space\*" OR "liminal space\*") OR ( TITLE-ABS-KEY ( "biomass" OR "biofuel\*" OR "bio-fuel\*" OR "bioenergy" OR "bio-energy" OR "biochemical\*" OR "bio-chemical\*" OR "biorefiner\*") ) AND ( TITLE-ABS-KEY ( "phytomanage\*" OR "phyto-manage\*" OR "phytoremediat\*" OR "phyto-remediat\*" OR "phytoextr\*" OR "phyto-extr\*" OR "phytostabil\*" OR "phyto-stabil\*" OR "phytodegrad\*" OR "phyto-degrad\*" OR "bio-remediat\*" OR "bio-remediat\*" OR "bio-remediat\*" OR "nature-based" OR "naturebased") ) AND ( TITLE-ABS-KEY ( "life cycle a\*" OR "lifecycle a\*" OR "life-cycle a\*" OR "LCA" OR "footprint") ) AND NOT ( TITLE ( "wastewater" OR "sludge") OR KEY ( "wastewater" OR "sludge") ) )

193 results were obtained for further screening. This literature body was first reduced to 168 by excluding all the documents that were not either Research or Review Articles. Then, after their thorough abstract reading, 13 articles were selected for an in-depth analysis. Articles referring to agriculture land or to water purification systems and floating islands were not included because they were considered out of scope. Out of two articles on the same case study (Vocciante et al., 2019, 2021), we considered only the former but still compared them because

they applied a different functional unit in the assessment. The time frame of the articles was from 2010 to 2024.

As observed by Hou and O'Connor (2020), the impacts of brownfields remediation projects go beyond the site's spatial and temporal boundaries. According to this rationale, brownfields remediation impacts can be categorized as primary (impacts caused by toxic substances in environmental media at a brownfield site), secondary (impacts caused by the remediation process itself), and tertiary (consequential impacts of the final land use) (Hou et al., 2023). In this case, the conceptual approach outlined by Lesage et al. (2007) was used in the impact assessment section to decide whether the primary impacts of remediation had been considered in the assessment. According to this framework, the primary impacts are mostly site-specific and are defined by both site contamination (where normally the effects of remediation are accounted for as negative impacts in the soil), and physical attributes that are typically represented by land use and land use changes.

The critical review of the selected literature was conducted using the approach proposed by Larrey-Lassalle et al. (2022). This approach involves analysing different parameters across the four phases of LCA (ISO standard 14040:2006) in each reviewed study (Table 1): "Phase 1—goal and scope definition, Phase 2—inventory analysis or life cycle inventory (LCI), Phase 3—impact assessment or life cycle impact assessment (LCIA), and Phase 4—interpretation of the results". This method allowed us to systematically examine the contents of the 13 studies based on specific issues and questions.

### 2.1. Analysis of LCA phase 1—goal and scope

This step is the starting point of every LCA and is crucial for all other phases. Here, practitioners describe, among other aspects, the aim and target of the analysis, the system considered, and its life cycle stages. Other aspects of this first part include the system boundaries, the time frame, and the Functional Unit (FU), which is the quantified performance of a system to which all flows are scaled (Arvidsson and Ciroth, 2021; European Commission, JRC-IES, 2010). The analysis of the scope definition includes (i) the functions and functional unit(s) considered,

**Table 1**  
Key issues and questions investigated within each reviewed study.

Phase 1: Goal and Scope definition			
Functions and functional unit(s) considered	System boundaries considered (life cycle stages)	Remediation options, plant species and period of analysis	Geographic location, site size, depth of contamination
Phase 2: Life Cycle Inventory			
Is CO <sub>2</sub> sequestration considered? (value)	Is it explicitly stated that the mass balance is respected for the carbon? Biomass yield?	Are emissions in the environment considered after application of mineral/organic fertilizers or pesticides?	Is the model/source mentioned, or details on calculations given? Irrigation? Remediation yield?
Phase 3: Life Cycle Impact Assessment			
Impact and damages categories considered and LCIA method(s) used	Climate change impact (value) Cumulative Energy Demand Land use changes	Normalization of the results (Yes/No) Weighting of the results (Yes/No)	ES accounted for (explicitly and implicitly) Primary impacts
Phase 4: Interpretation			
Contribution analysis Main contributors	Comparison with other remediation techniques	Sensitivity or uncertainty analysis	Climate change considerations

(ii) the system boundaries considered (life cycle stages), (iii) the remediation options, plant species and period of analysis, (iv) the geographic location, site size, and depth of contamination. For the specific case of phytoremediation, special attention was paid to the different surface and depth of interventions and possible end of life options (when included).

### 2.2. Analysis of LCA phase 2—life cycle inventory (LCI)

This phase involves data collection and calculation to quantify all the flows between the studied system and the environment, including resource inputs (e.g., raw materials, energy, freshwater, land occupation) and substance outputs (e.g., chemical emission) to air, water, and soil compartments. It is the core of the analysis, and the impact assessment phase depends on its results (European Commission, JRC-IES, 2010). In this work, the analysis of the LCI phase focused on specific features associated with phytoremediation, such as CO<sub>2</sub> sequestration, carbon balance, emissions in the environment due to fertilizers or pesticides, irrigation, and quantification of the remediation performances of different plants investigated in the literature.

### 2.3. Analysis of LCA phase 3—life cycle impact assessment (LCIA)

The LCIA phase assesses the impacts potentially caused by the extraction of natural resources and the use of land, as well as by the release of pollutants and waste, which are inventoried as elementary flows. In LCIA, those aggregated elementary flows in LCI are multiplied by a characterization factor (CF), which aids quantifying how much the resulting LCI can contribute to a given impact category. Two main types of impact categories can be selected (1) midpoint impact categories, which are intermediate measures of environmental impact reflecting changes in the natural environment due to human activities, and (2) endpoint or damage impact categories, which typically evaluate final impacts on human health, ecosystem quality, and resources. LCA practitioners can choose among many assessment models to characterize inventory flows and evaluate potential impacts (e.g., CML2001, TRACI, ReCiPe, IMPACT World+, LC-IMPACT (EU) and so on; Hauschild et al., 2018). Additionally, the LCIA phase allows for normalization and/or weighting of impact results (ISO 14044:2006). This paper covers the analysis of the LCIA phase including: (i) Consideration of impact and damage categories and the LCIA method(s) used, (ii) Climate change impact (value), (iii) Cumulative Energy Demand (CED), (iv) Expression of land use changes, (v) Normalization and/or weighting of the results, (vi) Eventual ES accounted for and (vii) Description of primary impacts of remediation.

### 2.4. Analysis of LCA phase 4—interpretation

The interpretation is the final phase of an LCA where results are considered together and analysed highlighting the uncertainties of the applied data and the assumptions that have been made and documented throughout the study (European Commission, JRC-IES, 2010). Therefore, we focused on (i) the results of the contribution analysis, which highlights possible hotspots of the impacts, (ii) the presence of a sensitivity or uncertainty analysis, (iii) climate change related considerations and (iv) the results in comparison with other remediation techniques.

## 3. Results

### 3.1. Phase 1: goal and scope definition

Some initial observations can be made by comparing the characteristics of the case studies (Table 2). For instance, the surface area considered in the studies varies significantly, ranging from hundreds of square meters to hectares. In terms of the depth of intervention in the soil, most of the studies clearly define this aspect. Otherwise, the Functional Unit (FU) is expressed in volume of soil, highlighting the

**Table 2**  
Analysis of LCA phase 1 of the selected literature.

CASE STUDY CHARACTERISTICS			PHASE 1: Goal and Scope			
Author	Pollutant(s)	Field area (m <sup>2</sup> )	Function - Functional Unit	System Boundaries*	Remediation options	Timeframe
Suer & Andersson-Sköld, 2011	Mineral oil: organic aliphatic compounds, with locally some aromatic compounds and BTEX.	5000	One site (5000 m <sup>2</sup> )	Cradle to gate	No action Biofuel (phytoremediation) Excavation and refill	20 years 40 days
Witters et al., 2012; Witters, Mendelsohn, Van Slycken, et al., 2012	Cd (Zn and Pb under regulations limit)	N.A.	1 ha of land that can be safely used	Cultivation and disposal (cradle to grave)	Three different energy crops with phytoremediation traits	1 year of CO <sub>2</sub> abatement
Vigil et al., 2015	Pb	10,000 (assumed)	1 ha of decontaminated land	Cradle to grave	No action Excavation and refill Phytoremediation	N.A. 40 days 32 years
O'Connor, Zheng, et al., 2019	Tetrachloroethylene (PCE) groundwater contamination,	9000	9000 m <sup>3</sup> volume of a PCE-contaminated aquifer	Cradle to grave	Phytoremediation	100 years
Vocciant e et al., 2019	mix, mainly As and Pb	712	1 m <sup>2</sup> of contaminated site	Cradle to grave	Phytoremediation	2 years GWP: 100 years
Vocciant e et al., 2021	mix, mainly As and Pb	712	1 m <sup>3</sup> of contaminated site	Cradle to grave	Phytoremediation	2 years GWP: 100 years
Lin et al., 2022	Tannery wastewater containing Cr, Cu, and Ni	960	24 days of excavation and refill (one time operation), vs 1 year of phytoremediation	Cradle to gate (no disposal). Cradle to grave (incineration)	In situ excavation and refill Phytoremediation	24 days (one time) 1 year
	Zn, Cr, Cu, and Ni	5678	49 days of excavation and refill (one time operation), vs 1 year of phytoremediation	Cradle to gate (no disposal) Cradle to grave (incineration)	In situ excavation and refill Phytoremediation	49 days (one time) 1 year
Espada et al., 2022	Pb	10,000	Decontamination of 1 ha of the considered soil (depth of 20 cm) up to the maximum Pb concentration allowed by the government regulations.	Cultivation and harvesting, conditioning and transport and use of the grown biomass	Phytoremediation  Soil washing Excavation and landfill deposition	31 years
Lynch & Satrio, 2022	Pb	10,000	8.15 tons (on dry basis) of switchgrass average amount yearly in one ha)	Cradle to grave	Phytoremediation	3.5 years
Todde et al., 2022	Pb, Zn, Cd	10,000	1 kg of dry matter industrial hemp product AND 1 ha of phytoremediated area	Cradle to grave	Phytoremediation	GWP: 100 years
Soleimani et al., 2023	Chloride (marine dredged sediment)	N.A.	1 m <sup>3</sup> sediment phytoremediation	Cradle to gate	Phytoremediation  Sediment landfill	Not achievable in less than 357 years. N.A.
Alshehri et al., 2023	Heavy metals, polyaromatic hydrocarbons, chlorinated solvents, ammonia	2,000,000	Treatment of 1 m <sup>3</sup> of polluted soil as per applicable standards	Cradle to grave	No action "London Olympic Park" (combination of remediation technologies) Phytoremediation	30 years 3 years 12 years
Espada et al., 2024	Cu, 627 ppm (77 ppm to be removed)	10,000	Decontamination of 1 hm <sup>2</sup> of the considered soil (20 cm depth) up to the maximum Cu concentration allowed by government regulations	Cradle to grave	Phytoremediation (3 solutions) Soil washing Soil excavation	7–22 years (depends on the crop)

\* The system boundaries define which parts of the life cycle and which processes belong to the analysed system, i.e. are required for providing its function as defined by its functional unit. They also define across which boundary the exchange of elementary flows with nature takes place (European Commission, JRC-IES, 2010). The scope can include the entire life cycle or be limited to part thereof, defining the following boundaries: Cradle-to-grave (full life cycle from raw materials extraction

through production, use, end-of-life treatment, recycling and final disposal), Cradle-to-gate (from raw resource extraction up to an in-between point of the life cycle), Gate-to-gate (considering only a limited section of the life cycle), specific parts of the life cycle (e.g., waste management, components of a product) (ISO14044:2006).

importance of understanding the depth of contamination for successful phytoremediation (Alshehri et al., 2023; Vocciante et al., 2021). Additionally, the contaminants studied are of different nature, including heavy metals, hydrocarbons, and chlorinated compounds. It is interesting to observe how different functional units (FUs) shift the focus of the analysis towards various goals of remediation, such as improving soil quality or achieving an acceptable level of pollutants for future land use. Specifically, the multifunctionality of remediation can be expressed through different FUs (as in Todde et al., 2022, “1 kg of dry matter industrial hemp product and 1 ha of phytoremediated area”) or with a comprehensive FU, as suggested in Espada et al. (2022). Here they indicate not only the area or volume of soil to be decontaminated, but also the threshold to be reached as “Decontamination of 1 ha of the considered soil (depth of 20 cm) up to the maximum Pb concentration allowed by the government”. Another clear example can be seen in the comparison between the work of Vocciante et al. in 2019 and 2021. While the case study remains consistent in both articles, the focus shifts; the former article emphasizes biomass disposal for phytoremediation, while the latter compares different remediation options. In 2019, the FU was “1 m<sup>2</sup> of contaminated site” whereas in 2021, it changed to “1 m<sup>3</sup> of contaminated site”, transitioning from a surface to a volume. This changes the results for example in the impacts related to the possible disposal options, where fast pyrolysis always provides better results than incineration. However, when considering a volume of soil, the gap is negligible. In contrast, when the FU is a surface, the results are considerably different.

