

Review

Life Cycle Assessment Applied to Nature-Based Solutions: Learnings, Methodological Challenges, and Perspectives from a Critical Analysis of the Literature

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Abstract: The use of life cycle assessment (LCA) allows work to go beyond the traditional scope of urban nature-based solutions (NBS), in which ecosystem services are provided to citizens, to include environmental impacts generated over the entire life cycle of the NBS, i.e., from raw material extraction, through materials processing, production, distribution, and use stages, to end-of-life management. In this work, we explored how LCA has been applied in the context of NBS through a critical analysis of the literature. Systems under review were not restricted to one typology of NBS or another, but were meant to cover a broad range of NBS, from NBS on the ground, water-related NBS, building NBS, to NBS strategies. In total, 130 LCA studies of NBS were analysed according to several criteria derived from the LCA methodology or from specific challenges associated with NBS. Results show that studies were based on different scopes, resulting in the selection of different functional units and system boundaries. Accordingly, we propose an innovative approach based on the ecosystem services (ES) concept to classify and quantify these functional units. We also identify and discuss two recent and promising approaches to solve multifunctionality that could be adapted for LCA of NBS.

Keywords: life cycle assessment (LCA); nature-based solutions (NBS); ecosystem services; multifunctionality; urban setting



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1. Introduction

The quality of life in most cities of the world is threatened by a number of major concerns, including increasing pollution levels, urban heat islands, flooding, and extreme events related to climate change [1]. Because more than half of the world's population currently lives in urban areas, a share expected to reach two thirds by 2050 [2], finding solutions to tackle these issues is extremely urgent.

In parallel, humans have changed ecosystems in the last decades more rapidly and extensively than in any comparable period of time of the human history, which has resulted in a substantial and largely irreversible biodiversity loss. Consequently, in 2005 already, the Millennium Ecosystem Assessment estimated that approximately 60% of the evaluated ecosystem services—the benefits people obtain from ecosystems, such as climate or water regulation or recreational services—had been degraded over the past 50 years [3].

Aware of the importance and urgency of this issue, many local, regional, and national public decision makers are promoting the design of urban settings integrating green spaces.

In particular, revegetation of cities is at the heart of current politics and programs, as shown by the increasing number of current political plans related to biodiversity and to the reintroduction of nature and trees in the city (e.g., [4–6]), or, for example, by the “Green wave” in last French municipal elections [7]. In line with this, the concept of nature-based solutions (NBS) was recently introduced to refer to the sustainable management and use of nature for tackling societal challenges. NBS are defined by the International Union for Conservation of Nature (IUCN) as actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits [8]. Since then, clarifications of the concept and typologies were proposed [9] and connections with other existing concepts related to ecosystem-based approaches were also explored [10].

The European Commission has recently fostered research on NBS with more than 30 European Union (EU)-funded projects under the Horizon 2020 research and innovation program dedicated to a better knowledge of NBS and with the OPPLA EU Repository of NBS. The NBS concept has also been rapidly adopted by the economic world, and, in the past few years, NBS were identified by companies as a strategic frame to reach their carbon neutral objectives as a way of offsetting their greenhouse gas emissions to meet the Paris climate goal (e.g., [11]).

Many NBS projects are flowering all around the world, and particularly in urban areas, as a response to urban concerns given the large range of ecosystem services they can provide for urban citizens [12]. However, studies on NBS often focus on the utilitarian aspect of natural capital and ecosystem services provided by NBS without putting them in perspective with the adverse impacts of these systems and potential environmental trade-offs [13]. Thus, to ensure a comprehensive assessment of environmental impacts generated by NBS and to give to the decision makers a complete picture of their environmental performance, the potential adverse impacts that NBS may have on the environment (environment in the broad sense, i.e., including ecosystems but also human health and resource depletion) need to be evaluated.

Some authors occasionally studied so-called ecosystem disservices but this concept mainly focuses on potential nuisance or disturbance for urban citizens (allergenic potential of plants, unsafety of green spaces, decrease of air quality, e.g., emissions of volatile organic compounds, undesired species, etc.) due to NBS during their operational life stage [14]. Moreover, they do not capture the upstream and downstream environmental impacts associated with upstream resource extractions and pollutant emissions that occur beyond urban borders. Taking a life cycle perspective thus appears necessary to account for the impacts occurring not only during the use phase of the NBS (when the ecosystem services are provided), but also during its fabrication/manufacturing, its installation, and its end of life with the disposal of wastes or the recovery of materials. These impacts can be assessed with the use of life cycle assessment (LCA), which is a mature, robust, internationally standardised [15,16], and globally applied multi-criteria analysis approach that helps cover a wide range of environmental issues (e.g., climate change, eutrophication, or resource depletion) over the entire life cycle of a product system. The most recognised advantage of this decision-support tool is to help in identifying hotspots and burden shifting between impact categories and life cycle stages [17,18] and in proposing appropriate solutions to mitigate them after the analysis is complete.

Literature studies that assess environmental impacts of NBS through LCA are growing fast. Some review analyses have already been published; however, because NBS is a very broad concept, those reviews have only partially tackled the topic, focusing on drainage systems and stormwater infrastructures [13,19–22] or green roofs [23,24]. Some other reviews have concentrated their analysis on the links between LCA (among other tools) and more general concepts encompassing NBS, such as environmental sustainability strategies for urban territories [25–27]. Nevertheless, no exhaustive works covering a large range of NBS, from NBS on the ground, water-related NBS, building NBS, to NBS strategies, have been conducted so far.

Filling this gap is the ambitious goal of our paper. Can the LCA methodology be used to drive decision makers towards a complete understanding of the NBS environmental impacts, and to ensure a fair comparison between NBS systems? Which methodological challenges does the application of LCA pose to complex, living, and multifunctional systems such as NBS? Should the LCA methodology be specifically adapted to NBS assessment? Thus, the objectives are twofold: (1) to derive global trends on the use of the LCA methodology for the environmental sustainability analysis of urban NBS in a broad sense, in order to guide LCA practitioners in future LCA studies of NBS, and (2) to identify common methodological challenges in the field of application of LCA to NBS and to propose solutions to tackle them.

2. Materials and Methods

2.1. Methodology for the Collection and Selection of the Literature

An extensive analysis of the literature was performed to compile and analyse all relevant papers related to LCA of NBS. This allowed the authors to: (1) identify the types of NBS to which LCA has already been applied, (2) understand how the LCA framework has been adapted to the specific case of NBS, and (3) underline the methodological challenges associated with the application of LCA in this domain.

The collection and selection of the analysed literature was performed according to a two-stage process.

