Journal of Environmental Management 329 (2023) 117068

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Offsetting environmental impacts beyond climate change: the Circular Ecosystem Compensation approach

Daniel Moore [a,*], Vanessa Bach [a], Matthias Finkbeiner [a], Theresa Honkomp [b,c], Heinz Ahn [b], Madlen Sprenger [c], Linda Froese [c], Dirk Gratzel [c]

[a] Chair of Sustainable Engineering, Technische Universität Berlin, Straße des 17. Juni 135, 10623, Berlin, Germany
[b] Innovationsgesellschaft der Technischen Universität Braunschweig MbH, Wilhelmsgarten 3, 38100, Braunschweig, Germany
[c] HeimatERBE GmbH, Im Welterbe 1-8, 45141, Essen, Germany

A R T I C L E I N F O

Keywords:
Offsetting
Life cycle assessment
Monetization
Ecosystem valuation
Renaturation
Environmental neutrality

A B S T R A C T

Since the Paris Agreement entered into force, climate neutrality and associated compensation schemes are even more on the agenda of politics and companies. Challenges of existing offsetting schemes include the rather theoretical saving scenario and the limited scope of considered impacts. To address some of these limitations, this paper proposes the Circular Ecosystem Compensation (CEC) approach based on monetization of LCA results and Ecosystem Valuation. CEC consists of six steps: i) carrying out a life cycle assessment, ii) reducing the environmental impacts, iii) determining environmental costs applying monetization methods, iv) deriving the environmental value based on restoration costs methods, v) implementing the ecological restoration of ecosystems and vi) monitoring of the renaturation measures. Thus, CEC allows to offset a broad set of environmental impacts beyond climate change (e.g., acidification, eutrophication, land use, water use) in a real ecosystem by renaturation of degraded ecosystems. Environmental burdens and environmental benefits are balanced on a monetary basis, as the renaturation measures are monetized and used to compensate the monetized LCA results, e.g., of a product, organization or individual. In a case study, the implementation of the approach is presented to show the practical implementation of the CEC. The challenges of CEC include the integration of further impact categories, the availability of up-to-date and reliable monetization methods, the asynchrony and time-lag of the compensation from an ecosystem and biodiversity perspective and the proof of cost-efficiency of the renaturation measures. It is further discussed, if CEC can be a step beyond "climate neutrality" towards "environmental neutrality". The proposed approach should be further tested and is intended to foster progress in more comprehensive and robust offsetting of environmental impacts beyond climate change.

1. Introduction

Climate neutrality is the key concept for tackling climate change. In order to remain below the 1.5 °C threshold of the Paris Agreement, climate neutrality should be achieved by 2050 at the latest (IPCC, 2018; UNFCCC, 2015). Strategies and approaches to achieve this are currently being discussed by various stakeholders and at various levels, e.g., for countries, municipalities, organizations and products (BMUB, 2016; European Commission, 2019; Li et al., 2022; SBTi, 2022a).

In addition to climate change, there are other environmental problems such as acidification, eutrophication, land use or water use, which lead to the degradation of ecosystems and thus to a loss of biodiversity (UN Environment, 2019). Therefore, following the "Decade of Biodiversity" from 2011 to 2020, the United Nations has declared the years 2021–2030 as the "Decade of Ecosystem Restoration" to counteract the loss of biodiversity or the degradation of ecosystems on a local and global scale (CBD, 2011; UNEP, 2021a). In this context, addressing the impacts of climate change is linked to the conservation of biodiversity, e.g., in that the restoration and conservation of biodiversity increases the potential for adaptation to climate change impacts and helps ensure that intact ecosystems contribute to people's livelihoods, health and well-being (IPBES, 2016). In the European Union, the no net loss (NNL) of biodiversity and ecosystem services caused by negative impacts of human activities is aimed to be implemented. The guidance on how to achieve NNL includes a mitigation hierarchy for biodiversity offset schemes with four steps: avoidance, minimization,

* Corresponding author.
E-mail address: daniel.lochner@tu-berlin.de (D. Moore).

https://doi.org/10.1016/j.jenvman.2022.117068
Received 13 October 2022; Received in revised form 2 December 2022; Accepted 15 December 2022
Available online 21 December 2022

rehabilitation/restoration, and offset (Tucker et al., 2020). Hence, the reduction of the negative impacts is prioritised over compensation measures.

The same mitigation hierarchy "reduction before compensation" is also the current scientific consensus for carbon offsetting (Andrews, 2014; Finkbeiner and Bach, 2021; UNFCCC, 2021). Reduction measures have priority over compensation measures, as they are more tangible, time-independent and verifiable. This also implies the need to take measures for the environmental impacts that cannot be avoided in order to achieve compensation. To avoid problem-shifting and to achieve scientifically robust solutions a life cycle perspective and as many environmental impacts as possible should be considered. In this way, double counting, greenwashing and mechanisms of carbon as well as beyond carbon leakage can be reduced. In addition, the efficiency of the measure can be determined and problem shifts between life cycle stages as well as environmental impacts can be limited.

There is a broad debate on the quality and effectiveness of different compensation mechanisms, projects and providers (Broekhoff et al., 2019; Wolters et al., 2018). Some of the most often addressed challenges are the definition of the baseline, additionality, lack of considering the life cycle perspective and the focus on climate change only, not considering other sustainability aspects. To address these limitations, this paper proposes the Circular Ecosystem Compensation (CEC) approach based on monetization of LCA results and Ecosystem Valuation.

A background is given in section 2 to briefly introduce the methods on which CEC is based on. In section 3, the CEC approach is described in detail, including a description of all six steps of CEC. A case study is presented in section 4 to show the practical implementation of the CEC approach. The general challenges of CEC and the possible contribution of CEC beyond achieving climate neutrality are discussed in section 5. Finally, a conclusion is given in section 6.

2. Background

2.1. Life cycle assessment

Human activities cause environmental burdens, e.g., over the life cycle of products and services. Life cycle assessment (LCA) can be used to determine potential environmental impacts of products and services over the whole life cycle and for several environmental aspects (ISO14040 and ISO 14044).

LCA can help to identify opportunities to improve the environmental performance of products and services at different stages of their life cycle. It can be used to reduce potential anthropogenic environmental impacts in several impact categories, with the possibility of avoiding or minimizing trade-offs between impact categories or life cycle stages (ISO, 2006a). Examples are:

- minimizing environmental impact by optimizing new, existing or developing products (by comparing alternatives, e.g., materials, substances, processes, logistics);
- optimization of process chains;
- optimization of operations.

In order to determine environmental impacts not only of products and services, but also of organizations (e.g., companies or corporate divisions) and individuals, the methods of Organizational-LCA (O-LCA) and Life-LCA (Goermer et al., 2020; ISO, 2014; UNEP/SETAC, 2015) have been developed. O-LCA has also been developed further to be also applicable for cities or urban districts (Cremer et al., 2020). For regional purposes, territorial LCA can also be used (Loiseau et al., 2018).

2.2. Monetization

The Background of the two monetization approaches used within CEC are described more in detail in sections 2.2.1 (Monetization of LCA results) and 2.2.2 (Ecosystem valuation).

2.2.1. Monetization of LCA results

By monetizing LCA results, the environmental impacts of different impact categories with specific metrics are converted into a single monetary unit (Amadei et al., 2021; Arendt et al., 2020). Doing so, the total environmental costs can be determined for a broad set of impact categories. The sum of the determined environmental costs as a single monetary value allows the attribution of the responsibility for environmental impacts to the polluter through environmental costs and the compensation by the polluter itself (Bünger and Matthey, 2018; Mace et al., 2012). This internalization of the environmental costs (e.g., of products and services) with subsequent compensation can contribute to tackling acute environmental problems such as climate change and loss of biodiversity (Drenckhahn et al., 2020). Various methods are available to monetize LCA results, e.g., the Environmental Prices Handbook (de Bruyn et al., 2018) for a European geographical scope and EPS (Steen, 2016) or Stepwise 2006 (Weidema, 2009; Weidema et al., 2008) for a global geographical scope. There is no general agreement or consensus about what method to choose. So, practitioners have to choose the method fitting for a certain purpose according to the specific decision context (Arendt et al., 2020).

2.2.2. Ecosystem valuation

A wide range of methods and tools related to the monetary valuation of ecosystems has been developed. One of the goals of ecosystem valuation is to include ecosystem services into decision making on a monetary basis and thus to support sustainable land, water and urban management (Bagstad et al., 2013; Harrison et al., 2018; Ruckelshaus et al., 2015). Among all the different methods and tools, cost-based approaches determine the costs to recreate ecosystem services through artificial means based on estimations (Garrod and Willis, 1999). One example are restoration cost methods, which calculate the cost of getting lost ecosystem services restored (Pascual et al., 2012). Thus, it is assumed that the restoration costs of degraded ecosystems are equal to the expenses incurred from the mitigation of these negative effects (Selivanov and Hlaváčková, 2021). For the implementation of this method, it is crucial that the needed data for calculation of the restoration costs is available (Pascual et al., 2012). Restoration cost methods can be used to maintain the environmental status quo or to contribute to avoid/reduce net loss for biodiversity (Pearce et al., 2006; Tucker et al., 2020).