The system boundaries considered in these studies are mostly cradle-to-grave (91.7 %), emphasizing the impacts of the interventions and the importance of biomass valorization through the right disposal. In the case of Suer and Andersson-Sköld (2011), the analysis stops at the gate once remediation has resulted in clean soil. Soleimani et al. (2023) define cradle-to-gate boundaries, but their model also incorporates end-of-life processes for biomass treatment, indicating that the boundaries may actually be cradle-to-grave.

Seven out of twelve studies compare phytoremediation with different remediation technologies or with “no action” scenarios.

### 3.2. Phase 2: life cycle inventory

In this phase we observe that a carbon mass calculation is never clearly expressed. Only Vocciante et al. (2019) mention that for biomass valorization a literature reference has been used for the elemental composition of the biomass, and that the incineration of biomass follows the stoichiometric combustion. In nine out of twelve studies, the biomass yield is reported after calculations (Soleimani et al., 2023), derived from lab experiments/pilot plants/field data (Lin et al., 2022; Lynch & Satrio, 2022; Todde et al., 2022; Vigil et al., 2015; Witters, Mendelsohn, Van Passel, et al., 2012; Witters, Mendelsohn, Van Slycken, et al., 2012) or from literature/reference tables (Alshehri et al., 2023; Espada et al., 2022, 2024; Witters, Mendelsohn, Van Passel, et al., 2012; Witters, Mendelsohn, Van Slycken, et al., 2012). Fertilizers are consistently included as input flows, whereas in only in one study herbicides and pesticides are considered as well as mobilizing agents. The necessity of using fertilizers likely arises because contaminated sites not only contain phyto-toxic concentrations of pollutants, but are also commonly characterized by unfavorable soil properties such as nutrient deficiency, poor soil structure, low organic matter (OM), etc. (Kidd et al., 2015). Eight out of twelve studies describe the contaminant extraction yield or the contaminant decay rate (O'Connor, Zheng, et al., 2019; Vigil et al., 2015). They also discuss the Bioconcentration Factor (BCF) (Espada et al., 2022, 2024; Soleimani et al., 2023) and provide experimental results on the plants' remediation traits (Lin et al., 2022; Vocciante et al., 2019; Witters, Mendelsohn, Van Passel, et al., 2012; Witters,

Mendelsohn, Van Slycken, et al., 2012). In three other studies the contaminant extraction yield is not explicitly stated, but the time required for phytoremediation is expressed in the needed years of intervention (Alshehri et al., 2023; Lynch & Satrio, 2022; Suer & Andersson-Sköld, 2011). Only one study focuses on biomass yield for energy, referring to one harvest cycle without specifying how many cycles are needed for complete remediation (Soleimani et al., 2023). As shown in Table 2, 50 % of the studies compare phytoremediation with other remediation techniques, often using different time frames for the selected solutions. When evaluating phytoremediation alone, researchers typically assess the most sustainable method of biomass disposal (Lynch & Satrio, 2022; Todde et al., 2022; Vocciante et al., 2019). Only three studies mention a numerical value of CO<sub>2</sub> sequestration by plants, which attains to 1.75 Mg ha<sup>-1</sup> y<sup>-1</sup> for *Festuca arundinacea* (Espada et al., 2022) 14,214 Mg ha<sup>-1</sup> y<sup>-1</sup> for energy maize, 4460 Mg ha<sup>-1</sup> y<sup>-1</sup> for commercial willow (*Salix* spp.) in short rotation coppice, 12,902 Mg ha<sup>-1</sup> y<sup>-1</sup> for breeding clone willow in short rotation coppice, 3165 Mg ha<sup>-1</sup> y<sup>-1</sup> for rapeseed (Witters, Mendelsohn, Van Passel, et al., 2012; Witters, Mendelsohn, Van Slycken, et al., 2012) and 2.78 Mg ha<sup>-1</sup> y<sup>-1</sup> for *Brassica juncea*, 5.42 Mg ha<sup>-1</sup> y<sup>-1</sup> for *Medicago sativa*, 4.89 Mg ha<sup>-1</sup> y<sup>-1</sup> in rotary cultivation (Espada et al., 2024).

### 3.3. Phase 3: life cycle impacts assessment (LCIA)

Fig. 1 summaries how the reviewed studies make use of the impact categories. Those categories are divided into “Endpoint” and “Midpoint” impacts (see Section 2.3), resulting in a general tendency towards midpoint indicators. This could depend on the fact that midpoint indicators are chosen early in the environmental mechanism, giving a more measurable and certain result compared with endpoint ones. These latter are downstream in the environmental mechanism, giving more relevant but hardly verifiable information. The ReCiPe LCIA method is adopted in most cases (41,7 %), as it is often preferred for studies conducted in Europe. Regarding the analysed impacts, only climate change (as endpoint impact or as Global Warming Potential, GWP, midpoint impact) is consistently considered. It is important to note that relying solely on GWP may not provide a comprehensive evaluation of the overall sustainability of an intervention, as results may vary when using multiple indicators frameworks. Moreover, meaningful potential trade-offs might be hindered when focusing the LCIA on a single issue impact indicator only. For example, the studies by Vigil et al. (2015) and Todde et al. (2022) both examine different biomass disposal options but focus on different impact categories, leading to different conclusions. Vigil et al. (2015) consider urban land occupation, agricultural land occupation, natural land transformation, particulate matter formation, fossil depletion, and climate change as main impact categories. On the other hand, Todde et al. (2022) focus only on GWP and Cumulative Energy Demand (CED). Since the use of fossil fuels for energy is an important driver of climate change, it has been shown (Huijbregts et al., 2006) that GWP and CED are strongly correlated, and therefore draw similar conclusions. Hence, in Todde et al. (2022) the main contributors to the final impacts are activities that consume the most diesel, such as harvesting and plowing, while fertilization, for example, has a minor impact. In contrast, the impacts considered by Vigil et al. (2015) have a broader vision and land-use categories are major contributors to the results of phytoremediation scenarios, along with intensive agricultural practices, application of mineral fertilizers and harvesting operations.

Another midpoint category that is linked with the possible disposal and valorization of the biomass is the Cumulative Energy Demand (CED). The CED quantifies both direct and indirect energy consumption in MJ over the entire life cycle, encompassing energy used in the extraction, production, and disposal of raw and auxiliary materials (Frischknecht et al., 1998). In only one third of the studies the CED

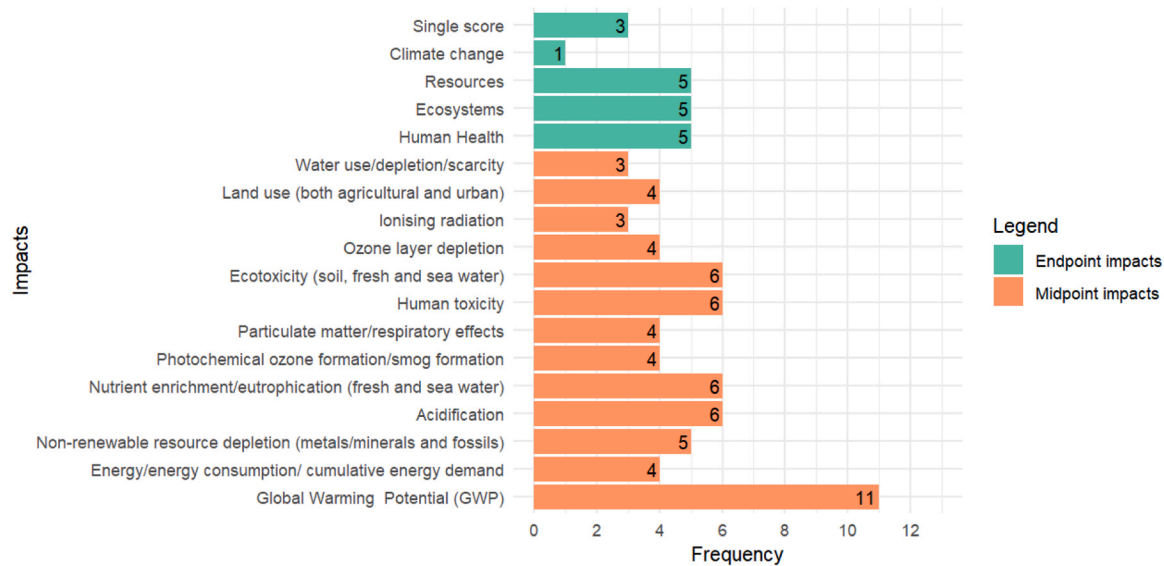


Fig. 1. Frequency of impact categories assessed in the studies. Since two of the selected studies, namely [Vocciante et al. \(2019\)](#) and [Vocciante et al. \(2021\)](#), refer to the same dataset, it has been decided to consider only the former (giving a total of 12 studies) to avoid double counting in the results.

([Espada et al. 2022](#), [Lynch and Satrio, 2022](#), [Todde et al., 2022](#)) or the energy consumption ([Suer & Andersson-Sköld, 2011](#)) are expressed. All these studies assess the valorization of biomass from contaminated land. It is therefore a crucial point to express the appraisal of both energy production and consumption of the process.

The evaluation of ES has been systematically considered only by [Alshehri et al. \(2023\)](#). They adapt the cascade ES-LCA framework proposed by [Rugani et al. \(2019\)](#) for a case study on remediation, expanding it with an additional goal and scope step. The goal is to capture the tertiary impacts of remediation (post-remediation development) of conventional and nature-based remediation options. Nevertheless, we considered in the analysis also the ES implicitly accounted for, with the requirement of being quantitatively expressed in the flows:

- Provisioning: biomass derived from phytoremediation is used as bioenergy source (e.g. conversion of produced biomass into energy reduces the need for natural gas and avoids the related impacts)
- Regulating: remediation effects of phytoremediation on soil quality and mediation of water flows (e.g., in the calculation for irrigation needs)

Results are plotted in [Fig. 2](#), based on the classification of phytoremediation’s environmental and social benefits by [Guidi Nissim and Labrecque \(2021\)](#), grouping them into corresponding ES flows following the CICES classification. ES directly related to phytoremediation (e.g. mediation of waste and toxics or energy provision) are highly reported, whereas other important ES provided by phytoremediation (e.g., mediation of flows such as urban hydrology) are underrepresented. Cultural ES (yellow) are instead completely absent from the assessments. This is likely due to the challenge of quantifying such ES, as noted by [Hirons et al. \(2016\)](#) [Kosanic and Petzold \(2020\)](#), [Langemeyer et al. \(2023\)](#) among others. Another significant omission concerns biodiversity, which is not an ES itself, but its conservation is essential for ES delivery ([Mace et al., 2012](#)).

