Master thesis

Method development for including land-use change greenhouse gas emissions in Life Cycle Assessment

Evaluating the UNEP-SETAC framework for LULUC impacts in LCA.

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Method development for including land-use change greenhouse gas emissions in Life Cycle Assessment

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By

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The aim of industrial ecology is to address sustainability challenges by taking an interdisciplinary approach in identifying, designing, and critically evaluating sustainability solutions. During the master's programme, I have learned to do so by means of various methods such as material flow analysis, environmental input-output analysis, and life cycle assessment (LCA). I have been particularly intrigued by LCA, as it combines my interests in exact sciences and building models with my passion for sustainability. This programme has provided me with a variety of hard and soft skills that will prepare me for a future career in sustainability, particularly in LCA. Hopefully, one day I can call myself a LCA expert.

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Executive summary

The UNEP-SETAC framework is the most well-known framework for including land use and land-use change (LULUC) impacts in life cycle assessment (LCA) in scientific literature. Yet issues regarding the framework's validity have been recognized by several researchers and the framework has not been implemented in common LCA practices. Due to the need in both policy and science for a consensus on a method to include greenhouse gas (GHG) impacts deriving from LULUC in LCA, research in an improved framework is warranted. Therefore, the objective of this master thesis was to evaluate the UNEP-SETAC framework and propose improvements, with the overall goal to advance the method development of LULUC frameworks that quantify LULUC GHG emissions of agricultural products in LCA studies.

To achieve this objective, a mixed method exploratory sequential design was followed. First, qualitative literature review was performed to explain the UNEP-SETAC framework to the reader and to reflect on the suitability of the UNEP-SETAC framework for the quantification of LULUC GHG emissions in LCA. Second, a literature review was conducted to propose an improved conceptual framework for quantifying GHG emissions of LULUC in LCA. Last, the UNEP-SETAC framework and the improved conceptual framework were applied in a comparative LCA case study to compare the LULUC GHG emissions of 1 kg of sunflower oil from France and 1 kg of palm oil from Indonesia cultivated in 2020.

A significant issue that was found was the UNEP-SETAC framework's applicability to an attributional LCA (ALCA). The framework provides the LCA practitioner with various methodological choices that should be taken based on either an ALCA (i.e., an LCA that provides information on what portion of global burdens are associated with a specific product life cycle) or consequential LCA (CLCA; i.e., an LCA that provides information on the environmental burdens that occur, directly or indirectly, as a consequence of a decision). The analysis showed that the UNEP-SETAC framework is largely based on consequential thinking, because emissions are calculated relative to alternative scenarios and based on future assumptions. Due to the design of the framework, the sum of all land transformation and occupation impacts does not equal the sum of all measurable anthropogenic land transformation and occupation impacts in the world. Therefore, it could be concluded that the UNEP-SETAC framework is not suitable in its current form for an ALCA study. Moreover, calculations are influenced by arbitrary value choices and a distinction is made between carbon dioxide (CO_2) originating from fossil carbon, temporary biogenic carbon or permanent biogenic carbon, while there is no scientific basis for this claim.

To advance method development, several weaknesses of the UNEP-SETAC framework were addressed in an improved conceptual framework. The improved framework is in line with both ALCA and CLCA separately and does not mix the characteristics of the two methods. The basis of the framework is aligned with ALCA, and optionally, forgone sequestration can be calculated for a CLCA study. Importantly, using this improved framework for ALCA studies leads to additive results of all measurable anthropogenic emissions, relative to a pre-anthropogenic baseline. For CLCA, the forgone sequestration can be quantified to indicate the impact of using the land for the functional unit, relative to abandoning the land and letting it regenerate. In the proposed framework, certain value choices have been made obsolete, such as the modelling period. Other arbitrary value choices (e.g., amortization period and method, and reference situation) have been standardized and (where possible) based on science.

The comparative LCA case study comparing the LULUC GHG emissions of sunflower oil cultivated in France and palm oil cultivated in Indonesia showed different results using the UNEP-SETAC framework and the improved conceptual framework. It was assumed that the land in France was transformed centuries ago and the land in Indonesia was transformed in 2009. The functional unit for which the two alternatives were compared was '1 kg of crude oil cultivated in 2020'. When applying the UNEP-SETAC framework, 1 kg of sunflower oil caused 3.46 kg CO_2-eq emissions (from occupation) and 1 kg of palm oil caused 0.472 kg CO_2-eq emissions (0.153 kg CO_2-eq from transformation and 0.319 kg CO_2-eq from occupation). When using the improved conceptual framework, 1 kg of sunflower oil caused 0 kg CO_2-eq emissions and had a forgone sequestration -14.7 kg CO_2 emissions and 1 kg of palm oil caused 1.57 kg CO_2-eq emissions (from transformation) and had a forgone sequestration of -2.61 kg CO_2-eq emissions. Thus, when using the UNEP-SETAC framework, it could be concluded that that the use of land

for 1 kg of sunflower oil caused more GHG emissions, while when using the improved conceptual framework, it could be concluded the use of land for 1 kg of palm oil caused more GHG emissions. In the improved framework, forgone sequestration (in CLCA) showed that if there is more oil production than demand, it is better to use palm oil and to regenerate the land that is used for sunflower seed cultivation. The results of the case study illustrated that the choice of LULUC framework can invert the conclusions of LULUC GHG emissions between two alternatives. This showed that it is highly important that the academic community reaches consensus on using one type of framework.

It is essential that governmental and international bodies are aware of the weaknesses in the UNEP-SETAC framework that were identified in this thesis, as they potentially lead to inverted conclusions and a misinterpretation of results. In this thesis, an improved conceptual framework is proposed that is consistent with ALCA and CLCA and that has limited arbitrary value choices. Further research is recommended to investigate the suitability of the proposed framework with other future-oriented modes of LCA. Moreover, it is highly essential that further research develops characterisation factors for the new framework to enable widespread use of the improved conceptual framework by LCA practitioners. In conclusion, for mitigation strategies of LULUC GHG emissions to be successful, it is important that the scientific community looks beyond the UNEP-SETAC framework and develops a more sound framework for including LULUC GHG emissions in LCA.

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List of abbreviations

ALCA	Attributional Life Cycle Assessment
C	Carbon
CF	Characterisation factor
CFP	Carbon footprinting
CLCA	Consequential Life Cycle Assessment
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
CRP	Climate Regulation Potential
df	Duration factor
EC JRC	European Commission Joint Research Centre
Eq.	Equation
ESM	Electronic Supplementary Material
FLAG	Forest Land use and Agriculture Guidance
FU	Functional unit
GHG	Greenhouse gas
GWP	Global Warming Potential
ha	Hectare
ISO	International Organization for Standardization
kg	Kilogram
LCA	Life Cycle Assessment
LU	Land use
LUC	Land-use change
LULUC	Land use and land-use change
PAS 2050	Publicly Available Specification 2050
PNV	Potential Natural Vegetation
Q	Quality
RQ	Main research question
SQ	Sub research question
t	Time
UNEP-SETAC	United Nationals Environmental Programme and Society of Environmental Toxicology and Chemistry

Glossary

Term	Definition	Also named
Active sequestration	Conducting activities to increase the carbon content of the land, with the aim to sequester faster than natural sequestration.	Active restoration
Amortization	Allocation of the LULUC impacts to the output of a parcel of land (Koellner et al., 2013).	
Amortization method	The method that is used to distribute the impacts within the amortization period to the products: equal or linear amortization.	
Amortization period	The timeframe that is used is to allocate impacts to products. E.g., if the amortization period is 20 years, it means that the change in quality within the modelling period is attributed to output of the land in the first 20 years after the land transformation.	Amortization window, temporal scope, allocation period
Biogenic carbon	Carbon that is sequestered from the atmosphere during biomass growth and stored in biomass.	
Carbon footprinting (CFP)	Quantifying the "sum of greenhouse gas emissions and removals in a product system expressed as CO2-eq" (ISO TS 14067).	
Carbon transfer	Measurable carbon transfer to the air due to the transformation.	
Climate Regulation Potential (CRP)	Impact assessment model (by Müller-Wenk & Brandão, 2010) that connects the UNEP-SETAC framework to the climate change impact category.	Carbon Sequestration Potential (CSP)
Discounting	When the measurable impact is larger than the quantified impact.	
Double counting	When the measurable impact is counted twice.	
Duration factor (df)	In the CRP framework, the duration factor is the average residence time in the atmosphere of the studied system's biogenic carbon divided by the average residence time in the atmosphere of fossil carbon.	
Forgone sequestration	The difference in carbon sequestration due to using the land for the FU, relative to abandoning the land and letting it regenerate. Forgone sequestration is calculated by subtracting the level of sequestration in the reference situation from the amount of sequestration in the studied system.	

Fossil carbon	Carbon that is stored in fossil fuels.	
Land management	“The sum of land-use practices (e.g., sowing, fertilizing, weeding, harvesting, thinning, clear-cutting) that take place within broader land-use categories" (IPCC, 2019). Land management is included in land use.	
Land quality (Q)	"The capability of an ecosystem (or a mix of ecosystems at the landscape scale) to sustain biodiversity and to deliver services to the human society” (Koellner et al., 2013). In the UNEP-SETAC framework, it is used to express the loss of quality due to LULUC. In the context of GHG emissions, the metric 'quality' is expressed by the parameter ‘Carbon (in tonnes/ha) in soil, living biomass and dead matter’.	
Land use (LU)	“The total of arrangements, activities and inputs applied to a parcel of land” (IPCC, 2019).	
Land use and land-use change (LULUC)	Land use and land-use change combined.	
Land use and land-use change (LULUC) characteristics	The LULUC characteristics of the system under study are, for example, the size of the land, the year of the transformation, and the location.	
Land use (LU) category	Land use is categorized into categories, for example 'agriculture' or 'infrastructure'.	
Land use (LU) type	Within one land use category (e.g., agriculture), multiple land use types can exist (e.g., pasture, cropland).	
Land-use change (LUC)	The change from one land use category to another, caused by human activities (IPCC, 2019).	
Measurable emissions	Emissions that have taken place and can be measured as carbon loss of the land.	Absolute or observable emissions
Modelling period	The timeframe over which the difference in quality due to land transformation is integrated.	Time horizon, temporal scope, time frame, modelling time
Occupation	“The use of a land area for a certain human-controlled purpose (e.g., agriculture) assuming no intended transformation of the land properties during this use” (Milà i Canals et al., 2007). Occupation is also called LU (Liptow et al., 2018), however this is incorrect because LU includes land management impacts (IPCC, 2019), while occupation excludes land management impacts (Milà i Canals et al., 2007).	Land use
Passive sequestration	The opposite of active sequestration. No activities are conducted to sequester carbon, it is only conducted by the forces of nature.	natural regeneration/relaxation

Permanent (transformation) impact	Permanent impacts can occur if the new steady state of the studied system is not equal to the reference situation (Milà i Canals et al., 2007) or if the regeneration towards the reference situation exceeds the modelling period (Koellner et al., 2013).	
Potential Natural Vegetation (PNV)	Reference situation, proposed by Koellner (2013), “which describes the expected state of mature vegetation in the absence of human intervention” (Chiarucci et al., 2010). It is similar to natural regeneration of Milà i Canals et al. (2007).	
Quasi-natural land cover	Reference situation, proposed by Koellner (2013): “the (quasi-) natural land cover predominant in global biomes and ecoregions”.	
Reference situation	The baseline to which the studied system is compared. In this baseline, the studied system would not have taken place.	Reference system, dynamic reference situation, baseline, reference scenario
Regeneration	After a change in land quality due to transformation or occupation, the forces of nature will restore the land quality to a new steady state, if occupation is absent.	Natural relaxation
Regeneration time	The time it takes for the regeneration process to reach a new steady state.	Regeneration period
Residence time	The time an average CO_2 molecule stays in the atmosphere before it is taken up by carbon pools.	Stay in the air
Steady state	When the regeneration process has reached an equilibrium.	
Studied system	The activity for which the impacts are calculated.	
Transformation	“The change of a land area according to the requirements of a given new type of occupation process” (Milà i Canals et al., 2007).	Land-use change
Transition period	The time it takes for the carbon stock to be in a new balance after an impact, assumed to be 20 years (IPCC, 2006).	

1. Introduction

1.1 Research context

1.1.1 Land use & land-use change

In 1700, nearly half of the Earth's land remained in a natural state, while the rest was in seminatural state, featuring minimal agriculture and settlements (Ellis et al., 2010). However, by the year 2000, a significant shift had occurred, with the majority of the (ice-free) land being used for agriculture and settlements, and only 20% of the land remaining wild and 15% semiwild (Ellis et al., 2010). In the previous six decades (1960-2019), land-use change (LUC) has affected almost a third (32%, 43 million km^2) of global land area (Winkler et al., 2021).

Land provides the basis for human livelihoods and well-being through various ecosystem services (IPCC, 2019). Land is used by society for a variety of activities, primarily for agriculture or human habitation. Ranking from most to least intensive use, land use in 2015 can broadly be divided into infrastructure (1%), cropland (12%), grazeland (37%), used forests (22%), and minimal to not used lands (28%) (Figure 1.1).

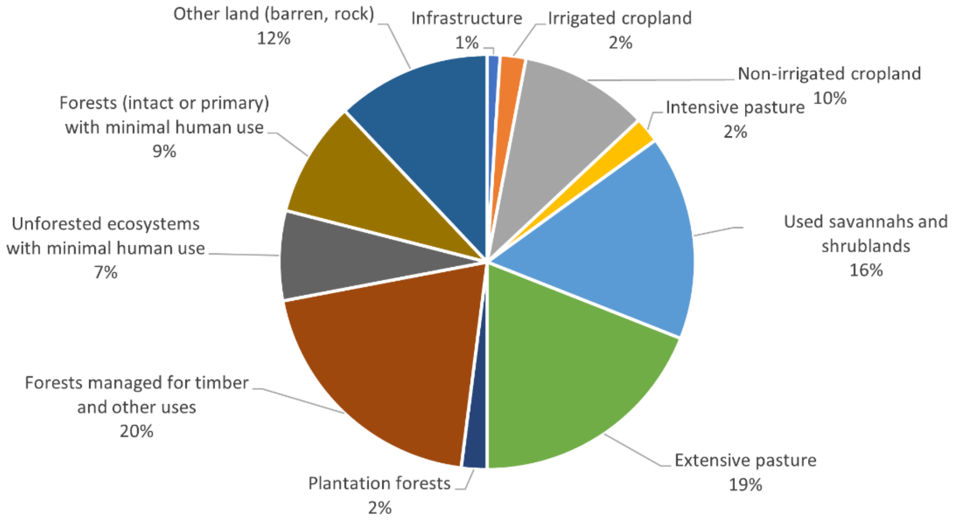

Figure 1.1. Land use as percentage of the global ice-free land surface (130 Mkm^2) in 2015 (IPCC, 2019).

