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# Mitigation Life Cycle Assessment: Best Practices from LCA of Energy and Water Infrastructure That Incurs Impacts to Mitigate Harm

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**Abstract:** Climate change will require societal-scale infrastructural changes. Balancing priorities for water, energy, and climate will demand that approaches to water and energy management deviate from historical practice. Infrastructure designed to mitigate environmental harm, particularly related to climate change, is likely to become increasingly prevalent. Understanding the implications of such infrastructure for environmental quality is thus of interest. Environmental life cycle assessment (LCA) is a common sustainability assessment tool that aims to quantify the total, multicriteria environmental impact caused by a functional unit. Notably, however, LCA quantifies impacts in the form of environmental “costs” of delivering the functional unit. In the case of mitigation infrastructures, LCA results can be confusing because they are generally reported as the harmful impacts of performing mitigation rather than as net impacts that incorporate benefits of successful mitigation. This paper argues for defining mitigation LCA as a subtype of LCA to facilitate better understanding of results and consistency across studies. Our recommendations are informed by existing LCA literature on mitigation infrastructure, focused particularly on stormwater and carbon management. We specifically recommend that analysts: (1) use a performance-based functional unit; (2) be attentive to burden shifting; and (3) assess and define uncertainty, especially related to mitigation performance.

**Keywords:** life cycle assessment; energy; water; climate; mitigation; sustainability

## 1. Introduction

Life cycle assessment (LCA) is a sustainability quantification tool used to assess and evaluate multicriteria impacts of all activities associated with an unit of analysis—for example, a product, process, system, or service [1–4]. This unit of analysis, called a functional unit, explicitly defines what is being assessed, usually with reference to a particular function over a period of time. Conventionally, LCA is used to evaluate negative environmental impacts resulting from life cycle activities from resource extraction through end-of-life associated with a product system [5,6]. LCA typically focuses on environmental assessment as one element of sustainability assessment [7], though there is increasing interest in including non-environmental markers of sustainability and expanding the meaning of “life cycle” accordingly in order to enable a more inclusive definition of sustainability [3,8–11].

Unlike single-issue sustainability quantification tools like carbon, energy, and water footprinting [12–15], LCA is designed as a multicriteria evaluation method [7]. Although in practice many life cycle studies specifically highlight climate pollution [16], the multicriteria nature of LCA is

crucial for a more holistic understanding of environmental sustainability because of the potential for burden shifting when seeking improved environmental performance in a specific area [17]. For example, an intervention designed to reduce climate change pollution from the energy sector might increase freshwater consumption, as in the case of biofuel substitution for oil [18–20]. Whether this outcome is more sustainable is ultimately a question of values [18,21], but the multicriteria nature of LCA makes the burden shift visible.

### 1.1. Environmental LCA for Mitigation Infrastructure

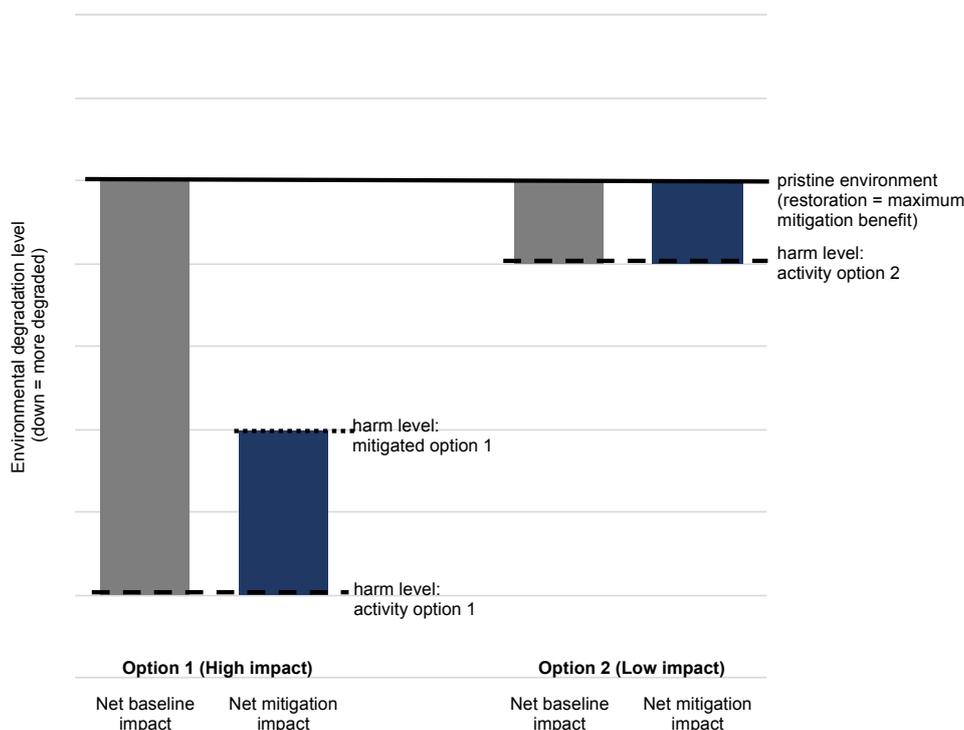
Understanding the nature and extent of these burden shifts, both within and beyond environmental impact, is particularly important in a world experiencing climate change. Climate change creates a nonstationary environmental context and exacerbates the need for new infrastructure types and intensities. Reducing harm from climate change in particular will likely lead to installation of substantial infrastructure intended to mitigate specific but uncertain environmental harms, which we call “mitigation infrastructure” in this work. This paper focuses specifically on environmental life cycle assessment of such infrastructures, which we call “mitigation LCA,” with the goal of guiding current LCA practice to be more relevant for analysts and decision makers seeking guidance in the context of sustainable infrastructural buildout under climate change. We recognize this use of the term “mitigation” in this paper differs from its use in some climate change literature where mitigation refers specifically to emissions reductions. For this paper, mitigation infrastructure can include approaches that would be considered both mitigation and adaptation in climate change literature.