In addition to soil remediation, which is commonly described, carbon sequestration and biomass for bioenergy are mentioned in almost every study, even if they are not explicitly defined as ES. All case studies suggest reinvesting biomass into the energy production as a way to mitigate the environmental impacts of phytoremediation and promote these remediation options over traditional techniques. For instance, in [Vocciante et al. \(2019\)](#) the use of biomass combustion for electricity generation results in the reduction of the overall impacts by about 45 %,

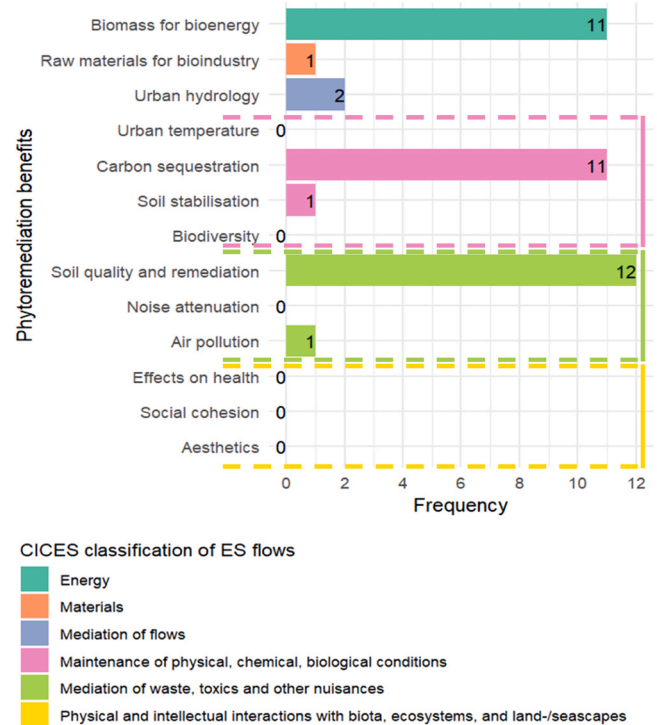


Fig. 2. Ecosystem Services accounted for in the reviewed studies; indicators retrieved from the list of phytoremediation’s benefits of [Guidi Nissim and Labrecque \(2021\)](#), grouped following the CICES classification of ES flows. Since two of the selected studies, namely [Vocciante et al. \(2019\)](#) and [Vocciante et al. \(2021\)](#), refer to the same dataset, it has been decided to consider only the former (giving a total of 12 studies) to avoid double counting in the results.

with the share of the disposal phase decreasing from 25 % to 16 % of the total contributions, making this Nature-based Solution (NbS) almost carbon neutral. This can be further improved by employing fast pyrolysis.

Another discriminating aspect is related to the use of water, which is described only in 50 % of the studies and not always quantitatively. Additionally, water depletion is only included as an indicator in three

out of twelve studies. Soleimani et al. (2023) consider water depletion and highlighted the positive performance of *Arundo donax* in terms of water requirements, but without providing a clear numerical expression of the ES. On the other hand, the water requirements are often expressed in volume/year (O'Connor et al., 2019; Vocciante et al., 2019) and in some cases, irrigation practices vary based on average rainfall values for the specific area (Espada et al., 2022, 2024; Todde et al., 2022). Finally, only two studies explicitly try to express the primary, secondary and tertiary impacts of remediation. O'Connor et al. (2019) use a model to quantify the primary impacts and then categorize the remediation activities as secondary impacts. On the other hand, Alshehri et al. (2023) evaluate the tertiary impacts of remediation in addition to the primary and secondary impacts by expanding the LCA-ES framework with an additional 5th "Valuation" step. They also consider the Urban Land Occupation to assess the efficiency of remediation options, monetizing it in step five as the cost of the land being out of use during remediation. Additionally, a "Truncation error estimate" is used to describe the proportion of impact not covered by the system boundaries of the LCA (as defined by Ward et al., 2018), demonstrating the percentage of overlooked impacts of traditional LCA compared to the ES-LCA outcomes.

### 3.4. Phase 4: interpretation

Given the high variety of contaminants, plants used, impacts methodologies, etc., it is not possible to identify any clear trends in the interpretation of the impacts. However, some interesting aspects can be observed. Conditioning of the biomass such as anaerobic digestion, is often one of the most impactful operations (Alshehri et al., 2023; Espada et al., 2022). As mentioned earlier, land use and land use change account for a significant portion of the final impacts when assessed (Suer and Andersson-Sköld, 2011; Vigil et al., 2015). In Vocciante et al. (2019), the site preparation requires asphalt removal, and this is the most impactful operation. This finding is crucial when considering the implementation of phytoremediation on sites with a high percentage of artificial land cover. Other significant hotspots include biomass harvest phases and fossil fuel combustion for various operations (e.g., personnel transportation, biomass transportation and disposal). A sensitivity or uncertainty analysis is conducted in 70 % of cases. In these cases, different biomass yields are tested (Vigil et al., 2015; Witters, Mendelsohn, Van Passel, et al., 2012; Witters, Mendelsohn, Van Slycken, et al., 2012), different scenarios are evaluated (Suer and Andersson-Sköld, 2011; Todde et al., 2022) or the data sets uncertainty is analysed. Including possible changes in the biomass yield is important in terms of climate uncertainties, which is crucial to assess in case of long-term remediation activities (Jaskulak et al., 2020; Soleimani et al., 2023). Otherwise, O'Connor et al. (2019) consider climate change by assessing the phytoremediation yield under various sea-level rise scenarios as well as the effects of changing hydroclimatic conditions, while Soleimani et al. (2023) consider different plant survival rates.

When phytoremediation is compared with other remediation techniques, results unanimously find it as the least impactful option, despite the longer operational times, and especially if combined with biomass valorization (Vigil et al., 2015; Todde et al., 2022; Lin et al., 2022; Soleimani et al., 2023; Alshehri et al. 2023). However, Suer and Andersson-Sköld (2011) point out that the main impact contributors of the traditional techniques and the ones for phytoremediation are linked to different environmental issues, and do not occur at the same geographical scale. Moreover, they suggest further developing the assessment of land use issues.

Finally, it is worth mentioning the work of Braun et al. (2024), which is not a standard LCA, but rather a sustainability assessment that develops a tool for selecting the best remediation technique. In this study, phytoremediation is compared with electrokinetics and excavation/disposal using a holistic approach to determine the most sustainable technique. The phytoremediation data in this study are derived from a previous work by da S Trentin et al., 2019, where a framework for

the "Quantitative Assessment of Life Cycle Sustainability" was proposed. The approach by Braun et al. (2024) stays in the holistic view of sustainability and in the high differentiated impact categories considered. They aim to address all three pillars of sustainability (i.e., environmental, social, economic), create a list of 63 impact components divided into 20 impact factors, and assign each a weighting value. Furthermore, an impact matrix is developed to evaluate each component, whether it has a negative or positive impact. The method by Braun et al. (2024) introduces uncertainties, such as in the selection of weighting factors, and should be validated with more case studies beyond those selected by the authors. However, it provides valuable insights creating sustainability indicators even for ES categories that are challenging to quantify (e.g., cultural). Moreover, many impact categories considered can be related to ES and their benefits (e.g., those with a positive impact in the matrix), such as "Protection of fauna-flora-natural habitats-landscape", "Public health and community safety", "Protection of groundwater" or "Cultural and tourist promotion". The results of this evaluation always describe phytoremediation as the most sustainable solution.

## 4. Discussion

This review confirms that LCA is a valuable tool for assessing the sustainability of phytoremediation in urban brownfields. It is a method that can be applied to sites of various sizes, pollutants and plant species involved, providing a reliable description of the hotspots in the intervention. These hotspots are the most impactful systems in the life cycle, where it would be most meaningful to consider different alternatives. Additionally, the case studies reviewed suggest that reinvesting biomass into energy production can help to balance the environmental impacts of phytoremediation. This finding supports the use of phytoremediation over traditional techniques. When planning for sustainable GRO, it is crucial to consider the transportation of harvested biomass, determining the maximum sustainable distances from the disposal facility (Vigil et al., 2022). Moreover, the designated disposal of contaminated biomass could intensely change the results. This is because, as observed by Vigil et al. (2015), there would be a significant difference in the impacts if the metal concentrations in plants are low enough to be accepted in an inert landfill or, on the contrary, if different legislation or a higher concentration would impose a treatment in a hazardous material landfill (as shown by Suer and Andersson-Sköld, 2011). For instance, for phytoextraction it could be interesting to evaluate whether replacing hyperaccumulator plants with fast-growth woody plants could lead to a better balance between remediation yield and ease of disposal.

Focusing on the disposal phases of the biomass is also important due to the issue of contaminated biomass, which requires dedicated management. In this regard, the main advantages of collecting biomass from phytoremediation systems include not competing with food crops for land, providing sustainable energy from marginal land, while cleaning up polluted soils (Grifoni et al., 2021; Khan et al., 2023). The potential use of this biomass as feedstock in the bioenergy market should be carefully evaluated, for example by applying consequential LCA (C-LCA) approaches that may "[...] provide information on the environmental burdens that occur, directly or indirectly, as a consequence of a decision, generally represented by changes in demand" (UNEP, 2011). This type of environmental assessment analyses how physical flows and related environmental burdens depend on socio-economic mechanisms through market information and economic models. C-LCA has already been utilized in studies within the bioenergy sector (Krogh et al., 2024; Marvuglia et al., 2013; Vázquez-Rowe et al., 2014). Conducting a C-LCA would enhance the sustainability analysis of phytoremediation by incorporating a more holistic socio-economic approach.

Even though the LCA is a standardized procedure, many aspects of the analysis depend on practitioners' choices, such as the goal and scope definition or the selection of impact assessment methods. This implicates a great variability in the analysis outcomes. However, some impacts could be included in the analysis more systematically. For

example, the “Land use” impact category is only mentioned in one third of the studies (Alshehri et al., 2023; Soleimani et al., 2023; Suer and Andersson-Sköld, 2011; Vigil et al., 2015). When land use and land use change are considered, those are among the major contributions of the impact score from a positive perspective. As pointed out by Lesage et al. (2007), changes in land use can provide relevant benefits when considering tertiary effects of remediation. This was demonstrated in a case study where the avoided pressure on vacant urban sites, greenfields and arable land was considered as a result of the redevelopment of brownfields for urban housing. Larrey-Lassalle et al. (2022) also observed a similar trend in the LCA of Nature-based Solutions (NbS) in general, suggesting that a more systematic inclusion of land use categories is welcome due to their relevance for the assessment of the benefits associated with the ES supply. Accordingly, many ES are driven by land-use change (Metzger et al., 2006), making it important to evaluate the impacts caused by long remediation processes on land availability for communities and ecosystems (Beames et al., 2015). Interestingly, Wu defines “Landscape sustainability science” as a “place-based, use-inspired science of understanding and improving the dynamic relationship between ecosystem services and human well-being in changing landscapes under uncertainties arising from internal feedbacks and external disturbances” (Wu, 2013).