2.3. Renaturation

Degraded ecosystems can be restored actively (through human interventions) or passively (by natural processes). The type of ecological restoration used towards a target ecosystem should be chosen depending on the initial state of degradation (Kiehl, 2019). For active restoration, recultivation, revitalisation or renaturation can be applied. These three types differ regarding the ecosystem functions (e.g., biomass, nutrient cycle, water balance) and ecosystem structure (habitat typical species and complexity) of the restored ecosystem. While recultivation aims high ecosystem functions of a specific type, revitalisation intends to develop a high specific ecosystem structure. Renaturation aims at both: a wide range of high ecosystem functions and high ecosystem structures to restore the natural conditions and functions of ecosystems. Thus, in contrast to approaches of revitalisation and recultivation, renaturation enables the development of degraded ecosystems into near-natural or traditional cultural landscapes and is thus considered as more holistic (Bradshaw, 1996; Kiehl, 2019; Zerbe, 2022a).

The implementation of the renaturation measures in degraded ecosystems can support to tackle the current challenges of biodiversity loss, ecosystem degradation and climate change, e.g., based on (Drenckhahn et al., 2020; IPBES, 2019; UNEP, 2021b):

- promoting near-natural ecosystems;
- expanding biotope connectivity systems that allow species to disperse and migrate to conserve local and genetic diversity;
- increasing ecosystem diversity and habitat heterogeneity at the local level;
- increasing habitat availability to strengthen populations;
- measures to adapt ecosystems and species to climate change.

To track an increase of the "ecological value" of the ecosystems through renaturation measures, point-based systems can be used, e.g., referring to the German biotope value procedure (dt.: Biotopwertverfahren) used in the German Impact Mitigation Regulation (dt.: Eingriffsregelung), in which the biotope values are determined according to their typical characteristics according to biotope habitat type lists (dt.: Biotoptyplisten) (Louis, 2010; Quétier and Lavorel, 2011).

As a result, renaturation measures could strengthen the resilience and adaptive capacity of ecosystems, ensure the restoration and conservation of terrestrial, marine and inland freshwater ecosystems. Further, a contribution can be made in reducing the degradation of natural habitats, in contributing to the halt of biodiversity loss and in climate change mitigation (UN, 2022; UNEP, 2021b).

3. The Circular Ecosystem Compensation approach

The CEC approach is presented in this section. To tackle some of the challenges of compensation schemes mentioned in section 1, CEC is based on the three elements LCA, monetization and renaturation (see section 2). The combination of these three elements as CEC is shown in Fig. 1.

With the first element (LCA), a life cycle perspective is added and a set of impact categories is considered. In addition, the "reduction before compensation" principle is implemented, as the environmental impacts are reduced based on the LCA analysis. Thus, it is ensured that emissions are in the first place reduced before the compensation takes place. With the second element (monetization), a broad set of environmental impacts can be compensated. Two different monetization approaches are used:

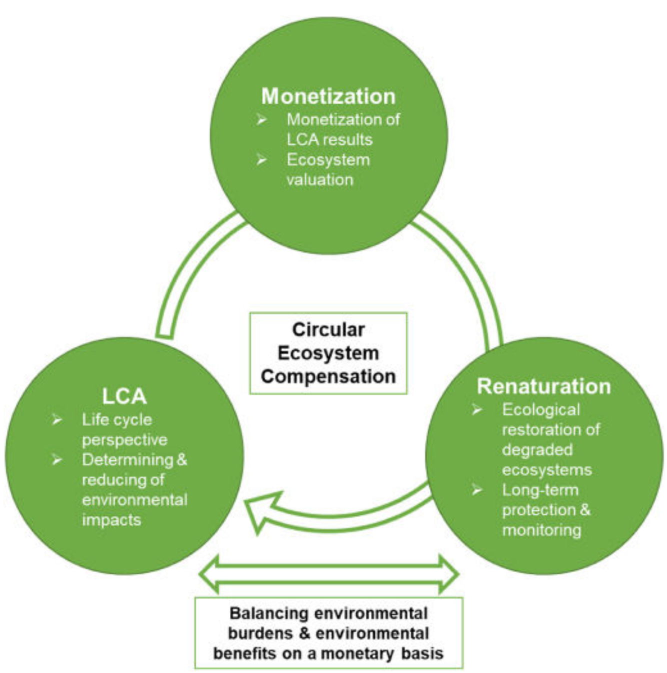

Fig. 1. Closing the circle between environmental burdens and benefits with CEC based on monetization.

i. The environmental impacts of the LCA are monetized to derive the environmental costs and
ii. the ecological restoration of degraded ecosystems as result of renaturation measures are monetized with restoration cost methods, which are converted into an environmental value.

Thus, environmental benefits created through ecosystem restoration are determined on a monetary basis (environmental value) to balance the environmental burdens, determined as environmental costs, as currency is the common unit. The summed up environmental costs determine the amount of the payment necessary to realize actions and measures for the ecological restoration of degraded ecosystems. Once this amount was invested in the compensation measures of renaturation, the environmental costs are balanced with environmental value generated for the same amount.

Finally, with the third element of renaturation of degraded ecosystems, the compensation measures are implemented to generate environmental benefits regarding biodiversity and climate change mitigation as well as to create and protect various habitats and biotopes. This includes a long-term protection and monitoring of the restored ecosystems to avoid a theoretical saving scenario, as the renaturation measures take place in an existing ecosystem. CEC is not limited to a specific type of ecosystem or natural habitats and can thus be implemented for ecological restoration for terrestrial as well as freshwater or marine ecosystems in an either rural or urban context.

As a consequence, the circle between environmental impacts (e.g., of products & services, organizations & urban areas and individuals) and environmental benefits (through implementing renaturation measures in an existing ecosystem) is closed (see Fig. 1). On a higher level, the circle of environmental impacts generated in the past (by degrading land) is closed by bringing this land back to an ecologically valuable state.

CEC consists of six steps, which are shown in Fig. 2: i) carrying out a life cycle assessment, ii) reducing the environmental impacts, iii) determining environmental costs applying monetization methods, iv) deriving the environmental value based on restoration costs methods, v) ecological restoration of ecosystems and vi) monitoring of the renaturation measures. The steps are described in detail in sections 3.1–3.6.

3.1. Step 1: Life cycle assessment

The first step of CEC is to carry out an LCA (see section 2.1.). For the LCA, the following methods can be used, which define the basic rules for preparing an LCA:

- ISO 14040/44 for assessing products and services (ISO, 2006a, 2006b);
- ISO/TS 14072 for evaluating organizations (O-LCA) according to (ISO, 2014; UNEP/SETAC, 2015) and for cities or urban districts according to (Cremer et al., 2020; Loiseau et al., 2018);
- Life-LCA for the accounting of individuals according to (Goermer et al., 2020).

Moreover, a broad set of relevant impact categories can be considered within CEC besides climate change, e.g., also eutrophication, acidification, land use or water use.

To select the impact categories to be compensated with CEC, mature and recognised impact assessment methods should be chosen, e.g., based on existing analyses (European Commission, 2022; Mikosch et al., 2022). Furthermore, the environmental impacts should be relevant for the analysed product, organization, individual etc. Moreover, current databases should allow a robust determination of environmental impacts by, among other things, taking into account all relevant elementary flows. In addition, monetization methods (see section 3.3.) for the chosen impact assessment methods have to be available to ensure consistency between step 1 (LCA) and step 3 (environmental costs).