Our focus on mitigation LCA within the context of sustainable water and energy infrastructure is motivated in part by the critical nature of such infrastructures under climate change. Concerns like water management under nonstationary climate conditions and pollution reduction from energy systems merit urgent attention because, given extant environmental harm, the “reference” or “do nothing” case for many mitigation infrastructures is not environmentally benign. For example, failing to control stormwater in urban settings can lead to damaging floods, and uncontrolled carbon dioxide emissions from power plants expected to run for many years into the future exacerbate climate change. We highlight, however, that lessening the impacts of existing harms through mitigation infrastructures is generally also not environmentally harmless.

Mitigation infrastructures, such as stormwater control measures (SCMs) and carbon capture and storage (CCS) systems, are physical systems that require environmental investment in the infrastructure itself, often in impact categories other than those the infrastructure is designed to alleviate. Inputs like steel, concrete, chemicals, and others have embodied environmental impact; operating the infrastructure requires ongoing investment of resources that create environmental harm; and managing end-of-life processes generates investment of environmental impact. Thus, characterizing mitigation infrastructures purely by the environmental remediation they perform is inappropriate, particularly when the invested impact is not categorically similar to the environmental impact the infrastructure is designed to improve. For example, a wastewater treatment plant (WWTP) might improve water quality by generating greenhouse gases (GHG) and solid wastes [22].

Denoting mitigation LCA as a subtype of LCA builds on prior observations that LCA focused on “end-of-pipe” technologies is distinct from other LCA because of the presence of some form of environmental benefit associated with financial or other investment [23] versus the more typical situation of environmental cost associated with financial gain (e.g., from production of a product for sale). We distinguish “mitigation LCA” from end-of-pipe LCA in part because of observations that, particularly under climate change, infrastructures are being built to mitigate environmental harm that is already occurring, as opposed to preventing the last stage of a process (e.g., preventing GHG formation). For example, stormwater control and post-combustion capture of carbon dioxide are both designed to ameliorate “committed” harms associated with prior or continued business-as-usual operation of human infrastructure, like impervious urban surfaces [24] or fossil fuel-burning power plants [25].

A fundamental characteristic distinguishing mitigation infrastructures from other infrastructures in the context of LCA, meriting specific consideration of mitigation LCA, is that these investments would not occur if there were not a need to improve a specific aspect of environmental quality. Further, these infrastructures are improving environmental quality only relative to a degraded baseline, reclaiming a portion of lost environmental carrying capacity rather than avoiding infringement of this carrying capacity in the first place [7]. The maximum achievable benefit is thus restoration of the pristine condition for the mitigation target (Figure 1).



**Figure 1.** Mitigation infrastructure improves environmental conditions relative to a degraded baseline, not relative to a pristine environment. Life cycle assessment (LCA) typically evaluates environmental burdens imposed by some activity (dark grey). Mitigation LCA is different than typical LCA studies because there is some implied improvement to environmental conditions, but it is important to note that this improvement is relative to the degraded, not pristine, environmental baseline (dark blue) when describing environmental outcomes as “benefits.” Mitigation cannot improve conditions relative to the pristine baseline, though more of a mitigation activity could theoretically result in a restored pristine condition for the mitigation target (as shown for Option 2). Thus, the “benefit” of mitigation differs from harms traditionally assessed by LCA in that doing more of the activity does not necessarily proportionately increase it.

For example, remediating chemical contamination reduces harm (i.e., by lowering chemical concentrations in soil) without actually improving environmental quality relative to the original pristine environmental condition. This harm reduction comes at the cost of shifting environmental burdens to other impact categories associated with the remediation outcome [26]. This after-the-fact harm reduction mission, versus a pre-harm prevention mission, makes mitigation LCA subtly different from LCA of systems designed to provide some non-environmental service in a more environmentally benign way.

To further illustrate this, consider that a zero-carbon power plant might be preferred over a carbon-emitting power plant, but both are generating electricity as their primary function. In the former case, less environmental harm per functional unit (e.g., electricity generated) is created due to characteristics of the main product system. This is distinct from the role, for example, of CCS infrastructure added to an existing power plant, which is purely to correct a committed environmental

harm (e.g., GHG production). It cannot be independently evaluated with the same electricity generation-related functional unit as a power plant.

Notably, a power plant with CCS would not be considered mitigation infrastructure in the way that a CCS addition to an existing plant for the purpose of remediating committed carbon emissions from the plant would be, as the former still represents a complete product system providing some service other than environmental harm mitigation. This observation also highlights that from a theoretical LCA perspective, mitigation infrastructures would ideally be components of more complete product systems that internalize their full impact profiles. In that case, wastewater treatment burdens are attributed to wastewater-generating activities; stormwater management burdens are attributed to stormwater-generating activities; and so on. In practice, however, substantial environmental burdens have accumulated or been committed already, sometimes from diffuse and unknown sources. These require management by new, distinct infrastructures. Being able to compare the environmental impacts of various harm mitigation solutions is valuable for reasons similar to those for comparing environmental impacts of nonenvironmental service-providing product systems. If the harm reduction effort is being undertaken, we would prefer to use the most environmentally benign approach to reducing harm.