This review also highlights the complete absence of any biodiversity impacts and/or benefits considerations in the reviewed studies. As pointed out by Damiani et al. (2023), the impacts of production and organization on biodiversity are only partially included in LCA (usually as the potential disappearance fraction of species due to land use), and there is a need for the development of robust and complete indicators. A more precise expression of biodiversity in LCA would allow for the accounting of benefits of interventions, such as the enhancement of ES provision, for example, the creation of habitat and shelter which would increase the supply of ES (Burgess et al., 2016; Garbisu et al., 2020). Biodiversity plays a crucial role in urban ecosystems, where conservation strategies are expanding to focus on both the quality and quantity of urban nature (Kowarik et al., 2020). Many studies emphasize the importance of healthy biodiverse green spaces in providing regulating, provisioning and cultural ES in cities (Haase et al., 2014; Schwarz et al., 2017), as well as promoting physical and mental health (Bratman et al., 2012; Hartig and Kahn, 2016). In the case of phytoremediation, the widespread lack of an LCIA on biodiversity and of the consideration of benefits should be addressed, since the chosen solutions can differently affect the peculiar biodiversity that exist in such extreme environments (Garbisu et al., 2020). Protecting and enhancing this biodiversity across diverse trophic levels can indeed improve the efficacy and resilience of the deployed plants (Burgess et al., 2016). Furthermore, monitoring of trade-offs and synergies between biodiversity and ES shall be part of a phytomanagement strategy (Garbisu et al., 2020), starting from the definition of the intervention’s beneficiaries (Maia de Souza et al., 2018). Good examples on how to address this issue can be found in LCA studies on agricultural practices, where spatial explicit, predictive information about the impacts on biodiversity and ES have been integrated to inform strategic planning and decisional processes (Chaplin-Kramer et al., 2017). Other studies in this field have proposed the use of spatial-explicit tools to quantify ES and calculate specific characterization factors (Lago-Oliveira et al., 2025) or used remote sensing technology to detect changes at local scale at different time and spatial resolution (Geyer et al., 2010; Rugani and Rocchini, 2017; Kaita and Harun, 2023).

Regarding the impact on water resources, less than one third of the reviewed studies evaluate some indicators of scarcity assessment. This could be a gap to address when evaluating the benefits and drawbacks of phytoremediation. Water use for irrigation is crucial for growing plants used for remediation. However, their selection must consider local climatic conditions and biogeographical characteristics, with long-term planning under the current changing rainfall predictions. Possible sustainable solutions include urban wastewater for irrigation (best if the

treatment plant is close to the phytoremediation site) or the selection of species resistant to water stress, extreme droughts or heat waves (Garbisu et al., 2020). Additionally, there is a generalized lack of modelling of climate change scenarios. This could be problematic for planning implementation phases, especially for techniques like phytoremediation that often require more than 10 years to be effective. Practitioners should consider that plant performances under current climate conditions may not be maintained in scenarios with increasing temperatures and drought. An applicative example stems from LCA for agricultural production, where Niero et al. (2015) implemented a LCA with scenarios based on a multi-factor simulation study. They started defining parameters to describe the impact of climate change on crops, and then recommended a multi-step method to develop a scenario analysis for future crop production. This modelling approach could also be applied to phytoremediation species. Previous studies have utilized a similar method to assess the yield of poplar cultivation under different CO<sub>2</sub> atmospheric concentrations (González-García et al. 2012). This could enhance the understanding of uncertainty in LCA scenarios for future climate conditions. Alternatively, system dynamics models can be used to evaluate the effectiveness of NbS under different climate change scenarios. Climate projections can be depicted as Representative Concentration Pathways (RCP, Gómez Martín et al., 2021), also combined with Global Climate Models (GCM, Marvin et al., 2023), which are dependent on varying levels of greenhouse gas emissions in the coming century (i.e., changes in radiative forcing). The changes would impact factors such as plant growth, precipitation and evapotranspiration, which can be integrated into the model to assess the future potential of the selected NbS (Gómez Martín et al., 2021; Marvin et al., 2023).

Given that the planning of phytoremediation should be viewed from a long-term perspective and may be influenced by the effects of climate change, it is important to incorporate such simulations into the LCA before implementation. This is particularly true if the goal of the study is to incorporate stakeholders’ feedback in a decision-making process to compare various remediation options.

As anticipated in previous studies, the inclusion of ES in the LCA framework is quite fragmented, and their evaluation is usually expressed ‘indirectly’ (i.e., impact on the capacity of ecosystems to supply services) and without explicit reference (Blanco et al., 2018; Bruel et al., 2016). This issue is reflected in the reviewed studies, while a systematic integration of ES accounting in LCA to describe the benefits of GRO could make those systems more competitive with traditional solutions. For example, O’Connor et al. (2019) discuss the importance of choosing phytoremediation due to benefits such as creating a pleasant microclimate, providing shade for pedestrians or even serving as a cultural habitat. However, they do not express them quantitatively, nor are the benefits balanced against the related environmental costs of the life cycle.

As described before, the incorporation of dynamic temporal and spatial scales of ES into LCA is still facing several challenges. A good solution to contain the efforts needed on data collection could be to limit the evaluation of the ES belonging to the foreground system only. The assessment of ES on an interregional level is indeed still complex (Maia de Souza et al., 2018, Xue and Bakshi, 2022, Taelman et al., 2024) and the databases are not yet as complete as the one of LCA for the background systems. In this regard, some interesting solutions have been studied, such as the framework based on telecoupling, an umbrella concept that considers socioeconomic and environmental interactions over distances (Koellner et al., 2019).

In this modelling integration effort, uncertainty analysis plays a pivotal role. The concept of uncertainty does not have a universally accepted definition, but it can be explained as everything unknown and that can be expressed with a specific probability or confidence degree. More specifically, the “unknown” encompasses random and systematic errors (arising from estimation, measurement, or data collection), mistakes, as well as epistemological (or epistemic) uncertainty—referring to the lack of scientific knowledge and resulting misinterpretations

(Hauschild et al., 2018). Alshehri et al. (2024) recently showed that a thorough uncertainty analysis is needed to enhance the reliability of the ES-LCA integrated assessment of NbS such as phytoremediation. Both ES assessment and LCA approaches are indeed affected by different sources of uncertainties, which for instance could arise from external parameters such as variable natural parameters (Alshehri et al., 2024). In the case of phytoremediation, more data from different field experiments are needed, since this technique is very much dependent on plants performance on different soils, with different pollutants and in different climatic conditions (Schwitzguébel, 2017, Fernández-Braña et al., 2023, Moreira et al., 2021). This empirical gap could also be solved with phytoremediation models, which could realistically assess the duration of phytoremediation under various scenarios, including soil amendments, agronomic practices, reactive transport, and the interactions among hydrological, biogeochemical, and ecological processes (Wang and Aghajani Delavar, 2024). This could help define a suitable time horizon for the LCA, and determine if a Dynamic-LCA (DLCA) approach should be preferred (Lueddeckens et al., 2020). DLCA is still an evolving field, and operational tools capable of calculating time-differentiated inventories and impacts need to be developed (Pigné et al., 2020).

As depicted in Fig. 2, the trend in the evaluation of ES in LCA of phytoremediation is currently prioritizing “Biomass for bioenergy” and “Carbon sequestration” along with “Soil quality and remediation”. For instance, biomass valorization is often seen solely as a source of energy. To enlarge the scope in a full circular economy framework, it would be important to assess the environmental performance of using biomass as a raw material for biorefineries, as demonstrated by Lynch and Satrio (2022). In this regard, the calculation of the CED can be a good way to analyse the energy consumption throughout the whole life cycle and to compare different scenarios of energy generation (as done by Todde et al., 2022). The CED, and especially the demand for fossil energy, has shown to correlate well with most midpoint impact categories of LCA (such as GWP or acidification potential), and could therefore be used as a proxy for these environmental impacts in case of data shortage (Huijbregts et al., 2006). Nevertheless, this is not the case for other categories such as land-use impacts that should be separately analyzed for a complete environmental performance assessment (Huijbregts et al., 2006). Moreover, Lynch and Satrio (2022) used this indicator to calculate the Energy Return On Investment (EROI), which is the ratio of the energy supplied by the process system to the non-renewable energy consumed directly and indirectly during the process (Cleveland, 1992). When dealing with energy-production systems, the EROI is an important environmental-feasibility index and helps to obtain a clear comparison among different solutions. However, there may be limitations when applying biomass from phytoremediation for pollutants extraction from soils. For example, the type and concentration of pollutants could influence the feasibility of using the resulting biomass as a raw material for biorefineries (Kick et al., 2024). As we could observe in the analysed studies, different pretreatment and disposal solutions can be compared via LCA (Todde et al., 2022, Lynch and Satrio, 2022) and the aim should be to find the most sustainable balance between operational costs (both environmental and economic) of the pre-treatments and the feasibility of either concentrating the pollutants into char and ashes, or to control the emissions of the most volatile ones into the air compartment (Jiang et al., 2015, Lee et al., 2018, Cozma et al., 2021). However, the valorization of biomass derived from phytoremediation still faces legal and policy obstacles. The scaling up of nature-based, sustainable soil remediation methods is indeed impeded by the absence of a harmonized legislation for soil protection at both supranational and national levels. Moreover, the recovery of biomass depends strictly on the waste legislation, which should classify these outflows as End-of-Waste or by-products (Fermeglia and Perišić, 2023b), once assured that “the re-use of the substance or product will be legal and not lead to further environmental and/or health impacts” (EU Waste Framework Directive, 2008). For this purpose, the distribution of the pollutants within the biorefinery products can be studied (Kick et al., 2024). Another step

forward to a wider deployment of phytoremediation, and to possible combinations of phytomanagement and traditional techniques could depend on a change in the legislation’s paradigm of remediation itself. The current trend is to abandon policies that involve removing pollutants to achieve the original reference state in favor of risk-based policies (Ramón & Lull, 2019). The latter involve remediating the bioavailable fraction of contaminants, considering only the acceptable residual risk. This would greatly reduce the time to reach threshold values, making GRO more competitive compared to conventional remediation techniques (Moreira et al., 2021).

Other benefits associated with GRO could be easily incorporated into the evaluation, effectively offsetting the impacts of the intervention. This is exemplified for instance by Babí Almenar et al. (2023) in a case study of an afforestation project in Madrid, where the “avoided run-off” indicator is balanced with “water depletion” and “filtration of air pollution by plants” with “particulate matter formation”.

It is clear that a phytoremediation stand does not have the same potential as an urban park to provide ES for human well-being. However, it can still offer some relevant ES that should be quantified more thoroughly. For instance, it would be significant to fill the gap of cultural ES related to urban phytoremediation; this could be done quantitatively in different ways, for example with non-monetary methods (combining participatory GIS, social media and questionnaires, interviews) or with monetary methods (such as the esthetic valuation that transformed areas can transfer to the house pricing of the neighborhood) (Romanazzi et al., 2023). For instance, many studies have proven the role of ornamental plants in phytoremediation, adding aesthetical value to the urban fabric while creating a multifunctional landscape (Khan et al., 2021, Kaushal et al., 2021, Rocha et al., 2022, Podhajska et al., 2023). Planning an effective design can help improve the acceptance of such solutions by the citizens along with their well-being (Keeler et al., 2019, Khan et al., 2021), creating a green space that can influence the prices of the surrounding properties (Chen et al., 2022). The improved estate value can thus be a way to quantify the cultural ES provided. In terms of urban hydrological regulation, most perennial woody species used for brownfield reclamation show an annual stormwater canopy interception rate comparable to most urban forest species (Kermavnar and Vilhar, 2017). The positive hydrological effects of fast-growing tree species used in phytoremediation, such as willows or poplars, can also reduce soil bulk density, allowing for better water infiltration (Kahle and Janssen, 2020). Moreover, expressing negative and positive impacts as a ratio may enable the communication of the net positive effects of phytoremediation. This can highlight areas where environmental performance can be improved in the system, or where the impacts of an intervention are not justified by the benefits. Liu and Bakshi (2019) suggested integrating the demand and supply of ecosystem goods and services at multiple spatial scales into conventional LCA to obtain “absolute environmental sustainability metrics”. This approach could help moving away from using monetary cost-benefit approaches, which have become common in aiding policy makers in analysing trade-offs (Drupp et al., 2024). When considering the importance of a healthy environment, balancing harmful impacts with benefits, rather than focusing on financial returns, would allow for a more holistic and ethical sustainability assessment. It would also provide a clearer expression of the actual social and environmental costs beside the economic ones. Various studies have focused on integrating transdisciplinary knowledge in the ES approach to avoid the risk of reducing basic values such as human well-being and biodiversity protection to financial terms (Norström et al., 2022; Spash and Hache, 2022). Future models of phytoremediation in urban settings should therefore consider the specific urban challenges involved on top of soil remediation; this requires a careful analysis of the socio-ecological asset, aiming for the sustainability of the process without forgetting about the complex social dynamics and equality issues to green infrastructures (Meerow and Newell, 2019). This could help highlight the demand for ES in a specific area, and hence the nexuses between it and the contributions that the chosen

GRO could give to the socio-ecological processes (Babí Almenar et al., 2021). On top of that, to organize complex environmental, economic and social aspects of phytoremediation in urban settings it could be advisable to perform more holistic analysis such as a Life Cycle Sustainability Assessment (LCSA), a way to combine environmental LCA, Social-LCA (S-LCA) and Life Cycle Costing (LCC) (Kloepffer, 2008; UNEP-SETAC, 2011).