Land use (LU) is the total of arrangements, activities and inputs applied to a parcel of land (IPCC, 2019). Often, (natural) land lacks the desired characteristics for a specific land use type, such as cropland. In that case, the land needs to be transformed to make it fit the new land use purpose. A well-known example is the deforestation of tropical forest to create cropland for soybean cultivation. The process of transforming land is called land-use change (LUC). LUC is the change from one land use category to another, caused by human activities (IPCC, 2019). Within one land use category (e.g., agriculture), multiple land use types can exist (e.g., pasture, cropland). As an umbrella term, land use and land-use change (LULUC) is used to refer to all LU and LUC activities.

1.1.2 The impact of land use and land use change

Society conducts LULUC activities because land provides various services for human livelihoods, but at the same time these LULUC activities have repercussions on both global and regional climates. In turn, these changes in global and regional climates pose various challenges to human livelihoods (IPCC, 2019).

On a regional level, modifications in land conditions can either mitigate or amplify warming and influence the frequency, intensity, and duration of extreme events like heatwaves and heavy precipitation (IPCC, 2019). Changes in land conditions redistribute water and energy, thereby changing temperature, pressure, moisture and subsequently precipitation locally. The extent of the effects differs based on the location and season. On a regional level, a change in land conditions causes a loss of natural ecosystems and decline in biodiversity (global decline of 11-14%) (IPCC, 2019). On a global level, changes in land conditions drive global warming due to biogeochemical effects (e.g., greenhouse gas emissions) and dampen global warming due to biophysical effects (increased surface albedo, decreased heat fluxes). LULUC (and the reinforcing effect of LULUC's environmental impacts) also have various social impacts on human livelihoods, such as decreased food security and loss of habitat (IPCC, 2019).

1.2 Research focus

1.2.1 Accounting of greenhouse gas emissions of agricultural LULUC activities

When land is transformed from one type to another, it results in a change in carbon in soil and vegetation per hectare of land (Brandão & Canals, 2013; Poeplau & Don, 2013). For example, if land is transformed from tropical forest to cropland, biomass is cut down, excavated, and lost, and a decrease in soil carbon will follow. The difference in carbon content will enter the atmosphere as CO_2, thereby increasing the radiative forcing of the atmosphere (Müller-Wenk & Brandão, 2010). This also works the other way around; carbon sequestration decreases the CO_2 in the atmosphere and increases the carbon in the soil and vegetation.

LULUC activities are responsible for one-fourth of the global greenhouse gas (GHG) emissions (IPCC, 2019). During 2007-2016, LULUC activities have caused net CO_2 emissions of 5.2 ± 2.6 $GtCO_2\ yr^{-1}$ (IPCC, 2019). These emissions are mostly due to deforestation (partly compensated by afforestation and reforestation) and emissions and removals from other LU activities. These LULUC GHG emissions contribute significantly to global warming and climate change, thereby posing a threat to ecosystems and consequently to human livelihoods, by disrupting ecological balances.

Political efforts focused on mitigating GHG emissions are crucial in addressing the existential threat of climate change. Through international agreements, legislative initiatives, and ambitious targets, governments strive to transition to renewable energy sources, implement carbon pricing mechanisms, and promote sustainable practices across industries. GHG emissions are the mostly used indicator for climate change reduction strategies, both nationally and globally (De Rosa, 2018). A well-known example is the Paris Agreement, where 196 parties agreed to limit global warming to 1.5°C, by achieving a reduction of 43% by 2030 (United Nations Climate Change, n.d.).

In recent years, there is growing recognition among policymakers of the significant contribution of LUC to GHG emissions, as well as the potential sequestration that the Agriculture, Forestry and Other Land Use (AFOLU) sector offers (IPCC, 2019). Governments and international bodies have increasingly incorporated land-use considerations into climate policies and agreements, understanding the crucial role that forests, agriculture, and other land-based activities play in the global carbon cycle (European Commission Joint Research Centre, n.d.). According to the European commission, "the need for an open deliberation and definition of a scientifically robust and detailed carbon accounting protocol is thus evident in the current political debate" (European Commission Joint Research Centre, n.d.).

The agricultural sector is the main driver of LULUC. About 5–14% of the global GHG emissions are attributable to LULUC due to agriculture (IPCC, 2019). Within the food system, during the period 2007–2016, LUC was responsible for 4.9 ± 2.5 $GtCO_2\ yr^{-1}$ emissions (IPCC, 2014). Due to the significant contribution of agricultural LULUC activities to the global GHG emissions and due to the need in policy for a carbon accounting protocol for LULUC activities, this thesis will be focused on the accounting of GHG emissions of LULUC activities in the agricultural sector.

1.2.2 Quantification of agricultural LULUC GHG emissions in an LCA framework

For reduction strategies of LULUC GHG emissions to be effective, it is important that the LULUC GHG emissions are attributed to the agricultural products that are responsible. This way, two alternative agricultural products can be compared, and the more sustainable alternative for LULUC GHG emissions can be favoured over the less sustainable alternative. The results of the comparison can be used in mitigation strategies that aim to reduce the LULUC GHG emissions of agricultural products.

Life cycle assessment (LCA) is the most used method for assessing the environmental impacts to (the use of) products. LCA is a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040). When conducting an LCA study for an agricultural product, the associated LUC GHG emissions can be included in the calculation. Therefore, this research focusses on the quantification of LUC GHG emissions in an LCA framework.

1.3 Research problem

1.3.1 Academic research gap

Most efforts to include LULUC impacts in LCA within the scientific community have been made by a specific task force of the United Nationals Environmental Programme and Society of Environmental Toxicology and Chemistry (UNEP-SETAC) Life Cycle Initiative. The first version of the UNEP-SETAC LULUC framework has been first published in 2007 (Milà i Canals et al., 2007). A follow-up of the UNEP-SETAC LULUC framework has been published in 2013 (Koellner et al., 2013), in which the framework was further elaborated and a guideline for implementation was provided. Throughout this thesis, 'the UNEP-SETAC framework' and 'the authors' refer to Mila et al. (2007) and Koellner et al. (2013). The UNEP-SETAC framework covers the assessment of impacts of land occupation (also called land use) and land transformation (also called land use change) on biodiversity and ecosystem services (Liptow et al., 2018). For the remainder of this thesis, the framework will be referred to as being a LULUC framework, even though it excludes the influence of land management[1].

Since the start of the UNEP-SETAC framework in 2007, the UNEP-SETAC seems to be the main framework within the scientific community for quantifying LULUC impacts in LCA. Most research that includes the UNEP-SETAC framework has been written by the co-authors of the UNEP-SETAC framework themselves. Examples of their work are the development of characterisation factors (Brandão & Canals, 2013), standardization of land use classification in the inventory (Koellner et al., 2012), extending the application of the framework to different land quality parameters such as biodiversity and carbon content (Müller-Wenk & Brandão, 2010; Souza et al., 2015), or conducting a case study (Milà i Canals et al., 2013).

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[1] According to the IPCC (2019), land management is "the sum of land-use practices (e.g., sowing, fertilizing, weeding, harvesting, thinning, clear-cutting) that take place within broader land-use categories (Pongratz et al., 2018)". In the LCA community, occupation is also called LU (Liptow et al., 2018), however this is incorrect because LU includes land management impacts (IPCC, 2019), while occupation excludes land management impacts (Milà i Canals et al., 2007). For the remainder of this thesis, for simplicity LULUC will be used to refer to LUC and LU excluding land management.

Besides the presence of the UNEP-SETAC framework and the work of its authors in literature, the framework does not appear to be widely used in practise. It has been recognized by few researchers that the UNEP-SETAC framework raises many issues and is still not yet implemented in common LCA practices (Othoniel et al., 2016). Only a small number of case studies have tested (amongst others) the UNEP-SETAC method, which "implies that LCA practitioners are not familiar with these methods yet and that they are thus not in wide-spread use" (Liptow et al., 2018).

The UNEP-SETAC framework has faced some criticism in the scientific literature. For example, the UNEP-SETAC framework seems to oversimplify biodiversity and ecosystem dynamics (Othoniel et al., 2016; Souza et al., 2015). And the choice of reference situation within the UNEP-SETAC framework has been highly debated (e.g., Brander, 2015, 2016; Koponen et al., 2018; Soimakallio et al., 2015, 2016). Brander (2015, 2016) has emphasized that (elements of) the UNEP-SETAC framework are not consistent with the existing LCA modes: attributional LCA and consequential LCA.

Even though the framework has received some criticism, the UNEP-SETAC framework has not changed in the past 15 years. And despite the efforts of researchers who have ended their published papers with a call to action for further research in LULUC frameworks in LCA in general, and the UNEP-SETAC framework in particular, it seems like research has stopped progressing. Currently, there is still no universally accepted method in scientific literature for addressing LULUC emissions and removals in LCA (Leinonen, 2022). Because there is no consensus amongst experts, there is no clear guidance to practitioners (Brandão et al., 2022). This is concerning, because Brandão et al. (2022) have found that the design of a LULUC framework in LCA significantly impact the results of a study. Moreover, the results of LULUC GHG impacts from an LCA study have an increasing influence on policy and decision making (Brandão et al., 2022; De Rosa, 2018). This creates a sense of urgency for a widely used and accepted framework specifically for including the GHG emissions of LULUC in LCA.

1.3.2 Problem statement

The UNEP-SETAC framework for including LULUC impacts in LCA is the most well-known framework for LULUC impacts in scientific literature, but it has been recognized by few researchers that the framework raises issues and is still not yet implemented in common LCA practices. Due to the need in both policy and science for consensus in a LULUC framework that can include GHG impacts in LCA, it is important that research continues progressing.

1.3.3 Research objectives

The goal of this master thesis is to advance the method development of LULUC frameworks that quantify LULUC GHG emissions of agricultural products in LCA studies. To address the knowledge gaps detailed in section 1.3, and to achieve this overall goal, the following research objectives have been established:

A) Identify and evaluate the weaknesses of the UNEP-SETAC framework that might prevent it from being widely accepted and widely used in LCA studies;
B) Identify improvements for the development of a new LULUC GHG framework in LCA;
C) Propose an improved generalized LULUC GHG framework in LCA;
D) Demonstrate how the new framework compares to the UNEP-SETAC framework.

1.3.4 Research questions

The main research question (RQ) is based upon the research objectives. The main research question is as follows: '*How can the UNEP-SETAC framework be improved to better quantify LULUC impacts of agricultural products in LCA?*'

To answer the main research questions, several sub questions (SQ) are formulated:

1. *How are LULUC impacts quantified in the UNEP-SETAC framework?*
2. *What are the weaknesses of the UNEP-SETAC framework?*
3. *How can the weaknesses of the UNEP-SETAC framework be resolved to achieve an improved conceptual framework?*
4. *How do the UNEP-SETAC framework and the improved conceptual framework compare in a comparative LCA case study of an agricultural product?*

1.4 Thesis structure

The research proposal will be presented in the following structure. Chapter 2 will provide the theoretical background around LCA. The research approach used in this thesis will be located in Chapter 3. An explanation of the UNEP-SETAC framework can be found in Chapter 4. Chapter 5 lays out the reflection on the UNEP-SETAC framework. An improved conceptual framework for quantifying LULUC frameworks can be found in Chapter 6. A comparative case study in which the UNEP-SETAC framework and the improved conceptual framework are compared, can be found in Chapter 7. Chapter 8 lays out the discussion and recommendations, and the conclusions can be found in Chapter.

2. Theoretical framework

The results of the UNEP-SETAC framework need to be implemented in the LCA framework. This chapter serves to familiarize the reader with the LCA framework.

2.1 The fundamentals of LCA

LCA results of biobased products are highly sensitive to the methodological choices that are made within a LULUC framework (De Rosa et al., 2018). It is important that these methodological choices are aligned with the goal and scope of an LCA study (e.g., Brandão et al., 2022; De Rosa et al., 2018; Milà i Canals et al., 2007). In this section, the reader is provided with essential background information about the LCA method.

2.1.1 What is LCA?

ISO14040 defines LCA as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (International Organization for Standardization, 2006). Thus, LCA is a method to assess all environmental impacts associated with all the life cycle stages that a product goes through. An LCA is not focused on assessing a product itself, rather it is focused on assessing the environmental impacts of the product's function or service.

LCA assesses the environmental impact of the use of the function of the product from cradle to grave. This involves a 'holistic' approach, where all environmental impacts should be assessed in one consistent framework, disregarding the potential different characteristics of those impacts (Guinée et al., 2002). LCA is quantitative in character, but qualitative aspects can be taken into account (Guinée et al., 2002).

2.1.2 Applications and limitations of LCA

LCA can have various applications, including analysing impact hotspots of current products, designing new products, and comparing alternative products (Guinée et al., 2002). While LCA has proven to be a widely used model for assessing environmental impacts, it also has various limitations that should be taken into account. Here, several limitations are mentioned that have an influence on the inclusion of LUC and occupation impacts in LCA.

LCA is not well suited for addressing localized impacts (Guinée et al., 2002). LUC affects various characteristics of the local climate (IPCC, 2019) and the local climate also has an influence on the extent of LUC impacts (Milà i Canals et al., 2007). In current conventional methods, land characteristics are determined based on ecoregions or nations and are assumed to be homogeneous within these units. Spatial heterogeneity within ecoregions and landscape configuration are ignored, even though these are key factors in determining LUC effects (Chaplin-Kramer et al., 2017).

LCA also cannot address the time aspect of impacts, because LCA is typically a steady-state instead of a dynamic approach (Guinée et al., 2002). In LCA, time is integrated until infinity or integrated over a set time horizon. Additionally, in LCA is it unknown when in time interventions take place and what the interventions are per unit of time. However, the timing of GHG emissions (when in time they enter the atmosphere) determines the impact of GHG emissions (Müller-Wenk & Brandão, 2010). Partly due to the absence of temporal information in LCA, the environmental impact of the timing of the LULUC GHG emissions and removals is currently not taken into account in LCA (Liptow et al., 2018).