### *1.2. Why LCA Is an Appropriate Sustainability Quantification Tool for Mitigation Infrastructure*

Perhaps a more familiar way to describe the difference between what LCA results show and what readers might expect LCA results to show is to analogize LCA with its sibling method of life cycle costing (LCC) and more generally with monetary cost quantification tools. Much like an LCC or other cost estimate reports the total amount of money that must be invested in a project, LCA reports the total amount of environmental burden (over multiple impact categories) that must be invested. Financial assessment tools differentiate between costs and returns, with a suite of terminology designed to express the differences among capital costs, operating costs, revenues, profits, and so on. Environmental assessment tools operate using roughly the same framework, but with the added complexity that environmental impact occurs in non-commensurable impact categories using different units (e.g., GHG emissions versus toxicity) rather than within a single financial framework. (Note: some impact assessment methods use weighting methods to report a single result but produce intermediate results in different categories.) In LCA, however, there is very little language to describe environmental return (analogous to revenue), in part because environmentally regenerative activities are typically performed in reference to a preexisting harm, as with waste management.

One of the current challenges associated with using LCA to assess mitigation infrastructure is that LCA is fundamentally designed to provide a quantitative estimate of the environmental harm associated with some activity, not the benefit or net impact [5,27]. (We note that this structure has been a particular challenge for the development of social life cycle assessment, or S-LCA, in part because many social impacts can be either positive or negative depending on context [28].) This emphasis on environmental burden associated with some functional unit means that when LCA of mitigation infrastructure is not designed around a functional unit that appropriately communicates the infrastructure's environmental harm mitigation, results can be confusing. For example, LCA results for SCMs are commonly presented as impact per unit of catchment area [29]. Users of these results are likely to understand this framing to be a net impact, accounting for both the investment of environmental burden and return in the form of environmental harm reduction from the SCM, because the SCM explicitly exists to provide some environmental service. Conventional LCA practice, however, would report invested impact only, with the environmental benefits of the SCM assumed as part of the product system. For example, Brudler et al. report emissions of 11,500 tonnes of carbon dioxide equivalent for "the management of all additional runoff expected due to CC [climate change] in a catchment area of 2.6 km<sup>2</sup>, while meeting well-defined flood safety requirements, for the next 100 years" by a cloudburst management plan in Copenhagen [30]. When results are presented without that functional context, the fact that LCA shows that investing in environmental remediation itself leads to environmental harm can lead to

a misunderstanding (and erroneous conclusion) that investing in the mitigation infrastructure is a bad decision, particularly when the LCA audience is not comprised of LCA experts [31].

With financial activities, there is no physical boundary on creation or loss of the technospheric resource of “money” under current institutional conditions; by contrast, environmental conditions are often interpreted as maximized under pristine natural conditions, with any human intervention leading to degradation. Questions of whether human activities can ever truly “improve” the environment remain controversial [32–34]. Thus, environmental impact is usually treated as a negative gradient starting from “no impact.” “Positive” environmental impacts are positive only in reference to an unnatural, degraded setting that is being nudged upward to “less bad” conditions (Figure 1). As Galindro et al. [31] write, LCA communication more generally can be hindered by the lack of contextualizing reference points and benchmarks. This issue is exacerbated for mitigation LCA, where it is important to communicate that some remediation is occurring; a do-nothing case is potentially environmentally harmful; and that any positive environmental impacts are positive only when considered relative to a degraded state and depend on the degree of that degradation.

Motivated by the preceding background and context on the nuances of mitigation LCA, the remainder of this article draws on a review of LCA work addressing water and energy mitigation infrastructures to propose best practices for mitigation LCA. We aim to leverage the inherent strengths of LCA and argue that this subtype of sustainability assessment problems can benefit from particular strategies during LCA analytical design. Effective evaluation of mitigation infrastructures, particularly focused on water and energy system technological interventions designed to prevent or remediate climate change-related harms, is a relevant goal for sustainable water-energy-climate nexus management in the built environment.

## 2. Materials and Methods

This paper aims to describe how the LCA and environmental assessment literature treats mitigation infrastructure, then recommends best practices for mitigation LCA. As such, a targeted literature review is the primary method used for analysis. We specifically investigate mitigation LCA in the context of water and energy systems, focusing on stormwater management and wastewater treatment on the water side and on pollution capture systems for energy, specifically retrofitted CCS and flue gas desulfurization (FGD) systems. A nonsystematic review targeting LCA studies in these realms forms the basis of this analysis. Articles were sought based on literature searches for LCA + wastewater, stormwater, CCS, and FGD, in addition to ad hoc inclusion of papers based on the authors’ experience. Groups of recent papers from the stormwater literature by Anna Petit-Boix and collaborators [35–40] and by Sarah Brudler and collaborators [30,41,42] were particularly closely examined due to their relevance and display of deepening nuance about what we call mitigation LCA over time.