As previously discussed, the impacts of remediation go beyond the spatial and temporal boundaries of the site, affecting a larger scale and long-term horizon. These impacts can be classified as primary, secondary and tertiary, and this classification should be better integrated into the sustainability assessments. For example, Hou et al. (2023) suggest that a risk assessment is necessary to describe primary impacts and avoid misleading conclusions when choosing the best option. Secondary impacts are related to remediation operations and are typically assessed in LCA. Tertiary impacts, although less analysed, are crucial to highlight how different brownfield remediation strategies affect environmental flows to and from the site during the post-remediation phase (Lesage et al., 2007). These last impacts could also exceed the previous ones (Lesage et al., 2007, Hou et al., 2014, Hou et al., 2023), and a consequential LCA should be applied to capture how the management choices will affect the environmental flows in the post-remediation management phase (Hou et al., 2023). An attributional analysis of this phase would indeed transfer only partial information about the consequences of the decisions and would lead to allocation issues (Lesage et al., 2007).

The integration of the ES framework into LCA still requires further standardization such as in the choice of classification systems or in the temporal and spatial scales of assessments, as noted by Rugani et al. (2019). Efforts should focus on conducting a broader validation of simulation models with real case studies to transparently promote Nature-based Solutions for addressing challenges in deteriorated urban areas like brownfields. This approach can foster sustainable urban development that addresses issues beyond remediation, such as resilience to climate change, mitigation of the urban heat island effect and biodiversity loss.

## 5. Conclusion

This systematic literature review on the application of LCA for the sustainability assessment of phytoremediation for brownfields redevelopment has highlighted current trends and knowledge gaps to be addressed in future research efforts. Moreover, we analysed the occurrence of the ES evaluation methodology and principles in the LCA approaches, revealing a great potential for their integration. This integration can further promote the application of these tools to provide policymakers and stakeholders with comprehensive information to evaluate different remediation strategies and creating reliable frameworks for policy support. Based on the results of this review, we recommend focusing on the following aspects for future research: (1) consider ES beyond biomass provisioning for energy purposes, such as air pollutants filtration or runoff control; (2) integrate LCA and ES assessment approaches to evaluate various remediation possibilities and demonstrate the environmental counterbalancing effects of GRO; (3) develop high spatial resolution analysis for an improved characterization of the effects on biodiversity at the implementation scale; (4) standardize the inclusion of primary-secondary-tertiary remediation impacts in sustainability assessments. Investigating the initial research questions showed that the complex challenges of brownfields redevelopment can be addressed quantitatively using industrial ecology tools like LCA. However, this type of analysis is not consistently applied in phytoremediation case studies. A larger number of examples and data could provide a better understanding of the potential and effectiveness of these solutions. To achieve this, it is crucial to expand the analysis by integrating a broader ES evaluation into the assessment, as the results differ when the benefits of GRO are considered. Lastly, for concrete planning that extends beyond remediation boundaries, it is essential to

incorporate life-cycle and long-term sustainable thinking. This can be achieved through a phytomanagement approach that includes the assessment of post-remediation alternatives in overall decision-making processes.

## CRedit authorship contribution statement

**Favaretto Lidia:** Writing – original draft, Visualization, Project administration, Investigation, Formal analysis, Conceptualization. **Rugani Benedetto:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Calfapietra Carlo:** Writing – review & editing. **Labra Massimo:** Writing – review & editing, Supervision, Funding acquisition. **Guidi Nissim Werther:** Writing – review & editing, Supervision, Conceptualization.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgments

The authors gratefully acknowledge financial support from the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.4 - Call for tender No. 3138 of 16 December 2021, rectified by Decree n.3175 of 18 December 2021 of Italian Ministry of University and Research funded by the European Union -NextGenerationEU; Award Number: Project code CN\_00000033, Concession Decree No. 1034 of 17 June 2022 adopted by the Italian Ministry of University and Research, CUP H43C22000530001 Spoke 5, Project title “National Biodiversity Future Center – NBFC”.

## References

- Adams, D., De Sousa, C., Tiesdell, S., 2010, January. Brownfield development: a comparison of North American and British approaches—David Adams. *Christ. De. Sous, Steven Tiesdell* 2010. (<https://journals.sagepub.com/doi/abs/10.1177/0042098009346868>).
- Akram, R., Turan, V., Hammad, H.M., Ahmad, S., Hussain, S., Hasnain, A., Maqbool, M. M., Rehmani, M.I.A., Rasool, A., Masood, N., Mahmood, F., Mubeen, M., Sultana, S. R., Fahad, S., Amanet, K., Saleem, M., Abbas, Y., Akhtar, H.M., Hussain, S., Nasim, W., 2018. Fate of organic and inorganic pollutants in paddy soils. In: Hashmi, In.M.Z., Varma, A. (Eds.), *Environmental Pollution of Paddy Soils*. Springer International Publishing, pp. 197–214. <https://doi.org/10.1007/978-3-319-93671-013>.
- Alshehri, K., Chen, I.-C., Rugani, B., Sapsford, D., Harbottle, M., Cleall, P., 2024. A novel uncertainty assessment protocol for integrated ecosystem services-life cycle assessments: A comparative case of nature-based solutions. *Sustain. Prod. Consum.* 47, 499–515. <https://doi.org/10.1016/j.spc.2024.04.026>.
- Alshehri, K., Harbottle, M., Sapsford, D., Beames, A., Cleall, P., 2023. Integration of ecosystem services and life cycle assessment allows improved accounting of sustainability benefits of nature-based solutions for brownfield redevelopment. *J. Clean. Prod.* 413, 137352. <https://doi.org/10.1016/j.jclepro.2023.137352>.
- Al-Swadi, H.A., Usman, A.R.A., Al-Farraj, A.S., Al-Wabel, M.I., Ahmad, M., Al-Faraj, A., 2022. Sources, toxicity potential, and human health risk assessment of heavy metals-laden soil and dust of urban and suburban areas as affected by industrial and mining activities. *Sci. Rep.* 12 (1), 8972. <https://doi.org/10.1038/s41598-022-12345-8>.
- Arvidsson, R., Ciroth, A., 2021. Introduction to “life cycle inventory analysis”. In: Ciroth, A., Arvidsson, R. (Eds.), *Life Cycle Inventory Analysis: Methods and Data*. Springer International Publishing, pp. 1–14. [https://doi.org/10.1007/978-3-030-62270-1\\_1](https://doi.org/10.1007/978-3-030-62270-1_1).
- Asante-Badu, B., Kgorutla, L.E., Li, S.S., Danso, P.O., Xue, Z., Qiang, G., 2020. Phytoremediation of organic and inorganic compounds in a natural and an agricultural environment: a review. *Appl. Ecol. Environ. Res.* 18 (5), 6875–6904. [https://doi.org/10.15666/aer/1805\\_68756904](https://doi.org/10.15666/aer/1805_68756904).
- Babí Almenar, J., Elliot, T., Rugani, B., Philippe, B., Navarrete Gutierrez, T., Sonnemann, G., Geneletti, D., 2021. Nexus between nature-based solutions, ecosystem services and urban challenges. *Land Use Policy* 100, 104898. <https://doi.org/10.1016/j.landusepol.2020.104898>.
- Babí Almenar, J., Petucco, C., Sonnemann, G., Geneletti, D., Elliot, T., Rugani, B., 2023. Modelling the net environmental and economic impacts of urban nature-based solutions by combining ecosystem services, system dynamics and life cycle thinking: an application to urban forests. *Ecosyst. Serv.* 60, 101506. <https://doi.org/10.1016/j.ecoser.2022.101506>.