LCA aims to be science-based, but the method includes assumptions and value choices (Guinée et al., 2002). These assumptions and choices should be made as transparent as possible. The quantification of LUC GHG emissions involves various choices, which have a large influence on the results.

LCA is a linear modelling tool, meaning that it assumes that all inputs and outputs scale linear regarding both the economy and environment (Guinée et al., 2002). However, in practice, inputs and outputs do not always scale linearly. For example, sometimes economies of scale exist in production processes, meaning that the environmental impact per production unit decreases if the production volume increases.

2.1.3 The LCA framework

The LCA framework can be divided into four phases: goal and scope definition; inventory analysis; impact assessment; and interpretation (Figure 2.1). The main guiding principle for reporting in LCA is that all issues (choices, assumptions, data, calculation rules, results, conclusions) should be reported, in a transparent way, and explicitly (Guinée et al., 2002). The following section will provide basic information for each phase and how it relates to including LUC impacts in LCA.

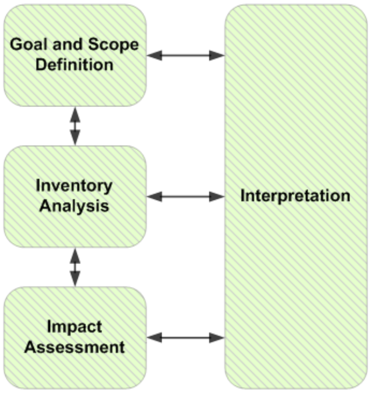

Figure 2.1. The four phases of LCA.

2.1.4 Goal and scope definition

The first phase of LCA consists of the goal and scope definition, in which the characteristics of the LCA study will be decided upon.

The goal definition should include an explanation of the goal of the study and should specify the intended use of the results (application), the initiator and commissioner, the practitioner, the stakeholders and the intended users of the study (target audience) (Guinée et al., 2002).

The scope definition covers the characteristics of the LCA study, such as the temporal, geographical and technology coverage, the mode of the analysis and the level of detail of the study (Guinée et al., 2002). It should also justify the next step of this phase and coming phases.

The function, functional unit (FU), alternatives and reference flows are defined in this stage (Guinée et al., 2002). The FU describes how much of the primary function of the product is considered in the LCA study. The FU forms the basis for selecting alternatives that can provide the same FU. For these alternatives, the reference flows will be determined. The reference flow is a measure of the outputs that is are required for the alternative to fulfil the functional unit.

2.1.4.1 LCA modes: ALCA and CLCA

There are two main modes of LCA: attributional LCA (ALCA) versus consequential LCA (CLCA). Other modes of LCA exist (Guinée et al., 2018), but that is beyond the scope of this thesis.

ALCA (also called accounting or descriptive approach) aims to assess the portion of global burdens attributable to a product and its entire life cycle (Life Cycle Initiative, 2011). The studied product system consists of processes that are connect by flows to the unit process that provides the FU or the reference flow (Life Cycle Initiative, 2011). ALCA utilizes data sourced from real suppliers or averages and uses allocation to deal with multifunctional processes or systems (Life Cycle Initiative, 2011). “In theory, if one were to conduct ALCAs of all final products, one would end up with the total observed environmental burdens worldwide (Life Cycle Initiative, 2011)”.

CLCA (also called change-oriented approach) strives to offer insights into environmental burdens that occur, directly or indirectly, as a consequence of decisions, typically due to a change in product demand

(Life Cycle Initiative, 2011). In theory, the studied system is made up by only the processes that are affected by the decision, i.e., processes that alter their output based due to cause-and-effect chain originating from the decision (Life Cycle Initiative, 2011). CLCA aims to use actual supplier data if the data reflects the change in output due to the decision, otherwise data representing marginal technology is utilized (i.e., suppliers that will actually respond to a change in demand) (Life Cycle Initiative, 2011). CLCA uses substitution to deal with multifunctional processes to expand the analysed system with additional processes (Schaubroeck et al., 2021). CLCA is often perceived as suitable for informing policy and decision-makers because it shows the consequences of a decision (Ekvall, 2020).

2.1.5 Inventory analysis

In the inventory analysis, the product system (or systems, in case of multiple alternatives) is defined (Guinée et al., 2002). The system boundaries are set between economy and environment, with regards to other product systems, and in relation to cut-offs. The flow diagrams are designed, and the unit processes are included. Data is collected for each of these processes. Allocation steps are performed for multifunctional processes. The result of the inventory analysis is the inventory table in which quantified inputs and outputs to the environment are listed for the FU.

2.1.6 Life cycle impact assessment

In the life cycle impact assessment phase, the results of the inventory analysis are processed and interpreted in terms of environmental impacts (Guinée et al., 2002). An impact assessment model will define characterisation factors (CF) for relating the environmental interventions (in the inventory table) to the impact categories. If an environmental intervention has an impact in a certain impact category, the quantified intervention is multiplied with a CF specific for that intervention in that impact category. This is calculated in the characterisation step. Optionally, the characterisation results can be normalized to a reference, to indicate (for example) the severity of the impacts compared to the total global or regional impacts in a certain year.

2.2 The inclusion of LULUC impacts in LCA

To include LUC GHG emissions of an agricultural product in an LCA study, three steps need to be taken.

First, the LULUC characteristics have to be determined for the agricultural product under study. This step entails the data collection for the LULUC situation. For example, this step concerns determining how much area has been transformed, when in time, and which types of LU before and after the LUC can be recognized (Milà i Canals et al., 2007). These characteristics can be determined based on measurements, statistical calculations, satellite imaging or spatial modelling methods.

Second, the GHG impacts associated with the LULUC activities for the agricultural product under study need to be quantified (Milà i Canals et al., 2007). This step can be conducted by means of a framework that provides calculation guidelines for the quantification of LULUC impacts. In this step, the data collection of the LULUC characteristics are used to quantify the LULUC impacts. As explained in the introduction (Chapter 1), the research objective is to enable progression of method development for LULUC frameworks. Specifically, the UNEP-SETAC framework for LULUC impacts it the subject under study in this thesis, which will be further explained in Chapter 4.

Third, the LULUC GHG impacts need to be attributed to the agricultural product under study in the LCA study. There are two main ways to attribute LULUC emissions to the agricultural product. In an ideal situation, the used database already contains an environmental intervention that matches the characteristics of the LULUC activities and a corresponding characterisation factor. Then, the LCA practitioner itself does not have to quantify the LULUC emissions, thus can skip step 2. However, if the used database and the used impact assessment model do not contain the LULUC activity's environmental intervention and no corresponding CF exists, the LCA practitioner should create its own process for land use in the LCA software. Then, the LCA practitioner should use the results of step 2 (the quantified GHG emissions) and add them to the corresponding process as emissions to air.

3. Research approach

This chapter elaborates on the research approach that was used for conducting this thesis.

3.1 Mixed method research approach

To answer the research question, a mixed method approach was used that starts with theory building (inductive research) and follows with theory testing (deductive research). A mixed method approach focuses on collecting, analysing, and mixing both quantitative and qualitative data in a single study (Creswell & Plano Clark, 2011). The use of deductive and inductive approaches provides a better understanding of research problems than either approach alone (Creswell & Plano Clark, 2011) and the strength of one approach can balance out the weaknesses of the other (Molina-Azorín & López-Gamero, 2016). The main purpose for which the mixed method approach is applied in environmental research is method development (Molina-Azorín & López-Gamero, 2016). The research objective is to enable progression of method development for LULUC frameworks, and therefore the mixed method approach suits best. The specific type of mixed method approach used is a 'mixed method exploratory sequential design' (Creswell & Plano Clark, 2011).

The first part of the mixed method exploratory sequential design was inductive research, during which a qualitative literature review was used to build the model. First, a qualitative literature review was performed, which consisted of two parts. In the first part, literature was collected to understand how the UNEP-SETAC framework worked. In the second part, literature was used to reflect on the suitability of the UNEP-SETAC framework for the quantification of LULUC GHG emissions in LCA. Next, the literature review was used to build the model. The model was the improved conceptual framework for quantifying GHG emissions of LUC in LCA.

The second part of the mixed method exploratory sequential design was deductive research, in which quantitative data was used to test the model. For the purpose of deductive theory testing, case research was employed in a positivist manner (Bhattacherjee, 2012). The improved conceptual framework was tested by means of a comparative LCA case study that compared the LULUC GHG emissions of two alternative agricultural products. The results of the improved conceptual framework were compared with the results of the UNEP SETAC framework and other existing frameworks.

3.2 Research flow, methods and requirements

In this section, the requirements (data, research methods, tools) for each sub research question are explained. First, an overview will be provided of the research flow. The research flow diagram gives an overview of data, methods and tools that have been used to answer each sub research question (Figure 3.1).

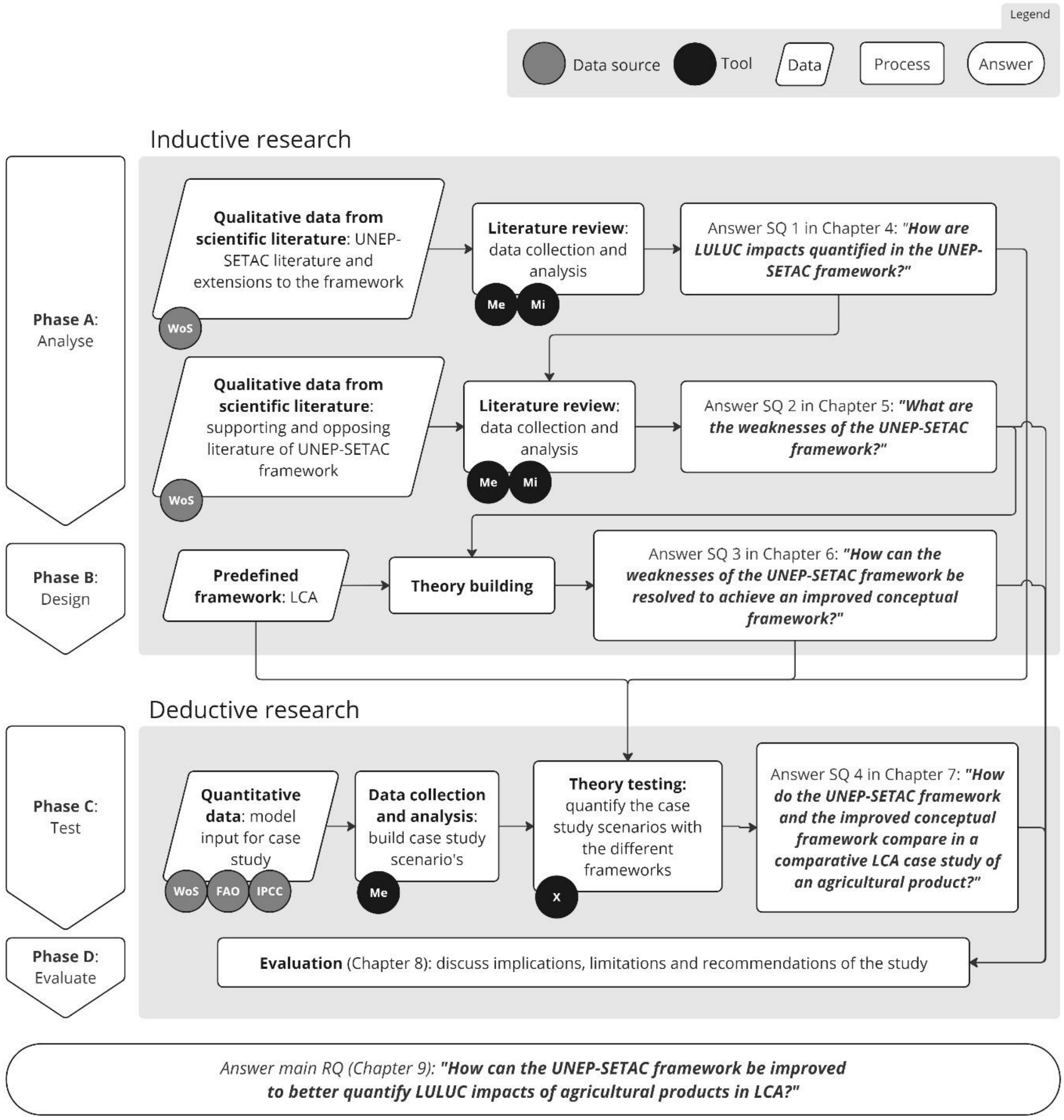

Figure 3.1. Research flow diagram. Data sources: WoS= Web of Science; FAO= FAOSTAT; IPCC= International Panel of Climate Change. Tools: Me= Mendeley; Mi=Miro; X= Excel.

To answer the first two SQ's, a literature review was performed (during October 2023) by means of a snowball approach. The snowball procedure of Wohlin (2014) (Figure 3.2) was used.

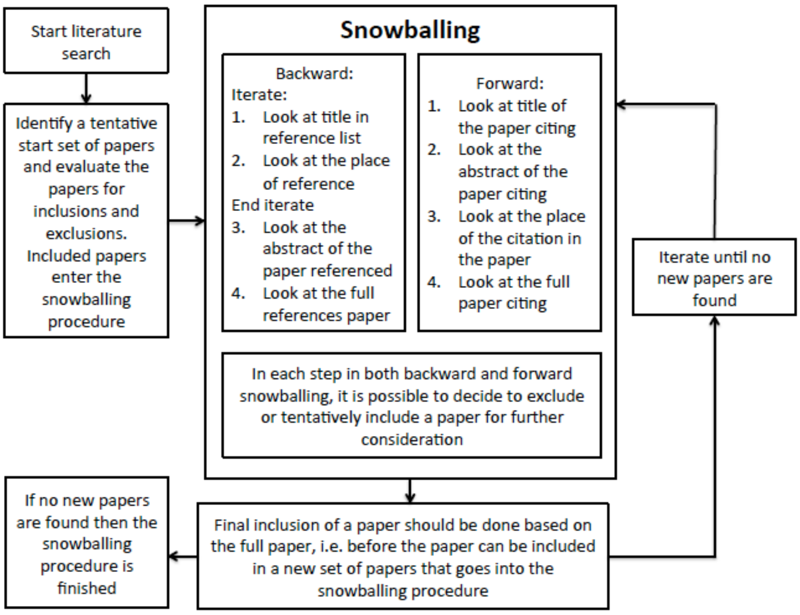

Figure 3.2. Snowballing procedure by Wohlin (2014).