In addition to the water and energy-related infrastructures specifically targeted for review in this paper, a broad review of potential mitigation LCA papers was undertaken. Web of Science (WoS) searches using the topics “avoided damage” AND “life cycle” and the topics “avoided” AND “life cycle assessment” were used to manually review potential areas of literature interest (“mitigation” AND “life cycle assessment” was insufficiently specific for the purposes of this review). These searches returned about 500 articles, including many of the core articles identified in the stormwater, wastewater, CCS, and FGD literatures assessed here, increasing confidence that the key words were appropriate for an exploratory review. As a result of this search, several additional articles focused on pollution control at landfills were also included. Additional exploratory literature review using WoS searches of “eco-efficiency” or “ISO 14045” or “net environmental impact” AND “life cycle assessment” also informed this work, as did extended searches beyond the LCA literature for “net environmental benefit” (71 total papers, including 16 also identified within the LCA literature) and “net environmental impact” (18 total papers, including 9 also identified within the LCA literature).

### 3. Results

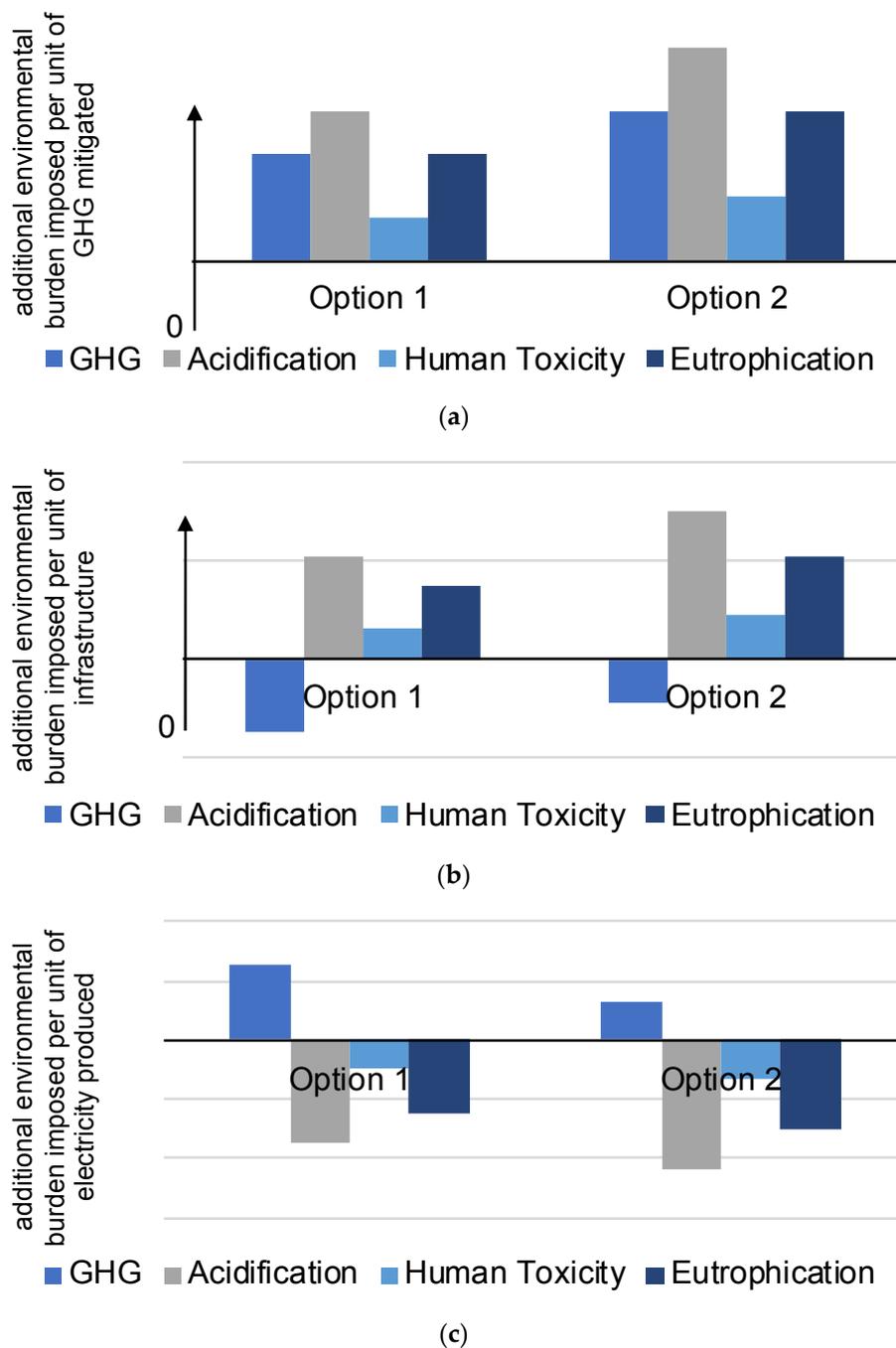
As an aspirationally holistic, multicriteria sustainability quantification tool, LCA is an appropriate approach to assessing burden shifts associated with the fact that mitigation infrastructure can cause environmental burdens in service of providing an environmental harm mitigation function [43]. Specific guidelines for conducting what we call mitigation LCA are important for maintaining clarity and effective communication of results. Here we present our findings in the form of three recommendations for best practice in mitigation LCA: (1) use a performance-based functional unit to ensure comparability across mitigation outcomes; (2) be attentive to burden shifting by carefully selecting analytical boundaries, including product system boundaries and inclusion of appropriate impact categories; and (3) assess and define uncertainty.