- Beames, A., Broekx, S., Heijungs, R., Lookman, R., Boonen, K., Van Geert, Y., Dendoncker, K., Seuntjens, P., 2015. Accounting for land-use efficiency and temporal variations between brownfield remediation alternatives in life-cycle assessment. *J. Clean. Prod.* 101, 109–117. <https://doi.org/10.1016/j.jclepro.2015.03.073>.
- Bielinskas, V., Burinskienė, M., Podviekzo, A., 2018. Choice of abandoned territories conversion scenario according to MCDA methods. *J. Civ. Eng. Manag.* 24 (1). <https://doi.org/10.3846/jcem.2018.303>.
- Blanco, C.F., Marques, A., Van Bodegom, P.M., 2018. An integrated framework to assess impacts on ecosystem services in LCA demonstrated by a case study of mining in Chile. *Ecosyst. Serv.* 30, 211–219. <https://doi.org/10.1016/j.ecoser.2017.11.011>.
- Bratman, G.N., Hamilton, J.P., Daily, G.C., 2012. The impacts of nature experience on human cognitive function and mental health. *Ann. N. Y. Acad. Sci.* 1249 (1), 118–136. <https://doi.org/10.1111/j.1749-6632.2011.06400.x>.
- Braun, A.B., Visentin, C., Thomé, A., 2024. Design of a central tool for sustainability evaluation and weighting to decision-making support of contaminated soils remediation. *J. Environ. Manag.* 351, 119624. <https://doi.org/10.1016/j.jenvman.2023.119624>.
- Bruel, A., Troussier, N., Guillaume, B., Sirina, N., 2016. Considering ecosystem services in life cycle assessment to evaluate environmental externalities. *Procedia CIRP* 48, 382–387. <https://doi.org/10.1016/j.procir.2016.03.143>.
- Burges, A., Epelde, L., Benito, G., Artetxe, U., Becerril, J.M., Garbisu, C., 2016. Enhancement of ecosystem services during endophyte-assisted aided phytostabilization of metal contaminated mine soil. *Sci. Total Environ.* 562, 480–492. <https://doi.org/10.1016/j.scitotenv.2016.04.080>.
- Chan, K.M.A., Satterfield, T., 2020. The maturation of ecosystem services: social and policy research expands, but whither biophysically informed valuation? *People Nat.* 2 (4), 1021–1060. <https://doi.org/10.1002/pan3.10137>.
- Chaplin-Kramer, R., Sim, S., Hamel, P., Bryant, B., Noe, R., Mueller, C., Rigarlfsford, G., Kulak, M., Kowal, V., Sharp, R., Clavreul, J., Price, E., Polasky, S., Ruckelshaus, M., Daily, G., 2017. Life cycle assessment needs predictive spatial modelling for biodiversity and ecosystem services. *Nat. Commun.* 8 (1), 15065. <https://doi.org/10.1038/ncomms15065>.
- Chen, K., Lin, H., You, S., Han, Y., 2022 Sep 7. Review of the impact of urban parks and green spaces on residence prices in the environmental health context. *Front. Public Health* 10, 993801. <https://doi.org/10.3389/fpubh.2022.993801>. PMID: 36159304; PMCID: PMC9490231.
- Cleveland, C.J., 1992. Energy quality and energy surplus in the extraction of fossil fuels in the U.S. *Ecol. Econ.* 6 (2), 139–162. [https://doi.org/10.1016/0921-8009\(92\)90010-P](https://doi.org/10.1016/0921-8009(92)90010-P).
- Cozma, P., Hlihor, R.-M., Roșca, M., Minuț, M., Diaconu, M., Gavrilăscu, M., 2021. Coupling phytoremediation with plant biomass valorisation and metal recovery: an overview. *Int. Conf. E-Health Bioeng. (EHB 2021)*, 1–4. <https://doi.org/10.1109/EHB52898.2021.9657551>.
- Crenna, E., Marques, A., La Notte, A., Sala, S., 2020. Biodiversity assessment of value chains: state of the art and emerging challenges. *Environ. Sci. Technol.* 54 (16), 9715–9728. <https://doi.org/10.1021/acs.est.9b05153>.
- Cristaldi, A., Conti, G.O., Jho, E.H., Zuccarello, P., Grasso, A., Copat, C., Ferrante, M., 2017. Phytoremediation of contaminated soils by heavy metals and PAHs. A brief review. *Environ. Technol. Innov.* 8, 309–326. <https://doi.org/10.1016/j.eti.2017.08.002>.
- Cundy, A.B., Bardos, R.P., Church, A., Puschenreiter, M., Friesl-Hanl, W., Müller, I., Neu, S., Mench, M., Witters, N., Vangronsveld, J., 2013. Developing principles of sustainability and stakeholder engagement for “gentle” remediation approaches: the European context. *J. Environ. Manag.* 129, 283–291. <https://doi.org/10.1016/j.jenvman.2013.07.032>.
- Cundy, A., Bardos, P., Puschenreiter, M., Witters, N., Mench, M., Bert, V., Friesl-Hanl, W., Müller, I., Weyens, N., Vangronsveld, J., 2015. Developing effective decision support for the application of “gentle” remediation options: the GREENLAND project. *Remediat. J.* 25 (3), 101–114. <https://doi.org/10.1002/rem.21435>.
- da S Trentin, A.W., Reddy, K.R., Kumar, G., Chetri, J.K., Thomé, A., 2019. Quantitative assessment of life cycle sustainability (QUALICS): framework and its application to assess electrokinetic remediation. *Chemosphere* 230, 92–106. <https://doi.org/10.1016/j.chemosphere.2019.04.200>.
- Damiani, M., Sinkko, T., Caldeira, C., Tosches, D., Robuchon, M., Sala, S., 2023. Critical review of methods and models for biodiversity impact assessment and their applicability in the LCA context. *Environ. Impact Assess. Rev.* 101, 107134. <https://doi.org/10.1016/j.eiar.2023.107134>.
- Drenning, P., Chowdhury, S., Volchko, Y., Rosén, L., Andersson-Sköld, Y., Norrman, J., 2022. A risk management framework for gentle remediation options (GRO). *Sci. Total Environ.* 802, 149880. <https://doi.org/10.1016/j.scitotenv.2021.149880>.
- Drupp, M.A., Hänsel, M.C., Fenichel, E.P., Freeman, M., Gollier, C., Groom, B., Heal, G. M., Howard, P.H., Millner, A., Moore, F.C., Nesje, F., Quaas, M.F., Smulders, S., Sterner, T., Traeger, C., Venmans, F., 2024. Accounting for the increasing benefits from scarce ecosystems. *Science* 383 (6687), 1062–1064. <https://doi.org/10.1126/science.adk2086>.
- U.S. EPA. Exposure Factors Handbook 2011 Edition (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-09/052F, 2011.
- U.S. EPA. Overview of EPA’s Brownfields Program. USEPA (<https://www.epa.gov/brownfields/>) overview-epas-brownfields-program 2022.
- Espada, J.J., Rodríguez, R., Delgado, A., Vicente, G., Bautista, L.F., 2024. Assessing environmental sustainability of phytoremediation to remove copper from contaminated soils. *Sustainability* 16 (6). <https://doi.org/10.3390/su16062441>.
- Espada, J.J., Rodríguez, R., Gari, V., Salcedo-Abraira, P., Bautista, L.F., 2022. Coupling phytoremediation of Pb-contaminated soil and biomass energy production: a comparative life cycle assessment. *Sci. Total Environ.* 840. <https://doi.org/10.1016/j.scitotenv.2022.156675>.
- EU Waste Framework Directive, 2008. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste, Article 2(f).
- European Commission. Joint Research Centre - Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance. First edition March 2010. EUR 24708 EN. Luxembourg. Publications Office of the European Union; 2010.
- Farraji, H., Zaman, N.Q., Tajuddin, R.M., Faraji, H., 2016. Advantages and disadvantages of phytoremediation: A concise review. 2, pp. 69–75..
- Fermeglia, M., Perišić, M., 2023a. Nature-based solution to man-made problems: fostering the uptake of phytoremediation and low-iluc biofuels in the EU. *J. Eur. Environ. Plan. Law* 20 (2), 145–167. <https://doi.org/10.1163/18760104-20020007>.
- Fermeglia, M., Perišić, M., 2023b. Unpacking the legal conundrum of nature-based soil remediation and sustainable biofuels production in the European Union. *Soil Secur.* 13, 100109. <https://doi.org/10.1016/j.soisec.2023.100109>.
- Fernández-Braña, A., Salgado, L., Gallego, J.L.R., Afif, E., Boente, C., Forján, R., 2023. Phytoremediation potential depends on the degree of soil pollution: a case study in an urban brownfield. *Environ. Sci. Pollut. Res.* 30 (25), 67708–67719. <https://doi.org/10.1007/s11356-023-26968-5>.
- Friskhnecht, R., Heijungs, R., Hofstetter, P., 1998. Einstein’s lessons for energy accounting in LCA. *Int. J. Life Cycle Assess.* 3 (5), 266–272. <https://doi.org/10.1007/BF02979833>.
- Garbisu, C., Alkorta, I., Kidd, P., Epelde, L., Mench, M., 2020. Keep and promote biodiversity at polluted sites under phytomanagement. *Environ. Sci. Pollut. Res.* 27 (36), 44820–44834. <https://doi.org/10.1007/s11356-020-10854-5>.
- Gerhardt, K.E., Gerwing, P.D., Greenberg, B.M., 2017. Opinion: taking phytoremediation from proven technology to accepted practice. *Plant Sci.* 256, 170–185. <https://doi.org/10.1016/j.plantsci.2016.11.016>.
- Geyer, R., Stoms, D.M., Lindner, J.P., Davis, F.W., Wittstock, B., 2010. Coupling GIS and LCA for biodiversity assessments of land use: Part 1: Inventory modeling. *Int. J. Life Cycle Assess.* 15 (5), 454–467. <https://doi.org/10.1007/s11367-010-0170-9>.
- Gómez Martín, E., Máñez Costa, M., Egerer, S., Schneider, U.A., 2021. Assessing the long-term effectiveness of nature-based solutions under different climate change scenarios. *Sci. Total Environ.* 794, 148515. <https://doi.org/10.1016/j.scitotenv.2021.148515>.
- González-García, S., Bacchetti, J., Murphy, R.J., Fiala, M., 2012. Present and future environmental impact of poplar cultivation in the Po Valley (Italy) under different crop management systems. *J. Clean. Prod.* 26, 56–66. <https://doi.org/10.1016/j.jclepro.2011.12.020>.
- Green, T.L., 2018. Evaluating predictors for brownfield redevelopment. *Land Use Policy* 73, 299–319. <https://doi.org/10.1016/j.landusepol.2018.01.008>.
- Grifoni, M., Pedron, F., Barbaferri, M., Rosellini, I., Petruzzelli, G., Franchi, E., 2021. Sustainable valorization of biomass: from assisted phytoremediation to green energy production. In: Prasad, M.N.V. (Ed.), *Handbook of Assisted and Amendment: Enhanced Sustainable Remediation Technology*, 1st ed. Wiley, pp. 29–51. <https://doi.org/10.1002/9781119670391.ch2>.
- Guidi Nissim, W., Labrecque, M., 2021. Reclamation of urban brownfields through phytoremediation: implications for building sustainable and resilient towns (Scopus). *Urban For. Urban Green.* 65. <https://doi.org/10.1016/j.ufug.2021.127364>.
- Haase, D., Larondelle, N., Andersson, E., Artmann, M., Borgström, S., Breuste, J., Gomez-Baggethun, E., Gren, Å., Hamstead, Z., Hansen, R., Kabisch, N., Kremer, P., Langemeyer, J., Rall, E.L., McPhearson, T., Pauleit, S., Qureshi, S., Schwarz, N., Voigt, A., Elmqvist, T., 2014. A quantitative review of urban ecosystem service assessments: concepts, models, and implementation. *AMBIO* 43 (4), 413–433. <https://doi.org/10.1007/s13280-014-0504-0>.
- Hardaker, A., Styles, D., Williams, P., Chadwick, D., Dandy, N., 2022. A framework for integrating ecosystem services as endpoint impacts in life cycle assessment. *J. Clean. Prod.* 370, 133450. <https://doi.org/10.1016/j.jclepro.2022.133450>.
- Hartig, T., Kahn, P.H., 2016. Living in cities, naturally. *Science* 352 (6288), 938–940. <https://doi.org/10.1126/science.aaf3759>.
- Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., 2018. *Life Cycle Assessment: Theory and Practice*. Springer International Publishing. <https://doi.org/10.1007/978-3-319-56475-3>.
- Hirons, M., Combetti, C., Dunford, R., 2016. Valuing cultural ecosystem services. *Annu. Rev. Environ. Resour.* 41 (1), 545–574. <https://doi.org/10.1146/annurev-environ-110615-085831>.
- Hou, D., Al-Tabbaa, A., Guthrie, P., Hellings, J., 2014. Using a hybrid LCA method to evaluate the 924 sustainability of sediment remediation at the London. *Olymp. Park. J. Clean. Prod.* 83 (87-95), 925.
- Hou, D., Al-Tabbaa, A., O’Connor, D., Hu, Q., Zhu, Y.-G., Wang, L., Kirkwood, N., Ok, Y. S., Tsang, D.C.W., Bolan, N.S., Rinklebe, J., 2023. Sustainable remediation and redevelopment of brownfield sites (Scopus). *Nat. Rev. Earth Environ.* 4 (4), 271–286. <https://doi.org/10.1038/s43017-023-00404-1>.
- Hou, D., O’Connor, D., 2020. - Green and sustainable remediation: concepts, principles, and pertaining research. In: Hou, D. (Ed.), *Sustainable Remediation of Contaminated Soil and Groundwater*. Butterworth-Heinemann, pp. 1–17. <https://doi.org/10.1016/B978-0-12-817982-6.00001-X>.
- Huijbregts, M.A.J., Rombouts, L.J.A., Hellweg, S., Friskhnecht, R., Hendriks, A.J., van de Meent, D., Ragas, A.M.J., Reijnders, L., Struijs, J., 2006. Is cumulative fossil energy demand a useful indicator for the environmental performance of products? *Environ. Sci. Technol.* 40 (3), 641–648. <https://doi.org/10.1021/es051689g>.
- Jaskulak, M., Grobelak, A., Vandenbulcke, F., 2020. Modelling assisted phytoremediation of soils contaminated with heavy metals – main opportunities, limitations, decision making and future prospects (Scopus). *Chemosphere* 249. <https://doi.org/10.1016/j.chemosphere.2020.126196>.