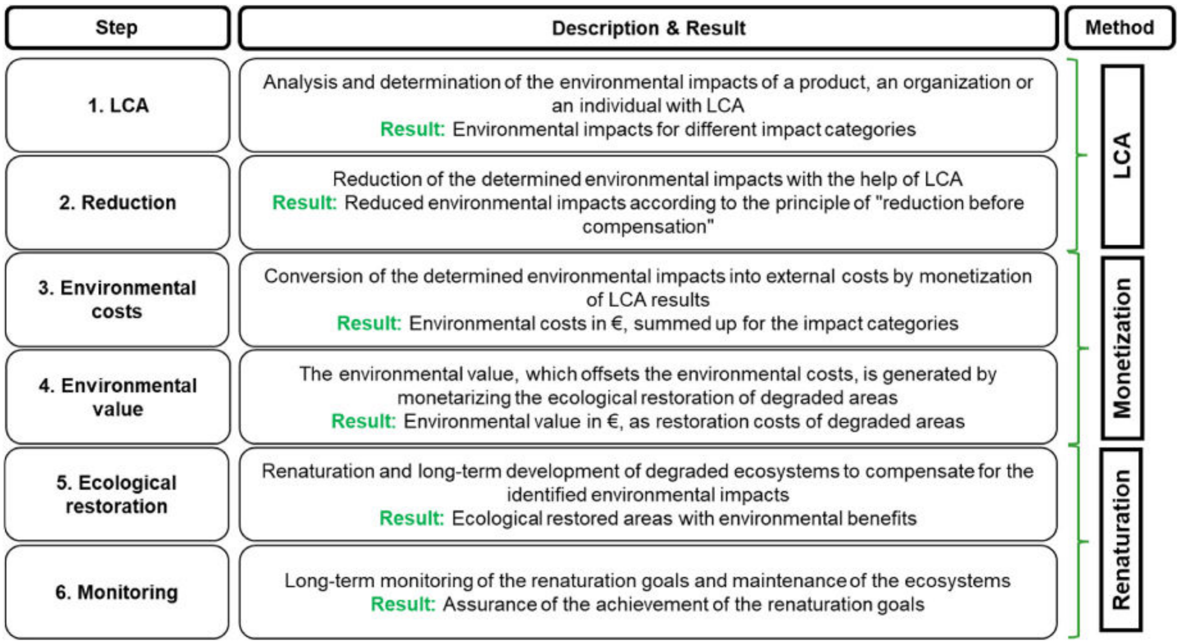

Fig. 2. Overview of the six steps of CEC: description & result and used method for each step.

In this way, LCA provides the necessary results with regard to potential environmental impacts, which are reduced (see section 3.2.) before monetizing them (see section 3.3.).

3.2. Step 2: Reduction

As second step, the environmental impacts are reduced with the help of LCA. This step is implemented in CEC in order to fulfil the priority of "reduction over compensation" (see section 1).

Proof of the successful reduction of environmental impacts is provided by LCA (see section 3.1.). If reduction steps have already been taken at the start of compensation, these results are quantitatively available in the LCA and serve as proof of the successful reduction of environmental impacts. Thus, LCA helps to identify and to achieve minimized environmental impacts for a broad set of impact categories to minimize the need for compensation measures.

Available and science-based reduction targets for the used impact categories should be applied to verify whether the magnitude of achieved reduction is in line with certain environmental targets, e.g., for climate change based on (IPCC, 2022; SBTi, 2022b).

3.3. Step 3: Environmental costs

After the LCA is performed (see section 3.1.) and the environmental impacts are reduced (see section 3.2.), the environmental costs are determined applying monetization methods within the third step. The environmental impacts of the chosen impact categories are monetized and summed up to determine the environmental costs as a single monetary value (see section 2.2.1.).

Different methods are available to monetize the environmental impacts. Two recently published review papers can support the selection of the method to monetize the LCA results (Amadei et al., 2021; Arendt et al., 2020). When choosing the monetization method, the consistency between the impact assessment method within LCA (see section 3.1.) and the cost rate within monetization is crucial, especially the used impact pathways and units. Same should also be ensured for the geographical context of the cost rate and the addressed product, organization, individual etc.

3.4. Step 4: Environmental value

In the fourth step of CEC, the environmental value is derived based on restoration costs methods (see section 2.2.2.). The measures that lead to the ecological restoration of degraded land are quantified on a monetary basis in order to realize the compensation between the environmental costs and environmental value. Thus, the costs of the realized measures are taken as proxies for the environmental value of the restored ecosystems.

The measures can include planning activities (e.g., inventory review of the degraded state, development of the restoration measures towards a target state, monitoring planning) as well as implementation (e.g., removing and renaturing of sealed areas, creation of specific habitats and biotopes etc.) and maintenance measures. Applying restoration costs as proxies for the environmental value means that the environmental costs are used as a cash payment from the polluter to a compensation provider to finance the renaturation measures that lead to environmental benefits.

Approaches to determine the restoration costs can be chosen based on (Harrison et al., 2018; Pascual et al., 2012; Selivanov and Hlaváčková, 2021).

3.5. Step 5: Ecological restoration

The ecological restoration of ecosystems following renaturation principles is the fifth step of CEC. Using renaturation in the sense of the CEC allows to develop degraded ecosystems towards target ecosystems with high ecosystem functions and high ecosystem structures (see section 2.3.). Thus, renaturation enables to transform ecosystems into near-natural or traditional cultural landscapes (see e.g., (Kollmann et al., 2019a; Zerbe, 2022b)) within CEC.

Depending on the initial state of the degraded ecosystems, the renaturation goals are defined and then verified in the sixth step by monitoring (see section 3.6.). Based on the renaturation goals, the target state of the restored ecosystem is described and the renaturation measures are planned and implemented based on the specific ecosystem characteristic. CEC can be used for the renaturation of near-natural ecosystems (e.g., forests, streams, lakes etc.) and the renaturation of anthropogenic shaped ecosystems (e.g., different types of grasslands, hedgerows etc.).

The renaturation measures within CEC can be planned and implemented based on a wide range of publications, e.g., (Gann et al., 2019; Kollmann et al., 2019b; Palmer et al., 2016; SER, 2004; Zerbe, 2019, 2022b). An increase of the "ecological value" of the ecosystems can be tracked within CEC based on point-based systems (see section 2.3.). In addition, the proof of cost efficiency can be added to this step, e.g., based on cost-benefits-analysis (BBOP, 2009; Hampicke, 2009; Kollmann, 2019a; Pearce et al., 2006).

3.6. Step 6: Monitoring

As sixth and last step of CEC, the monitoring of the renaturation measures takes place. Based on the renaturation goals (set up in step 5, see section 3.5.), a monitoring concept is set up for evaluating the effectiveness and efficiency of the renaturation measures. Thus, the development of the newly created structures towards near-natural dynamics is reported. For the monitoring concept within CEC, indicators of target achievement are derived and a recording programme for data collection in the field is drawn up.

Based on the renaturation goals, indicators must be defined in order to quantify the developments of the ecosystem after certain renaturation measures. Examples for indicator types are: change in abiotic site factors (e.g., pH and nutrients), development of the biocoenosis (e.g., total number of species and target species) and change of the ecosystem (e.g., vegetation cover and plant communities & distribution) (Kollmann, 2019b; Loreau et al., 2001). Thus, a monitoring of these indicators within CEC allows simplified insights into the development of biodiversity and important ecosystem functions after the ecological restoration in the fifth step (see section 3.5.). Several publications can give guidance in setting up the monitoring concept, e.g., (Kollmann, 2019b; SER, 2004).

4. Case study: example of implementation by GREENZERO

In this section, a case study is presented to show the practical implementation of the CEC approach by GREENZERO as of the year 2023 (GREENZERO, 2022). As the GREENZERO approach follows the described 6 steps of CEC (see section 3), additional details are described in the following.

In the first step (*LCA*, see section 3.1.), the life cycle impact assessment (LCIA) results are determined for the impact categories climate change, acidification, freshwater eutrophication, marine eutrophication, photochemical ozone creation and ozone depletion (see Table 1). In order to increase the robustness of the approach, the impact categories will be extended in the future to ionizing radiation and particular matter formation, land use and water use, since consistency issues between the LCIA method and the monetization methods have to be solved regarding the specific used impact pathways and units. The impact assessment methods are chosen to be compatible with the environmental costs' calculation in step 3.

Next, the second step asks for a *reduction of the environmental impacts* (see section 3.2.). If no reduction steps have been taken at the beginning of the compensation, the customer must provide quantitative proof of a reduction by means of an improvement in the LCA after 3 years at the latest. If no reduction can be achieved, the efforts might be demonstrated qualitatively in exceptional cases. The customers therefore give a self-commitment to strive for a reduction of the environmental impact. In both cases, the reductions are verified by authorized external service providers. In the event of significant changes to the analysed system that also require an update of the LCA, further reduction efforts must be made and verified as described above.

After the environmental impacts have been reduced, they are converted into *environmental costs* in the third step (see section 3.3.). The results of the considered impact categories are converted into environmental costs according to the cost rates listed in Table 2. The cost rates are based on the Environmental Prices Handbook and the Handbook on the External Costs of Transport (only for climate change) by CE Delft (de Bruyn et al., 2018; van Essen et al., 2019). Handbook on the External Costs of Transport is used for climate change, as the CO_2-eq. cost rate in the Environmental Prices Handbook is not updated according to the current climate change mitigation policy of the European Union. Thus, the updated cost rates of the Handbook on the External Costs of Transport are used (van Essen et al., 2019). Furthermore, the cost rates are inflation-adjusted to €-2020 based on (Eurostat, 2021; Thompson, 2009). The environmental costs of each impact category are then added up to a value that corresponds to the total environmental costs. This determines the costs (in €) that are invested in the ecological restoration of degraded ecosystems.

For the fourth step (*environmental value*, see section 3.4.) an extended restoration cost approach is implemented (Ahn and Honkomp, 2021, 2022). Environmental value is generated when degraded ecosystems are ecologically restored according to renaturation principles. The environmental value represents the full cost basis of restoration calculated over several decades, including possible risks (e.g., from existing contaminated sites or from climate change impacts). This value is calculated for one square metre and one calendar year and is based on the following principles:

- Environmental value as product = planned full costs actually incurred in ecological restoration per planned square metre (rolling, discounted), based on one year.
- Environmental value as a reflection of the environmental costs = compensation for the environmental impacts determined by means of environmental benefits.

