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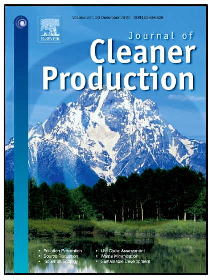


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# Advances and challenges of Life Cycle Assessment (LCA) of Greenhouse Gas Removal Technologies to Fight Climate Changes

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## Abstract

Several greenhouse gas removal technologies (GGRTs), also called negative emissions technologies (NET) have been proposed to help meet the Paris Climate Agreement targets. However, there are many uncertainties in the estimation of their effective greenhouse gas (GHG) removal potentials, caused by their different levels of technological development. Life Cycle Assessment (LCA) has been proposed as one effective methodology to holistically assess the potential of different GGRT removal approaches but no common framework is currently available for benchmarking and policy development. In this article, challenges for LCA are reviewed and discussed together with some alternative approaches for assessment of GGRTs. In particular, GGRTs pose challenges with regards to the functional unit, the system boundary of the LCA assessment, and the timing of emissions. The need to account within LCA of GGRTs for broader implications which involve environmental impacts, economic, social and political drivers is highlighted. A set of recommendations for LCA of GGRTs are proposed for a better assessment of the GGRTs and better accounting of their carbon removal potentials to meet the targets established within the Paris Agreement.




**Keywords:** Greenhouse gas removal technologies, Negative emission technologies, methodology, environmental assessment, Life Cycle Assessment, climate change

# 1. List of abbreviations

ALCA Attributional Life Cycle Assessment

BECCS Bioenergy and Carbon Capture and Storage

CDR Carbon dioxide removal

CLCA Consequential Life Cycle Assessment

DAC Direct Air Capture

DEFRA UK Department of Environment Food and Rural Affairs

EPD Environmental Product Declarations

GGR Greenhouse gas removal

GGRT Greenhouse gas removal technology

GHG Greenhouse gas

GWP Global warming potential

LCA Life cycle assessment

NET Negative Emission Technologies

PCR Product Category Rules

TRL Technological readiness level

## 2. Introduction

Net zero emissions are needed to avoid the worst effects of climate change, and to limit the 'end-of-the-century' increase in global temperatures to less than 2 °C above its preindustrial value as agreed in the Paris Agreement (UNFCC, 2015). Integrated approaches are therefore necessary to reduce anthropogenic emissions of greenhouse gases, and the introduction of greenhouse gas (GHG) removal technologies (GGRTs), also called negative emission technologies (NET), will be needed to balance residual emissions and meet the climate targets (Tavoni and Socolow, 2013; Williamson, 2016). Most proposed GGRTs involve carbon dioxide removal (CDR), although the GGRTs terminology is more general, as GGRTs can be defined as any technology capable of removing major greenhouse gases (GHGs) from the atmosphere or of converting a higher global warming potential (GWP) gas to a lower GWP gas. For instance a GGRT can be a technology which converts methane into carbon dioxide. GGRTs are otherwise very diverse and each GGRT has a specific sets of aims, challenges and side effects (Fuss et al., 2018; Williamson, 2016).

Land-based technologies have particular importance for their greenhouse gas removal potential, with bioenergy combined with carbon capture and storage (BECCS) and afforestation/reforestation being the techniques specifically identified in the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014). Minx et al. (2018) estimated that BECCS could remove up to 20 Gt of $CO_2$ $y^{-1}$ from the atmosphere. Enhanced management of forests and forestry may be capable of removing 0.5 to 3.6 Gt of $CO_2$eq $y^{-1}$ worldwide (Fuss et al., 2018), and agroforestry could sequester up to 2 Gt of atmospheric $CO_2$eq $y^{-1}$ worldwide (Jose and Bardhan, 2012).

Methods to increase C storage in soils include innovative cropland management, biochar production and application, and enhanced root phenotypes (Paustian et al., 2016). Wide application of each approach could, in theory, remove at least 0.2 Gt of atmospheric $CO_2$eq $y^{-1}$ without any change in land use and the consequent impact on emissions; or the production of food, fibre and energy from agriculture (Paustian et al., 2016).