The start set of the snowballing approach comprised the UNEP-SETAC framework papers (Koellner et al., 2013; Milà i Canals et al., 2007). Forward and backward iterations were performed for the start set. Backward snowballing identifies new papers that have been cited by the paper that is being examined (Wohlin, 2014). Forward snowballing identifies new papers that have cited the paper that is being examined (Wohlin, 2014). Web of Science offered more options than Google Scholar to search for keywords and to use filters, so Web of Science was further used in the snowball procedure.

The 64 backward references of Milà i Canals et al. (2007) have been disregarded for further snowballing. Milà i Canals et al. (2007) was the first conceptual paper for a LUC framework in LCA, therefore its citations did not go into the desired depth for this thesis. Milà i Canals et al. (2007) was cited 361 times according to Web of Science. Snowballing forward was performed by using the keywords ‘land-use change’ and ‘LCA’ and by sorting ‘citations: highest first’. This resulted in 91 hits. Of these 91 hits, 7 papers were selected based on their focus on LULUC frameworks in LCA (Table 3.1).

Table 3.1. Snowball results of Milà i Canals et al. (2007).

Authors and publication date	Title
Bessou et al. (2020)	Accounting for soil organic carbon role in land use contribution to climate change in agricultural LCA: which methods? Which impacts?
Brandão & Canals (2013)	Global characterisation factors to assess land use impacts on biotic production
Helin et al. (2013)	Approaches for inclusion of forest carbon cycle in life cycle assessment - a review
Müller-Wenk & Brandão (2010)	Climatic impact of land use in LCA-carbon transfers between vegetation/soil and air
Schmidinger & Stehfest (2012)	Including CO_2 implications of land occupation in LCAs—method and example for livestock products
Liptow et al. (2018)	Accounting for effects of carbon flows in LCA of biomass-based products—exploration and evaluation of a selection of existing methods
Souza et al. (2015)	Assessing biodiversity loss due to land use with Life Cycle Assessment: are we there yet?

The same approach was followed for Koellner et al. (2013). Koellner et al. (2013) had cited 64 references. Through backward snowballing, only 1 paper (Chiarucci et al., 2010) was selected. Other papers were disregarded because they did not fit the scope, or they were already selected through snowballing for Milà i Canals et al. (2007). According to Web of Science, Koellner et al. (2013) have been cited 241 times. Snowballing forward was performed by using the keywords 'land-use change' and 'LCA' and by sorting 'citations: highest first'. This resulted in 57 hits. Of these 57 hits, 3 papers were selected based on their focus on LULUC frameworks in LCA (Table 3.2).

Table 3.2. Snowball results of Koellner et al. (2013).

Author	Title
Othoniel et al. (2016)	Assessment of Life Cycle Impacts on Ecosystem Services: Promise, Problems, and Prospects
Soimakallio et al. (2015)	Attributional life cycle assessment: is a land-use baseline necessary?
Soimakallio et al. (2016)	On the validity of natural regeneration in determination of land-use baseline

The extensive snowballing approach was stopped after the forward and backward snowballing procedure of the start set. Next to the extensive snowballing procedure, literature searches were performed through Web of Science and Google Scholar to search for the literature with the following characteristics: literature created by authors that frequent the snowballing literature set; literature that created independently from UNEP-SETAC (and thus did not appear in the snowballing method); and specific topics in a LULUC framework that needed more explanation or alternative views. All literature was collected in Mendeley.

SQ1 is *"How are LULUC impacts quantified in the UNEP-SETAC framework?"*. The starting set of the snowball (i.e., Koellner et al., 2013 and Milà i Canals et al., 2007) formed the basis for answering SQ1, because that is the original literature of the UNEP-SETAC framework that is available. Moreover, additional literature was included in the review that extended the application of the framework, such as the inclusion of carbon impacts (Müller-Wenk & Brandão, 2010). To answer SQ1, the framework was described objectively, without including evaluations or judgements, to ensure a clear distinction between the description of the framework for SQ1 and the evaluation of the framework for SQ2. The literature was analysed in Mendeley and Miro was used to create visual analyses.

SQ2 is "*What are the weaknesses of the UNEP-SETAC framework?*". Several steps were taken to research the weaknesses of the framework. First, initial thoughts about issues within the UNEP-SETAC framework were written down after answering SQ1. For example, these issues included claims that were not supported by science, or inconsistencies that were found within the framework. Second, from the snowball procedure, literature was reviewed that included evaluations or applications of the UNEP-SETAC framework. Third, a literature search was performed for specific topics that were included in the UNEP-SETAC framework. For newly found literature about specific topics, supporting and opposing views were included by means of forward and backward snowballing. When further literature searches did not result in new hits anymore, the literature search was stopped. Fourth, the collected evaluations from literature were combined with the initial issues that were found in the UNEP-SETAC framework. These reflections were used to take another look at the UNEP-SETAC literature, to identify if there were more weaknesses to be found. Fifth, all collected weaknesses were analysed and categorized. The literature was analysed in Mendeley and Miro was used to create visual analyses.

SQ3 is *"How can the weaknesses of the UNEP-SETAC framework be resolved to achieve an improved conceptual framework?"*. The weaknesses of the framework (SQ2) were used as a basis to answer SQ3. The list of weaknesses was divided into two categories: 'essential to improve' and 'optional to improve'. Based on trial and error, several ideas were developed to improve the UNEP-SETAC framework. This was continued until one framework was created that resolved all weakness of the UNEP-SETAC that were essential to improve. Once these essential weaknesses were resolved, an attempt was made to alter the framework to also improve weaknesses that were optional to improve. Finally, a comparative list was made of the differences between the UNEP-SETAC framework and the improved conceptual framework.

SQ4 is *"How do the UNEP-SETAC framework and the improved conceptual framework compare in a comparative LCA case study of an agricultural product?"*. To answer this questions, a case study was designed. The requirements for the case study were as follows: the two compared products are alternatives of each other; the alternatives have different LULUC characteristics; and data is easily available for both alternatives. It was decided to also include two carbon footprinting (CFP) frameworks in the comparison, to illustrate the difference of the UNEP-SETAC framework and the improved conceptual framework relative to the CFP frameworks. Data was mainly collected from IPCC and FAOSTAT and was added to the Excel spreadsheet. Next, the results were calculated for each framework. The differences in results are discussed based on the different characteristics of the frameworks and based on the analyses that were made in the previous SQs.

4. UNEP-SETAC framework for LU impacts

In this chapter, the UNEP-SETAC framework will be explained to the reader.

4.1 Introduction to the UNEP-SETAC framework

The UNEP-SETAC framework serves to quantify two different kinds of LULUC impacts: transformation and occupation. A transformation impact "occurs when the land properties are modified" (Milà i Canals et al., 2007). An occupation impact occurs "when the current man-made properties are maintained [of an area of land]" (Milà i Canals et al., 2007).

Land transformation is "the change of a land area according to the requirements of a given new type of occupation process" (Milà i Canals et al., 2007). Milà i Canals et al. (2007) and Koellner et al. (2013) use the term 'land transformation', which they perceive as the preferred term in LCA literature for 'LUC' (Müller-Wenk & Brandão, 2010). However, outside of the LCA community, the term LUC is standardized. In this thesis, for consistency with the UNEP-SETAC framework, the term 'transformation' will be used in the context of the UNEP-SETAC framework. A well-known example of transformation is the transformation of rainforest to cropland.

Land occupation is "the use of a land area for a certain human-controlled purpose (e.g., agriculture) assuming no intended transformation of the land properties during this use" (Milà i Canals et al., 2007). Occupation is also called LU (Liptow et al., 2018), however this is incorrect because LU includes land management impacts (IPCC, 2019), while occupation excludes land management impacts (Milà i Canals et al., 2007). In this thesis, for consistency with the UNEP-SETAC framework, the term 'occupation' will be used in the context of the UNEP-SETAC framework. Occupation can be measured in surface-time units (e.g., ha.yr), because it occupies an area of a land (e.g. 1 ha of cropland) over a certain time (e.g. 10 years). During occupation, it is assumed that there is no intended further transformation of the land characteristics (Lindeijer et al., 2002; Milà I Canals et al., 2007). An example of occupation is the occupation of land for annual cropland.

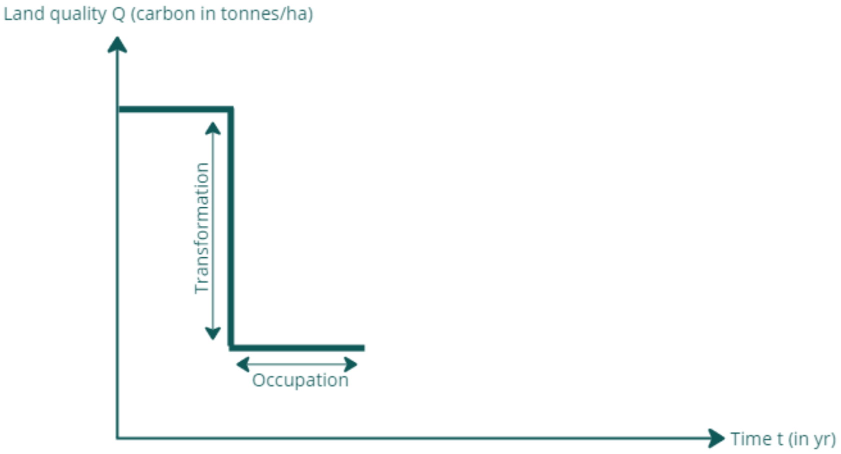

Figure 4.1. Changes in land quality over time due to transformation and occupation.

Figure 4.1 shows an example of the change in land quality due transformation and occupation in the UNEP-SETAC framework. In the framework, the authors use the metric 'land quality' to measure the impact of transformation and occupation. Land quality is defined as "the capability of an ecosystem (or a mix of ecosystems at the landscape scale) to sustain biodiversity and to deliver services to the human society" (Koellner et al., 2013). Land quality can be represented by many different parameters that express the "intrinsic value of biodiversity and natural landscape or the functional value of ecosystems in terms of their goods and services" (Koellner et al., 2013). One of the services of ecosystems is their capability to sequester carbon. The ability to sequester carbon can be expressed by carbon (in tonnes) that is measured in the soil, living biomass and dead matter. Thus, the quality metric can be expressed by the parameter 'Carbon (in tonnes/ha) in soil, living biomass and dead matter'.

The size of a transformation or occupation impact is "the difference between the effect on land quality from the studied case of land use and a suitable reference land use on the same area (Milà i Canals et al., 2007). The reference situation is what would have happened if the studied system would not have taken place. The studied system is the activity for which the impacts are calculated. In the context of GHG emissions, the impact of land transformation or occupation is the difference in carbon of the studied system versus the reference situation. The difference in carbon that is used to calculate the amount of GHG emissions that have entered the atmosphere: 1 tonne of carbon corresponds to an emission of 3.67 tonnes of CO_2 (44 molar mass CO_2 / 12 molar mass C = 3.67).

4.2 The concept of regeneration

Essential in the UNEP-SETAC framework is the concept of regeneration. Milà i Canals et al. (2007) assume that after a change in land quality due to transformation or occupation, the forces of nature will restore the land quality to a new steady state, if occupation is absent (fallow land) (Figure 4.2). This restoration process is called (natural) relaxation (Milà i Canals et al., 2007) or regeneration (Koellner et al., 2013). For the remainder of this thesis, the term 'regeneration' will be used (unless the term 'relaxation' is used in a quote), because this is the term that is used in the most recent papers and regeneration is used in biology for the restoration of (for example) organisms and ecosystems after disturbance (e.g., Chazdon & Guariguata, 2016).

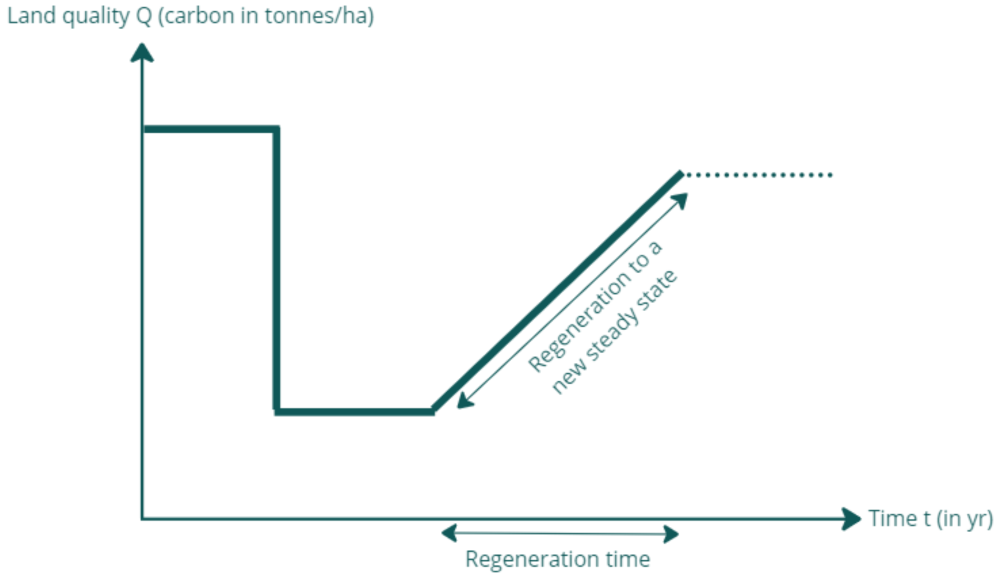

Figure 4.2. Regeneration after occupation to a new steady state.

The regeneration time is the time it takes for the land quality to regenerate to a new steady state after the land is abandoned. According to the UNEP-SETAC workgroup (Koellner et al., 2013; Milà i Canals et al., 2007), the regeneration time mainly depends on the following factors:

- The impact pathway, which is dependent on the indicator of ecosystem quality being regenerated;
- The land quality of the studied system;
- The end state at which the regeneration reaches a steady state of land quality;
- The biogeographical conditions of the location.