First, a *screening stage* was conducted based on the search of LCA studies at 15 April 2020 for all NBS typologies described in the list established in the Nature4Cities EU project (www.nature4cities.eu, accessed on 15 April 2020). The NBS are classified into four categories: on the ground (e.g., parks and gardens, network structures, food production, ecological restoration, or systems for erosion control), water-related (including natural and semi-natural water bodies, but also built structures for water management), on buildings and structures (typically green roofs and green walls), and strategies and actions for green space management, waste management, conservation, and urban planning strategies. The literature survey was limited to the last 20 years (from 2000 to 2020), since the development of the NBS concept, which dates back to the middle of the 2000s (e.g., [28]), as well as their assessment through LCA being rather recent. Keywords relative to LCA and to each NBS type were searched for in both Science Direct and Google Scholar. The keywords used for the selection of LCA studies were a combination of (i) keywords for LCA (“life cycle assessment”, “life cycle analysis”, LCA, “Life cycle management”, “life cycle thinking”, “life cycle sustainability”, “environmental assessment”, and “carbon footprint”) and (ii) keywords relative to the NBS type, using words close semantically to the NBS type (see Supplementary Material A), according to the Nature4Cities classification of NBS [29]. Some systems of the classification not relevant for LCA (mainly urban strategies and actions) were excluded (see Supplementary Material A). This first search returned about 3000 documents among scientific and grey literature studies.

Second, a stricter, consecutive selection was performed on title and abstracts (and full-text, if needed); after reviewing those 3000 documents collected with the first search, only the studies *actually assessing* NBS from an *environmental* point of view (e.g., pure life cycle costing has been excluded) in an *urban context* (i.e., studies in a rural context have been excluded) were selected, which represented less than 4% of the above number. In contrast, studies *only mentioning* LCA without applying it on a case study, or the review papers, were excluded. In addition, for comparison purposes, only individual components were considered, i.e., combination/deployment of several NBS on a territorial system were excluded.

Following this selection process, the final corpus of the literature was composed of 110 documents: 42 studies on NBS on the ground, 28 studies on water-related NBS, 30 studies on NBS on buildings and structures, and 10 studies on strategies and actions for NBS. The final corpus was essentially composed of scientific publications (97) and conference papers (4), of bachelor, master, and PhD theses (5), and of technical or scientific

reports (4). The list of all the studies analysed can be found in Supplementary Material B. It is important to note that some authors carried out the LCA of several, different NBS [30–38]. For comparison purposes, the analysis has been conducted on the *LCA study of an individual NBS* rather than on the publication. Because a system can sometimes be classified in several NBS categories, a main type and a secondary type (if needed) have been assigned to each system. Consequently, in total, 130 LCAs of individual NBS were analysed (44 LCAs of NBS on the ground, 43 of water-related NBS, 33 of NBS on buildings and structures, and 10 of strategies and actions).

2.2. Approach to Analyse the Selected Literature

The selected studies were analysed according to several qualitative and quantitative criteria derived from the respective four phases of LCA (ISO standard 14040:2006): 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. For each phase, a set of criteria was selected from the ISO [15,16], ILCD guidelines [39] and Environmental Footprint [40], and from specific challenges associated with NBS, as detailed below and summarised in Table 1.

Table 1. Description of criteria taken into account within the LCA-NBS literature review.

Analysis Grid			
LCA phase 1—Goal and Scope			
Functions and functional unit(s) considered	System boundaries considered (life cycle stages)	Lifetime of the system or period of analysis	Geographic location of the study
LCA phase 2—Life Cycle Inventory (LCI)			
Is CO ₂ sequestration considered? (if so, value)	Is it explicitly stated that the mass balance is respected for the carbon?	Are emissions in the environment considered after application of mineral/organic fertilisers or pesticides? Is the model/source mentioned, or details on calculation given?	
LCA phase 3—Life Cycle Impact Assessment (LCIA)			
Impact and damages categories considered and LCIA method(s) used	Climate change impact (value)	Normalisation of the results (Yes/No)	Weighting of the results (Yes/No)
LCA phase 4—Interpretation			
Contribution analysis (Yes/No)	Main contributors	Sensitivity or uncertainty analysis (Yes/No)	Main limitations of the study

2.2.1. Criteria for LCA Phase 1—Goal and Scope

An LCA starts with an explicit statement of the goal and scope of the study, which sets out the context of the study and the reason(s) for executing the LCA. This key step includes the precise description of the studied system, its life cycle stages, its boundaries, and the definition of the functional unit.

The analysis of the scope definition included (i) the choice of the function and the functional unit (FU), (ii) the definition of system boundaries, and (iii) key information about the system (lifetime of the system or period of analysis, and geographic location of the studied system). Regarding the system boundaries, these should define which phases of the life cycle and which processes belong to the analysed system or are required for providing its function as defined by the FU [39]. For the specific case of NBS, the analysis investigated whether or not the case studies included the NBS fabrication (i.e., raw materials extraction, manufacturing), transportation and installation processes, operation (and maintenance, if necessary), and possible dismantlement and end of life stages.

2.2.2. Criteria for LCA Phase 2—Life Cycle Inventory

The LCI identifies, quantifies, and compiles all the flows between the studied system and the environment, i.e., all resource consumptions (e.g., raw materials, energy, freshwater, land occupation) and all substance emissions (e.g., chemical emission) to air, water, and soil compartments.

In this work, the analysis of the LCI phase focused on specific challenges associated with NBS, i.e., carbon dioxide sequestration, carbon balance, and emissions in the environment from application of mineral/organic fertilisers or pesticides.

2.2.3. Criteria for LCA Phase 3—Life Cycle Impact Assessment

The impacts potentially caused by the use of resources and land, and/or the release of emissions from the system are then assessed in the LCIA phase. The inventoried flows are first classified according to the potential effect(s) they have on the environment, and then multiplied by a characterisation factor (CF), which aids quantifying the extent to which the resulting LCI can contribute to a given environmental impact category. Two main types of impact categories can be chosen at two different positions along the environmental cause–effect chain: (1) midpoint impact categories, which indicate a change in the environment caused by a human intervention, and (2) endpoint or damage impact categories, which generally assess detrimental impacts on three areas of protection, i.e., human health, ecosystem quality, and resources. The large number of midpoint indicators and their partially abstract meaning can make their appropriation by decision makers difficult [41]. Endpoint indicators are generally considered more understandable to the decision makers, even if their level of comprehensiveness is reduced (not all the potential damages associated with midpoint impacts can be characterised) and their uncertainties are higher than the midpoints' ones (due to a significant number of additional, unsubstantiated assumptions and/or value choices to fill in missing gaps) [41]. Damage modelling also aids in the understanding and interpretation of midpoint indicators by making results in different midpoint categories cross-comparable within areas of protection. Various impact assessment models exist to characterise the inventory flows and assess their potential impacts, and these characterisation models are generally grouped into LCIA methods (e.g., IPCC, CML2001, TRACI, ReCiPe, IMPACT 2002+, etc.) [42]. In addition, the LCA practitioner can carry out the normalisation and/or the weighting of the results, which are two optional steps under ISO 14044:2006 to support the interpretation towards a fully aggregated result.

The analysis of the LCIA phase included (i) the impact categories considered of relevance to the NBS study (at both midpoint and endpoint levels), (ii) the associated LCIA method(s), (iii) the climate change impact of the system (kg CO₂ eq./FU), and (iv) the application of results normalisation and weighting steps.

2.2.4. Criteria for LCA Phase 4—Interpretation

Last, the interpretation identifies the most significant contributors to the impacts, evaluates the study considering completeness, sensitivity, and consistency checks, and provides conclusions, limitations, and recommendations.