- Jiang, Y., Lei, M., Duan, L., Longhurst, P., 2015. Integrating phytoremediation with biomass valorisation and critical element recovery: a UK contaminated land perspective. *Biomass - Bioenergy* 83, 328–339. <https://doi.org/10.1016/j.biombioe.2015.10.013>.
- Kahle, P., Janssen, M., 2020. Impact of short-rotation coppice with poplar and willow on soil physical properties. *J. Plant Nutr. Soil Sci.* 183 (2), 119–128. <https://doi.org/10.1002/jpln.201900443>.
- Kaita, M.S., Harun, S.N., 2023. Application of integrated LCA-GIS model in the agricultural sector: a brief overview. *IOP Conf. Ser.: Earth Environ. Sci.* 1167 (1), 012015. <https://doi.org/10.1088/1755-1315/1167/1/012015>.
- Kaushal, J., Mahajan, P., Kaur, N., 2021 Dec. A review on application of phytoremediation technique for eradication of synthetic dyes by using ornamental plants. *Environ. Sci. Pollut. Res. Int.* 28 (48), 67970–67989. <https://doi.org/10.1007/s11356-021-16672-7>. Epub 2021 Oct 12. PMID:34636019.
- Keeler, B.L., Hamel, P., McPhearson, T., Hamann, M.H., Donahue, M.L., Meza Prado, K.A., Wood, S.A., 2019. Social-ecological and technological factors moderate the value of urban nature. *Nat. Sustain.* 2 (1), 29–38. <https://doi.org/10.1038/s41893-018-0202-1>.
- Kermavannar, J., Vilhar, U., 2017. Canopy precipitation interception in urban forests in relation to stand structure. *Urban Ecosyst.* 20 (6), 1373–1387. <https://doi.org/10.1007/s11252-017-0689-7>.
- Khan, A.H.A., Kiyani, A., Mirza, C.R., Butt, T.A., Barros, R., Ali, B., Iqbal, M., Yousaf, S., 2021. Ornamental plants for the phytoremediation of heavy metals: present knowledge and future perspectives. *Environ. Res.* 195, 110780. <https://doi.org/10.1016/j.envres.2021.110780>.
- Khan, A.H.A., Kiyani, A., Santiago-Herrera, M., Ibáñez, J., Yousaf, S., Iqbal, M., Martel-Martín, S., Barros, R., 2023. Sustainability of phytoremediation: post-harvest stratagems and economic opportunities for the produced metals contaminated biomass. *J. Environ. Manag.* 326, 116700. <https://doi.org/10.1016/j.jenvman.2022.116700>.
- Kicińska, A., Wikar, J., 2024. Health risk associated with soil and plant contamination in industrial areas. *Plant Soil* 498 (1), 295–323. <https://doi.org/10.1007/s11104-023-06436-2>.
- Kick, C., Kidikas, Ž., Kasiulienė, A., Maletić, S., Zeremski, T., Rubežius, M., Eschen, M., Ortner, M., 2024. Feasibility of using phytoremediation biomass for sustainable biofuel production via thermochemical conversion. *Biofuels, Bioprod. Bioref.* 18 (4), 1010–1026. <https://doi.org/10.1002/bbb.2656>.
- Kidd, P., Mench, M., Álvarez-López, V., Bert, V., Dimitriou, I., Friesl-Hanl, W., Herzig, R., Olga Janssen, J., Kolbas, A., Müller, I., Neu, S., Renella, G., Ruttens, A., Vangronsveld, J., Puschenreiter, M., 2015. Agronomic practices for improving gentle remediation of trace element-contaminated soils. *Int. J. Phytoremediat.* 17 (11), 1005–1037. <https://doi.org/10.1080/15226514.2014.1003788>.
- Kloepffer, W., 2008. Life cycle sustainability assessment of products: (With Comments by Helias A. Udo de Haes, p. 95). *Int. J. Life Cycle Assess.* 13 (2), 89–95. <https://doi.org/10.1065/lca2008.02.376>.
- Koellner, T., Bonn, A., Arnold, S., Bagstad, K.J., Fridman, D., Guerra, C.A., Kastner, T., Kissinger, M., Kleemann, J., Kuhlcke, C., Liu, J., López-Hoffman, L., Marques, A., Martín-López, B., Schulp, C.J.E., Wolff, S., Schröter, M., 2019. Guidance for assessing interregional ecosystem service flows. *Ecol. Indic.* 105, 92–106. <https://doi.org/10.1016/j.ecolind.2019.04.046>.
- Kosanic, A., Petzold, J., 2020. A systematic review of cultural ecosystem services and human wellbeing. *Ecosyst. Serv.* 45, 101168. <https://doi.org/10.1016/j.ecoser.2020.101168>.
- Kowarik, I., Fischer, L.K., Kendal, D., 2020. Biodiversity conservation and sustainable urban development. *Sustainability* 12 (12). <https://doi.org/10.3390/su12124964>.
- Krogh, A., Junginger, M., Shen, L., Grue, J., Pedersen, T.H., 2024. Climate change impacts of bioenergy technologies: a comparative consequential LCA of sustainable fuels production with CCUS. *Sci. Total Environ.* 940, 173660. <https://doi.org/10.1016/j.scitotenv.2024.173660>.
- Kuykendall, D.C., McMullan, A., 2014, March 17. Using an environmental footprint analysis to evaluate the sustainability of remedial alternatives. *SPE Int. Conf. Health, Saf., Environ.* <https://doi.org/10.2118/168492-MS>.
- Lago-Oliveira, S., Moreira, M.T., González-García, S., 2025. Quantifying spatially explicit LCA midpoint characterization factors to assess the impact of specific farming practices on ecosystem services. *Ecosyst. Serv.* 71, 101686. <https://doi.org/10.1016/j.ecoser.2024.101686>.
- Langemeyer, J., Ghermandi, A., Keeler, B., van Berkel, D., 2023. The future of crowd-sourced cultural ecosystem services assessments. *Ecosyst. Serv.* 60, 101518. <https://doi.org/10.1016/j.ecoser.2023.101518>.
- Laprise, M., Lufkin, S., Rey, E., 2018. An operational monitoring tool facilitating the transformation of urban brownfields into sustainable neighborhoods. *Build. Environ.* 142, 221–233. <https://doi.org/10.1016/j.buildenv.2018.06.005>.
- Larrey-Lassalle, P., Armand Decker, S., Perfido, D., Naneci, S., Rugani, B., 2022. Life cycle assessment applied to nature-based solutions: learnings, methodological challenges, and perspectives from a critical analysis of the literature. *Land* 11 (5). <https://doi.org/10.3390/land11050649>.
- Lee, K., Bakshi, B.R., 2023. Quantifying the direct and indirect demand for ecosystem services. In: Bakshi, B.R. (Ed.), *Engineering and Ecosystems: Seeking Synergies Toward a Nature-Positive World*. Springer International Publishing, pp. 47–64. [https://doi.org/10.1007/978-3-031-35692-6\\_3](https://doi.org/10.1007/978-3-031-35692-6_3).
- Lee, J., Park, K.Y., Cho, J., Kim, J.Y., 2018. Releasing characteristics and fate of heavy metals from phytoremediation crop residues during anaerobic digestion. *Chemosphere* 191, 520–526. <https://doi.org/10.1016/j.chemosphere.2017.10.072>.
- Lemming, G., Hauschild, M.Z., Bjerg, P.L., 2010. Life cycle assessment of soil and groundwater remediation technologies: literature review. *Int. J. Life Cycle Assess.* 15, 115–127. <https://doi.org/10.1007/s11367-009-0129-x>.
- Lesage, P., Ekvall, T., Deschênes, L., Samson, R., 2007. Environmental assessment of brownfield rehabilitation using two different life cycle inventory models. *Int. J. Life Cycle Assess.* 12 (7), 497–513. <https://doi.org/10.1065/lca2006.10.279.2>.
- Lin, L.-D., Ho, J.-R., Yang, B.-Y., Ko, C.-H., Chang, F.-C., 2022. Life cycle assessment of heavy metal contaminated sites: phytoremediation and soil excavation. *Int. J. Phytoremediat.* 24 (4), 334–341. <https://doi.org/10.1080/15226514.2021.1937933>.
- Liu, X., Bakshi, B.R., 2019. Ecosystem services in life cycle assessment while encouraging techno-ecological synergies. *J. Ind. Ecol.* 23 (2), 347–360. <https://doi.org/10.1111/jiec.12755>.
- Lueddeckens, S., Saling, P., Guenther, E., 2020. Temporal issues in life cycle assessment—a systematic review. *Int. J. Life Cycle Assess.* 25 (8), 1385–1401. <https://doi.org/10.1007/s11367-020-01757-1>.
- Lynch, M.N., Satrio, J.A., 2022. Utilization of grassy biomass grown in heavy-metal contaminated soil as feedstock for bioenergy production—an LCA study. *IOP Conf. Ser.: Earth Environ. Sci.* 1034 (1), 012022. <https://doi.org/10.1088/1755-1315/1034/1/012022>.
- M.E.A., 2005. *A report of the Millennium ecosystem assessment. Ecosystems and Human Well-Being*. Island Press, Washington DC.
- Mace, G.M., Norris, K., Fitter, A.H., 2012. Biodiversity and ecosystem services: a multilayered relationship. *Trends Ecol. Evol.* 27 (1), 19–26. <https://doi.org/10.1016/j.tree.2011.08.006>.
- Maia de Souza, D., Lopes, G.R., Hansson, J., Hansen, K., 2018. Ecosystem services in life cycle assessment: a synthesis of knowledge and recommendations for biofuels. *Ecosyst. Serv.* 30, 200–210. <https://doi.org/10.1016/j.ecoser.2018.02.014>.
- Marvin, D.C., Sleeter, B.M., Cameron, D.R., Nelson, E., Plantinga, A.J., 2023. Natural climate solutions provide robust carbon mitigation capacity under future climate change scenarios. *Sci. Rep.* 13 (1), 19008. <https://doi.org/10.1038/s41598-023-43118-6>.
- Marvuglia, A., Benetto, E., Rege, S., Jury, C., 2013. Modelling approaches for consequential life-cycle assessment (C-LCA) of bioenergy: critical review and proposed framework for biogas production. *Renew. Sustain. Energy Rev.* 25, 768–781. <https://doi.org/10.1016/j.rser.2013.04.031>.
- Meagher, R.B., 2000. Phytoremediation of toxic elemental and organic pollutants—ScienceDirect. (<https://www.sciencedirect.com/science/article/pii/S1369526699000540>).
- Meerow, S., Newell, J.P., 2019. Urban resilience for whom, what, when, where, and why? *Urban Geogr.* 40 (3), 309–329. <https://doi.org/10.1080/02723638.2016.1206395>.
- Metzger, M.J., Rounsevell, M.D.A., Acosta-Michlik, L., Leemans, R., Schröter, D., 2006. The vulnerability of ecosystem services to land use change. *Agric. Ecosyst. Environ.* 114 (1), 69–85. <https://doi.org/10.1016/j.agee.2005.11.025>.
- Moreira, H., Pereira, S.I.A., Mench, M., Garbisu, C., Kidd, P., Castro, P.M.L., 2021. Phytomanagement of metal(loid)-contaminated soils: options, efficiency and value. *Front. Environ. Sci.* 9. (<https://www.frontiersin.org/articles/10.3389/fenvs.2021.661423>).
- Niero, M., Ingvordsen, C.H., Jørgensen, R.B., Hauschild, M.Z., 2015. How to manage uncertainty in future life cycle assessment (LCA) scenarios addressing the effect of climate change in crop production. *J. Clean. Prod.* 107, 693–706. <https://doi.org/10.1016/j.jclepro.2015.05.061>.
- Norrman, J., Volchko, Y., Hooimeijer, F., Maring, L., Kain, J.-H., Bardos, P., Broekx, S., Beames, A., Rosén, L., 2016. Integration of the subsurface and the surface sectors for a more holistic approach for sustainable redevelopment of urban brownfields, 879–889 *Sci. Total Environ.* 563–564. <https://doi.org/10.1016/j.scitotenv.2016.02.097>.
- Norström, A.V., Agarwal, B., Balvanera, P., Baptiste, B., Bennett, E.M., Brondízio, E., Biggs, R., Campbell, B., Carpenter, S.R., Castilla, J.C., Castro, A.J., Cramer, W., Cumming, G.S., Felipe-Lucia, M., Fischer, J., Folke, C., DeFries, R., Gelcich, S., Groth, J., Spierenburg, M., 2022. The programme on ecosystem change and society (PECS) – a decade of deepening social-ecological research through a place-based focus. *Ecosyst. People.* (<https://www.tandfonline.com/doi/abs/10.1080/26395916.2022.2133173>).
- O'Connor, D., Müller-Grabherr, D., Hou, D., 2019. Strengthening social-environmental management at contaminated sites to bolster green and sustainable remediation via a survey. *Chemosphere* 225, 295–303. <https://doi.org/10.1016/j.chemosphere.2019.03.035>.
- O'Connor, D., Zheng, X., Hou, D., Shen, Z., Li, G., Miao, G., O'Connell, S., Guo, M., 2019. Phytoremediation: Climate change resilience and sustainability assessment at a coastal brownfield redevelopment. *Environ. Int.* 130, 104945. <https://doi.org/10.1016/j.envint.2019.104945>.
- Othoniel, B., Rugani, B., Heijungs, R., Benetto, E., Withagen, C., 2016. Assessment of life cycle impacts on ecosystem services: promise, problems, and prospects. *Environ. Sci. Technol.* 50 (3), 1077–1092. <https://doi.org/10.1021/acs.est.5b03706>.
- Petruzzelli, G., Gorini, F., Pezzarossa, B., Pedron, F., 2010. The fate of pollutants in soil. Peuke, A.D., Renneberg, H., 2005. Phytoremediation: Molecular biology, requirements for application, environmental protection, public attention and feasibility. *EMBO Rep.* 6 (6), 497–501. <https://doi.org/10.1038/sj.embo.7400445>.
- Pigné, Y., Gutiérrez, T.N., Gibon, T., Schaubroeck, T., Popovici, E., Shimako, A.H., Benetto, E., Tiruta-Barna, L., 2020. A tool to operationalize dynamic LCA, including time differentiation on the complete background database. *Int. J. Life Cycle Assess.* 25 (2), 267–279. <https://doi.org/10.1007/s11367-019-01696-6>.
- Podhajka, E., Drzeniecka-Osiadacz, A., Halarewicz, A., Grech, D., Podhajski, B., Zienowicz, M., Babelowski, P., Liszewski, M., 2023. Phytoremediation as an urban paradigm in promoting the health-potential of small green areas. *Sustain. Cities Soc.* 96, 104684. <https://doi.org/10.1016/j.scs.2023.104684>.