#### *3.1. Use a Performance-Based Functional Unit to Ensure Comparability across Mitigation Outcomes*

One of the most consistent findings of our review is that mitigation LCA benefits greatly when different infrastructures with the same mitigation target can be easily compared between alternatives and studies. Based on our review of mitigation LCA, we argue that normalizing the environmental impact of mitigation by the mitigation function itself is the most effective way of enabling clear communication and cross-system comparison. That is, we recommend the use of a mitigation performance-based functional unit as best practice. Such a choice of functional unit allows for the environmental performance of fundamentally different types of infrastructure that provide the same mitigation service to be directly compared. For example, describing environmental intensity per unit of GHG emissions abated enables analysts to compare water loss control and lightbulb replacements as GHG mitigation infrastructures [44]. Using common alternative approaches to define a functional unit, such as on the basis of size, leads to loss of decision-relevant information (Table 1, Figure 2).

**Table 1.** Functional unit approaches and examples in the context of carbon capture and storage infrastructure.

Functional Unit Type	Functional Unit	Environmental Impact Reported as:	Advantages and Disadvantages of Approach
Performance-based (linked to mitigation effectiveness)	Unit of environmental burden mitigated (Figure 2, Panel A)	Multicriteria environmental burden/unit of environmental burden mitigated (e.g., toxicity per unit of CO <sub>2</sub> captured and stored)	<p><u>Advantages:</u> (1) clearly differentiates between additional burden imposed by the mitigation infrastructure and the mitigation itself; (2) enables clear reporting of differential environmental impact of disparate mitigation alternatives</p> <p><u>Disadvantage:</u> difficult to account for infrastructure-specific context</p>
Capacity-based (linked to input capital)	Capacity, size, or equivalent unit of infrastructure (Figure 2, Panel B)	Multicriteria environmental burden/infrastructure size (e.g., toxicity per square meter of scrubber area, including that associated with the greenhouse gases (GHG) capture itself)	<p><u>Advantages:</u> (1) enables some analysis when operational characteristics of mitigation infrastructure are unknown or unclear; (2) might match available data more easily</p> <p><u>Disadvantage:</u> requires loss of information about mitigation function, e.g., through reporting of net environmental benefit/impact or a single criterion eco-efficiency metric</p>
Production-based (linked to operational output from a larger system)	Unit of output of the harm-causing product system (Figure 2, Panel C)	Multicriteria environmental burden/unit of output whose creation caused the initial harm that is being mitigated by the mitigation infrastructure (e.g., toxicity per unit of electricity produced, including that associated with the GHG capture itself)	<p><u>Advantage:</u> enables direct reintegration of mitigation infrastructure as a subsystem of the causal product system (e.g., carbon capture and storage (CCS) impacts normalized per kWh can be added to LCA results for the power plant)</p> <p><u>Disadvantages:</u> (1) requires loss of information about mitigation function, e.g., through reporting of net environmental benefit/impact or a single criterion eco-efficiency metric; (2) leads to nonsensical stand-alone results, e.g., reversing the sign of impact caused by the mitigation infrastructure, when the mitigation infrastructure reduces product system output (e.g., CCS consumes electricity)</p>



**Figure 2.** Mitigation LCA interpretability varies by functional unit approach: (a) Performance-based functional unit; (b) capacity-based functional unit; (c) production-based functional unit. Figure 2 illustrates hypothetical GHG, acidification, human toxicity, and eutrophication burden of CCS mitigation infrastructure using functional unit types described in Table 1. Visualizing the impact on a performance basis (here, tonnes of CO<sub>2</sub> sequestered by a hypothetical power sector carbon sequestration infrastructure) (Panel A) leads more easily to the interpretation that Option 1 is a more environmentally efficient negative carbon technology than Option 2 versus Panel B's visualization on a capacity basis. As Panel C shows, trying to evaluate this retrofitted CCS unit using a production-based functional unit in the form of a typical power plant's functional unit (kilowatt hour, kWh) results in nonsensical results because the delivered kWh are negative.

Essentially, a mitigation performance-based functional unit guides mitigation LCA toward a special case of eco-efficiency [23,38,40,45–47]. Eco-efficiency, per ISO 14045, defines system environmental

performance relative to system value [48]. In principle, system value can be evaluated using any value metric, but in practice, it is often defined financially (e.g., as “economic-ecological efficiency” [46,47]). Like the functional unit itself, eco-efficiency normalizes environmental impacts on the basis of a common output. Our recommendation of a mitigation performance-based functional unit is effectively a recommendation to use the reduction in environmental pressure from the mitigation activity as the value metric for eco-efficiency. Recommending that this be implemented directly in the form of the functional unit, however, has the benefit of clarity and direct compatibility with normal LCA practice. Further, by avoiding the eco-efficiency terminology, it separates mitigation LCA from the notion of financial value and anchors it in the provision of a mitigation service, which can encourage focus on a longer-term goal of remediating environmental harm (see, e.g., [49] for a discussion of the strategic weakness of eco-efficiency as a concept).