The criteria used for analysing the interpretation phase included (i) the identification of hotspots based on the relative contributions of each system process to the impacts if a contribution analysis has been conducted either in the text or through a graph, (ii) whether a sensitivity check was performed or not (i.e., sensitivity analysis and uncertainty characterisation), and (iv) the identification of the main limitations of the study.

3. Results

Even though the search included studies from 2000, all 110 selected documents were published after 2004, and about half of them within the past five years (Figure 1).

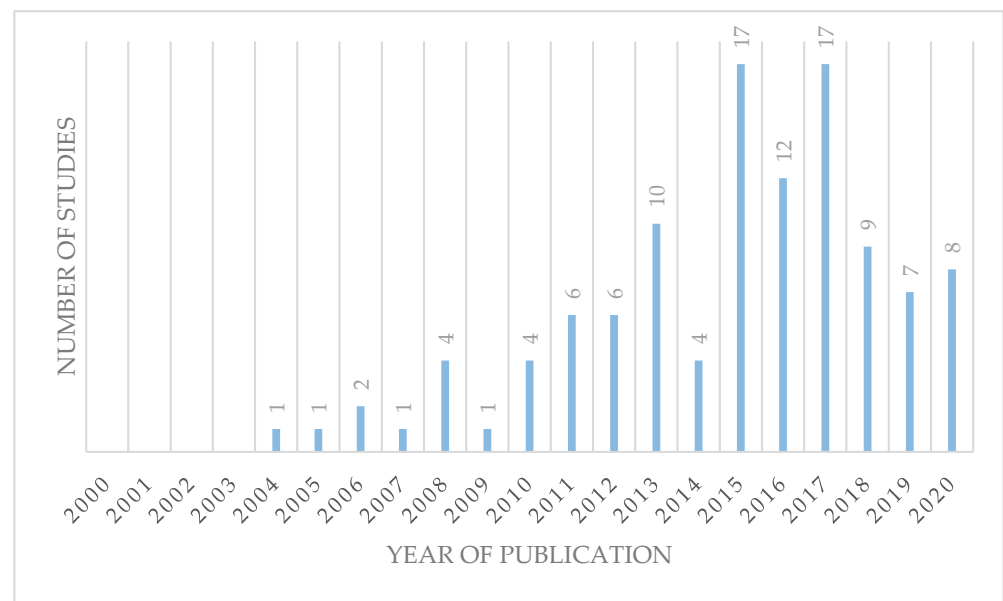


Figure 1. Year of publication of the analysed documents.

Given the large diversity of NBS [29], the ultimate evaluation mainly provided general qualitative conclusions on current practices in terms of goal and scope definition, LCI and LCIA methodological choices, as well as a few quantitative results (e.g., LCIA results on climate change impact) that must be considered with caution because the diversity of boundaries, modelling hypotheses, LCI databases and impact methods make the comparison among studies difficult.

3.1. LCA Phase 1—Goal and Scope

Regarding NBS coverage, the analysis shows that not all the types of NBS described in Table S1 in the Supplementary Material A have been assessed with the use of LCA yet (Table S2 in the Supplementary Material B). One explanation is that the NBS types that did not come up in the literature are less common solutions than the ones that came up. For example, heritage gardens, botanical gardens, green cemeteries, or flower fields are less common than public green spaces, such as places or squares, or sport fields. In the same way, urban orchards or vineyards are less common than urban farms. Natural and semi-natural water bodies, such as reopened streams, reprofiling riverbanks, or gravity fountains, are also less studied than built structures for water management. In addition, many NBS from the strategies and actions group are not studied. A limitation can be the complexity in defining the FU for the assessment, setting the system boundaries and collecting the data.

The analysis shows that the studies are often based on different scopes and consider various FUs and system boundaries. This result can be explained by the large variability of NBS types, which cover many different technological systems; as expected, functions (and FUs) greatly differ depending on the type of NBS assessed (Table 2).

Table 2. Functions and FUs considered in the studies analysed, classified according to the NBS type.

		NBS Typologies	Functions (Functional Units)
On the ground	Parks and Gardens	Urban space with specific uses (recreational areas, safari park, sports fields)	- Source of biomass to produce bioenergy (mass/year) - Operational use of a safari park (activity/year) - To provide a sports field (area of field/year)
		Lawn	- To provide a surface of lawn/to manage lawn (area of lawn/year)
		Large urban public park/public urban green space	- To treat wastewater—wetland park (water flow/day) - To provide park service facilities (energy consumption in the park/year) - To sequester carbon (mass of CO ₂)
		Single tree/wood	- To incorporate/grow single trees in urban landscape (1 single tree during its lifespan) - To provide a grove (area of wood)
	Urban network structures	Green strip (Buffer strip)	- To protect the water body and to mobilize locally sourced biomass for electricity production (area of buffer strip or energy produced) - To provide greenway (area of buffer strip) - To control stormwater runoff/to treat discharge (impervious drainage area)
	Food and resources production	Vegetable garden	- To produce vegetables (mass of vegetable/year)
		Urban farm	- To deliver agricultural products (mass of product or area of land/roof or number of kcal/capita/day) - To use land for multiple functions: food production, housing, and afforestation (area of land)
	Ecological restoration/ systems for erosion control/works on soil	Management of polluted area by plants (phytoremediation)	- To reduce leachate (volume of leachate treated/year) - To remediate a contaminated site (one site of a certain area) - To produce biomass (mass of dry biomass) - To provide energy from biomass cultivated on a contaminated site (area/year)
		Soil and slope revegetation/mulching/use of pre-existing vegetation	- To stabilise failed slope (area of failed slope) - To mulch agricultural land (area of mulched land) - To landscape an open space (area of open space)
		Rain/infiltration garden	- Detention and treatment of stormwater (volume of water treated or water storage capacity) - Stormwater treatment (impervious drainage area)
Water	Swales	- To store and transport water for stormwater management (volume of stormwater) - To control stormwater runoff (impervious drainage/catchment area) - To convey discharge (length)	
	Constructed wetland for wastewater treatment	- To treat wastewater (volume of treated water, or number of person equivalents of treated wastewater with an effluent discharge requirement) - To reduce emissions of nutrients and biochemical oxygen demand (BOD) to acceptable levels (mass of daily organic load of domestic sewage treated to legal standards)	
	Remeander rivers	- To supply potable water to the end users (volume of supplied water)	
	Excavation of new waterbodies (ponds, lakes)	- To provide clean, potable water (volume of water delivered to consumers)	
		- To control stormwater runoff/to treat discharge (impervious drainage area) - To store water (storage volume)	

Table 2. Cont.