Enhanced weathering and carbonation of rock has an apparently high potential, with Beerling et al., 2018; Moosdorf et al., 2014 estimating that 0.4-1.0 t of $CO_2$ can be sequestered per t silicate rock by soil carbonation. Global estimates of $CO_2$ removal by carbonation are up to 1 Gt $CO_2$eq $y^{-1}$ (Fuss et al., 2018; Minx et al., 2018). Carbonation could also be used for ocean weathering and a theoretical sequestration of 1.25 t $CO_2$ $t^{-1}$ of olivine is feasible, which is a magnesium iron silicate (Hartmann et al., 2013).

Ocean liming has the potential to reduce atmospheric $CO_2$ by several Gt $y^{-1}$ (Fuss et al., 2018; McLaren, 2012). EASAC (2018) observed that while ocean fertilisation (the addition of iron to enhance planktonic biomass growth) could produce real GGR benefits, it could also cause major negative environmental impacts by disrupting marine biodiversity and ecology (EASAC, 2018) due to a change the marine ecosystem and food chain (Zhang et al., 2015). This could lead to a reduced yield of fisheries elsewhere by depleting other nutrients or increasing the risk of water deoxygenation (Williamson, 2016).

Some industrial GGRTs have been proposed for sequestering $CO_2$ directly from the atmosphere. Systematically curing concrete with $CO_2$ on a wide scale could reduce $CO_2$ emissions by 17% in comparison with conventional concrete production through $CO_2$ removal and could additionally result in 38% less energy consumption (Hasanbeigi et al., 2012). Given that the cement industry is responsible for 7% of global GHG emissions with 1.8 Gt of $CO_2$eq every year (Oh et al., 2014), this is a significant GHG emission reduction.

Other potential GGRTs include electrolysis (Rau et al., 2018), biopolymer production (Lu et al., 2012), direct air capture (DAC) (Keith et al., 2018), the use of wood as a construction material (McLaren, 2012), polyol and polycarbonate production from $CO_2$ (Bui et al., 2018). Keith et al. (2018) estimated that direct air capture could remove about 110 kg of $CO_2$ $GJ^{-1}$ of natural gas with a cost of \$94-232 $t^{-1}$ of $CO_2$ removed. Hydrogen production through electrolysis was estimated to remove up to 938 Gt $y^{-1}$ of $CO_2$ worldwide with an estimated removal rate of 0.14-0.22 Gt $CO_2$ $EJ^{-1}$ using non fossil fuel electricity (Rau et al., 2018). Biopolymer production, polyol and polycarbonate production from $CO_2$ and the use of wood as construction material are considered as carbon capture and utilisation (CCU) (Bui et al., 2018).

McLaren (2012) highlighted technology readiness levels (TRL) of GGRTs. There are also uncertainties about their effectiveness in GGR (Williamson, 2016), partly due to their complex production and consumption chains (Bui et al., 2018).

The authors discuss in this article the utility of life cycle assessment (LCA) for comparing the benefits of these different approaches. LCA has been used to assess the net environmental impacts and benefits of some GGRTs (Goglio et al., 2014; Klein et al., 2015), as end-of-pipe methods are not sufficient to characterise net GGRT potential. LCA is a more effective method to assess GGRTs than other methods due to its flexibility and adaptability (Klöpffer and Curran, 2014). LCA notably quantifies several environmental impacts at the same time, therefore offering the possibility of characterizing life cycle environmental trade-offs among diverse impacts (Styles et al., 2014). For some land-based technologies, several authors proposed a multi-functional unit approach to better assess the overall systems through life cycle assessment (Goglio et al., 2014; Nemecek et al., 2011). Other researchers proposed and used attributional, consequential and anticipatory LCA to assess some of these GGRT and this choice raises issues regarding the system boundary (Plevin et al., 2014b; Plevin, 2017). The question of data quality within LCA is often debated for many technologies including GGRTs (Anex and Lifset, 2014).

Several LCA frameworks have been proposed to establish Environmental Product Declarations (EPD) based on Product Categories Rules (PCR), as established by the ISO 14020 series (ISO, 2010, 2001a, 2001b, 2001c) as "set of specific rules, requirements and guidelines for developing Type III environmental declarations (3.2) for one or more product categories"(ISO, 2010). Despite the clear need for LCA of these technologies and several recent reviews and estimates of their potential (Bui et al., 2018; Fuss et al., 2018), a specific LCA framework for the assessment of GGRTs that addresses the comparisons of disparate technologies, to reduce uncertainties and to support better benchmarking is currently lacking. This paper uniquely i) identifies key methodological elements to ensure LCA comparability of GGRTs across sectors and ii) proposes a methodological framework for LCAs for GGRT across sectors to guide future policy-making.