4.3 Quantification of the transformation impact

The transformation impact is the difference between the effect on land quality from transformation (studied system) and the reference situation. The effect of transformation on land quality is a sudden drop in quality during the transformation and what is assumed to happen after the transformation. The authors of the UNEP-SETAC framework assume that the land quality will regenerate, if land occupation is absent.

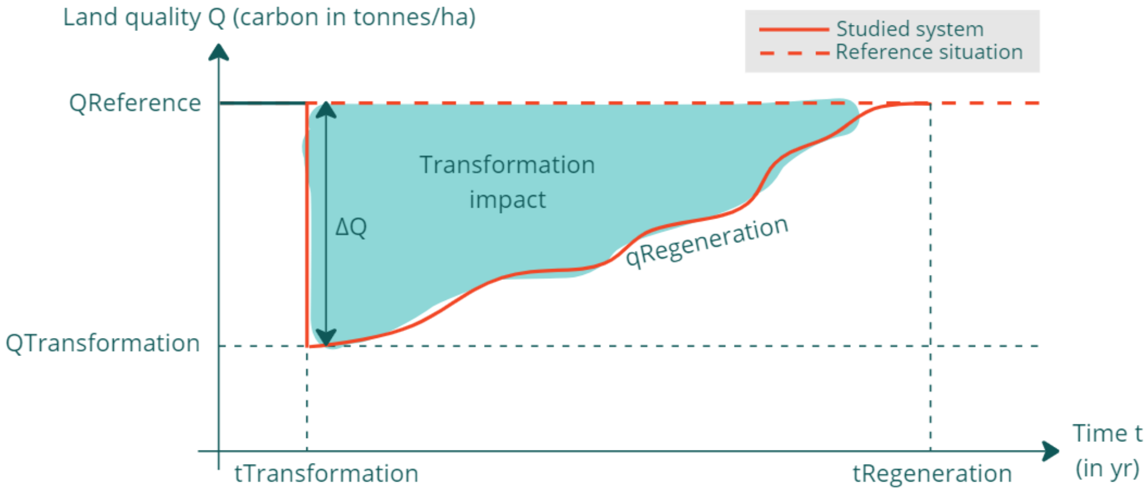

Figure 4.3. Impact of transformation (blue shaded area) on natural land without occupation (adapted from Milà i Canals et al., 2007).

In Figure 4.3, ΔQ represents the change in land quality due to transformation, and the blue shaded area represents the total transformation impact. In the context of GHG emissions, ΔQ represents the change in carbon in soil, biomass and dead matter (in tonnes/ha) at a certain point in time. Thus, the total impact of transformation can be calculated by taking the integral of ΔQ over time (Eq. 4.1):

(Eq. 4.1)

$$Transformation\ impact = A \times \int_{t_{Transformation}}^{t_{Regeneration}} \Delta Q\ dt =$$

$$A \times \int_{t_{Transformation}}^{t_{Regeneration}} (QReference - QRegeneration)\ dt$$

where *A* (in ha) is the land area, *tTransformation* (in yr) is the time at which transformation takes place, *tRegeneration (in yr)* is the time after which regeneration has finished (reached its steady state) after transformation, *QReference* (in carbon tonnes/ha) is the quality of the reference situation, *QTransformation* (in carbon tonnes/ha) is the quality of land after transformation, *QRegeneration* (in carbon tonnes/ha) is the quality of the land during regeneration, and ΔQ (in carbon tonnes/ha) is the difference in land quality due to transformation between the reference situation and the regeneration quality. Thus, the transformation impact (in carbon tonnes.year) is the total change in carbon due to transformation.

In the framework, the vertical drop in quality at *tTransformation* does not have a temporal dimension. The authors assume that the temporal dimension of transformation impacts can be neglected, because they reason that large transformation impacts could happen in a short time (Koellner et al., 2013). For example, cutting down a forest can happen very fast and thus the amount of carbon stored on that land area (in trees) decreases very fast.

4.4 Quantification of the occupation impact

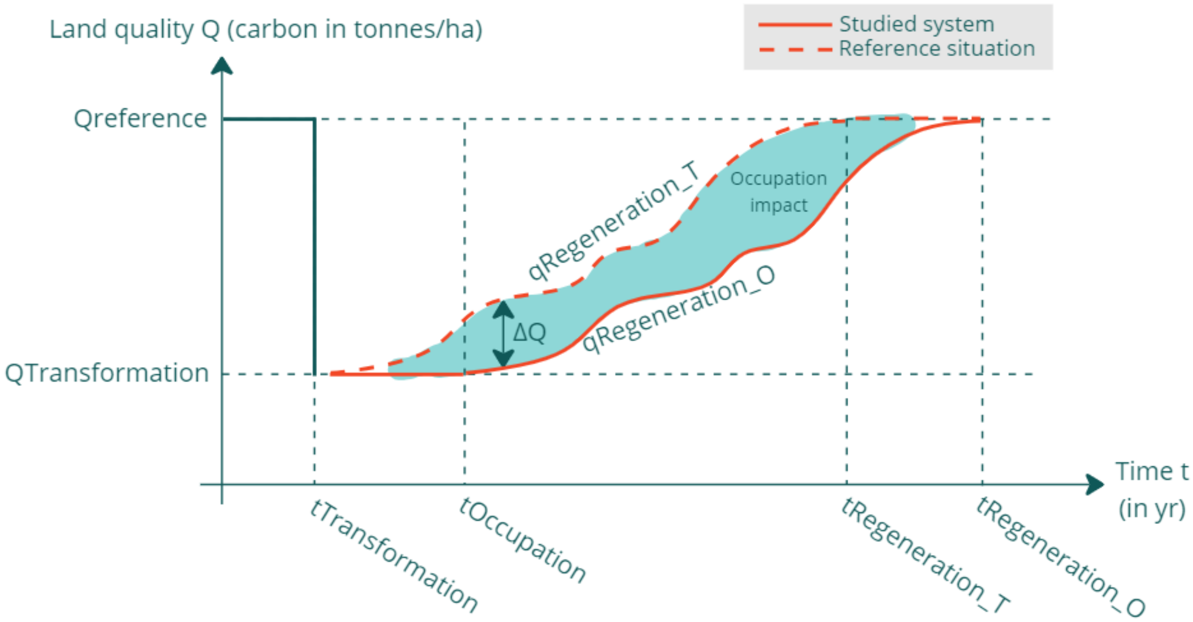

Figure 4.4. Impact of occupation (blue shaded area) (adapted from Milà i Canals et al., 2007).

The authors argue that without occupation, the land would have regenerated. They reason that due to occupation, the natural regeneration of the land is postponed for the duration of the occupation (Milà i Canals et al., 2007). They quantify the occupation impact as the difference between the natural regeneration after transformation (the reference situation), and the natural regeneration after occupation (the studied system) (Figure 4.4). In the content of GHG emissions, the occupation impact (in carbon tonnes.year) is the difference in carbon content in soil, biomass, and dead matter, between the studied system and the reference situation. This can be calculated by taking the difference between the integral of the natural regeneration after transformation and the natural regeneration after the occupation (Eq. 4.2):

(Eq. 4.2)

$$Occupation\ impact = A \times \int_{t_{Transformation}}^{t_{Regeneration\_O}} \Delta Q\ dt =$$

$$A \times \int_{t_{Transformation}}^{t_{Regeneration\_O}} (QRegeneration\_T - QRegeneration\_O)\ dt$$

where A (in ha) is the land area, t*Transformation* (in yr) is the time at which transformation takes place, *tOccupation (in yr)* is the time at which occupation ends, t*Regeneration_T (in yr)* is the time after which regeneration has finished (reached its steady state) after transformation, , *tRegeneration_O (in yr)* is the time after which regeneration has finished (reached its steady state) after occupation, *QReference* (in carbon tonnes/ha) is the quality of the reference situation, *QTransformation* (in carbon tonnes/ha) is the quality of land after transformation, *QRegeneration_O* (in carbon tonnes/ha) is the quality of the land during regeneration after transformation, *QRegeneration_T* (in carbon tonnes/ha) is the quality of the land during regeneration after occupation, and ΔQ (in carbon tonnes/ha) is the difference in land quality due to occupation between the studied system (relaxation after occupation) and the reference situation (relaxation after transformation).

4.5 Combining transformation and occupation impacts

The impacts of transformation and occupation can be combined into one basic framework for transformation and occupation (Figure 4.5). For simplicity, from now on the quality changes are drawn linearly, instead of wavy like the pictures above.

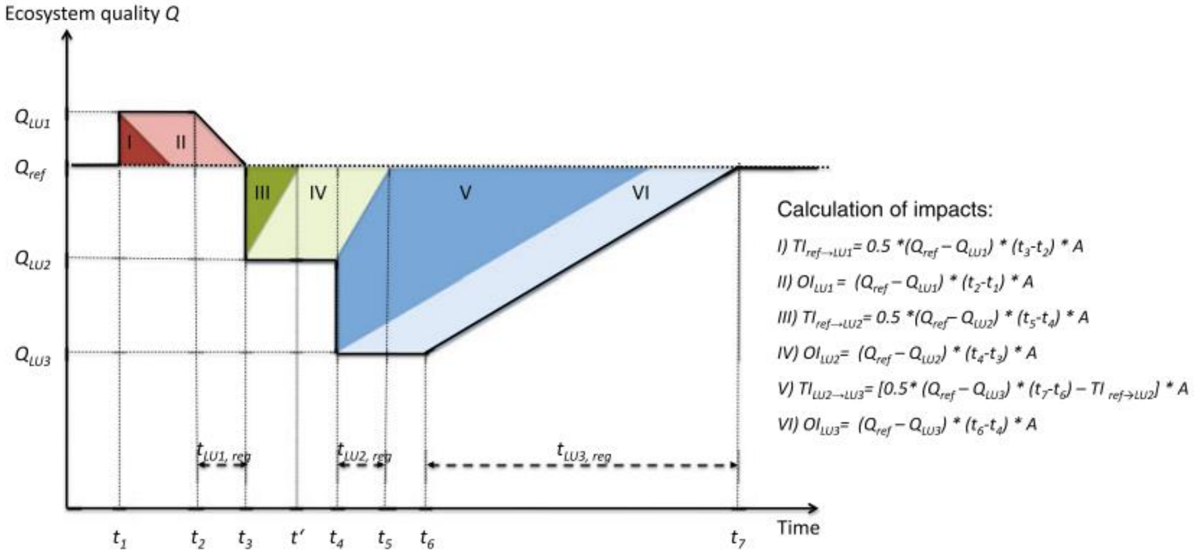

Figure 4.5. Simplified illustration of transformation impact (TI) and occupation impact (OI) for three land use types (LU1 in red; LU2 in green; and LU3 in blue) with different regeneration rates (tLU1, reg; tLU2, reg; and tLU3, reg) (reproduced from Koellner et al., 2013).

Figure 4.5 shows the UNEP-SETAC framework for three LU types with different regeneration rates (LU1 in red; LU2 in green; and LU3 in blue) (Koellner et al., 2013). The corresponding calculations can be found on the right sight of the figure. Instead of calculating the surface by means of integrals (as seen in the sections above), the authors now quantify the impact by means of geometry, for example calculating the surface of a triangle (*0.5*width*height*). At t1, transformation is conducted from the reference situation to LU type 1, which creates higher ecosystem quality. The transformation impact is given as the difference in ecosystem quality (Qref−QLU1) multiplied by the time it would take after abandoning LU1 to restore the reference. Both the transformation (area I) and occupation impact (area II) result in negative values, thus an increase in ecosystem quality. At t3, transformation is conducted from the reference situation to LU type 2, where the transformation (area III) and occupation (area IV) both have damaging effects on ecosystem quality. At t4, transformation is conducted from LU2 to LU3. The impact of transformation can be calculated by subtracting the impact of transformation from the reference situation to LU2 from the impacts of transformation from the reference to LU3 (eq. V in Figure 4.5).

4.6 The choice of reference situation

Transformation and occupation impacts are calculated relative to a reference situation. However, Milà i Canals et al. (2007) and Koellner et al. (2013) have different opinions about what a suitable reference situation is.

Milà i Canals et al. (2007) suggest using the term dynamic reference situation. 'Dynamic' highlights that the reference situation can change over time (Koponen et al., 2018), i.e. that the natural situation is influenced over time by external factors. The dynamic reference situation should be the non-use of the area, but what the non-use situation is, depends on the chosen LCA mode. With attributional LCA (ALCA), the LCA study should include all impacts caused by the studied system, compared to a situation where this activity would not have taken place (Milà i Canals et al., 2007). According to Milà i Canals et al. (2007), the reference situation for ALCA should be the steady state that is achieved by natural regeneration. Depending on the biogeochemical conditions, the steady state achieved by natural regeneration could be equal to the previous land quality, lower, or higher. With consequential LCA (CLCA), the LCA study should focus "on the effects of substitutions among alternative product systems" (Milà i Canals et al., 2007; Weidema, 2001). Milà i Canals et al. (2007) argue that CLCA study should only consider the transformation due to the studied system, compared to an alternative system. The alternative LU system is the most likely LU if the land was not used for the studied purpose. What the most likely alternative system might be and how it should be determined according to Milà i Canals et al. (2007), is unclear.

Koellner et al., (2013) propose three main options to describe the reference. The first option is Potential Natural Vegetation (PNV), "which describes the expected state of mature vegetation in the absence of human intervention" (Chiarucci et al., 2010), which is similar to natural regeneration of Milà i Canals et al. (2007). Data for PNV is available in satisfactory quality for many biogeographical regions (Koellner et al., 2013). The second option is "to use the (quasi-) natural land cover predominant in global biomes and ecoregions as a reference when assessing land use impact on a global scale". Thus, the reference situation is the regeneration towards the quasi-natural land cover. Koellner et al. (2013) uses 'quasi-natural' to explain that while certain parameters can be completely regenerated in specific conditions (for example carbon in soil), others might not (e.g., extinction of species), thus an ecosystem will never be the same as before. The third option is the current mix of land uses as reference as proposed for Europe (Koellner & Scholz, 2008), however, this is impractical due to the change of the mix over time (Koellner et al., 2013). Koellner et al., (2013) recommend using the second option, the (quasi-)natural land cover. Nevertheless, Koellner et al. (2013) mention that defining a reference situation is an area for further exploration and is a value choice (Koellner et al., 2013).