	NBS Typologies	Functions (Functional Units)
On building and structures	Intensive/extensive green roofs	<ul style="list-style-type: none"> - To serve as a roof = building component (rooftop area, or volume stratigraphy) - To produce vegetables (mass of vegetables) - To minimise runoff quantity and improve runoff quality (volume of runoff, or impervious drainage area) - To transfer energy (energy, or area with a given thermal transmittance, also known as U-value)
	Green facade	<ul style="list-style-type: none"> - To serve as a facade = building component (facade area)
Strategies and Actions	Composting	<ul style="list-style-type: none"> - To manage organic waste (mass of waste)
	Sustainable use of fertilisers	<ul style="list-style-type: none"> - To produce fertiliser (mass of fertiliser) - To fertilise arable land (mass of fertiliser with a specific nutrient composition per land area) - To manage a nutrient-containing substrate (mass of substrate) - To harvest crop (crop response = (mass of crop/ha)/(mass fertiliser)) - To produce seaweed extract (mass of product)

Table 2 also shows that, for the same NBS type, various functions may be considered depending on the goal and scope. A total of 49 out of 130 studies consider the NBS surface area (m², ha, etc.) as a functional unit. In six LCA studies [32,43–47], two FUs are considered for the same function. These are LCA studies of agricultural products (vegetables or wood products), for which it is common to consider both the mass of product and the cropland/forest area.

Despite the fact that multifunctionality of NBS is often mentioned in the studies (44%), it is actually considered only in three studies. Two ways of addressing this issue exist. The first one consists in considering a different FU for each function. In Golkowska et al. [48], the authors consider that a buffer strip can, at the same time, (1) protect the water body (corresponding FU: 1 ha of buffer strip) and (2) mobilise locally sourced biomass for electricity production through anaerobic digestion (corresponding FU: 1 kWh of electricity produced). The second way of addressing multifunctionality is to consider a single, inclusive, functional unit for the whole system. In Rothwell et al. [49], the identified functions of the urban farm/forest system are (1) food production, (2) housing, and (3) afforestation. Those are combined in a unique function (to use land for multiple functions), and the authors consider one FU for the whole scenario, i.e., a surface of peri-urban land. In addition, results are provided for the horticultural system separately for a mass of agricultural product. In Li et al. [50], the identified functions of desealed areas are (1) to increase available water resource, (2) to alleviate urban water logging disasters, and (3) to reduce rainfall runoff pollutants. The authors consider a general FU for the whole system, i.e., a surface of rainwater harvesting (RWH) construction areas.

With regard to the scope of the studies, and, in particular, to the system boundaries, less than half of the LCA studies (40%) assess cradle-to-grave systems. This mainly concerns parks and gardens (8 out of 15 studies), ecological restorations (5 out of 8 studies), strategies and actions (5 out of 10 studies), and building structures (16 out of 33 studies). Structures characterised by food and resource production mainly consider cradle-to-gate (generally retail gate or consumer gate) systems (only 4 out of 17 studies had cradle-to-grave boundaries) because of the chosen function (i.e., to produce food).

Regarding geographic location, 40% of the studies refer to European sites, a third of them (31%) to North American sites, and 18% to Asian sites. Only five studies are located in South America, four in Oceania, and two in Africa, while three studies do not specify any location. This information can have a direct effect on the chosen LCIA method (e.g., TRACI method for studies from USA).

System timeframes are generally chosen to be large enough to consider long-term mechanisms, such as CO₂ sequestration, landfill emissions, life of the system (e.g., building), etc. In total, 25 studies consider a lifetime of the system or period of analysis of less than 20 years, 54 studies with timeframes from 20 years to 45 years (about half of them are set to 30 years), and 25 studies with timeframes greater than 50 years (with 20 of them set to 50 years). Note that 26 studies do not specify this information, which is yet crucial for the analysis.

3.2. LCA Phase 2—Life Cycle Inventory (LCI)

The carbon sequestration capacity of the NBS considered in the studies analysed is presented in Table 3. Carbon sequestration for NBS on the ground ranged between 0.08 and 290 kg CO₂/m²/year. Two publications show a higher carbon sequestration compared to other systems: Strohbach et al. [51] (carbon storage in tree above-ground biomass) and Tidåker et al. [52] (carbon storage in turf of golf courses). If we exclude these two outliers, all carbon sequestrations were lower than 3.4 kg CO₂/m²/year.

Table 3. Carbon sequestration of NBS (kg CO₂/m²/year) in studies analysed.

Type of NBS	Number of Studies	Minimum	Maximum	Average	Standard Deviation
On the ground	7	7.81×10^{-2}	3.00×10^1	5.18	1.10×10^1
Water	5	3.39×10^{-1}	2.32	7.95×10^{-1}	8.59×10^{-1}
Building	3	4.89×10^{-2}	1.88×10^{-1}	1.11×10^{-1}	7.04×10^{-2}

Regarding water and building systems, all carbon sequestrations were, respectively, lower than 2.3 and 0.2 kg CO₂/m²/year.

Only in two studies published by authors from the same research group [53,54] is the mass balance respected about the elements (including carbon) on the system. Because pollutant mass balance is crucial to determine wastewater treatment efficiency, those two studies are pivotal to represent an important aspect in the LCA of constructed wetlands. Yet, mass balance is also crucial for other natural systems, but no other publication analysed here performs this exercise.

Only 22 studies out of 69 using organic/mineral fertilisers or pesticides take into account the emissions occurring in the environment (N₂O, NH₃, P, heavy metals, active substances, etc.) after the application of these products. In addition, out of those 22 studies, only 6 provide information on the models/sources used or the details on the calculations. Yet, all studies that consider these field emissions emphasize their significance on the environmental impacts of the studied systems.

3.3. LCA Phase 3—Life Cycle Impact Assessment (LCIA)

Table 4 shows the LCIA indicators considered per category of NBS. At midpoint level, the impact categories considered by the authors almost systematically include climate change (with different names of indicators depending on the LCIA method, i.e., Global Warming/Global Warming Potential (GWP) or Climate Change), very often eutrophication, acidification (which may be explained by the management of NBS likely to generate this type of impact), and abiotic resource depletion, and frequently human toxicity, ozone layer depletion, ecotoxicity (soil, fresh and sea water), photochemical ozone formation, and respiratory effects. To a lesser extent, indicators to address energy-based impact categories (e.g., indicator of cumulative energy demand), water deprivation, and ionizing radiation are also considered. Surprisingly, impacts due to land use (occupation) and/or land use change (transformation), although specifically relevant when dealing with NBS, are not much considered (in 23 studies out of 130). At the endpoint level, typical endpoint impact

indicators referring to the three areas of protection (i.e., human health, ecosystems, and resources) are almost equally considered.

Table 4. Midpoint and endpoint indicators' recurrence in the studies analysed, per NBS category and in total.

Impact Category	Category (Number of Studies)	On the Ground (44)	Water-Related (43)	On Building and Structures (33)	Strategies and Actions (10)	TOTAL (130)
Midpoint categories						
Global Warming		41	41	29	10	123
Energy/energy consumption/ cumulative energy demand		12	10	5	0	27
Non-renewable resource depletion (metals/minerals and fossils)		17	24	18	8	68
Acidification		20	28	20	9	78
Nutrient enrichment/eutrophication (fresh and sea water)		24	34	20	10	89
Photochemical ozone formation/smog formation		11	21	14	7	54
Particulate matter/respiratory effects		11	16	8	5	40
Human toxicity		14	22	15	7	59
Ecotoxicity (soil, fresh and sea water)		12	24	14	5	55
Ozone layer depletion		9	24	16	6	56
Ionising radiation		3	8	2	4	17
Land use (both agricultural and urban)		7	8	4	4	23
Water use/depletion/scarcity		11	8	2	3	24
Endpoint categories						
Human Health		5	6	4	0	15
Ecosystems		5	6	5	0	16
Resources		4	6	4	0	14
Aggregated impacts						
Single score		7	4	4	2	17

Colour code: pale yellow: the number of studies considering this impact category is lower than 25% of the total number of studies for this NBS category; pale orange: the number of studies considering this impact category ranges between 25% and 50% of the total number of studies for NBS category; dark orange: the number of studies considering this impact category ranges between 50% and 75% of the total number of studies for this NBS category; red: the number of studies considering this impact category is higher than 75% of the total number of studies for this NBS category.