The calculation model based on Equation 1 relates the ecological restoration of an area to the economic expenditure required to achieve it, taking into account the determination of the (increasing) value of the area. The result is a (planned) product price in € per m^2 and year of a certain area.

The environmental value is calculated according to Equation 1:

Table 1
Considered impact categories and impact assessment methods (CML-IA based on (CML, 2016; Guinée et al., 2002)*,* ReCiPe 2016 *based on* (Huijbregts et al., 2017)*) of the GREENZERO approach.*

Impact category	Characterization factor	Impact assessment method
Climate change	GWP	CML-IA or ReCiPe 2016 (H)
Acidification	AP	CML-IA
Eutrophication (freshwater)	FEP	ReCiPe 2016 (H)
Eutrophication (marine)	MEP	ReCiPe 2016 (H)
Photochemical ozone creation, ecosystems	POCP	ReCiPe 2016 (H)
Ozone depletion	ODP	ReCiPe 2016 (H)

Table 2
Currently used cost rates of the GREENZERO approach in €-2020 (Climate Change based on (van Essen et al., 2019)*, all others based on* (de Bruyn et al., 2018)*).*

Impact category	Characterization factor	Unit	Cost rate in €-2020
Climate change	GWP	€/kg CO_2-eq.	**0,1052**
Acidification	AP	€/kg SO_2-eq.	**5,29**
Eutrophication (freshwater)	FEP	€/kg P-eq.	**1,98**
Eutrophication (marine)	MEP	€/kg N-eq.	**3,31**
Photochemical ozone creation	POCP	€/kg NMVOC-eq.	**1,22**
Ozone depletion	ODP	€/kg CFC-eq.	**32,3**

$$\text{Environmental value} = \frac{\text{planned area costs} \bullet \text{estimated risk factor} \bullet (\text{reinvestment rate} + \text{profit rate})}{\text{planned square meters}}$$

Equation 1: Calculation of the environmental value in the GREEN-ZERO approach.

The plan calculation on a full cost basis comprises the following aspects, which are implemented in Equation 1:

- recording of all costs for an area (including initial costs for examination due to contamination and legal/social framework conditions),
- classification of costs into overhead and direct costs,
- formation of a cost annuity,
- formation of a risk factor,
- calculation of the environmental value and
- summary of all information for pricing purposes.

Thus, in addition to the price per m^2, a price per environmental value unit can also be determined. As a result, the mean value of the increase in environmental value is now based on the maximum development horizon of the biotopes for each year.

The environmental value is calculated for several decades in advance. This forecast is used for planning as well as for estimating how much environmental value will be generated. Thus, for each area that is ecologically restored, the planning of the activities that lead to the ecological restoration of the areas differs from the implementation in practice. After the area development plan is determined, the environmental value calculation is updated for each area at the end of the year. This ensures that only measures and activities that have actually taken place are included in the calculation of the environmental value for the current year. After the update, the generated environmental value is recorded and transferred to an annual overview.

The fourth and the fifth step (*ecological restoration*, see section 3.5.) proceed in parallel. The planning of the ecological restoration of degraded ecosystems provides the basis for the calculation of the environmental value. Investments are made in areas in a degraded state providing a low ecological value. Reasons for a degraded state are intensive anthropogenic use (historical or current), abandonment of use and subsequent fallow. For areas able to be ecologically restored, a degraded condition of the area or a strong effect of the previous use must be detectable (e.g., species-poor open land or non-native pure forest stands) or a restoration potential due to anthropogenic overuse of the area (e.g., formerly intensive used agricultural or forest areas or industrial wasteland with sealed surfaces) must be clearly recognizable so that environmental benefits can be achieved.

The ecological value and the increase in value through ecological restoration are thereby determined by using point-based systems. For the implementation in Germany, the point-based-system based on the German biotope value procedure (dt.: Biotopwertverfahren) and biotope habitat type lists (dt.: Biotoptyplisten) is applied (see also section 2.3. and 3.5.) using habitat types and biotope points according to the Federal Compensation Regulation (dt.: Bundeskompensationsverordnung (BKompV)) (BfN, 2021; BMU, 2020; Louis, 2010).

The planning of the ecological restoration takes place in three phases:

1. Phase 1 – Basic planning: The landscape ecological, legal and logistical conditions are examined and the potentials and risks of the area are determined.
2. Phase 2 – Development planning: Based on the potentials and characteristics of the areas, specific development objectives and measures are defined with the aim of permanently creating the greatest possible variety of habitats and ecological services.
3. Phase 3 – Implementation of measures: Deconstruction work, debris removal, site preparation and biotope creation measures are carried out under ecological construction supervision.

With the preparation and implementation of the defined planning on the area to be restored, environmental value is generated, which offsets the environmental costs and thus compensates for the environmental impacts quantified by means of LCA. According to Equation 1, environmental value is generated by the fact that measures or activities related to the ecological restoration of degraded areas have been implemented and have thus caused costs.

In Figs. 3 and 4, the biotope mapping based on the point-based system of BKompV is shown for the initial state (Fig. 3) and the target state (Fig. 4) for the ecological restoration for the area Kurl 3. Kurl 3 is located in the Lünen-Niederaden in the district of Unna and was used as site for the ventilation shaft of the Kurl coalmine until the year 1995 (HeimatERBE GmbH, 2021a, HeimatERBE GmbH, 2021b). In general, the point-based biotope value of BKompV range from 0 to 24. Fig. 3 shows that the biotope value of the initial state of Kurl 3 ranges between very low values (0–4, e.g., for sealed surfaces) and low values (5–9, e.g., anthropogenic used open areas) up to high values for (16–18, e.g., for forest areas). Fig. 4 shows the target state for a biotope development time of 100 years. The biotope values are supposed to increase significantly, reaching up to very high values (19–21, e.g., species-rich meadows and mixed deciduous forest areas).

To ensure the achievement of the renaturation goals formulated in the development planning, a *monitoring* concept is implemented (see step 6, section 3.6.). The development of the biotic composition of the respective area is monitored and documented in a long-term perspective. Moreover, the monitoring is carried out according to scientifically established methods of renaturation and restoration ecology (see section 2.3. and 3.6.). The monitoring concept is drawn up and implemented on a site-specific basis, taking into account general requirements and indicators, e.g., the biotope types and vegetation units as a basis for all animal species and various faunistic species groups as indicators, which are typical for the respective target biotopes on the areas. Examples for used species group indicators are birds, breeding birds, butterflies, grasshoppers and amphibians. Furthermore, a survey of the status at the end of the planned development period is necessary in order to check the final achievement of the renaturation objectives. In the meantime (depending on the dynamics and basic development duration of the respective target biotope), repeated surveys may be necessary in order to be able to follow the developments after the creation and during the maintenance measures.

5. Discussion

The presented CEC has some challenges regarding the methodology and the implementation (see section 5.1.). Moreover, it is discussed whether the CEC can foster progress in the field of compensation beyond climate neutrality towards environmental neutrality (see section 5.2.).

5.1. General Challenges

According to the mitigation-hierarchy, the environmental impacts have to be reduced before compensation. For CEC, showing the reduction of the environmental impacts is done with LCA. However, so far