For mitigation LCA, presenting LCA results as environmental burdens imposed per unit of specific environmental burden mitigated serves two especially important purposes. First, it enables comparison of performance across diverse mitigation infrastructures with the same function. That is, CCS infrastructure can be easily compared with other GHG mitigation activities that might not be at all physically similar to the CCS infrastructure. This ability to compare the environmental intensity of different mitigation activities directly allows analysts to select the most environmentally efficient approach to mitigation or benchmark performance, sometimes even comparing across different economic sectors or applications [44], to judge the value of a particular approach or project. Conducting comparative LCA that evaluates multiple options for achieving a given, harmonized objective is a common strategy in LCA and can be particularly informative as a method of evaluating the environmental performance of mitigation infrastructure [50–52]. Although the use of a functional unit based on the output of the harm-causing product system (e.g., electricity, for CCS) would appear to also enable this comparability and more, due to its greater compatibility with more traditional objects of LCA analysis, results using this approach can be confusing because mitigation infrastructure is likely more a consumer than a producer of these outputs (Figure 2). CCS infrastructure consumes electricity; a bioswale retrofitted to manage parking lot runoff consumes space that could potentially be used for parking.

The second especially important reason to use a mitigation performance-based functional unit for mitigation LCA is that it clearly separates burdens (costs) from mitigation (benefits). Given that the invested burdens might be in different impact categories and/or different places and times relative to the mitigated burden, this separation leverages LCA’s strengths as a method of understanding the impacts of a given system while simultaneously reducing ambiguity of results.

For communication reasons, approaches that do not present impacts per unit of harm alleviated tend to encourage the use of net impact metrics. It would be confusing to most audiences to hear that a unit of CCS infrastructure leads to additional GHG emissions, so there is an incentive to report net environmental benefit [23,26,53–55] or impact [39] (NEB or NEI; for clarity, we will refer to this method as NEB in the discussion that follows, understanding that some studies will implement it as NEI), reflecting that the CCS infrastructure mitigates some GHG emissions, as follows:

$$\text{NEB} = [\text{PI}_N - \text{PI}_M] - \text{PI}_{\text{MI}} \quad (1)$$

where PI is potential impact, N is the no action state, M is the mitigation state, and MI is mitigation infrastructure (so,  $\text{PI}_{\text{MI}}$  is the life cycle impact of the mitigation infrastructure itself), for each impact category in an LCA [54]. This formulation essentially calculates a performance-based functional unit in the form of the term  $[\text{PI}_N - \text{PI}_M]$ , but results are presented as a net impact that might be positive or negative rather than always positive. Although some do not use the language of NEB, many mitigation LCA studies effectively report NEB when their functional units are not defined relative to a mitigation activity, often in the form of separate reporting of induced versus avoided impact [39,56–58].

Although NEB results in the form of Equation (1) involve effectively the same calculations as those required for a performance-based functional unit approach, we argue that presenting results in terms

of NEB is less useful for mitigation LCA than presenting results per performance-based functional unit for three main reasons. First, it obscures the relative efficacy of mitigation infrastructure focused on the same target but using different processes. For example, if two studies evaluated the ecotoxicity reduction potential of a suite of wastewater versus stormwater treatment infrastructures directly, the studies would be more easily compared than the situation where each study reports NEB in terms of number of installations.

Second, NEB is less effective when the mitigation activity is not directly mappable to an environmental LCA impact category. For example, Pillot et al. [59] evaluate multiple approaches for avoiding the production of one cubic meter of drinking water, a clear, performance-based functional unit. However, because drinking water supply is not a standard impact category in LCA, applying a NEB framework would require disaggregation across several conventional impact-assessment linked categories.

Third, the language of “net environmental benefit” and the potential for a result expressing negative harm is confusing within LCA and suggests that more mitigation infrastructure linearly leads to more benefit—that is, that mitigation infrastructure could improve the environment relative to a pristine baseline. If NEB is performed consistently and all underlying data are reported, however, it could be a reasonable approach to mitigation LCA when a mitigation performance-based functional unit is impractical.

One disadvantage of the mitigation performance-based functional unit approach is that it can be difficult to define a functional unit that adequately accounts for differing contexts. For example, as Godin et al. [54] note, wastewater treatment plant performance is dependent on influent quality. Defining a performance-based functional unit on, e.g., percentage of pollutant removed or effluent quality, either of which could be linked to the mitigation activity, does not capture variability related to the influent quality and can lead to inappropriate comparisons when benchmarking within a specific infrastructural category. Comparing multiple infrastructural choices or reporting results on the basis of more than one possible functional unit for the same system can alleviate this issue, but this context-specific concern challenges broader benchmarking. In this case, techniques like NEB that do not rely on a fixed pristine environment baseline can be useful because they can account for expected continuing degradation associated with the do-nothing case. That is, while a mitigation performance-based functional unit expresses burdens relative to “what is,” NEB expresses burdens relative to “what would otherwise have been.” As Godin et al. [54] characterize, NEB is an implementation of LCA that entails conducting LCA of both the null option and the mitigation infrastructure option, then comparing the two.

### *3.2. Be Attentive to Burden Shifting by Carefully Selecting Analytical Boundaries*

A second recommended best practice for mitigation LCA is that analysts be particularly attentive to burden shifting by carefully selecting analytical boundaries. Selecting appropriate, clear analytical boundaries is a major challenge for LCA generally [60], but the challenge is amplified for mitigation LCA. This amplification is a result of two major characteristics: (1) mitigation infrastructure is built and operated in response to a burden caused by another activity, which complexifies the product system’s boundaries; and (2) mitigation requires some form of burden shifting, usually by reducing environmental pressure in one category at the expense of increasing environmental pressure in others.