## 3. Material and Methods

This short review was carried out using common databases: "Scopus", "Google Scholar", "Web of Science". Key word utilised included "life cycle assessment (LCA)", "Negative Emission Technology", "Climate Change", "Greenhouse Gas Removal Technologies", "carbon capture and utilisation" and the name of each specific GGRT. For instance words like "tillage", "afforestation", "ocean fertilisation" were employed. Other key words includes "consequential LCA", "prospective LCA", "anticipatory LCA", "attributional LCA". The papers were then screened for their relevance for the topic and duly cited in this paper.

## 4. Results and Discussion

### 4.1. Key elements to compare GGRT environmental performance through LCAs

Life cycle assessments consist of the compilation and evaluation of the inputs, outputs and the potential environmental impacts of product systems throughout their life cycles (ISO, 2006a, 2006b). It is composed of four phases: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation. The first phase defines the objectives of the assessment, the system boundary of the analysis, the functional units and main assumptions including allocation methods. The second phase consists of collecting and processing data of energy flows, emissions and releases to the environment, and of resource use. The life cycle impact assessment consists of calculating the potential impacts associated with each impact category. Finally, in the interpretation phase, the results are interpreted, data quality is assessed, the limitations of the assessment are clarified and the contribution and sensitivity analyses are conducted (ISO, 2006a, 2006b).

Several key aspects of applying LCA to GGRT present real challenges, e.g. the definition of the functional unit and system boundaries, the level of technological readiness and the availability of underlying data, for assessing the GHG-energy nexus, and the timings of emissions and removals.

The main function of GGRT is to remove GHG from the atmosphere (Tavoni and Socolow, 2013; Williamson, 2016), so a potential functional unit is the unit mass (e.g., kg, t, Gt) of $CO_2$eq removed. Land-based technologies are, however, related to the production of food products, materials and bioenergy, while industrial processes produce specific products such as cement, carbon fibre, and wood products. Several authors proposed therefore a framework using different functional units to take multi-functionality of systems into account (Nemecek et al., 2011). The production of these outputs from GGRT is an existing function of the system, together with the economic function of generating income from these outputs. These could be for instance cement, carbon fibre, food. Thus together with kg of $CO_2$ removed, two separate functional units should also be accounted for the amount of the product, e.g. unit mass of product, and the corresponding economic value of the outputs.

For land based technologies, another function is land occupation, so the area of occupied land should be included as a functional unit for these systems (Goglio et al., 2017; Nemecek et al., 2011), along with the functional units noted above. If the GGRTs involve the cultivation of crops, the relationship within the cropping systems should also be taken into account (Goglio et al., 2017). If the land based GGRTs cause major changes in crop or livestock outputs, then their secondary implications on food, biomaterial, fibre and energy market and availability must be addressed within the assessment.

In contrast, for targeted technologies such as direct air capture and enhanced weathering, the main function is to remove GHG from the atmosphere. We define targeted technologies as GGRT that remove only $CO_2$ from the atmosphere and do not produce any product or co-product but just waste and emissions flows. If there is a market for reducing GHGs, the functional unit could be represented by the mass of $CO_2$eq removed and possibly the corresponding economic value of this removal. This economic value of removal can be for instance the economic and social price of "carbon removal". That may only constitute a hypothetical, rather than a real, market value depending on national and international approaches to climate mitigation. This does not reflect the long-term social implications related to GGRTs. There is no consensus yet on the cost/benefits of removal and the results to be potentially achieved by widespread utilization of the GGRTs (Fuss et al., 2018).

A major challenge for LCA in assessing GGRTs is the definition of the system boundaries. This can be difficult when considering the comparability of systems, that have very little in common, except for delivering the same core function, which is GHG removal (ISO, 2006b). For a system comparison of the GGRT's performance, the system boundaries should include all upstream processes to the GHG removal stage (Figure 1). If LCA is also used to perform multifunctional assessment, the system boundary should include all the downstream phases up to the consumption of the different products (Figure 1). Multifunctional assessments can be defined as the assessment of systems with more than one function. Examples of functions are greenhouse gas removal, land occupation, the production of an economic income or the production of a specific product. For instance, a multifunctional assessment could be carried out for a series of systems: i) a system producing wood for construction where the wood production contributes in removing $CO_2$ from the atmosphere during tree cultivation but it is also used as a building material in construction; ii) a BECCS system producing electricity and $CO_2$ which is stored geologically, iii) an afforestation system where the trees are planted and managed for GGR.