4.7 Assuming a future scenario after the studied system

The studied system refers to the activity for which the impacts are calculated. In the UNEP-SETAC framework, the studied system is either transformation or occupation (or both). The authors assume that it is unknown what happens to the land in the future, after the studied system. This is an issue, because the authors want to quantify all impacts of the studied system, thus also the future impacts that the studied system may cause. Therefore, assumptions need to be made regarding the future scenario after the studied system.

Milà i Canals et al. (2007) propose two possible future scenarios after the studied system. The first possible scenario is land abandonment after the studied system (Figure 4.6a & 4.6c). In that case, the quantified impact is the difference between natural regeneration and the reference situation. The alternative possible scenario is continued land use in the future (Figure 4.6b & 4.6d). Then, it is assumed that the current occupation continues infinitely. In that case, the impact is the difference between continued occupation and the natural regeneration. The impact is calculated until the end of the modelling period (Chapter 4.8), and that quantified impact is attributed to the studied system (Milà i Canals et al., 2007).

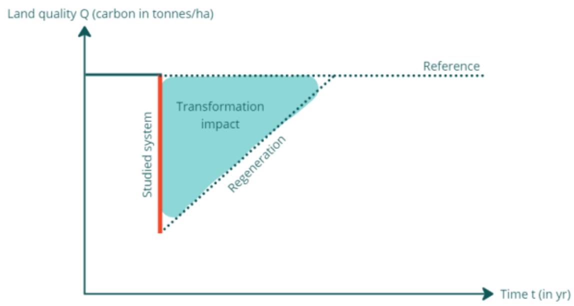

Figure 4.6a. Transformation impact (blue shaded area) if the studied system is land transformation and the assumed future is regeneration.

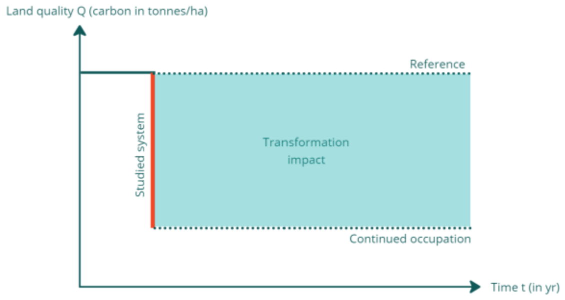

Figure 4.6b. Transformation impact (blue shaded area) if the studied system is land transformation and the assumed future is continued occupation.

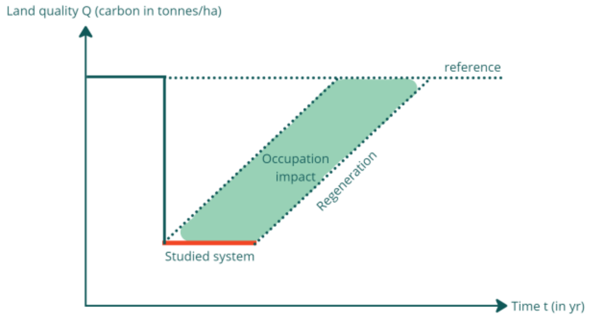

Figure 4.6c. Occupation impact (blue shaded area) if the studied system is land occupation and the assumed future is regeneration.

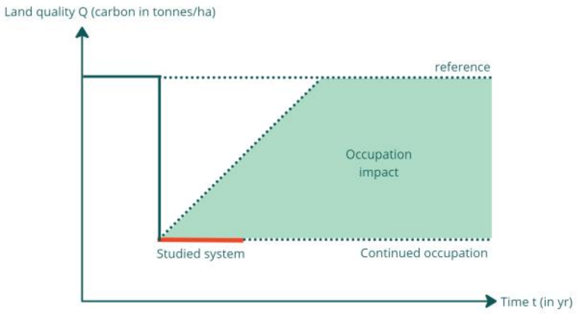

Figure 4.6d. Occupation impact (blue shaded area) if the studied system is land occupation and the assumed future is continued occupation.

In contrast with Milà i Canals et al. (2007), Koellner et al. (2013) do not consider the alternative of continued land use as a possibility for the future. To quantify the total impacts of the studied system, Koellner et al. (2013) assumes that the future scenario after the studied system is natural regeneration.

4.8 The choice of modelling period

In the examples provided earlier of the quantification of transformation (Figure 4.3) and occupation impacts (Figure 4.4), the impact could be calculated because the blue surface in the graph is enclosed by the lines of the reference situation and the studied system. However, it can also happen that the reference situation and the studied system do not completely enclose a surface. For example, if the future scenario of the studied system is continued occupation (Figure 4.6b & 4.6d) or if the regeneration of the studied system does not reach the reference situation, a permanent impact occurs (Figure 4.7) (Koellner et al., 2013). In the situations where the reference situation and the studied system do not enclose a surface in the graph, defining a modelling period is necessary to enclose the surface in the graph.

The modelling period defines the timeframe over which the difference in quality due to the land transformation is integrated. Milà i Canals et al. (2007) suggest that impacts should be calculated over two modelling periods: 1) "overall impacts (baseline) over an infinite or very long term, at least until a new steady state is reached both for the reference and the studied system" and 2) "100 years as a shorter term with likely smaller uncertainties". According to Milà i Canals et al. (2007), "the impacts on ecosystem quality should be assessed at least until a new steady state in ecosystem quality is reached by natural or human-induced relaxation". In other words, Milà i Canals et al. (2007) recommend to use a modelling period that is (at least) as long as the regeneration time. However, Koellner et al. (2013)

deviate from that, saying that it creates inconsistencies between transformation types (e.g., regeneration from cropland to grassland has a shorter regeneration time than cropland to tropical rainforest) and it would not be feasible in background systems (e.g., life cycle inventory databases) (Koellner et al., 2013). Instead, they recommend choosing an arbitrary and finite modelling period (Koellner et al., 2013). The UNEP-SETAC framework recommends a modelling period of 500 years, as it resembles the duration of the long-term natural processes (Koellner et al., 2013).

4.9 Quantifying permanent impacts

Permanent impacts can occur if the new steady state of the studied system is not equal to the reference situation (Milà i Canals et al., 2007) or if the regeneration towards the reference situation exceeds the modelling period (Koellner et al., 2013). Milà i Canals et al. (2007) and Koellner et al. (2013) are not in consensus about how to deal with permanent impacts.

Milà i Canals et al. (2007) suggest including a qualitative note in the interpretation phase that permanent impacts are detected. Or alternatively, the impact size can be calculated by assuming that the dynamic reference situation is reached after an unrealistic large regeneration time (e.g., 10 000 years).

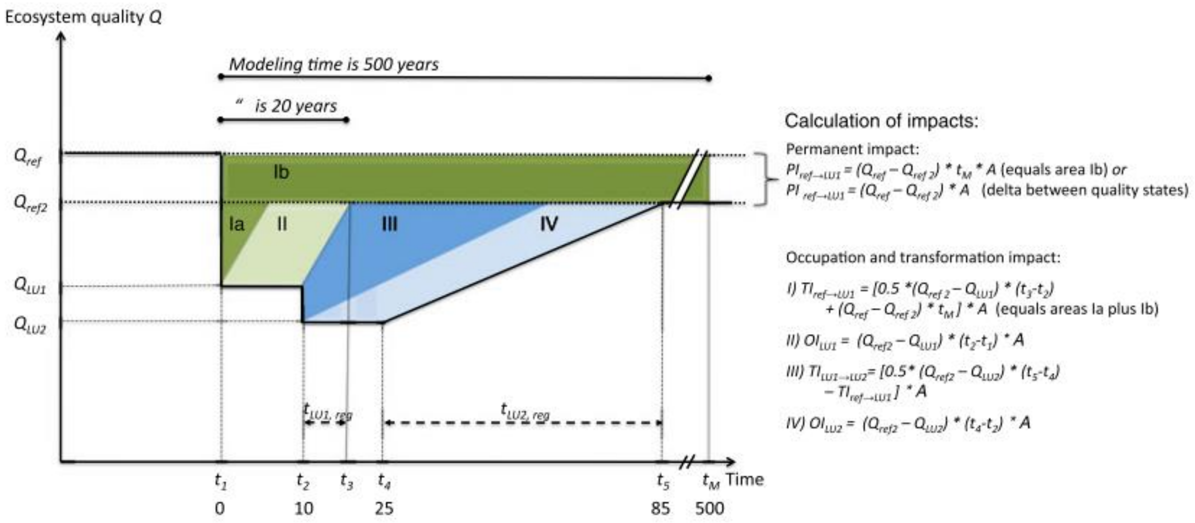

Figure 4.7. Calculation of permanent impacts caused by transformation at t1.

Koellner et al. (2013) calculated the permanent impacts by multiplying the difference in quality (between the reference situation and the new steady state) by the area and the modelling period (Figure 4.7). Impacts after the modelling period (in this example 500 years) were not included (in Figure 4.7 after 500 years). Koellner et al. (2013) recommend to express permanent transformation impacts as 'quality.year. However, the authors mentioned that the permanent impacts can also be expressed without choosing an (arbitrary) modelling period (Koellner et al., 2013). Without the modelling period (also called time horizon), the permanent impact is not expressed in 'quality.year'. However, temporary transformation and occupation impacts are expressed in 'quality.year', which allows them to aggregate these impacts (Koellner et al., 2013). Therefore, they recommend expressing the permanent impact as 'quality.year', to be able to aggregate transformation, occupation and permanent impacts.

However, the UNEP-SETAC working group is not in consensus whether the aggregation of permanent transformation, temporary transformation and occupation impacts is justified. Permanent impacts represent "diminishing options for future development of a piece of land", while occupation and transformation impacts "rather describe actual, temporary impacts occurring during the occupation/regeneration phase" (Koellner et al., 2013). Therefore, "it can be argued that aggregation of temporary and permanent impacts is equivalent to aggregation of different impact categories" (Koellner et al., 2013). Additionally, the choice of modelling period over which the permanent impacts are considered is a value choice. The UNEP-SETAC workgroup has not reached consensus over aggregating or not, and if so, what the modelling period should be.

4.10 The choice of amortization period

Land transformation impacts and permanent impacts have to be allocated to the output (functional unit) of a parcel of land (Koellner et al., 2013). This allocation process is called amortization, and the timeframe that is used is called the amortization period or allocation period (Koellner et al., 2013).

The amortization period is the period to which the change in quality is allocated. This differs from the modelling period; the modelling period determines the period over which the change in quality is included in the calculation. For example, if the modelling period is 100 years, the change in quality after those 100 years is not included in the calculation of transformation quality impacts. If the amortization period is 20 years, it means that the change in quality within the 100 years is attributed to output of the land in the first 20 years after the land transformation.

According to Koellner et al. (2013), there is currently not a "clear, scientifically robust alternative" for the amortization period. They recommend using a 20-year amortization period "in line with standards and regulations for land use-derived greenhouse gas emissions allocation" (e.g., IPCC). An amortization period of 20 years "represents a good compromise between allocating them all to the first year (and thus quickly losing sight of the effects of transformation) and using a long allocation period (which could lead to a quasi-elimination of transformation impacts in the LCA results)" (Koellner et al., 2013). Koellner et al. (2013) use the 20-year amortization period for both temporary and permanent transformation impacts. It is not explicitly mentioned by Koellner et al. (2013), but it seems like occupation impacts are not allocated based on an amortization period, because they seem to be (equally) allocated over the years of the occupation period. Alternatively, Koellner et al. (2013) mentions that "a linear depreciation along the regeneration pathway could be applied" for transformation impacts.

4.11 Connection to the climate impact category

In the UNEP-SETAC framework, the authors use the metric 'land quality' to quantify the impacts. In the context of GHG emissions, this leads to an environmental flow of CO_2 with the unit tonnes.year. However, commonly used impact assessment models are not able to connect that flow to the climate change impact category. According to Bessou et al. (2020), the only impact assessment model that connects the UNEP-SETAC framework to the climate change impact category is the Climate Regulation Potential (CRP) framework by Müller-Wenk & Brandão (2010). In the following paragraphs, the CRP framework will be explained.

The key concept of the CRP framework is that the impact of CO_2 does not only depend on the CO_2 quantity but also the residence time of CO_2 in the atmosphere. Müller-Wenk & Brandão (2010) use the term 'average/mean stay in the air' to refer to the residence time, but for the remainder of this thesis, 'residence time' is the preferred term as it is in line with literature. In the CRP framework, Müller-Wenk & Brandão (2010) calculate the ratio between the average residence time in the atmosphere of biogenic carbon (of the studied LULUC system) versus fossil carbon. The ratio is used to determine the impact of LULUC relative to fossil carbon.

4.11.1 Average residence time of fossil carbon in the atmosphere based on the Bern carbon cycle

Müller-Wenk & Brandão (2010) determine the average residence time of fossil carbon in the atmosphere based on the Bern carbon cycle (Figure 4.8). According to the Bern carbon cycle model, a CO_2 unit pulse gradually disappears over time from the atmosphere, due to the uptake of the CO_2 by the various carbon pools (e.g., terrestrial, ocean). Thus, the Bern carbon cycle is based on the current conditions of the earth. The line in Figure 4.8 portrays the (average) fraction of the CO_2 emissions pulse that is still left after *N* years. On average, one unit of CO_2 will decrease to 0.36 units after 100 years, 0.23 units after 500 years and 0.22 units is expected to remain in the atmosphere for “many millennia” (IPCC, 2007). The Bern carbon cycle model is valid for 2000 years, but even with an infinite t, the average CO_2 pulse in the atmosphere would not reach zero.

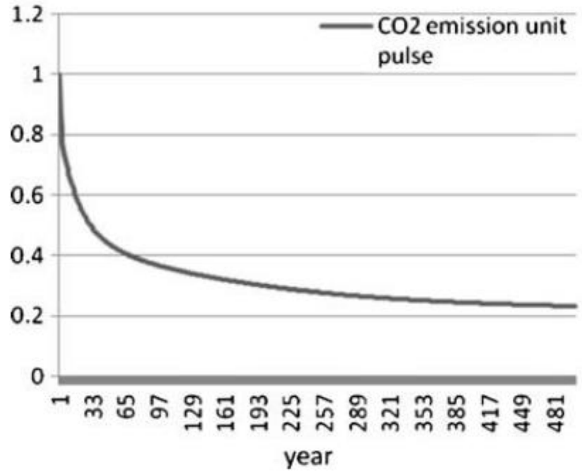

Figure 4.8. Fraction of a CO_2 emission pulse which is still in the air after N years according to the Bern carbon cycle model (reproduced from Müller-Wenk & Brandão, 2010).