In total, 21 studies are mono-criterion (20 only considered GWP or CO₂ emissions, and one only dealt with water), while 9 multicriteria studies consider two indicators (mostly GWP and energy, with one exception considering GWP and land use), while 100 multicriteria studies consider more than two indicators. In 12 studies (9%), both midpoint and endpoint indicators are selected for the impact calculation phase.

The most applied LCIA methods are ReCiPe2008 or 2016 (36 studies) and CML2000 or 2001 (27 studies), followed by TRACI US (14 studies) and IMPACT2002+ (8 studies), Eco-Indicator (6 studies), and the ILCD method (3 studies). The use of one or another method necessarily depends on the date of the publication and the geographic location of the studies. Mix of methods are often used, and sometimes the names of the methods are

not specified at all (in 21% of the studies). This certainly introduces an uncertainty factor for the interpretation and comparability of the results from such LCIA studies.

Only values of climate change per square area and per a timeframe have been selected to compare the climate change impact of NBS (i.e., publications expressing climate change per water volume, agricultural product, or other FU, or publications giving values in mass of CO₂ without precisions on the area or the time have been excluded). All values have been converted to a common unit of kg CO₂/m²/year. However, the area can refer to two different areas: either a real, physical area (footprint area) for NBS on the ground, on buildings, or for some water systems; or a theoretical area (drainage/catchment area), which is specific to drainage water systems. Thus, results are presented separately for these two considered areas in Figure 2 and plotted on a logarithmic scale (excluding four negative values of −0.0073, −0.0058, −0.017, and −0.23 kg CO₂/m²/year due to consideration of carbon storage, respectively, for a green strip, a green roof, a wood, and a constructed wetland).

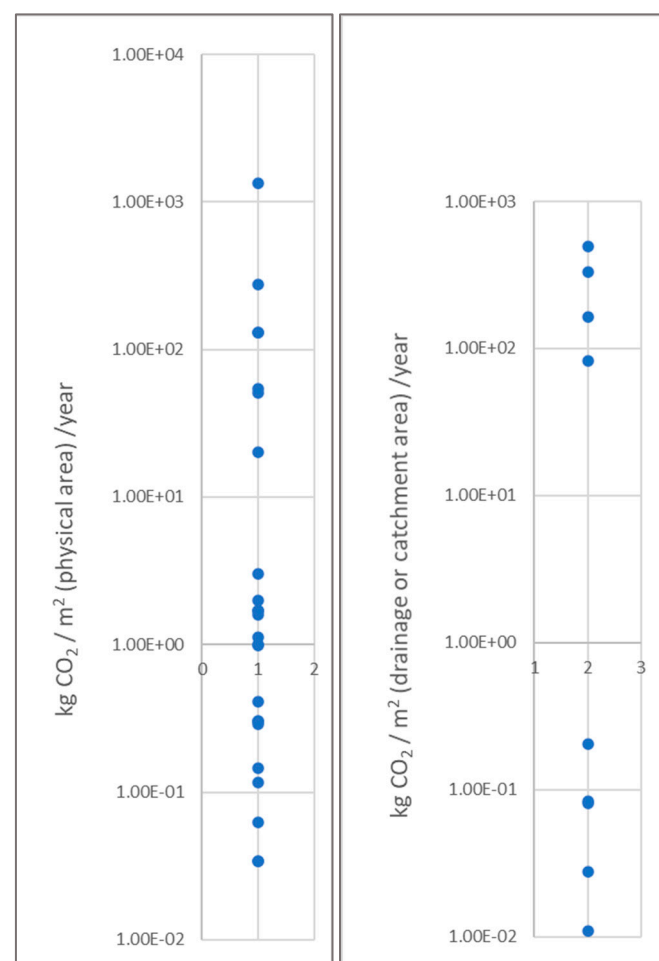


Figure 2. Impact of NBS on climate change (kg CO₂/m²/year) in studies analysed.

Regarding climate change impacts expressed per footprint area (mainly NBS on the ground and on buildings), the NBS contributing most to climate change are three urban farms, a public green space, a golf course, and a green roof. All other NBS have a climate change impact lower than 10 kg CO₂/m²/year. Except for one green roof (50 kg CO₂/m²/year), all building systems have climate change impacts comprised between 0.4 and 3 kg CO₂/m²/year (note that mainly green roof systems are considered due to a lack of details on units for green wall systems). The NBS with the smallest impacts (i.e., < 1 kg CO₂/m²/year) are two lawns, one green strip, one green roof, and two water-related systems (expressed per footprint area).

Regarding climate change impacts expressed per drainage/catchment area (only water systems), there is a high variability which cannot be explained by differences between systems, but rather by differences between publications: all values from Bixler et al. [31] are higher than the ones from Xu et al. [38].

Regarding normalisation and weighting of the results, the analysis of the papers shows that authors typically normalise results in 39 studies (30% of the total) and weight them in 20 studies (15% of the total).

3.4. LCA Phase 4—Interpretation

Given the great variety of analysed NBS, no global trend can be observed for the interpretation of the results. Yet, some recurrent hotspots—i.e., life cycle stage responsible for the largest relative portion of the impacts and the main processes contributing to the impacts—can be identified: on the ground, the application of fertilisers and pesticides and irrigation, and, to a lesser extent, the transportation of materials and maintenance operations (mowing, pruning) are often responsible for a large part of the impacts. For water-related and building systems, the consumption and road transportation of materials often represents the life cycle stage with the largest impacts. However, generally, construction stage and operational stage do not contribute to the same impacts: the construction stage is a relevant contributor to abiotic depletion and GWP, while maintenance operations have large impacts on eutrophication or ecotoxicity.

A sensitivity or uncertainty analysis is performed in almost half of the studies (47%).

The main limitations of the studies are represented by the general lack of data and their large variability (in terms of field emissions inventories, e.g., N₂O emissions from decomposition of grass clippings, or crop yields, etc.), which is linked to the variability of NBS within the same type, the excluded life-cycle stages, and the limiting hypotheses (e.g., not considering production and application of pesticides and fertilisers, or limited emissions and leaching of contaminants, not considering indirect land use change nor carbon sequestration and storage, etc.).

4. Discussion

Some methodological challenges raised by the application of LCA to NBS were identified. The most interesting and debatable issues are predominantly related to the goal and scope and LCI phases of the LCA method.