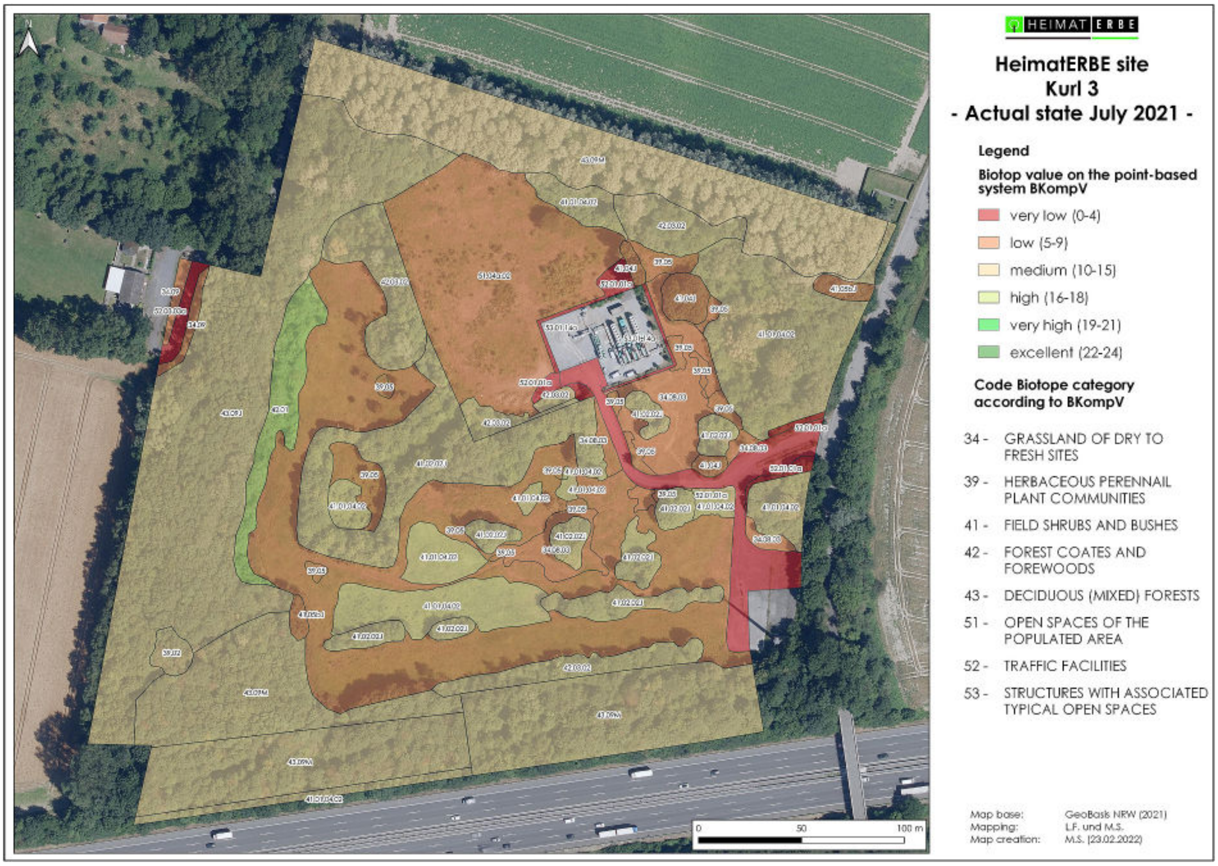

Fig. 3. Example of biotope mapping based on the point-based system BKompV as the starting point for the ecological restoration for Kurl 3.

climate targets are formulated mainly on country, sector or organization level (BMU, 2019; European Commission, 2021; Giesekam et al., 2021; SBTi, 2022b; UNFCCC, 2015) but not on product level. As CEC aims to compensate the environmental impacts also of products or individuals, there is no clear guidance on how reduction targets should be set. Furthermore, the reduction targets are exclusively available for climate change and are missing for all other impact categories. There is also the need to define how to deal with trade-offs between impact categories, e. g., when the impacts are reduced significantly in the majority of analysed impact categories, but not in all. Thus, further research should focus on how to define reduction targets on a product and individual level, how to define reduction targets for a broad set of impact categories and how to deal with trade-offs between impact categories in CEC.

Several challenges are linked to the monetization of the LCA results. When implementing the CEC, there is the need to choose a monetization method. The cost rates vary significantly among different monetization methods with the geographical area being the most influential criterion. The cost rates for human health are often related to welfare data, meaning that the richer the reference area, the higher the cost rates. Thus, the environmental costs determined for CEC are varying depending on the region. Practitioners, who implement CEC, should thus pay attention to the coherence between their geographical context and chosen monetization method (Amadei et al., 2021; Arendt et al., 2020). Guidelines should be developed to support practitioners on how the monetary valuation methods have to be chosen and used according to the relevant decision contexts (Amadei et al., 2021). Moreover, an accurate determination of the environmental costs within CEC needs reliable and up-to-date cost rates. Monetization methods for LCA rely in some cases on few key literature studies that are more than 10 years old (Amadei et al., 2021). Further research is necessary to keep monetization methods for LCA up-to-date, based on robust and reliable data and thus, to increase the robustness and accuracy of environmental costs determined within CEC, especially related to biodiversity (Arendt et al., 2021).

From a global view, CEC can thereby support to mobilize financial resources from polluters to be invested in conservation and sustainably use biodiversity and ecosystems, which is demanded also from SDG 15 (UN, 2022). As the environmental costs are internalized and paid by the polluter, this opens up a new economic perspective and can trigger changed sustainable production and consumption patterns as well as more sustainable courses of action (Bünger and Matthey, 2018; Ferron-Vilchez et al., 2018; Folkens et al., 2020). In consequence, CECcan support in correcting externalities as type of market failure, as the polluters pay for it and an inefficient use of a society's resources could be avoided (Bachmann, 2019).

As described in section 3.4., the used method for ecosystem valuation can be classified as restoration cost method and a form of an out-of-kind offset, as the environmental costs are a cash payment to finance renaturation measures and to generate environmental value (BBOP, 2009; Pascual et al., 2012). These offsets are not directly linked with any affected biodiversity component impacted by the project. As such, the environmental benefits generated by CEC could take place directly at the ecosystems where the environmental burdens occur. But it is more likely that the renaturation measures take place without a direct link to affected ecosystems. Two main challenges result from this: First, the compensation is asynchronous, as the environmental benefits and burdens are balanced on a monetary basis without a proof for each impact categories. That means that if the main impacts are climate change and eutrophication, the impacts are not necessarily be balanced in the very same impact categories. Moreover, the environmental costs do not only include damages to the Area of Protection ecosystem quality, but also to others, e.g., human health. For the environmental value, benefits are considered mainly for the Area of Protection of ecosystem quality. Second, there is a time lag occurring regarding the environmental

Fig. 4. Example of biotope mapping based on the point-based system BKompV of the target state of the ecological restoration for Kurl 3.

benefits, as the renaturation measures including biotope development with positive impacts on the ecosystems take place in a long-term perspective and mainly after the environmental burdens took place. On the monetary basis, the compensation can take place immediately, but from an ecosystem perspective, interim losses occur caused by long biotope development times until the full maturity of the targeted biotopes and ecosystems.

Further research is necessary to enhance CEC regarding the potentially asynchronous compensation, as future regulations could demand this (European Commission, 2019, 2020a, 2020b). It should be further investigated how a proof can be added that the environmental burdens are balanced with environmental gains not only on a monetary basis – which is already implemented in CEC as a basis principle – but also on impact category level. This means that the environmental burdens and gains should be linked from an ecosystem and biodiversity perspective in order to proof their balance, which can't be done using monetization of LCA results and ecosystem valuation alone. For the impact category climate change, existing standards can be used as guidance (Gold--Standard, 2019; Verra, 2019). For other impact categories, the proof of balance is more challenging, as no guidelines exist. Further, this could potentially require analysing ground samples at the renaturation sites with an area size up to several hectares (HeimatERBE GmbH, 2021a). Further research should address whether an evaluation at endpoint level instead of the so far implemented midpoint level might solve some of these challenges. However, the matching of the impacts in LCA and the benefits through renaturation measures on endpoint level is also challenging, because the determination and monitoring of the endpoints in the field is complex. Moreover, co-benefits of the renaturation measures for human health should be integrated to lower the asynchrony of compensation regarding damage on human health and ecosystem quality and benefits mainly on ecosystem quality. The ecosystem valuation should thus be extended to integrate human health co-benefits.

To counteract the potentially time lag issue of CEC, the (partly) use of biodiversity banking mechanisms could be a solution. Interim losses can be avoided or reduced by (partly) implementing the restoration actions in advance of the impacts. Thus, the underlying investment model would need to be extended or exchanged with a (partly) fonds model (Bull et al., 2013; Dietrich et al., 2014; Schweppe-Kraft, 1998). In consequence, the environmental benefits are (partly) generated before the environmental impacts take place and time lag can be (partly) avoided. The practical implementation of CEC by GREENZERO can be classified as a partly fonds model in order to reduce the time lag. Only already generated environmental value is used to balance environmental costs (see section 4). That means, that renaturation measures where already implemented in the degraded ecosystems and thus, biotopes started to develop towards the target state, but without having reached their full maturity.

Additional challenges exist regarding the renaturation measures. As the restoration costs are used as a proxy to determine the environmental value in order to compensate the environmental costs, evidence is necessary to proof that for the chosen measures, the costs and the way of ecological restoration are proportionate to each other. This helps to lower the risk of overestimating the replacement costs and thus the generated ecosystem value. In the GREENZERO approach, this challenge can be solved by including a cost-benefit-perspective based on ecosystem services or by external and independent verification that the chosen measures are both cost-efficient and adequate from an ecology point of view. Furthermore, it has to be defined which ecosystems to be restored in a degraded area. The definition of the targeted ecosystems should follow renaturation principles (see section 2.3. and 3.5.), which was also shown in implementation example of the GREENZERO approach (see section 4). In addition, target based approaches (Simmonds et al., 2020) could be used and implemented. Moreover, systematically mapped knowledge about restoration ecology could give a guide for practitioners in addition to the wide range of available paper, reports and books (Heger et al., 2022). The planning and implementation of renaturation measures within CEC should also include known conditions from biodiversity offsetting, e.g., based on (Gardener et al., 2013):

1. environmental burdens and benefits are comparable in type and amount;
2. environmental benefits are additional compared to the absence of the project in the targeted area;
3. environmental benefits are lasting in a long-term perspective, i.e., until the biotopes are fully developed and protected beyond that.