Considering the climate change challenges and the complexity of economic sectors upon which the GGRTs may impact, a global consequential LCA should include comparisons of competing technologies to assess and to compare the full GGRT's potential, together with the consequences of their introduction in the world economic system. As shown in Figure 2, the assessment of the environmental impact of GGRTs should consider possible alternative GGRTs. This could be an assessment at global scale between DAC, BECCS and afforestation. In alternative, an assessment at regional level may help to identify the best group of GGRT for a certain region/country to halve its GHG emissions. However, this approach has limited applicability as it requires more data from different technologies and more data processing. An example is the consequential assessment of enhanced soil management of wheat (*Triticum aestivum* L.) as a land-based technology compared with afforestation. One should consider the impact on at least the wheat market and potentially other crop markets together with wood markets as well as the potential GGRTs markets.

We need to distinguish between the two main forms of LCA: attributional (ALCA) and consequential (CLCA). ALCA normally assesses existing systems in considerable detail, but does not (necessarily) explore “what if” scenarios of change. It has relatively low uncertainties (Dale and Kim, 2014) and is most suited to identifying where improvements can be made in a system. CLCA was designed for supporting policy-making and hence a core feature of CLCAs is in quantifying or including existing scenarios of change (Anex and Lifset, 2014; Plevin et al., 2014b). It is usually driven by partial or global market equilibrium models, economic market statistics and historical data. It has higher associated uncertainties than ALCA (Dale and Kim, 2014; Wicke et al., 2012). It is increasingly used to link micro-economic actions to macroeconomic consequences, by identifying the marginal suppliers and technologies prone to be affected by large scale fluctuations in demand (Vázquez-Rowe et al., 2013).

The implementation of any GGRT may be affected by both economic and non-economic drivers (Bui et al., 2018; Nemet et al., 2018). As suggested for bioenergy introduction in the USA and Europe (Baustert and Benetto, 2017; Miller et al., 2013), farmer behaviour can also be affected by farm organisation, societal factors, government policies and other economic drivers (Marvuglia et al., 2017). The UK’s Department of Environment Food and Rural Affairs (DEFRA) uses a segmentation model of farmer socio-economic typologies to better analyse the uptake of GHG mitigation measures in England considering societal factors and policies (Barnes et al., 2010). Similar segmentation models are used in the rest of the UK.

GGRTs have different technological readiness levels, which makes comparisons of diverse GGRTs challenging, as the LCA data may not be equally available or of equal quality for each GGRT at an established industrial scale (McLaren, 2012; Nemet et al., 2018). While many estimates and life cycle inventory data are available for some land based technologies (Ecoinvent, 2018), other technologies are still at the conceptual, laboratory or pilot stages (McLaren, 2012; Nemet et al., 2018) and their economic market is non-existent.

Such LCA comparisons would be extensively based on potentially debatable assumptions, uncertain estimates, modelled data inputs and probably with relatively low data quality. Others maintain that the LCA would still provide preliminary insights of the environmental performance of this technology and help inform policy (Anex and Lifset, 2014; Roy et al., 2012), apart from identifying where future research is needed to improve data quality.

Low data quality and high reliance on assumptions have been reported for consequential LCAs (Anex and Lifset, 2014; Dale and Kim, 2014) and anticipatory LCAs for the introduction of bioenergy (Bichraoui-Draper et al., 2015; Miller et al., 2013). For some GGRT, the technology is not fully developed and the economic markets do not exist and cannot, therefore be fully analysed with LCA (Bichraoui-Draper et al., 2015; Miller et al., 2013). Anticipatory LCAs assess potential and emerging technologies, which are currently not available at industrial scale or are not implemented at large scale. This is particularly challenging for the LCA of GGRTs as (a) technologies are being developed and (b) even when some good data are available, some GGRTs have GHG removal potentials that are strongly dependent on geographical variability (Goglio et al., 2015). Both anticipatory LCA and consequential LCA, despite these limitations, are essential preliminary environmental assessment tools to be used to help to inform policy development and implementation (Anex and Lifset, 2014). The main difference between these two types of LCA is that while consequential LCA examines the consequences of "what-if" scenario in relation to real developed technologies in most cases, the anticipatory LCA focuses more on future technologies or future scenarios.