4.1. NBS Coverage in LCA Literature

Many NBS types, as described in Table S1 in the Supplementary Material A, did not come up in the literature. If we exclude uncommon solutions, we still have some common NBS that were never studied. For example, quarry restoration projects have never been assessed with LCA according to our review; these projects are usually subject to an environmental impact assessment (EIA), which is more pertinent than LCA to capture the local dimension of NBS projects and potentially their impacts on flora and fauna. Many NBS from the strategies and actions group have also never been assessed with LCA. The fact that LCA has been historically conceived, developed, and applied to products and services makes its application to urban planning projects or urban strategies less straightforward than for human technologies or semi-natural or artificial systems. These NBS cover a wider area, and the application of LCA to urban scales could present several drawbacks [55], such as the huge amount of LCI data to compute, a more complicated definition of their functional unit and boundaries, and a more difficult interpretation of the results, so the LCA framework needs to be adapted to apply at the regional scale as support to urban strategies [56]. Yet, LCA could provide valuable information to decision makers and help them in the elaboration of urban strategies.

In this regard, relevant LCA-based studies that make use of LCI data and/or single-issue footprint indicators have recently emerged in the literature. For example, the use of integrated carbon accounting approaches based on the combination between a carbon

footprint and a carbon sequestration evaluation results in effective showcasing of climate change mitigation benefits associated with improved management of municipal green waste [57], forests management strategies [58,59], NBS potential for wetlands–peatlands and oceans [60,61], solutions of soil amendment with powdered basalt in natural ecosystems [62], and potential implementation of plants and soils within the built environment [63,64]. This is also true in cases where additional indicators of ecological benefit, such as the capacity of NBS to remove water pollutants, are added to carbon sequestration indicators for enhancing the overall impact assessment [65–67], making the LCA approach an effective tool for tradeoffs and synergies analysis. Research should thus be directed towards improving the application of LCA to such and other innovative NBS projects, possibly undertaking an “impacts Vs. benefits” balance (not only of environmental, but also of economic nature), as highlighted by studies published in the latest months [68–70].

In addition, while, in the European sites’ case, a large number of typologies of NBS are considered, for other regions, this is not the case. The reason for this finding is not clear, but it is probably due to a simple issue of occurrences: the more studies are made for a region, the higher the probability that more NBS typologies are assessed. Such observation nevertheless requires further analysis and feedback in the future, since hydrological, climatic, and socioeconomic conditions can affect the effectiveness of NBS [71], and thus can play a role in the choice of NBS. For example, none of the studies conducted in South America, Oceania, and Africa evaluates NBS typologies on the ground (except for two studies that assess urban farms), or green walls, hampering the ability to understand whether this is due to the lack of implementation of NBS in those regions or to the higher fragmentation of evaluations compared to European sites.

4.2. Use of the Ecosystem Services (ES) Concept to Classify and Quantify the FUs of NBS

NBS are generally implemented to address challenges faced by cities, such as climate change, increase in flood events, decline in biodiversity, air pollution, etc. Therefore, it is logical to assume that the functional units chosen in LCA studies shall reflect the urban services delivered by the NBS, or, in other words, the benefits people obtain from these ecosystems. These services, named “ecosystem services” (ES), can be divided into four categories: (1) provisioning services, i.e., the products obtained from ecosystems, such as food, fibre, fuel, freshwater, ornamental resources; (2) regulating services, such as air quality regulation, climate regulation, water regulation, erosion regulation, water purification and waste treatment, pollination, natural hazard regulation; (3) cultural services that provide recreational, aesthetic, and spiritual nonmaterial benefits; and (4) supporting services, which are generally indirect or long-time occurring processes necessary for the production of all other ecosystem services, e.g., soil formation, photosynthesis, primary production, nutrient cycling, and water cycling [3]. Following this classification, the functions described in Table 2 can be grouped into the four types of ES provided by the NBS (Figure 3).

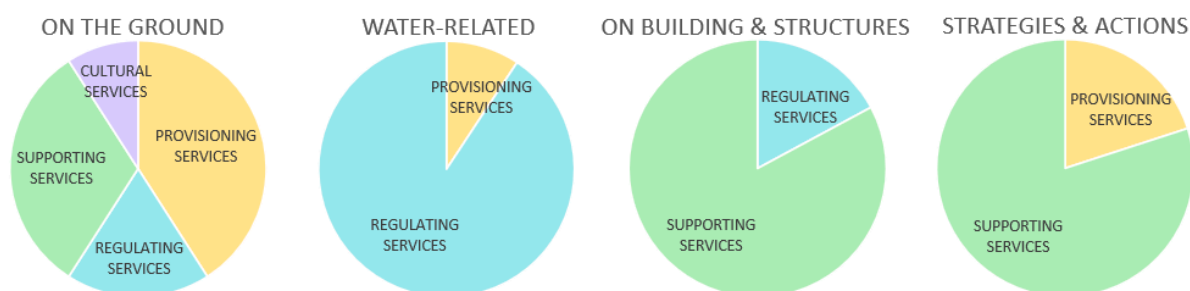


Figure 3. FUs classified according to the ES concept, for each category of NBS covered by the literature review.

NBS on the ground show a more balanced share of delivered ecosystem services than other systems, with 18 LCA studies that consider a function related to the provision of

a product (41%), 8 studies related to regulation services (18%), 14 studies to supporting services (32%), and 4 studies to nonmaterial benefits (9%). Note that only NBS on the ground consider cultural services, mostly in relation to recreational aspects of NBS (football field, golf course, safari park, leisure activities). Functions of water-related NBS are mainly focused on water regulation services provided by the NBS (91%), with only three studies that consider as function the supply of a volume of freshwater (provisioning service). Conversely, the functions of building NBS are primarily related to supporting services (83%), because the studies often consider as function the surface area of a building component (i.e., wall or roof), which is an indirect, inclusive function covering many services generated by green walls and roofs (building structure support, climate, water, air quality regulations, etc.), and secondarily to direct regulating services (17%), through the function of runoff management (FU = impervious drainage area) of six green roofs studies. Finally, regarding strategies and actions NBS, only two studies consider a provisioning service (production of a seaweed-based biostimulant), whereas other functions are mainly related to support services (80%), and, more precisely, to nutrient cycling, because NBS were related to a sustainable use of fertilisers and to the treatment of organic waste through composting. Nevertheless, the classification of these systems in supporting or provisioning services is not straightforward because the treatment of organic waste can be just as well associated with nutrient cycling management as to the provision of a new product (e.g., compost). Although the link between ES and LCA has been extensively discussed [72–82], it has been, for now, mainly restricted to the *LCIA phase* of LCA, and only partially to the *LCI phase*. To our knowledge, the use of the ES concept and classification to qualify the functions and FUs of life cycle models is new in LCA. Using ES directly as FU paves the way to more relevant and accurate FU and for territorial approaches given that an NBS can have as many FU as provided ES. This is a change of paradigm: the ES are no longer seen as positive externalities but rather directly as “units” for comparing NBS.

In addition, note that, if the implementation of an NBS generally provides new urban services, it can also mean losing some other functionalities (e.g., transformation of a meadow into a park or it can generate ecosystem disservices, e.g., pollen allergies, introduction of invasive species, emissions of volatile organic compounds (VOC) from plants [14], and these aspects should be taken into account in LCA studies.