- Ramón, F., Lull, C., 2019. Legal measures to prevent and manage soil contamination and to increase food safety for consumer health: the case of Spain. *Environ. Pollut.* 250, 883–891. <https://doi.org/10.1016/j.envpol.2019.04.074>.
- Rocha, C.S., Rocha, D.C., Kochi, L.Y., Carneiro, D.N.M., Dos Reis, M.V., Gomes, M.P., 2022 Jan. Phytoremediation by ornamental plants: a beautiful and ecological alternative. *Environ. Sci. Pollut. Res. Int.* 29 (3), 3336–3354. <https://doi.org/10.1007/s11356-021-17307-7>. Epub 2021 Nov 11. PMID: 34766223.
- Roman, L.A., Conway, T.M., Eisenman, T.S., Koeser, A.K., Ordóñez Barona, C., Locke, D. H., Jenerette, G.D., Östberg, J., Vogt, J., 2021. Beyond 'trees are good': disservices, management costs, and tradeoffs in urban forestry. *Ambio* 50 (3), 615–630. <https://doi.org/10.1007/s13280-020-01396-8>.
- Romanazzi, G.R., Koto, R., De Boni, A., Ottomano Palmisano, G., Cioffi, M., Roma, R., 2023. Cultural ecosystem services: a review of methods and tools for economic evaluation. *Environ. Sustain. Indic.* 20, 100304. <https://doi.org/10.1016/j.indic.2023.100304>.
- Rugani, B., Maia De Souza, D., Weidema, B.P., Bare, J., Bakshi, B., Grann, B., Johnston, J. M., Pavan, A.L.R., Liu, X., Laurent, A., Verones, F., 2019. Towards integrating the ecosystem services cascade framework within the life cycle assessment (LCA) cause-effect methodology. *Sci. Total Environ.* 690, 1284–1298. <https://doi.org/10.1016/j.scitotenv.2019.07.023>.
- Rugani, B., Rocchini, D., 2017. Boosting the use of spectral heterogeneity in the impact assessment of agricultural land use on biodiversity. *J. Clean. Prod.* 140, 516–524. <https://doi.org/10.1016/j.jclepro.2016.09.018>.
- Schwarz, N., Moretti, M., Bugalho, M.N., Davies, Z.G., Haase, D., Hack, J., Hof, A., Melero, Y., Pett, T.J., Knapp, S., 2017. Understanding biodiversity-ecosystem service relationships in urban areas: a comprehensive literature review. *Ecosyst. Serv.* 27, 161–171. <https://doi.org/10.1016/j.ecoser.2017.08.014>.
- Schwitzguébel, J.-P., 2017. Phytoremediation of soils contaminated by organic compounds: Hype, hope and facts. *J. Soils Sediment.* 17 (5), 1492–1502. <https://doi.org/10.1007/s11368-015-1253-9>.
- Seth, C.S., 2012. A review on mechanisms of plant tolerance and role of transgenic plants in environmental clean-up. *Bot. Rev.* 78 (1), 32–62. <https://doi.org/10.1007/s12229-011-9092-x>.
- Soleimani, T., Sordes, F., Techer, I., Junqua, G., Hayek, M., Salgues, M., Souche, J.-C., 2023. Comparative environmental and economic life cycle assessment of phytoremediation of dredged sediment using *Arundo donax*, integrated with biomass to bioenergy valorization chain. *Sci. Total Environ.* 903, 166160. <https://doi.org/10.1016/j.scitotenv.2023.166160>.
- Song, Y., Kirkwood, N., Maksimović, Č., Zheng, X., O'Connor, D., Jin, Y., Hou, D., 2019. Nature based solutions for contaminated land remediation and brownfield redevelopment in cities: a review. *Sci. Total Environ.* 663, 568–579. <https://doi.org/10.1016/j.scitotenv.2019.01.347>.
- Spash, C.L., Hache, F., 2022. The Dasgupta review deconstructed: an exposé of biodiversity economics. *Globalizations*. (<https://www.tandfonline.com/doi/abs/10.1080/14747731.2021.1929007>).
- Suer, P., Andersson-Sköld, Y., 2011. Biofuel or excavation? - Life cycle assessment (LCA) of soil remediation options. *Biomass Bioenergy* 35 (2), 969–981. <https://doi.org/10.1016/j.biombioe.2010.11.022>.
- Taelman, S.E., De Luca Peña, L.V., Préat, N., Bachmann, T.M., Van der Biest, K., Maes, J., Dewulf, J., 2024. Integrating ecosystem services and life cycle assessment: a framework accounting for local and global (socio-)environmental impacts. *Int. J. Life Cycle Assess.* 29 (1), 99–115. <https://doi.org/10.1007/s11367-023-02216-3>.
- Todde, G., Carboni, G., Marras, S., Caria, M., Sirca, C., 2022. Industrial hemp (*Cannabis sativa* L.) for phytoremediation: Energy and environmental life cycle assessment of using contaminated biomass as an energy resource. *Sustain. Energy Technol. Assess.* 52, 102081. <https://doi.org/10.1016/j.seta.2022.102081>.
- UNEP, 2011. Global guidance principles for life cycle assessment Databases, Shonan.
- UNEP-SETAC Life Cycle Initiative 2011. Towards a life cycle sustainability assessment: making informed choices on products. ISBN: 978-92-807-3175-0.
- United Nations, UN, 2019. World Urbanization Prospects 2018; Department of economic and social affairs, population division. New York, NY, USA.
- VanderWilde, C.P., Newell, J.P., 2021. Ecosystem services and life cycle assessment: a bibliometric review. *Resour., Conserv. Recycl.* 169, 105461. <https://doi.org/10.1016/j.resconrec.2021.105461>.
- Vázquez-Rowe, I., Marvuglia, A., Rege, S., Benetto, E., 2014. Applying consequential LCA to support energy policy: land use change effects of bioenergy production. *Sci. Total Environ.* 472, 78–89. <https://doi.org/10.1016/j.scitotenv.2013.10.097>.
- Vigil, M., Franco-Vazquez, L., Marey-Pérez, M.F., 2022. New methodology for assessing the environmental efficiency of transport: application to the valorization of biomass from phytoremediation (Scopus). *Sci. Total Environ.* 846. <https://doi.org/10.1016/j.scitotenv.2022.157434>.
- Vigil, M., Marey-Pérez, M.F., Martínez Huerta, G., Álvarez Cabal, V., 2015. Is phytoremediation without biomass valorization sustainable? - comparative LCA of landfilling vs. anaerobic co-digestion. *Sci. Total Environ.* 505, 844–850. <https://doi.org/10.1016/j.scitotenv.2014.10.047>.
- Vocciant, M., Caretta, A., Bua, L., Bagatin, R., Franchi, E., Petruzzelli, G., Ferro, S., 2019. Enhancements in phytoremediation technology: Environmental assessment including different options of biomass disposal and comparison with a consolidated approach. *J. Environ. Manag.* 237, 560–568. <https://doi.org/10.1016/j.jenvman.2019.02.104>.
- Vocciant, M., de Folly D'Auris, A., Franchi, E., Petruzzelli, G., Ferro, S., 2021. CO2 footprint analysis of consolidated and innovative technologies in remediation activities. *J. Clean. Prod.* 297. <https://doi.org/10.1016/j.jclepro.2021.126723>.
- Wang, J., Aghajani Delavar, M., 2024. Modelling phytoremediation: concepts, methods, challenges and perspectives. *Soil Environ. Health* 2 (1), 100062. <https://doi.org/10.1016/j.seh.2024.100062>.
- Wang, L., Rinklebe, J., Tack, F.M.G., Hou, D., 2021. A review of green remediation strategies for heavy metal contaminated soil. *Soil Use Manag.* 37 (4), 936–963. <https://doi.org/10.1111/sum.12717>.
- Wang, X., Shi, R., Zhou, Y., 2020. Dynamics of urban sprawl and sustainable development in China. *Socio-Econ. Plan. Sci.* 70, 100736. <https://doi.org/10.1016/j.seps.2019.100736>.
- Ward, H., Wenz, L., Steckel, J.C., Minx, J.C., 2018. Truncation error estimates in process life cycle assessment using input-output analysis. *J. Ind. Ecol.* 22 (5), 1080–1091. <https://doi.org/10.1111/jiec.12655>.
- Witters, N., Mendelsohn, R., Van Passel, S., Van Slycken, S., Weyens, N., Schreurs, E., Meers, E., Tack, F., Vanheusden, B., Vangronsveld, J., 2012. Phytoremediation, a sustainable remediation technology? II: Economic assessment of CO2 abatement through the use of phytoremediation crops for renewable energy production. *Biomass Bioenergy* 39, 470–477. <https://doi.org/10.1016/j.biombioe.2011.11.017>.
- Witters, N., Mendelsohn, R.O., Van Slycken, S., Weyens, N., Schreurs, E., Meers, E., Tack, F., Carleer, R., Vangronsveld, J., 2012. Phytoremediation, a sustainable remediation technology? Conclusions from a case study. I: energy production and carbon dioxide abatement. *Biomass Bioenergy* 39, 454–469. <https://doi.org/10.1016/j.biombioe.2011.08.016>.
- Wu, J., 2013. Landscape sustainability science: ecosystem services and human well-being in changing landscapes. *Landsc. Ecol.* 28 (6), 999–1023. <https://doi.org/10.1007/s10980-013-9894-9>.
- Xue, Y., Bakshi, B.R., 2022. Metrics for a nature-positive world: a multiscale approach for absolute environmental sustainability assessment. *Sci. Total Environ.* 846, 157373. <https://doi.org/10.1016/j.scitotenv.2022.157373>.