Recent predictions on climate changes (Myhre et al., 2013) show that the timing of GHG removal has become an essential element in the assessments for both science and policy (Brandão et al., 2013; Fuss et al., 2016). The negative impact of 1 unit of $CO_2$eq released in year n is unlikely to be the same as one unit of $CO_2$eq sequestrated in year n+m. This should be addressed in LCA methods, but current methods to account for the impact of timing of emissions and removals on climate change have limited applicability due to their demand for the high quality and quantity of data and expertise and uncertainties in the atmospheric chemistry dynamics (Myhre et al., 2013; Petersen et al., 2013). There is currently no consensus in the scientific community on the methods to account for temporal dynamic impacts of GHG emissions and removals on climate changes (Brandão et al., 2019; Bui et al., 2018). The methods adopted could strongly influence the results of the impacts (Myhre et al., 2013). Depending on when the emissions occur, the effects on climate change may differ on the basis of the time horizon selected rather than on the timing of the emissions themselves (Allen et al., 2018; Myhre et al., 2013). Understanding and quantifying these dynamics is critical for supporting decision-making. Major emitters may wish to and some will defer GHG emission mitigation programmes in anticipation of implementing large scale GGRTs, but the net impact effect may not be forecastable and this could cause further delay in net GHG emission reduction and climate change mitigation.

GGRTs also have different time ranges of removal, with forest management storing $CO_2$ for decades until the wood is used and forest residues gradually decay, while $CO_2$–cured concrete stores $CO_2$ on long term basis (Hasanbeigi et al., 2012; Zhang et al., 2015). Examples of wood use in relation to timing of emissions and removals are construction with more storage for several decades, combustion with potentially instant release of GHGs. The time of removal should be considered in assessing GGRT potential. The question of time of emission and removals is critical for GGRT, especially for CCU technologies with regards to use of the products made from $CO_2$ (Bui et al., 2018).

Some GGRTs require significant amounts of energy to be both implemented and operated, e.g. direct air capture and $CO_2$ use (Deutz et al., 2018; Fuss et al., 2016). The nature of the energy sources used now and in the future will have a large impact on the outcomes (Keith et al., 2018). Other research is needed to assess potential environmental trade-offs, including those related to energy and climate change nexus (Brandão et al., 2011). By energy and climate change nexus we indicate the relationships between energy systems and climate which is evaluated with integrated energy climate assessments (Brandão et al., 2011). LCA has been used to assess these trade-offs between impacts of global warming, energy consumptions with other impacts (Brandão et al., 2011; Klöpffer and Curran, 2014).

### 4.2. Future perspectives

LCA of GGRTs opens a new set of developments for which current LCA approaches have been only partially developed. The implementation of GGRTs is dependent on economic drivers and, unlike many most subjects of LCA, on government policies and societal factors (Griscom et al., 2017; Nemet et al., 2018). This has been partly addressed within consequential LCA (Anex and Lifset, 2014; Plevin et al., 2014a, 2014b), as within this framework only economic drivers have been included, to date (Anex and Lifset, 2014; Goglio et al., 2015). Current economic models depend on many assumptions and may not adequately address the impacts of climate changes upon the ecological systems and societal systems (Anex and Lifset, 2014; Dale and Kim, 2014).

To provide inputs for science-based policies regarding GGRTs, clear and transparent LCAs must be planned and performed. They should be based upon best available data  and so improvements in data quality and data collection are essential (Goglio et al., 2017; Klöpffer and Curran, 2014). The improved data quality is based on the collection of primary data based on full scale real GGRT systems (ISO, 2006a, 2006b), this cannot be often possible as many technologies are not fully developed or implemented worldwide (McLaren, 2012; Nemet et al., 2018). Together with improved data quality, LCAs of new technologies should be performed at earlier stages to have better assessments of their potential for functions such as $CO_2$ industrial utilisation (Deutz et al., 2018; Zhang et al., 2015).