Implementing the first named point to CEC has already been addressed by discussing the potentially asynchronous compensation. Fulfilling this condition means, that the restoration costs are linked to the ecological value of the affected ecosystems and thus, it can be checked if the environmental benefits generated through renaturation measures are comparable in type and amount with the environmental burdens to compensate.

Finally, from an overall perspective, the following challenges should be on the agenda for further research and development of CEC:

- Verification: The implementation of CEC should be externally and independent in order to proof the correct use and documentation of the described methods and principles regarding LCA, monetization and renaturation. A formulation of the practical implementation in a standard document could increase the transparency and credibility of the compensation approach, which is currently planned for the GREENZERO approach. This remains a challenge, as the whole approach is multidisciplinary.
- Scale-up: Further research should investigate the potential for scale-up of CEC and whether there are limits regarding the availability of areas for ecosystem restoration.
- Global supply chains: Depending on the product, organization or individual, the environmental burdens occur along a global supply chain. A decoupling from burdens to benefits in the form that the renaturation measures take place just at one end of the supply chain should be avoided, as that would mean that the externalities regarding the burdens would still exist.

As the compensation takes place in an existing ecosystem, CEC faces, as discussed, similar challenges as typical biodiversity offsets (Bull et al., 2013). It is noted that even if CEC has similarities and is based on elements of biodiversity offsets, the scope is not to be used in urban or spatial planning like typical biodiversity offsets. The scope is to compensate the environmental impacts of products, organizations or individuals (see section 3), and thus has the potential to offer the possibility to compensate a broad set of environmental impacts to polluters which are so far not included in typical biodiversity offsets.

5.2. *Moving from carbon neutrality towards environmental neutrality?*

Carbon offsets are used to balance the gross emissions in order to achieve “carbon neutrality”. In this context, “carbon neutrality” is used to describe a state in which the activities of a products, organization (e.g., company, city, country) or an individual result in net-zero emissions of CO_2-eq. There is a rather academic debate on differences between carbon neutral, climate neutral and the net-zero concept. In the purpose of this paper, we use them as synonyms and thus propose “environmental neutrality” as wording in the sense of the CEC, analogous to the concept of “carbon neutrality”. Net-zero is achieved when activities do not release any greenhouse gases (GHG) or the GHG released after decarbonization are compensated (Butler et al., 2015; Finkbeiner and Bach, 2021).

Similar to the concept of “carbon neutrality”, the introduced compensation approach CEC aims to balance a broad set of environmental impacts including GHG-emissions. The mitigation-hierarchy is implemented within CEC, following the scientific calls to do the same for carbon offsets. Based on the broad sets of impact categories that can be compensated with CEC, problem shifting from one impact category to another can be identified. Thus, the proposed approach can be a step beyond “climate neutrality” towards “environmental neutrality”.

“Environmental neutrality” should be based on a broad set of considered impact categories. For the shown practical implementation of CEC by GREENZERO (see section 4), the compensation is currently based on six impact categories (climate change, acidification, freshwater eutrophication, marine eutrophication, photochemical ozone creation and ozone depletion), while four additional impact categories (ionizing radiation, particulate matter formation, land use, water use) will be implemented in the next years. Such an extension does not mean that all relevant impacts are covered, though. Further research is necessary to implement more impact categories to the CEC approach. In addition, conditions need to be derived which impact categories have to be considered for the global term “environmental neutrality” or rules need to be developed, how transparency is ensured, which environmental impacts are covered by this claim respectively, which environmental impacts are not yet covered by it.

6. Conclusion

The introduced CEC approach proposes a new compensation concept beyond climate change. It intends to compensate a broad set of environmental impacts in an existing ecosystem by renaturation of degraded ecosystems for products & services, organization and urban areas and individuals. It was demonstrated that the CEC approach can be implemented in practice based on the case study GREENZERO. CEC therefore might be able to contribute to offset climate change impacts as well as other environmental problems (e.g., acidification, eutrophication, land use or water use) at the same time, not considering only one aspect and neglecting the others. As an example, climate change and the degradation of ecosystems through human intervention and thus the loss of biodiversity can be lowered with the proposed approach, which is important for a more holistic transition towards sustainability. The consideration of the life cycle perspective and the fact, that compensation is achieved in real time and the real world are additional strengths compared to many of the existing carbon compensation measures. The proposed approach should be further tested and is intended to foster progress in more comprehensive and robust offsetting of environmental impacts beyond climate neutrality.

Author Contributions

Conceptualization, D.M., V.B. and M.F.; Methodology, D.M., V.B., M.F., T.H., H.A. M.S., L.F. and D.G.; Writing – original draft preparation, D.M., T.H., M.S. and L.F.; Writing – review & editing, V.B., M.F., H.A., D.G.; Visualization, D.M., M.S. and L.F.; Supervision, V.B., M.F., H.A. and D.G.; Project administration, D.M. and M.S.; All authors have read and agreed to the published version of the manuscript.

Funding

This work was partly funded by HeimatERBE GmbH, Essen, Germany.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