Müller-Wenk & Brandão (2010) calculate the residence time in the atmosphere of an average CO_2 pulse over time. They integrate the Bern carbon cycle over a chosen time horizon and divide it by the chosen time horizon to achieve an average residence time in the atmosphere of an average CO_2 pulse. The average fraction of an CO_2 pulse in the graph would never reach zero, and the quantified surface under the graph would be infinite. Thus, a cut-off (i.e., an arbitrary chosen time horizon) is needed. After the time horizon, the impact of the remaining CO_2 in the atmosphere is not taken into account anymore. Müller-Wenk & Brandão (2010) propose an (arbitrary chosen) time horizon of 500 years. With a time horizon of 500 years, they quantify a mean residence time in the atmosphere for fossil CO_2 of 157 years.

4.11.2 Average residence time of biogenic carbon in the atmosphere

Müller-Wenk & Brandão (2010) determine the average residence time of biogenic carbon differently based on whether the biogenic carbon originated from land transformation impact or land occupation impact.

For transformation, Müller-Wenk & Brandão (2010) determine the average residence time of biogenic carbon based on the regeneration time. Müller-Wenk & Brandão (2010) assume that the loss of biogenic carbon of the land is equal to the amount of biogenic carbon entering the atmosphere. Consequently, they reason that the regeneration time is the time it takes for the (same) atmospheric biogenic carbon to leave the atmosphere and re-enter the land again. According to Müller-Wenk & Brandão (2010), the average residence time in the atmosphere is 50% of the regeneration time, because it is the average between 0% of the regeneration time (start of transformation) and 100% of the regeneration time (the end of the regeneration time after transformation) (Figure 4.9) (Eq. 4.3). Note, this is only true in case of a linear regeneration time (Müller-Wenk & Brandão, 2010).

(Eq. 4.3) $$Average\ residence\ time\ of\ occupation = \frac{0 + tRegeneration}{2} = 0.5tRegeneration$$

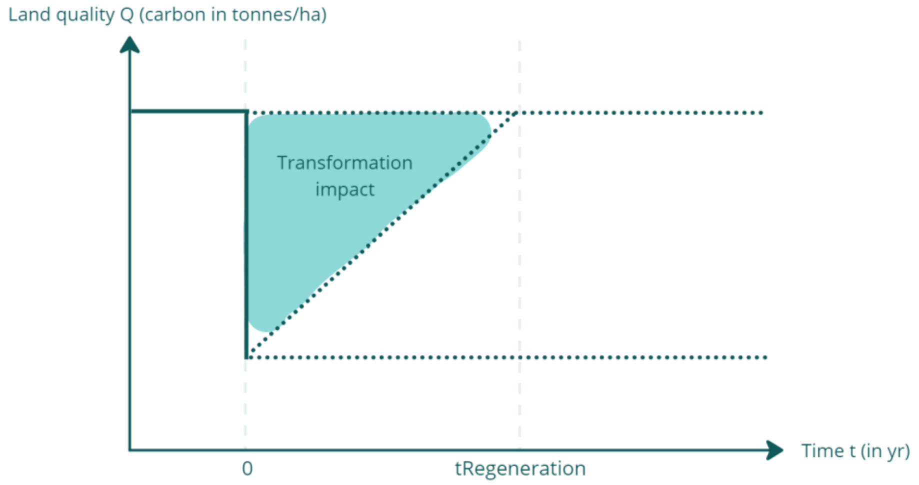

Figure 4.9. The average residence time in the atmosphere of transformation impact is 50% of the regeneration time.

For occupation, Müller-Wenk & Brandão (2010) reason that every year of occupation is responsible for delaying the regeneration of the land with one year, thereby keeping the CO_2 one year longer in the atmosphere. Therefore, Müller-Wenk & Brandão (2010) reason that the average residence time in the atmosphere of one year occupation is one year.

4.11.3 Calculating the CRP by means of the duration factor

To calculate the CRP value, Müller-Wenk & Brandão (2010) multiply the duration factor (df) with the carbon transfer. The carbon transfer is the carbon transferred to the air due to the transformation. The duration factor is the average residence time in the atmosphere of the studied system's biogenic carbon divided by the average residence time in the atmosphere of fossil carbon. Thus, for occupation the duration factor is *1/157*, and for transformation, the duration factor is *0.5*tRegeneration/157*. If for example, the transformation from forest to cropland leads to a carbon transfer of 135 tonnes/ha, the carbon transfer for both occupation and transformation is 135 tonnes/ha. The CRP is expressed as 'fossil-combustion-equivalent' carbon in tonnes/ha transferred to air. This way, Müller-Wenk & Brandão (2010) can sum the biogenic carbon as 'fossil-combustion-equivalent' into the LCA indicator for global warming.

4.12 List of assumptions

Table 4.1 lists the assumptions that can be recognised in the framework. The left column of the table outlines the assumptions that are made in the UNEP-SETAC framework. In the middle column, it can be found in which literature this assumption was recognised. In the right column can be found why this assumption can be discredited. The implications of some of these assumptions will be explained in Chapter 5.

Table 4.1. Assumptions made in the UNEP-SETAC framework.

Nr	Assumption	Recognised by	Counterargument
1	*Discrete land use types are sufficient for an assessment of land use impacts*	(Koellner et al., 2013)	Parameters that express ecosystem quality can vary considerably within one LU type (Eigenbrod et al., 2010)
2	*Ecosystem quality remains constant over occupation time*	(Koellner et al., 2013)	Quality can change (Milà i Canals et al., 2007). The use of land during occupation may increase or decrease soil carbon due to fertilizer or tillage (IPCC 2000, section 4.4.1) (Müller-Wenk & Brandão, 2010)

3	*Time and area of occupation are substitutable;* *i.e., a small area occupied for a long time has the same impact or can deliver the same output as a large area occupied for a short time.*	(Koellner et al., 2013)	Size and time can matter for the ecological impact (Koellner & Scholz, 2007)
4	*Transformation time is negligible*	(Koellner et al., 2013)	Transformations that worsen ecosystem quality often require little time, however transformations that improve the ecosystem quality might not (Koellner et al., 2013). Unrealistic for biodiversity, changes can be delayed (Souza et al., 2015). Also not true for processes in soil regarding carbon, only stabilization after a disruption is already assumed to take 20 years (IPCC, 2006)
5	*Regeneration is linear*	(Koellner et al., 2013)	In the UNEP-SETAC framework, it is often recommended to calculate impacts until a new steady state has reached. However, a recovery process is dynamic (and possibly non-linear) and may have multiple equilibrium states (Souza et al., 2015).
6	*“Regeneration is independent from land use history; i.e. only the last land use before abandonment is important and time of occupation is not relevant”*	(Koellner et al., 2013)	Not appropriate for many cases (Koellner et al., 2013)
7	*Regeneration is independent from landscape configuration*	(Koellner et al., 2013)	The duration of the regeneration is dependent on the area’s size (because larger areas take a longer time regenerating than smaller areas) (Milà i Canals et al., 2007)
8	*Biodiversity and multiple ecosystem services are independent;*	(Koellner et al., 2013; Othoniel et al., 2016)	Research shows that there is interaction between them (Balvanera et al., 2006; Bennett et al., 2009; Raudsepp-Hearne et al., 2010; Seppelt et al., 2011)
9	*The ecological impact is linearly increasing with the intervention;*	(Koellner et al., 2013)	It might respond non-linear (Carpenter et al., 2009)
10	*There is no interaction between land use and other drivers such as climate change.”*	(Koellner et al., 2013)	Combined effects can lead to non-additive reactions (Koellner et al., 2013).
11	*The framework does not assume active restoration*	(Koellner et al., 2013)	It is uncertain (according to the authors) what the effect is for ecosystem services on the larger scales.
12	*The relation between quality loss and land use area is linear*	(Souza et al., 2015)	Not always true.
13	*There is no temporary carbon storage in biobased-products.*	This thesis	If, for example, felled trees contain carbon, but are not immediately burned but used for furniture, there is a long time delay between carbon loss in soil and vegetation, and the emission of carbon.

5. Reflecting on the UNEP-SETAC framework

In this chapter, the UNEP-SETAC framework is evaluated based on literature and conclusions that were derived from the previous chapters of this thesis.

5.1 CLCA reasoning

The UNEP-SETAC framework provides the LCA practitioner with methodological choices. For example, Milà i Canals et al. (2007) argue that the reference situation should be chosen depending on the LCA mode: ALCA or CLCA. This implies that the authors perceive the UNEP-SETAC framework suitable for both ALCA and CLCA. However, in this thesis it is argued that the UNEP-SETAC framework is largely based on consequential thinking and is therefore not suitable in its current form for an ALCA study. In next paragraphs, it will be explained why the UNEP-SETAC framework is largely based on CLCA.

5.1.1 Double counting of emissions

In ALCA, the system boundary of one study should not overlap with a system boundary of another product, i.e. there should be no double counting of emissions (Brander et al., 2009). Brander (2015) argues that ALCA should lead to additive results of all anthropogenic emissions, relative to a pre-anthropogenic baseline: “In theory, if one were to conduct ALCAs of all final products, one would end up with the total observed environmental burdens worldwide” (Life Cycle Initiative, 2011). This is also referred to as the 100% rule (Finnveden et al., 2022). The 100% rule could only be correct if one would (hypothetically) be able to only sum the impact of ‘final products’, where ‘final products’ are defined as “as a product that is directly consumed by humans and not used in the life cycle of another product” (Schaubroeck et al., 2021). However, in practice, pinpointing final products according to this definition could pose a challenge (Finnveden et al., 2022).

The UNEP-SETAC framework does not comply with the additive character of ALCA, because of the following examples. First, in the UNEP-SETAC framework, forgone sequestration due to occupation is counted as factual emissions (Chapter 5.2.1). Second, measurable transformation impacts are discounted on hypothetical unlikely future regeneration (Chapter 5.2.2.1). Third, when continued occupation is the assumed future scenario, forgone sequestration due to occupation could be counted in perpetuity (Brander, 2015) (Chapter 5.2.2.2). Thus, a sum of all land transformation and land occupation impacts calculated by means of the UNEP-SETAC framework, does not equal to a sum of all anthropogenic land transformation and occupation impacts in the world.

Some authors counterargue that “bookkeeping of absolute (observable) emissions, such as all the global consumption-based emissions, does not describe the environmental impacts of occupying land which is not in natural steady state” (Soimakallio et al., 2015). Soimakallio et al. (2015) argue that a bookkeeping of absolute (observable) flows only may be in contradiction with the 100% rule of final products in ALCA. However, in Chapter 5.2.1, it is argued that occupation does not have measurable impacts. Thus, bookkeeping of observable emissions would still correctly describe the impacts of LU related activities and is therefore not in contradiction with the 100% rule for final products in ALCA.

In CLCA, the system boundary of one product may overlap with another one and thus emissions could be double counted (Brander et al., 2009). CLCA estimates changes in emissions relative to an alternative and therefore does not quantify absolute existing emissions (Brander et al., 2009). Since both are true for the UNEP-SETAC framework, we consider the UNEP-SETAC framework in line with CLCA.

5.1.2 Combining CLCA and ALCA to capture the consequences of a decision

Even though there is a wide variety of existing LCA modes (Guinée et al., 2018), the debate about LCA modes in the LULUC LCA community only concerns the difference between ALCA and CLCA (Brander, 2015; Soimakallio et al., 2015). According to Life Cycle Initiative (2011), ALCA provides information on what portion of global burdens can be associated with a specific product life cycle, while CLCA provides information on the environmental burdens that occur, directly or indirectly, as a consequence of a decision (usually represented by changes in demand for a product). Brander (2015) recognises the trend that in LULUC literature, ALCA is perceived as needing to "capture the total consequences of an activity (i.e., both direct and indirect effects), possibly in recognition of the principle that decision-making should be based on an understanding of the total consequences of the decision at hand. However, capturing the total consequences of an activity is not in line with the widely accepted definition of ALCA by the Life Cycle Initiative (2011).

As described in Chapter 5.1.1, it seems like the authors of the UNEP-SETAC framework have tried to capture all environmental impacts as a consequence of a decision. Therefore, the framework is more aligned with the characteristics of a CLCA study, and not suitable in its current form for an ALCA study. However, the UNEP-SETAC framework is used in ALCA studies. Brander et al. (2009) argue that failure to distinguish between CLCA and ALCA can result in a combination of the two modes within a single study, leading to a misinterpretation of results. A good example of the effects of combining two LCA modes within one study, can be found in the case study about margarine by Milà i Canals et al. (2013).

Milà i Canals et al. (2013) have performed a case study for margarine, where they have assessed the impacts of land transformation and occupation by means of the UNEP-SETAC framework. The case study was a partial descriptive ALCA, and the FU of the study was 500 g of packaged margarine used as a spread in the UK and Germany. The inventory flows were assessed using new CF for new land use-related environmental impact categories published in the paper: biodiversity damage potential (BDP) (De Baan et al., 2013), climate regulation potential (CRP) (Müller-Wenk & Brandão, 2010), production potential (BPP) (Brandão & Canals, 2013), freshwater regulation potential (FWRP) (Saad et al., 2013), erosion regulation potential (ERP) (Saad et al., 2013), water purification potential physicochemical filtration (WPP-PCF) (Saad et al., 2013), and water purification potential mechanical filtration (WPP-MF) (Saad et al., 2013). Milà i Canals et al. (2013) have compared the contribution of transformation and occupation to these impact categories. They found that land occupation (compared to transformation) was the major contributor for all impact categories (except WWP-MF).

There are several main explanations for the high contribution of occupation according to the authors. First, the same reference situation ('regeneration to a potential quality or natural climax steady state') was used for both transformation and occupation. Second, transformation does not always occur and when it does, it is equally allocated over 20 years. As a consequence, "land occupation tends to dominate the impact results unless very long regeneration times are considered in the calculation of transformation CF". This is because the occupation impact was calculated independent from the regeneration time (surface of a parallelogram) and the transformation impact became larger with a larger regeneration time. Moreover, the large occupation impact is mainly caused because of the conceptualisation of the occupation impact: Milà i Canals et al. (2013) recognise that they compared the current occupation quality with an "idealistic potential which might never be reached again in reality".