Product system boundaries need to be carefully defined to avoid omitting or double counting impacts, among other issues. Consider the example of a SCM implemented to reduce water quality impacts from human activity: the SCM and its impacts could be considered to be a boundary expansion for LCA assessing the original polluting activity (see, e.g., [41])—that is, any negative impact of the SCM could arguably be counted as an impact of the polluting activity. Defining boundaries clearly and explicitly can enable users to avoid double counting impacts when combining LCA results to assess an expanded system. Further, ensuring that the mitigation infrastructure portion of the product system is clearly delineated is important because decision makers considering after-the-fact mitigation would benefit from being able to compare environmental intensity across equally effective mitigation options.

The multicriteria nature of environmental intensity motivates the second caution to carefully define analytical boundaries. During our review of work we identified as part of an emerging mitigation LCA literature, we noted that few papers explicitly catalog impacts across all impact categories that are relevant to a particular activity. Given the very common outcome that mitigation infrastructure leads to burden shifting away from the mitigation target and towards other impact categories, the value of mitigation LCA increases when all relevant impact categories are included and rationales for selection are provided. Burden shifting can be environmentally significant [61–63]. Retaining information on the nature of category-specific impact is necessary because reducing impacts to common units (e.g., money or some form of ecological damage equivalence metric) masks these shifts in a way that causes an important loss of information for decision makers. For example, for a single water treatment project, the scale of burden shift from water pollution to air pollution could be acceptable, but if every project considered causes the same burden shift, the overall impact could exceed acceptable limits. Preserving information about what, where, and when burdens occur is a valuable characteristic of a multicriteria assessment method like LCA. Maintaining use of multiple impact categories is an important best practice.

### 3.3. Assess Uncertainty

Preserving detail on category-specific environmental harms is relevant to our third and final major recommended best practice for mitigation LCA: carefully assess and define uncertainty. Although uncertainty is fundamental to sustainability quantification approaches like LCA, which fundamentally addresses potential rather than experienced environmental impact [64], mitigation LCA is particularly sensitive to uncertainty in part because of the relevance of a type of uncertainty that most LCA does not address. Because most LCA evaluates midpoint rather than endpoint indicators (e.g., GHG emissions versus climate change-induced deaths and extinctions or volume of floodwater captured versus flood-induced deaths and property damage), mitigation LCA fundamentally includes uncertainty about the value of the mitigation itself. How much climate change mitigation is caused by the capture and storage of a unit of CO<sub>2</sub>? When the mitigation infrastructure is designed to mitigate an endpoint indicator, this uncertainty manifests as mismatches between the design function (e.g., for SCM, preventing flooding) and the experienced performance (e.g., given external future climatic conditions, a SCM might never prevent the flooding it is designed for or the actual flood that occurs might completely overwhelm its capabilities).

Leveraging the fact that invested impact is more certain than the return benefit can aid in comparing mitigation options, especially when impact is being compared per unit of the same uncertain mitigation benefit. For example, an effective mitigation LCA can differentiate across different levels of risk and carefully catalog spatiotemporal as well as categorical burden shifts. Fundamentally, multicriteria environmental impact is invested at the beginning of a mitigation project's lifetime in order to mitigate a specific environmental impact with uncertain value later. Thus, temporal issues might be of particular interest in many mitigation cases. One management approach is to develop and use a diverse set of future scenarios to test system robustness. Similarly, analysts should carefully consider the appropriateness of analytical impact of applying discount rates or other factors to various impact categories to account for temporality [65]. As Oreggioni et al. [66] write, for example, bioenergy carbon capture and storage (BECCS) with long rotation period woody biomass displays a long time gap between CO<sub>2</sub> emitted and CO<sub>2</sub> sequestered which can affect the environmental conclusions of LCA. Although the reviewed literature does not often directly address the issue of discounting related to this time delay (though see [53,67,68]), we posit that mitigation LCA would benefit from consideration of environmental impact discount rates that are appropriately matched to the type of impact. Just as financial discount rates are often based on financial realities about risk, alternative income streams, and other issues, environmental discount rates can be developed that appropriately account for the impact of time delay between environmental investment and environmental return through mitigation infrastructure. Uncertainty is a major issue in any environmental assessment, and

it should be particularly closely considered for mitigation LCA because both impacts and function are related to environmental outcomes.

#### 4. Discussion

Human activity has caused substantial environmental harm that is not remediated as part of the causal activity. Infrastructure designed to reduce this harm relative to a degraded baseline, which we call mitigation infrastructure, reduces specific environmental pressures at the cost of infrastructure-related investment of environmental harm. Often, this dynamic results in some form of environmental burden shifting, whether across impact categories, location, time, or other category. LCA is a sustainability quantification method designed to assess the multicriteria environmental pressure associated with a given human activity, which makes it a useful tool for evaluating mitigation infrastructure. Based on our review of the literature, we argue that mitigation LCA has special characteristics that distinguish it as a subtype of LCA, mostly because mitigation infrastructure is explicitly designed to provide some environmental benefit in the form of harm reduction or remediation without providing new financially valuable output.