4.3. Perspectives to Deal with the Multifunctionality of NBS

The impacts shall be calculated for a functional unit that reflects the service(s) provided by the system. Yet, NBS are almost systematically multifunctional systems, as confirmed by Table 2, which shows that multiple functions for the same NBS type may exist depending on the study. Nevertheless, the literature review shows that, despite being often mentioned by the authors (e.g., filtration of air pollutants, carbon dioxide capture, cooling a building/street, water regulation, etc.), multifunctionality is rarely considered. A probable explanation is that this issue constitutes a methodological challenge in LCA [83]. Some guidance has been already provided to handle the multifunctionality issue in the ISO 14044:2006 [16] and in the ILCD Handbook [39], with different approaches for solving multifunctionality (subdivision of multifunctional processes, system expansion including substitution, and allocation). More recently, Laurent [84] proposed in her PhD a score-based procedure to define the main function of the studied system in close relation to the territory where it is located. To complete the assessment, once a single FU has been selected (focusing on the main ES supplied by the NBS, or considering an inclusive, general FU, such as the surface area), the LCA practitioner should, when possible, account for other functions/services provided by the NBS in the LCI (e.g., energy savings through negative energy flows, air pollutant removal through negative air emissions flows, other production of material goods through the consideration of co-products). Multifunctionality is thus considered through the quantification of additional externalities. However, if this is feasible for regulating or provisioning ES, it would appear more difficult to envisage for supporting and cultural ES, because those are less compatible with the set of elementary flows in

LCI [72]. Loiseau et al. [85–87] propose another radically different but promising approach, which allows the selection of a main functional unit to be overcome through a change in paradigm compared to a classic product LCA. These authors have developed a “territorial LCA” methodology for territories—which are by nature multifunctional systems—in which a set of land use functions needs to be defined and quantified, as for environmental impacts. The vector of land-use functions and the vector of environmental impacts are then used to compute eco-efficiency ratios (impact per functional unit), and there is no more need to determine the appropriate “main function” of the studied system. The same approach could also be applied, with little adjustments, to NBS, and decision makers, such as urban municipalities, could rely on eco-efficiency ratios related to the specific urban challenges they want to tackle. For example, for an urban park, eco-efficiency ratios giving the climate change impact (in kg CO₂ eq.) per m² of recreational area or the eutrophication potential (in PO₄³⁻ eq.) per m³ of wastewater treated could be computed. Another recent and promising approach has been proposed for agricultural systems by Boone et al. [88] to deal with the multiple ES provided by ecosystems. Recognising that LCA does not account for all ES supplied by agroecosystems, thus failing to provide a fair and complete comparison between organic and conventional systems, the authors propose an allocation procedure based on the capacity of agricultural systems to deliver ES (including provisioning services, i.e., agricultural outputs). This approach, if applied to NBS, could pave a way to deal with multifunctionality (i.e., allocation of impacts between all ES rendered by NBS), whilst ensuring a more complete comparison of the environmental sustainability of NBS and grey solutions. However, the main challenge for the application of territorial LCA from Loiseau et al. or ES allocation from Boone et al. is the quantification of the ecological functions of NBS, which are generally complex and which depend on specificities of the systems, on their implementation/maintenance practices and on their environment [72]. In addition, for the ES allocation method, further research should focus on developing allocation factors adapted to NBS. On a more philosophical level, multifunctional and complex systems challenge the whole LCA framework because forcing activities into producing one function (or even producing anything at all) can limit the LCA practitioner’s ability to see underlying concepts or truths. Finally, in relation to territorial LCA, a more regional approach to the LCA of NBS is also needed. NBS should not be planned in isolation if we are calling for more sustainable and green urban planning, and knowing which combinations are optimal is essential. The impacts and benefits of several combined NBS might also not be equal to the sum of the impacts and benefits of each NBS taken into account separately. Few articles have dealt with combinations of NBS [89–93] and they all focus on urban water management solutions. They often study water-related NBS at the urban watershed scale at which water management strategies are deployed. Further research should be dedicated to investigating the combination of other types of NBS (i.e., not only water-related) in order to study the additional benefits of NBS combination compared to individual NBS, and also to propose optimal NBS combinations to urban planners.

4.4. Pros and Cons of a “Surface Area” Function

In order to build a generalised framework encompassing all the benefits provided by the NBS, a compromise frequently adopted by LCA practitioners in the literature review is to consider the NBS surface area as a single, inclusive functional unit (in 38% of the studies analysed). This FU is—often implicitly—associated with the function “to provide multiple services (social, economic, environmental)”. This is in compliance with the idea that a piece of land is a source of multiple benefits and resources, as proposed in other assessment methodologies. For example, the ecological footprint method uses the notion of “productive land” [94], while the ecosystem services approach uses the notion of “service providing unit (SPU)” [95] or, more recently, of “service providing area (SPA)” [96]. Nevertheless, the surface type differs according to the type of NBS. For example, studies on ground NBS analysed in this paper consider an area of lawn, of sports field, of buffer strip, of

agricultural land, or of contaminated site to remediate, while studies on building NBS use a façade area or a rooftop area (see Table 2).

On one hand, considering “surface area” as FU presents the following advantages: (i) it eases the comparison between NBS providing the same service(s). For example, when analysing NBS with multiple functions, fixing an FU based on Function A for NBS #1 and an FU based on Function B for NBS #2 would prevent comparison of NBS #1 and NBS #2 if they also have a same Function C. (ii) It allows a baseline scenario to be taken more easily into account. Precisely because the implementation of an NBS is motivated by the need to provide at least a new, currently lacking, service, it can be difficult to define the same function before and after implementing the NBS. Considering the occupation of 1 m² as FU may allow this issue to be overcome, (iii) it provides consistency between different types of assessments (e.g., environmental and socioeconomic) and facilitates the comprehensive assessment of NBS.

On the other hand, considering “surface area” as FU presents the following disadvantages: (i) a generic FU based on “surface area” may not be applicable to all NBS, i.e., according to the literature review, some NBS have never been assessed through LCA with surface area as FU (e.g., swales, constructed wetlands for wastewater treatment, or composting); (ii) in addition, even if applicable, an FU based on “surface area” may not be the most relevant FU that can be chosen for an NBS, as an NBS is rarely implemented to “occupy an area” per se.

4.5. Baseline Scenario and Comparison of NBS with Grey Solutions

The literature review further shows that the case studies pursue different goals: they are either conducted for eco-design purpose or with a comparative perspective, generally comparing NBS (“green solutions”) with so-called “grey solutions”. In the first case, and in the case of assessing the environmental performances before and after implementing NBS to support urban planning decisions, the baseline scenario is generally a “no NBS” scenario, which can also be referred to as “before NBS implementation” (or “business-as-usual”), assuming that the main services provided by the NBS are not provided before NBS implementation. This is justified by the fact that, if we implement an NBS in a city, it is because we want to provide some services that are currently lacking. Yet, this choice is often implicit in LCA studies and it should be explicitly stated to avoid any bias in potential comparisons of LCA results.