A method to assess the timing of emissions into the atmosphere should be developed to integrate atmospheric processes with the time when the emissions and removals occur. Here we indicate the timing of emissions as the temporal period when emissions and removal of GHG occurs. Different GHG have different life times in the atmosphere depending on their chemistry dynamics in the atmosphere, many models have been used to assess the life time of GHG in the atmosphere but no common consensus has been achieved on the method to adopt (Brandão et al., 2019; Myhre et al., 2013). This method to assess timing of emissions in LCA of GGRT should reconcile applicability, comprehensiveness and accuracy as proposed in previous research  for cropping system assessment (Goglio et al., 2017, 2015). One future-proofing approach could be to require the LCA analysts to lodge time series data of all GHG emissions and removals that are included in their assessment so that these can be used in future climate models to provide enhanced revisions of the expected impacts on the climate.

### 4.3. Recommendations

Following this discussion, a set of recommendations are proposed:

- Use a functional unit that considers carbon sequestration, e.g. Gt or Mg of $CO_2$eq removed;
- Combine the use of functional units for assessing GGRTs with units used to assess other system functions such as productivity, income generation, and land occupation; this approach considers the multifunctionality of GGRT systems by providing a more comprehensive view of their environmental profile
- Choose more than one impact category to quantify trade-offs among environmental impacts, as discussed by Arzoumanidis et al. (2014). For instance, the use of silicate rock can reduce climate change impacts, but also causes a higher impact on resource use (Lefebvre et al., 2019), while no tillage cultivation can also reduce climate change impacts, but generally increases ecotoxicity and human toxicity from higher pesticide use (to control weeds and pests).
- The accounting methodology and the system boundaries should be clearly defined to allow for further benchmarking, in agreement with the ISO standards (ISO, 2013, 2006a, 2006b);
- Analyses should be based on best available data to provide the most reliable policy inputs. Systems for evaluating and updating data in a timely manner should also be developed and used (Bellon-Maurel et al., 2014) and

- A comprehensive method is needed for LCA of GGRT to address the impacts of timing of emissions and removals on atmospheric chemistry, based on a wide consensus of the scientific community, as discussed by Brandão et al. (2019).

This set of recommendations is a contribution to a better understanding of the comparative potentials of diverse GGRTs, the drivers affecting their implementation and for providing a better understanding of the potential comparisons across sectors. This could serve as an initial framework for a potential  product category rules (PCR) of GGRTs and so lead to better comparisons among GGRTs to inform policy makers, in agreement with the ISO standards (ISO, 2010, 2001a, 2001b, 2001c). For the PCR, GGRTs could considered a product for which common LCA assessment rules need to be defined to allow meaningful comparability among them (ISO, 2010, 2001b, 2001a, 2001c).  The authors solicit comments from all the readers of the present paper on this topic.

## 5. Conclusion

The challenges related to making comparative assessments of GGRTs with CLA were discussed, especially key aspects such as functional units, system boundaries, the climate change-energy nexus and the timing of GHG emissions and removal. The diverse GGRTs offer potentially valuable options, which, if used in concert with major societal shifts to renewable energy and improved energy efficiency throughout society, could make valuable differences in the climate changes of the future on planet earth. The use of consequential LCAs to assess the comparative effectiveness of new GGRT technologies, constitutes a challenge, but it is critical to meet this. Recommendations were presented to overcome this challenge, by providing a consistent basis for a better understanding of the potential for GGRTs, their drivers and barriers and comparisons of them. These recommendations provide an initial framework for Product Category Rules for GGRTs, which can improve the assessments of the GGRTs and their comparative GHG removal capacities to help to meet and to exceed the targets established by the Paris Agreement.

## 6. Conflicts of interest

There are no conflicts to declare.

## 7. Acknowledgements

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**Declaration of interests**

☒ 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.