One of the reasons we argue that mitigation infrastructures should be evaluated on the basis of mitigation-related performance, rather than in the form of a net impact or similar analysis, is that mitigation LCA fundamentally deals with different baselines than most LCA. That is, a mitigation process would never be considered to improve the environment over a pristine baseline: it is providing a net benefit only relative to a state of degradation. Mitigation LCA is a special subtype of LCA, and mitigation LCA results are clearest and most consistent with typical LCA practice when results are normalized by the remediation service itself in the functional unit. Expressing the environmental impact of this remediation in terms of units of remediation, rather than as, say, a positive impact, clarifies this relationship. Selecting a performance-based functional unit, rather than, e.g., a capacity-based functional unit, also enables direct comparison of the environmental performance of disparate mitigation infrastructures that deliver similar remediation services. For example, a berm or a bioswale might both prevent flood damage. Comparing the two is much easier when impacts are presented per unit of flood damage prevented rather than per unit of length (berm) or catchment area (bioswale). This functional unit-based approach performs better than, for example, a net impact approach because it enables the use of a mitigation outcome not directly linked to an LCA impact category; does not imply that mitigation is environmentally beneficial relative to a pristine baseline; and forces a clear articulation of the precise service that mitigation infrastructure is assumed to deliver.

Defining a performance-based functional unit can be challenging in certain circumstances, particularly when multipurpose infrastructure is being installed. In these cases, reporting category-specific eco-efficiency metrics defined as  $\text{input}_{\text{category}}/\text{output}_{\text{category}}$ , e.g., kilograms CO<sub>2</sub> invested/kilograms CO<sub>2</sub> sequestered, can be an effective alternative. Relevantly, this approach preserves information about both the expected additional harm (invested impact) and the expected remediation, which is important for enabling future users of a statistic to place it in context, adjust assumptions, and harmonize results across studies. Presenting a single net impact value destroys this context, making it more difficult to compare diverse mitigation infrastructures with the same mitigation target. Similarly, limiting reports to one or a few impact categories diminishes the value of LCA as a multicriteria assessment method, particularly since burden shifting is a primary concern for mitigation infrastructures.

In general, it is important to acknowledge the difficulty of environmentally evaluating mitigation infrastructures. As with other forms of analysis that involve both positive and negative impacts, like cost-benefit analysis, analyses suffer from asymmetrical certainty. The impact of building mitigation infrastructure is often more certain than the impact of having mitigation infrastructure in place, particularly when the mitigation goal is something dynamic, like flood damage prevention. Being precise and explicit in our analyses can improve this situation, as such care makes it clearer to potential future users how assumptions might be changed, harmonized, or interpreted. LCA's

particular strengths are in enabling multicriteria cataloging and evaluation of impacts associated with a well-defined analytical object, the functional unit. Leveraging those strengths is a major guiding principle for this work's recommendations. Improvements made to mitigation LCA practice, a particularly challenging subtype of LCA, can strengthen LCA overall.

This paper draws specifically on literature related to mitigation infrastructures for stormwater, wastewater, and power plant stack emissions management. A few examples of other mitigation infrastructures that we suggest would be productively assessed using the mitigation LCA best practices we identify here are presented in Table 2.

**Table 2.** Example applications for evaluation using mitigation LCA best practices.

Water	Energy	Other
Building sea walls to protect against sea level rise	Electrifying carbon-based infrastructure before end of life	Climate-adaptive agricultural practices
Injecting water underground to maintain groundwater pressure in depleted basins	Replacing lightbulbs with LEDs before end of life	Replacing infrastructure before end of life

We caution that during our review of existing LCA research on water and energy mitigation infrastructure, we might have overlooked key papers. The lack of standardized language referring to this type of work makes literature review challenging. One major reason we propose the term “mitigation LCA” for the type of research we describe here is to improve discoverability and cross-comparison of findings.

Identifying best practices that can inform mitigation-focused LCA research is particularly important given the emerging need for infrastructures that address nonstationarity brought on by climate change. As we design and implement more mitigation infrastructure, understanding the relative performance of various options can inform more environmentally sustainable decisions. Coming to consensus on how to address the environmental implications of mitigation infrastructure could expand opportunities to address some of the major harm mitigation approaches that we anticipate will be implemented at scale, particularly through increased confidence in the methodological approach. Particularly under climate change, we inhabit a degraded environment that will likely motivate increasing installations of mitigation infrastructure over time.

In the long term, careful and precise consideration of fundamental LCA elements like functional unit, boundaries, and uncertainty could facilitate the integration of environmentally-focused mitigation LCA to broader sustainability assessment, such as the simultaneous assessment of cost, environmental impact, and social impact that is sometimes called life cycle sustainability assessment (LCSA) [10,11,18,21]. The fundamental sociotechnical embeddedness of many mitigation infrastructures, which often require near-term monetary, environmental, and social investment designed to achieve an uncertain, value-mediated goal, makes the possibility of LCSA all the more relevant. Given the strong possibility for burden shifting when installing infrastructure to mitigate environmental harm, using LCA to understand the potential negative environmental, and perhaps financial and social, impacts of this mitigation infrastructure itself is important for evaluating the relative performance and desirability of different mitigation options. Mitigation LCA is proposed as a term to help researchers discover and track work in this area, with the goal of enabling a more systemic approach to LCA practice and sustainability assessment more generally. Water and energy mitigation infrastructures have particular relevance under climate change. Understanding their environmental potential can aid in decision making for multicriteria sustainability.

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