References

Ahn, H., Honkomp, T., 2021. Projektbericht HeimatERBE: Produktisierung ökologischer Aufwertung. Braunschweig, Germany.
Ahn, H., Honkomp, T., 2022. Änderungsbericht zum Projekt „HeimatERBE: Produktisierung ökologischer Aufwertung ". Braunschweig, Germany.
Amadei, A.M., De Laurentiis, V., Sala, S., 2021. A review of monetary valuation in life cycle assessment: state of the art and future needs. J. Clean. Prod. 329, 129668 https://doi.org/10.1016/j.jclepro.2021.129668.
Andrews, J., 2014. Greenhouse Gas Emissions Inventory Reports: FY 14 Briefing. The Sustainability Institute, Durham, UK.
Arendt, R., Bachmann, T.M., Motoshita, M., Bach, V., Finkbeiner, M., 2020. Comparison of different monetization methods in LCA: a review. Sustain. Times 12, 1–39. https://doi.org/10.3390/su122410493.
Arendt, R., Bach, V., Finkbeiner, M., 2021. Carbon offsets: an LCA perspective. In: Albrecht, S., Fischer, M., Leistner, P., Schebek, L. (Eds.), Progress in Life Cycle Assessment 2019. Springer, Cham, Switzerland, pp. 189–212. https://doi.org/10.1007/978-3-030-50519-6_14.
Bachmann, T.M., 2019. Optimal pollution: the welfare economic approach to correct related market failures. Encycl. Environ. Heal. 4, 767–777. https://doi.org/10.1016/B978-0-12-409548-9.09382-9.
Bagstad, K.J., Semmens, D.J., Waage, S., Winthrop, R., 2013. A comparative assessment of decision-support tools for ecosystem services quantification and valuation. Ecosyst. Serv. 5, 27–39. https://doi.org/10.1016/j.ecoser.2013.07.004.
BBOP, 2009. Biodiversity Offset Cost-Benefit Handbook. BBOP, Washington, D.C., USA.
BfN, 2021. Eingriffsregelung [WWW Document]. URL. https://www.bfn.de/eingriffsregelung. accessed 12.3.21.
BMU, 2019. Klimaschutzprogramm 2030 der Bundesregierung zur Umsetzung des Klimaschutzplans 2050 Inhaltsverzeichnis. Bonn, Germany.
BMU, 2020. Verordnung über die Vermeidung und die Kompensation von Eingriffen in Natur und Landschaft im Zuständigkeitsbereich der Bundesverwaltung (BKompV). Berlin, Germany.
BMUB, 2016. Climate Action Plan 2050 - Principles and goals of the German government's climate policy. Berlin, Germany.
Bradshaw, A.D., 1996. Underlying principles of restoration. Can. J. Fish. Aquat. Sci. 53, 3–9. https://doi.org/10.1139/cjfas-53-s1-3.
Broekhoff, D., Gillenwater, M., Colbert-Sangree, T., Cage, P., 2019. Securing Cimate Benefit: A Guide to Using Carbon Offsets. Stockholm. Sweden & Washington, D.C., USA.
Bull, J.W., Suttle, K.B., Gordon, A., Singh, N.J., Milner-Gulland, E.J., 2013. Biodiversity offsets in theory and practice. Oryx 47, 369–380. https://doi.org/10.1017/S003060531200172X.
Bünger, B., Matthey, A., 2018. Methodenkonvention 3.0 zur Ermittlung von Umweltkosten - Methodische Grundlagen. Dessau-Roßlau, Germany.
Butler, T., Lode, B., Parker, A., Mar, K., Schmidt, F., Lawrence, M., 2015. Long-term Climate Goals: Decarbonisation, Carbon Neutrality, and Climate Neutrality. Potsdam, Germany. https://doi.org/10.2312/iass.2015.029.
CBD, 2011. Convention on Biological Diversity, United Nations Decade on Biodiversity 2011-2020 Factsheets. Montreal, Canada.
CML, 2016. CML-IA Characterisation Factors [WWW Document]. C. Ind. Ecol. URL. https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors. accessed 12.4.21.
Cremer, A., Müller, K., Berger, M., Finkbeiner, M., 2020. A framework for environmental decision support in cities incorporating organizational LCA. Int. J. Life Cycle Assess. 25, 2204. https://doi.org/10.1007/s11367-020-01822-9, 2216.
de Bruyn, S., Bijleveld, M., de Graaff, L., Schep, E., Schroten, A., Vergeer, R., Ahdour, S., 2018. Environmental Prices Handbook - EU28 version. Delft, Netherlands.
Dietrich, K., Schweppe-Kraft, B., Haarnacke, S., 2014. Methods to calculate offsets to compensate for time lags in the recovery of ecosystems and biodiversity. Bonn, Germany.
Drenckhahn, D., Arneth, A., Filser, J., Haberl, H., Hansjürgens, B., Herrmann, B., Homeier, J., Leuschner, C., Mosbrugger, V., Reusch, T., Schäffer, A., Scherer-Lorenzen, M., Tockner, K., 2020. Globale Biodiversität in der Krise-Was können Deutschland und die EU dagegen tun? Dokumentationsband zu Diskussion Nr. 24. Nationale Akademie der Wissenschaften Leopoldina, Halle (Saale), Germany.
European Commission, 2019. The European Green Deal - COM(2019) 640 final. Brussels, Belgium.
European Commission, 2020a. Initiative on Substantiating Green Claims [WWW Document]. URL. https://ec.europa.eu/environment/eussd/smgp/initiative_on_green_claims.htm. accessed 14.7.22.
European Commission, 2020b. Circular Economy Action Plan COM/2020/98 final. Brussels, Belgium.
European Commission, 2021. European Climate Law - Regulation (EU) 2021/1119. Official Journal of the European Union, Brussels, Belgium.
European Commission, 2022. European Platform on Life Cycle Assessment - Environmental Footprint (EF) Impact Assessment [WWW Document]. URL. https://eplca.jrc.ec.europa.eu/EFVersioning.html. accessed 15.9.22.
Eurostat, 2021. Database - harmonised indices of consumer prices (HICP) [WWW Document]. URL. https://ec.europa.eu/eurostat/web/hicp/data/database. accessed 12.4.21.
Ferron-Vilchez, V., Torre-Ruiz, J.M. de la, Mandojana, N.O., 2018. How much would environmental issues cost? The internalization of environmental costs in the European Transport industry. Environ. Eng. Manag. J. 14, 2149–2162. https://doi.org/10.30638/eemj.2015.229.
Finkbeiner, M., Bach, V., 2021. Life cycle assessment of decarbonization options—towards scientifically robust carbon neutrality. Int. J. Life Cycle Assess. 26, 635–639. https://doi.org/10.1007/s11367-021-01902-4.
Folkens, L., Wiedemer, V., Schneider, P., 2020. Monetary valuation and internalization of externalities in German agriculture using the example of nitrate pollution: a case-study. Sustain. Times 12. https://doi.org/10.3390/su12166681.
Gann, G.D., McDonald, T., Walder, B., Aronson, J., Nelson, C.R., Jonson, J., Hallett, J.G., Eisenberg, C., Guariguata, M.R., Liu, J., Hua, F., Echeverría, C., Gonzales, E., Shaw, N., Decleer, K., Dixon, K.W., 2019. Second Edition. Restor. Ecol. 27. International principles and standards for the practice of ecological restoration, pp. S1–S46. https://doi.org/10.1111/rec.13035.
Gardener, T.A., von Hase, A., Brownlie, S., Ekstrom, J.M.M., Pilgrim, J.D., Savy, C.E., Stephens, R.T.T., Treweek, J., Ussher, G.T., Ward, G., Ten Kate, K., 2013. Biodiversity offsets and the challenge of achieving No net loss. Conserv. Biol. 27, 1254–1264. https://doi.org/10.1111/cobi.12118.
Garrod, G., Willis, K.G., 1999. Economic Valuation of the Environment. Edward Elgar Publishing, Cheltenham, UK.
Giesekam, J., Norman, J., Garvey, A., Betts-Davies, S., 2021. Science-based targets: on target? Sustainability 13, 1657. https://doi.org/10.3390/su13041657.
Goermer, M., Lehmann, A., Finkbeiner, M., 2020. Life-LCA: assessing the environmental impacts of a human being—challenges and perspectives. Int. J. Life Cycle Assess. 25, 141–156. https://doi.org/10.1007/s11367-019-01645-3.
Gold-Standard, 2019. GOLD STANDARD FOR THE GLOBAL GOALS - Principles and Requirements. Geneva, Switzerland.
GREENZERO, 2022. Gemeinsam umweltneutral handeln [WWW Document]. URL. https://greenzero-group.com/#standard. accessed 29.11.22.
Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., Koning, A. de, Oers, L. van, Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., Bruijn, H., Duin, de, van, R., Huijbregts, M.A.J., 2002. Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards. Kluwer Academic Publishers, Dordrecht, Netherlands.
Hampicke, U., 2009. In: Zerbe, S., Wiegleb, G. (Eds.), Kosten der Renaturierung. Renaturierung von Ökosystemen in Mitteleuropa. Springer Spektrum, Berlin & Heidelberg, Germany, pp. 441–457.
Harrison, P.A., Dunford, R., Barton, D.N., Kelemen, E., Martín-López, B., Norton, L., Termansen, M., Saarikoski, H., Hendriks, K., Gómez-Baggethun, E., Czúcz, B., García-Llorente, M., Howard, D., Jacobs, S., Karlsen, M., Kopperoinen, L., Madsen, A., Rusch, G., van Eupen, M., Verweij, P., Smith, R., Tuomasjukka, D., Zulian, G., 2018. Selecting methods for ecosystem service assessment: a decision tree approach. Ecosyst. Serv. 29, 481–498. https://doi.org/10.1016/j.ecoser.2017.09.016.
Heger, T., Jeschke, J.M., Febria, C., Kollmann, J., Murphy, S., Rochefort, L., Shackelford, N., Temperton, V.M., Higgs, E., 2022. Mapping and assessing the knowledge base of ecological restoration. Restor. Ecol. https://doi.org/10.1111/rec.13676.
HeimatERBE GmbH, 2021a. See our projects [WWW Document]. URL. https://heimaterbe.de/en/hompage/our-projects/. accessed 7.7.22.
HeimatERBE GmbH, 2021b. Deconstruction work for more naturalness on Kurl 3 [WWW Document]. URL. https://heimaterbe.de/en/deconstruction-work-for-more-naturalness-on-kurl-3/. accessed 7.7.22.
Huijbregts, M., Steinmann, Z.J.N., Elshout, P.M.F.M., Stam, G., Verones, F., Vieira, M.D.M., Zijp, M., van Zelm, R., 2017. ReCiPe 2016 v1.1 - A Harmonized Life Cycle Impact Assessment Method at Midpoint and Endpoint Level Report I: Characterization. National Institute for Public Health and the Environment, Bilthoven, Netherlands.
IPBES, 2016. Summary for Policymakers of the Assessment Report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) on Pollinators, Pollination and Food Production. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany.
IPBES, 2019. Global assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany.
IPCC, 2018. Global warming of 1.5°C [WWW document]. URL. https://www.ipcc.ch/sr15/. accessed 22.5.19.
IPCC, 2022. Climate Change 2022 - Mitigation of Climate Change. Geneva, Switzerland.
ISO, 2006a. ISO 14040: Environmental management – Life cycle assessment – Principles and framework. Geneva, Switzerland.
ISO, 2006b. ISO 14044: environmental management - life cycle assessment - requirements and guidelines. Geneva, Switzerland.
ISO, 2014. ISO/TS 14072: environmental management - life cycle assessment - requirements and guidelines for organizational life cycle assessment. Geneva, Switzerland.
Kiehl, K., 2019. In: Kollmann, J., Kirmer, A., Tischew, S., Hölzel, N., Kiehl, K. (Eds.), Was Ist Renaturierungsökologie?. Renaturierungsökologie. Springer Spektrum, Berlin, Germany, pp. 13–22. https://doi.org/10.1007/978-3-662-54913-1_2.
Kollmann, J., 2019a. Gesellschaftlicher rahmen der Renaturierung. In: Kollmann, J., Kirmer, A., Tischew, S., Hölzel, N., Kiehl, K. (Eds.), Renaturierungsökologie. Springer Spektrum, Berlin, Germany, pp. 87–98. https://doi.org/10.1007/978-3-662-54913-1_7.
Kollmann, J., 2019b. In: Kollmann, J., Kirmer, A., Tischew, S., Hölzel, N., Kiehl, K. (Eds.), Monitoring von Renaturierungen. Renaturierungsökologie. Springer Spektrum, Berlin, Germany, pp. 71–85. https://doi.org/10.1007/978-3-662-54913-1_6.