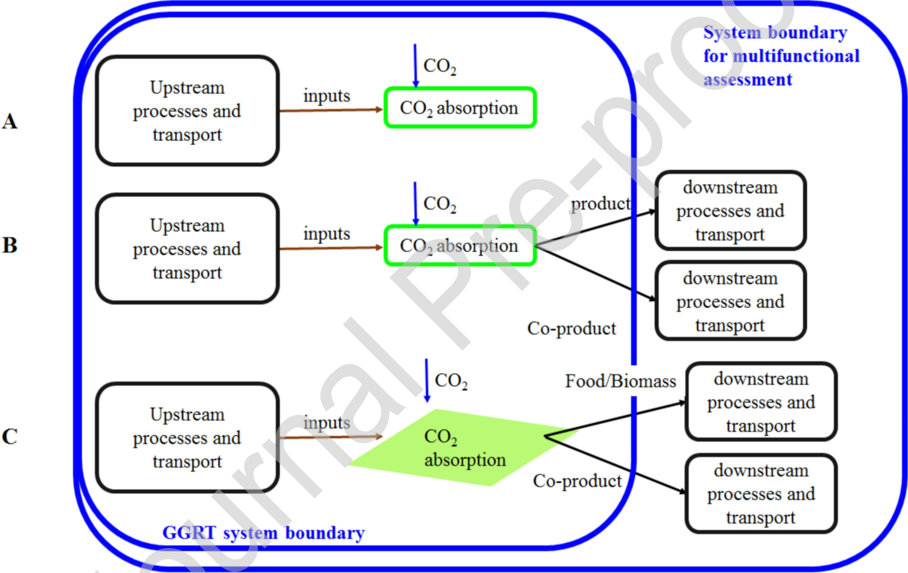
☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

**Figure captions**

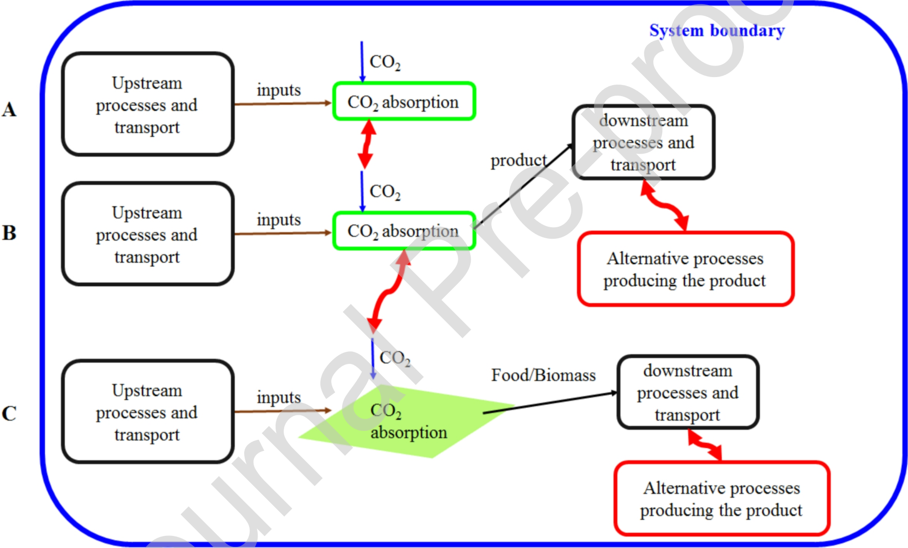
**Figure 1. System boundaries for attributional LCA for greenhouse gas removal assessment and multifunctional assessment. From top to bottom: A) targeted industrial systems (the only function of the system is $CO_2$ removal, no other product/co-product is produced), B) non-targeted industrial systems and C) land based systems.**

**Figure 2. Schematic representation for a consequential LCA of GGRT. From top to bottom: A) targeted industrial GGRT (the only function of the system is $CO_2$ removal, no other product/co-product is produced), B) non-targeted industrial GGRT and C) land based GGRT.**

- LCA functional units of greenhouse gas removal technologies (GGRTs) were proposed
- System boundaries are a GGRT challenge as they involve different production systems
- Emission time is key in the LCA of GGRT as removals do not happen at the same time
- LCA of GGRTs should address environmental, economic, social, political implications
- Recommendations to improve LCAs of GGRTs were proposed



System boundary for multifunctional assessment
A
Upstream processes and transport
inputs
CO2
CO2 absorption
B
Upstream processes and transport
inputs
CO2
CO2 absorption
product
downstream processes and transport
downstream processes and transport
Co-product
C
Upstream processes and transport
inputs
CO2
CO2 absorption
Food/Biomass
downstream processes and transport
Co-product
downstream processes and transport
GGRT system boundary



System boundary
A
B
C
Upstream processes and transport
inputs
$CO_2$
$CO_2$ absorption
Upstream processes and transport
inputs
$CO_2$
$CO_2$ absorption
product
downstream processes and transport
Alternative processes producing the product
Upstream processes and transport
inputs
$CO_2$
$CO_2$ absorption
Food/Biomass
downstream processes and transport
Alternative processes producing the product