4.6. Recommended System Boundaries and Time Scale of the System

The present study reveals that only 56 studies consider the end of life of the system within the life cycle boundaries. Yet, in order to provide a comprehensive assessment and to identify burdens shifting from one life-cycle stage to another, the boundaries of the NBS should be from cradle to grave, i.e., from raw material extraction, through materials processing, production, distribution, and use stages (including NBS management), to end-of-life management, e.g., disposal or recycling. Regarding the time scale of the system, even if it will be NBS-specific, it must be long enough, i.e., at least 50 years, to consider long-term mechanisms, such as CO₂ sequestration, landfill emissions, lifetime of buildings, etc., as shown in the literature review. In addition, most of the LCA studies selected static parameter values while, in reality, the values are changing with time for NBS and other technologies. Considering the dynamic nature of NBS can play an important role in the results. Note that the system time scale is different from the time scale of impacts, which can range from years (e.g., acidification, eutrophication, and ecotoxicity) to very long time scales (e.g., climate change, ozone depletion, fossil and mineral depletion).

4.7. Consideration of Emissions in the Environment from the Application of Fertilisers and Pesticides

The LCI should include material, energy, and emissions flows from the fabrication of the NBS, through its use phase, up to its disposal. Yet, emissions of pollutants in the

environment during the application of mineral/organic fertilisers or pesticides, when used, are generally neither detailed nor even mentioned in the LCA studies analysed. This is a recurrent shortcoming, yet crucial for the LCA of bio-systems (see, for example [97]). For instance, emissions, such as nitrous oxide (N_2O) emissions, both direct and indirect (i.e., due to volatilisation, leaching/runoff), ammonia (NH_3), nitrate (NO_3^-), and phosphorus (P) emissions due to nitrogen- and phosphorous-containing fertiliser application, heavy metals from fertiliser application, and harmful chemical compounds (e.g., active substances of pesticides), should be taken into account with calculation procedures and hypotheses described, and sources provided (e.g., [98]) in future assessments of NBS. This can make more robust the calculation of impacts on climate change, acidification, eutrophication, or ecotoxicity, provided that LCIA methods have a complete coverage of elementary flows in order to properly evaluate the impacts. The inclusion of elementary flows will depend on the targeted impact categories: if we are assessing a climate-change-related indicator, it is important to include the quantities of powerful greenhouse gases, such as N_2O ; if we are assessing acidification, it is crucial to take into account the deposits of nitrogen and sulphur pollutants (NH_3 , NO_x , SO_2 , etc.); if we are including eutrophication within the selected impact categories, it is important to include N and P discharge to water bodies; and, finally, if we plan to assess ecotoxicity, the inclusion of heavy metals and harmful chemical compounds is essential. Furthermore, for all NBS where plants are grown, the boundaries between the LCI and the LCIA are less clear because the soil is both part of the system and an emission compartment, which is a methodological challenge in LCA [99–101]. Thus, clearly defining the boundaries between the LCI and the LCIA (i.e., where the LCI stops and the LCIA models take over) is key for a proper LCA of NBS.

4.8. Carbon Dioxide Sequestration and Carbon Balance

The LCA practitioner must also pay attention to the balance of chemical elements. Apart from 2 LCA studies out of the 130 LCA studies identified in the literature, in which the balance of chemical elements was carried out, none of the studies analysed lists the input and output flows or respects the carbon balance of the system. This is particularly critical for NBS, because they are often composed of plants that capture carbon dioxide (CO_2) through photosynthesis and store carbon. Thus, the balance on the carbon (C) element should be respected and detailed in the LCA study (including, if applicable, carbon dioxide sequestration from plants, carbon content of compost or substrate, emissions from composting, emissions from biowaste treatment, etc.). The LCA practitioner should also be careful regarding other nutrient balances (e.g., on nitrogen, phosphorus, potassium, etc.) for NBS which consider, for example, agricultural production.

4.9. Differentiation between the Impacts to Ease the Decision-Making Process

An indicator related to global warming is included in the majority of the LCA studies on NBS. Other impact categories very often considered by the authors are eutrophication and acidification. The differentiation between local/regional (such as eutrophication) and global impacts (such as GWP) is key for the interpretation of the results. Local impacts occurring on-site are generally essential for municipalities (while local impacts occurring off-site may not be as important for municipalities), but, over the last decade, global environmental issues, such as climate change and resource sustainability, have also become more important in policy making. The results of this review have been used to feed some of the datasets included in the tool “Environmental assessment” within the Nature4Cities Platform (www.nature4cities-platform.eu/#/assessProject, accessed on 1 February 2022), which aims at helping municipalities obtain information about the environmental impacts of their NBS project. In addition, even if none of the studies distinguish between on-site impacts (direct impacts due to emissions occurring on the NBS site) and off-site impacts (indirect impacts due to emissions occurring outside of the NBS site, e.g., manufacturing plants in other parts of the globe), this information is also key for the interpretation of the results [85,102]. These impacts may not be given the same weight in decision making for

NBS implementation. Moreover, in order to identify the main contributors to these impacts and to propose appropriate solutions to mitigate them (e.g., eco-design), the inventory data should be accessible and detailed enough, but this is not often the case at present. Access to the detailed inventory data is, thus, a challenge to ensure a useful interpretation of LCA results leading to the identification of hotspots.

5. Conclusions

This critical analysis of the literature attempted to derive global trends on the LCA methodology applied to NBS so far. This exercise was limited in generalisable outcomes because the NBS greatly differ from one another in their definition, their impacts, and the issues they are facing. Even if general, harmonised LCA guidelines applicable to all NBS would be beneficial for the comparison of LCA studies, building such guidelines would not be feasible in practice due to the variability of such systems. Nevertheless, some common methodological challenges and research needs in the field of application of LCA to NBS were identified and propositions to deal with them were made.

First, the definition of the functional unit in the case of multifunctional systems such as NBS is crucial. We discussed the pros and cons of considering the NBS surface area as a single, inclusive functional unit. Then, we proposed an innovative approach, shifting from the use of the ecosystem services (ES) concept in the LCIA phase as usually discussed in the LCA literature to its use in the scope phase of LCA in order to classify the functional units of NBS. We also identified two promising approaches to deal with the multifunctionality of NBS: (1) one based on the “territorial LCA” methodology developed by Loiseau et al. [87], for territories, which computes eco-efficiency ratios, (2) another one proposed for agricultural systems by Boone et al. [88], which suggests an allocation procedure based on the capacity of those systems to deliver ES. These two approaches not only allow dealing with multifunctionality of NBS, but can also ease the assessment of a combination of several NBS. However, the main challenge for the application of these two approaches is the quantification of the ecosystem services generated by the NBS.

Another major challenge is the consideration of emissions in the environment from the application of fertilisers and pesticides. Approximately 70% of the studies using organic/mineral fertilisers or pesticides did not take the field emissions into account, which is a huge lack given their significant impact on the environment. Overall, more attention should be given to the mass balance on chemical elements (nitrogen, carbon, etc.) in order to avoid neglecting meaningful input or output flows.

Finally, as a perspective, differentiations between local and global impacts from one hand, and on-site and off-site impacts from the other hand, are proposed to facilitate decision-making processes. In addition, depending on the objective of the study, the assessment of NBS can be carried out at different scales (e.g., object, neighbourhood, city), and this scale assessment should be adapted to the decision maker.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/land11050649/s1>. Table S1: Keywords for the selection of LCA studies, Table S2: LCA studies analysed.

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