Kollmann, J., Kirmer, A., Tischew, S., Hölzel, N., Kiehl, K., 2019a. Renaturierungsökologie. Springer Berlin Heidelberg, Berlin & Heidelberg, Germany. https://doi.org/10.1007/978-3-662-54913-1.
Kollmann, J., Kirmer, A., Tischew, S., Hölzel, N., Kiehl, K., 2019b. Renaturierungsökologie. Springer Berlin Heidelberg, Berlin & Heidelberg, Germany. https://doi.org/10.1007/978-3-662-54913-1.
Li, H., Hao, Y., Xie, C., Han, Y., Wang, Z.-R., 2022. Emerging technologies and policies for carbon–neutral transportation. Int. J. Transp. Sci. Technol. https://doi.org/10.1016/j.ijtst.2022.09.002.
Loiseau, E., Aissani, L., Le Féon, S., Laurent, F., Cerceau, J., Sala, S., Roux, P., 2018. Territorial Life Cycle Assessment (LCA): what exactly is it about? A proposal towards using a common terminology and a research agenda. J. Clean. Prod. 176, 474–485. https://doi.org/10.1016/j.jclepro.2017.12.169.
Loreau, M., Naeem, S., Inchausti, P., Bengtsson, J., Grime, J.P., Hector, A., Hooper, D.U., Huston, M.A., Raffaelli, D., Schmid, B., Tilman, D., Wardle, D.A., 2001. Biodiversity and ecosystem functioning: current knowledge and future challenges. Science 84 294, 804–808. https://doi.org/10.1126/science.1064088.
Louis, H.W., 2010. Das neue bundesnaturschutzgesetz. Nat. Recht 32, 77–89. https://doi.org/10.1007/s10357-010-1807-y.
Mace, G.M., Norris, K., Fitter, A.H., 2012. Biodiversity and ecosystem services: a multilayered relationship. Trends Ecol. Evol. 27, 19–26. https://doi.org/10.1016/j.tree.2011.08.006.
Mikosch, N., Dettmer, T., Plaga, B., Gernuks, M., Finkbeiner, M., 2022. Relevance of impact categories and applicability of life cycle impact assessment methods from an automotive industry perspective. Sustainability 14, 8837. https://doi.org/10.3390/su14148837.
Palmer, M.A., Zedler, J.B., Falk, D.A. (Eds.), 2016. Foundations of Restoration Ecology, second ed. Island Press, Washington, D.C., Covelo, USA & London, UK.
Pascual, U., Muradian, R., Brander, L., Gómez-Baggethun, E., Martín-López, B., Verma, M., Armsworth, P., Christie, M., Cornelissen, H., Eppink, F., Farley, J., Loomis, J., Pearson, L., Perrings, C., Polasky, S., McNeely, J.A., Norgaard, R., Siddiqui, R., David Simpson, R., Kerry Turner, R., Simpson, R.D., 2012. The economics of valuing ecosystem services and biodiversity. Econ. Ecosyst. Biodivers. Ecol. Econ. Found. 183–256. https://doi.org/10.4324/9781849775489.
Pearce, D., Atkinson, G., Maurato, S., 2006. Cost-Benefit Analysis and the Environment - Recent Developments, Cost-Benefit Analysis and the Environment. OECD Publications, Paris, France.
Quétier, F., Lavorel, S., 2011. Assessing ecological equivalence in biodiversity offset schemes: key issues and solutions. Biol. Conserv. 144, 2991–2999. https://doi.org/10.1016/j.biocon.2011.09.002.
Ruckelshaus, M., McKenzie, E., Tallis, H., Guerry, A., Daily, G., Kareiva, P., Polasky, S., Ricketts, T., Bhagabati, N., Wood, S.A., Bernhardt, J., 2015. Notes from the field: lessons learned from using ecosystem service approaches to inform real-world decisions. Ecol. Econ. 115, 11–21. https://doi.org/10.1016/j.ecolecon.2013.07.009.
SBTi, 2022a. Companies taking action [WWW Document]. URL. https://sciencebasedtargets.org/companies-taking-action. accessed 29.11.22.
SBTi, 2022b. Science Based Targets Initiative Annual Progress Report, p. 2021. Version 1.2.
SER, 2004. The SER International Primer on Ecological Restoration. Tuscon, USA.
Schweppe-Kraft, B., 1998. Monetäre Bewertung von Biotopen und ihre Anwendung bei Eingriffen in Natur und Landschaft. BfN-Schr.-Vertrieb im Landwirtschaftsverlag, Bonn-Bad Godesberg, Germany.
Selivanov, E., Hlaváčková, P., 2021. Methods for monetary valuation of ecosystem services: a scoping review. J. For. Sci. 67, 499–511. https://doi.org/10.17221/96/2021-JFS.
Simmonds, J.S., Sonter, L.J., Watson, J.E.M., Bennun, L., Costa, H.M., Dutson, G., Edwards, S., Grantham, H., Griffiths, V.F., Jones, J.P.G., Kiesecker, J., Possingham, H.P., Puydarrieux, P., Quétier, F., Rainer, H., Rainey, H., Roe, D., Savy, C.E., Souquet, M., ten Kate, K., Victurine, R., von Hase, A., Maron, M., 2020. Moving from biodiversity offsets to a target-based approach for ecological compensation. Conserv. Lett. 13, 1–11. https://doi.org/10.1111/conl.12695.
Steen, B., 2016. Calculation of monetary values of environmental impacts from emissions and resource use the case of using the EPS 2015d impact assessment method. J. Sustain. Dev. 9, 15. https://doi.org/10.5539/jsd.v9n6p15.
Thompson, G., 2009. Statistical Literacy Guide: How to Adjust for Inflation. London, UK.
Tucker, G., Quétier, F., Wende, W., 2020. Guidance on Achieving No Net Loss or Net Gain of Biodiversity and Ecosystem Services. Report to the European Commission, DG Environment on Contract ENV.B.2/SER/2016/0018, Brussels, Belgium.
UN, 2022. The 17 goals | sustainable development [WWW document]. URL. https://sdgs.un.org/goals. accessed 6.28.22.
UN Environment, 2019. Global Environment Outlook – GEO-6: Healthy Planet, Healthy People. Cambridge University Press, Nairobi, Kenya. https://doi.org/10.1017/9781108627146.
UNEP, 2021a. UN Decade on Ecosystems Restoration - Excecutive Summary [WWW Document]. URL. https://unenvironment.widen.net/s/qh9glfnvj9. accessed 12.3.21.
UNEP, 2021b. Making Peace with Nature: A Scientific Blueprint to Tackle the Climate, Biodiversity and Pollution Emergencies, Making Peace with Nature. UNEP, Nairobi, Kenya. https://doi.org/10.18356/9789280738377.
UNEP/SETAC, 2015. Guidance on Organizational Life Cycle Assessment. Berlin, Germany.
UNFCCC, 2015. Adoption of the Paris Agreement (Paris, France). FCCC/CP/2015/L.9/Rev.1.
UNFCCC, 2021. Race To Zero [WWW Document]. United Nations Framew. Conv. Clim. Chang. URL. https://unfccc.int/climate-action/race-to-zero-campaign#eq-3. accessed 12.3.21.
van Essen, H., van Wijngaarden, L., Schroten, A., Sutter, D., Bieler, C., Maffii, S., El Beyrouty, K., 2019. Handbook on the external costs of transport - Version 2019 - 1.1. Delft, Netherlands. https://doi.org/10.2832/51388.
Verra, 2019. Verified Carbon Standard Program Guide v4.0. Washington, DC, USA.
Weidema, B.P., 2009. Using the budget constraint to monetarise impact assessment results. Ecol. Econ. 68, 1591–1598. https://doi.org/10.1016/j.ecolecon.2008.01.019.
Weidema, B.P., Wasnae, M., Hermansen, J., Kristensen, I., Halberg, N., 2008. Environmental Improvement Potentials of Meat and Dairy Products 23491.
Wolters, S., Schaller, S., Götz, M., 2018. Freiwillige CO2-Kompensation durch Klimaschutzprojekte. Dessau-Roßlau, Germany.
Zerbe, S., 2019. Renaturierung von Ökosystemen im Spannungsfeld von Mensch und Umwelt. Springer Berlin Heidelberg, Berlin & Heidelberg, Germany. https://doi.org/10.1007/978-3-662-58650-1.
Zerbe, S., 2022a. What's so important about traditional cultural landscapes? In: Zerbe, S. (Ed.), Restoration of Multifunctional Cultural Landscapes. Springer Nature, Cham, Switzerland, pp. 77–126. https://doi.org/10.1007/978-3-030-95572-4_3.
Zerbe, S., 2022b. Restoration of multifunctional cultural landscapes. In: Landscape Series. Springer Cham, Cham, Switzerland. https://doi.org/10.1007/978-3-030-95572-4.