The authors perceive the large occupation impact as a limitation of the UNEP-SETAC framework, because it does not conform to policy. In policy, more attention is directed towards the impact of transformation, instead of occupation (Milà i Canals et al., 2013). They recommend that "the results of the impact assessment need to be interpreted as a view of the differences in biodiversity or ecosystem services that are being maintained with respect to an ideal or theoretical potential rather than a description of the actual change in land quality" (Milà i Canals et al., 2013).

In this case study, it is clearly visible that the authors are confusing the differences between ALCA and CLCA. They argue that this ALCA case study could support decisions that consider "long-term effects of hypothetical land use policies", however "if decision makers wish to consider shorter-term effects of land use change, the modelling framework and associated impact categories could actually lead to the wrong decision" (Milà i Canals et al., 2013). Brander (2015) rightfully counterargues that "perverse outcomes are to be wholly expected if attributional LCA is used (on its own) for decision-making, precisely because the method does not necessarily capture the total impacts of the decision at hand (Plevin et al., 2014)".

5.2 Consequences of the framework's design

5.2.1 Occupation impacts

Due to occupation, natural regeneration is postponed by the time duration of occupation. UNEP-SETAC tries to measure the impact of postponing regeneration with the 'quality' indicator, by comparing the current situation (occupation) with 'what could have happened' (regeneration). This leads them to quantifying the occupation impact as the quality difference between 'natural regeneration after occupation' and 'natural regeneration before occupation', in the unit 'carbon tonnes/year' for GHG emissions.

According to Koellner et al. (2013), occupation impacts describe actual impacts ("occupation and transformation impacts rather describe actual, temporary impacts occurring during occupation/regeneration phase"). However, the framework assumes that during occupation, the quality of land is always kept stable on purpose (Milà iil Canals et al., 2007). This means that the measurable quality change during occupation is zero. As a counterargument, Milà i Canals et al., (2007) argue that even "if a land occupation process does not cause any sizeable quality change of the occupied land, it may nevertheless cause an impact, because the forces of nature are prevented from changing the land qualities during the occupation time". In the UNEP-SETAC framework, the occupation impacts are quantified as the difference between the studied system (occupation) and an alternative system (regeneration). However, an evidence based analytical accounting method (i.e., ALCA) should not quantify impacts based on an alternative scenario. When a factual event happens, it automatically means that there are several possible alternatives that did not happen. However, the impact of an event should not only be determined based on the relative impact compared to one alternative. This is broadly what CLCA does, which is confusing because it can lead to negative impacts and consequently wrong interpretations of the impact of a product system. Brander (2015) recognizes that the postponement of natural regeneration follows consequential logic instead of attributional logic, because it considers what would happen to the land in absence of the studied land use. Even though a delay of the natural regeneration is a consequence of land occupation, it is not an impact relative to a pre-anthropogenic baseline, thus it does not belong in ALCA (Brander, 2015).

For GHG emissions, the current UNEP-SETAC method leads to an occupation impact in 'carbon tonnes.year'. However, occupation has no measurable impact in 'carbon tonnes.year', as there are no measurable carbon uptakes or emissions if the occupation quality is constant. Thus what the authors wrongfully try to quantify as an emission in 'carbon tonnes.year' is instead 'forgone sequestration': the difference in carbon sequestration due to using the land for the FU, relative to abandoning the land and letting it regenerate. An inventory flow 'occupation' in 'carbon tonnes.year' should not be characterized in the current impact assessment model for climate change, as occupation (under the assumption that quality remains constant) does not create measurable GHG emissions.

Additionally, while the assumption of constant occupation quality seems practical, it also seems too simplistic: "The ecosystems and their provision of services thus keep evolving over time, following natural mechanisms and under the influence of different pressures both linked and nonlinked to the product system under study" (Othoniel et al., 2016; Seppelt et al., 2011). If one assumes a constant quality during land occupation, it implies that "any land occupation can be durably sustained, whatever are its location, the surrounding environment or the history of land uses" (Othoniel et al., 2016).

5.2.2 Discounting or double counting impacts

Milà i Canals et al., (2007) recognize two options for the land situation after the current system: regeneration (abandonment) or continued occupation. Koellner et al. (2013) did not mention any possible scenarios for after the current system. It is suspected that they implicitly assume that after land transformation or occupation, land will be abandoned and will regenerate. However, land abandonment is not a realistic scenario; even if society succeeds in taking measures to reduce land demand, cropland is still expected to increase between 5% to 20% between 2010 and 2050 (FAO, 2018; IPCC, 2019). Therefore, it is much more likely that the land use after the studied system is continued occupation. Nevertheless, any assumption regarding the hypothetical future scenario has an effect on the quantification of environmental impacts.

5.2.2.1 Assuming future land abandonment

Due to land transformation, quality is lost, but instead of assuming that land transformation impacts are forever lost (Figure 4.6a), the authors assume that land transformation impacts will be recovered due to regeneration (Figure 4.6b). They quantify the land transformation by discounting the measurable land transformation quality loss with potential future regeneration. This means that the UNEP-SETAC framework takes an advance on the future, while the future scenario 'regeneration' is unlikely to happen. Thus, in the UNEP-SETAC framework, the emitter receives a "discount" on an emission that it factually caused, due to the unlikely hypothesis that some moment in time, somebody else will take up those emissions. This results in a lower quantified land transformation impact than the measurable impact.

Taking an advance on the future is highly debatable, also in policy. This can be demonstrated by the nitrogen discussion in the Netherlands. To put it simply, the Dutch government provided permits for emissions based on a hypothetical future decrease of the nitrogen emissions. The Dutch Council of State ruled that an advance on future possible decrease of emissions is not according to European law and that decreases should be measurable in order to take them into account when permitting new projects (Raad van State, 2019).

5.2.2.2 Assuming future continued occupation

Milà i Canals et al. (2007) also mention the possible scenario of assuming continued occupation; however, that scenario also creates the possibility of double counting forgone sequestration due to occupation in perpetuity (Brander, 2015). In the UNEP-SETAC framework, the forgone sequestration is quantified for each year of occupation, which could be continuing indefinitely in case it is assumed that occupation is the continued future scenario (Figure 4.6d). Brander (2015) recognizes that "unless there is a way of allocating (i.e., amortize) the forgone sequestration across all future production from the land, the same forgone sequestration may be double-counted ad infinitum".

5.2.3 Regeneration time

To quantify transformation and occupation impacts in the UNEP-SETAC framework, regeneration data is needed. For soil carbon, Koellner et al. (2013) propose to use the regeneration times values for specific transformation types provided by Müller-Wenk & Brandão (2010) for the impact pathway climate regulation potential (Chapter 5.4). However, regeneration times data is hardly available (Koellner et al., 2013). The data that is used often lacks a scientific foundation and is often outdated or hypothetical (e.g., Müller-Wenk & Brandão, 2010). This research gap was already identified in 2010 (Müller-Wenk & Brandão, 2010), but since then not much has been improved. This is a source of uncertainty in the framework, because the impact results of land transformation and occupation are highly sensitive to regeneration times (Koellner et al., 2013).

5.2.4 Assigning permanent impacts based on the modelling period

In the UNEP-SETAC framework, the authors make a distinction between temporary and permanent transformation impacts. Whether a permanent transformation is detected, depends on the modelling period and the assumed quality of the land after the studied system. The modelling period is a value choice for which the UNEP-SETAC proposes 500 years (Chapter 4.8). The assumed quality of the land after the studied system can be land abandonment, i.e. regeneration, or continued occupation (indefinitely) (Chapter 4.7). These options create many possible situations in which permanent impacts occur or do not occur.

There are two different types of permanent impacts: i) the studied land quality will “never” reach the reference situation and ii) the studied land quality will not reach the reference situation within the set modelling period. The first impact is considered to be a ‘true’ permanent impact: even with an infinite modelling period, the assumed land quality after the system (either regeneration or continued occupation) will stabilize at a quality that is different from the reference situation. The second permanent impact type is dependent on the value choice of the modelling period.

If we assume land abandonment after the studied system, there are currently three possible situations regarding permanent impacts. First, impacts could be ‘truly’ permanent, meaning that permanent impacts will be detected regardless of the size of the modelling period, because the regeneration will stabilize before it reaches the reference situation (Figure 5.1a). Second, the regeneration could reach the reference before the end of the modelling period, meaning that there are no permanent impacts detected (Figure 5.1b). Third, the regeneration does not reach the reference before the end of the modelling period, leading to a permanent impact (Figure 5.1c).

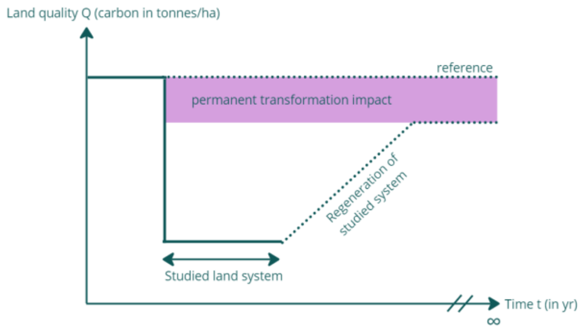

Figure 5.1a. ‘True’ permanent impact: the regeneration will never reach the reference situation.

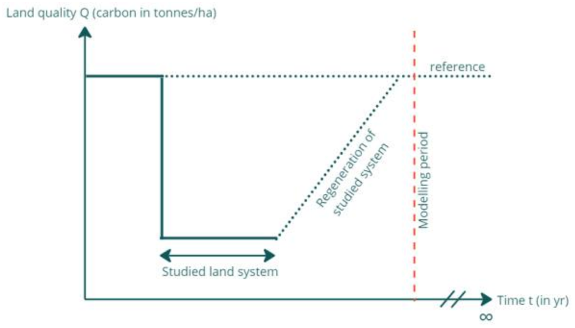

Figure 5.1b. No permanent impact: regeneration reaches the reference situation before the end of the modelling period.

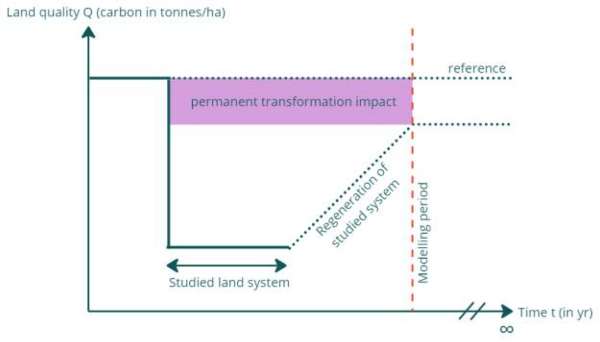

Figure 5.1c. Permanent impact: regeneration does not reach the reference before the end of the modelling period.

If we assume continued occupation, with (Figure 5.2a) or without (Figure 5.2b) a modelling period, permanent impacts are detected. These impacts are also ‘truly’ permanent, because if we assume an infinite continued occupation, there will be an infinite permanent impact. Of course, this is only true if the occupation quality is not equal to the reference quality.

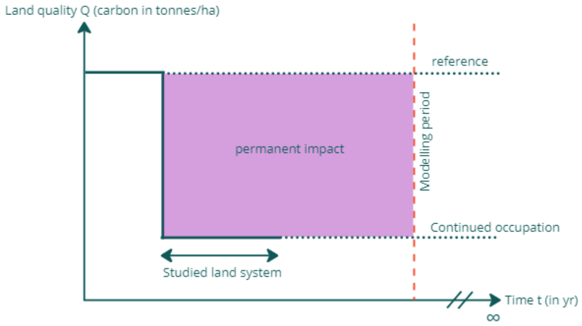

Figure 5.2a. Continued occupation with any modelling period leads to a permanent impact.

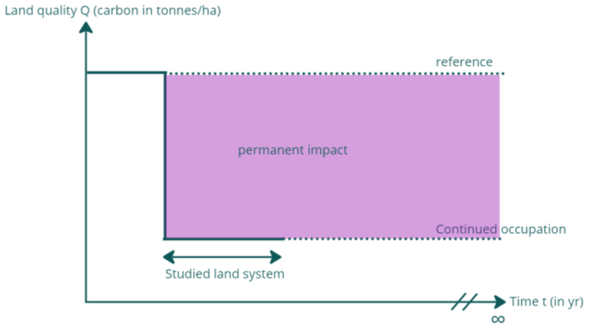

Figure 5.2b. Continued occupation without a modelling period leads to a (true) permanent impact.

These many options for permanent impacts show that the current modelling framework is not rigid enough for a consistent application of the concept of permanent impacts. The modelling period is currently either determined by an arbitrary chosen number within a framework or chosen by the LCA practitioner itself. The modelling period is a value choice that determines whether an impact is permanent. Therefore, it does not really provide information on whether an impact is permanent. It only indicates whether the regeneration of the studied system reaches the reference situation within or outside of the modelling period (which leads to a detected “permanent” impact).

As mentioned in Chapter 4.9, Koellner et al. (2013) recommend to express permanent transformation impacts in the context of GHG emissions as carbon in the unit ‘tonnes.year’, which allows them to aggregate permanent transformation impacts with temporary transformation and occupation impacts. However, assigning a modelling period, and thereby making a distinction between temporary and permanent impacts and aggregating these impacts together, leads to a distortion of the quantified impacts. The size of the modelling period has a huge influence on the size of the total transformation impact and the relative importance of temporary versus permanent impacts. For example, a large modelling period leads to a larger total impact and a larger importance of temporary impacts (Figure 5.3a and 5.3b). Additionally, the formula to quantify impacts changes in case permanent impacts are detected (Figure 4.7).

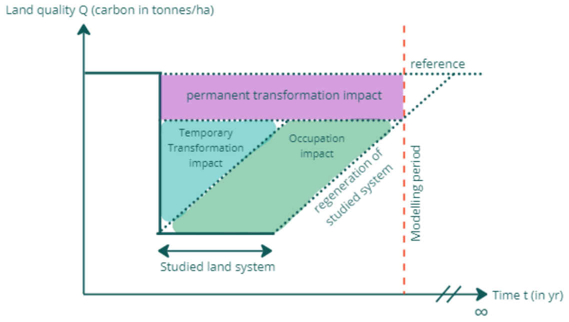

Figure 5.3a. A larger modelling period leads to a larger total impact and a relative larger importance of temporary transformation and occupation impacts.

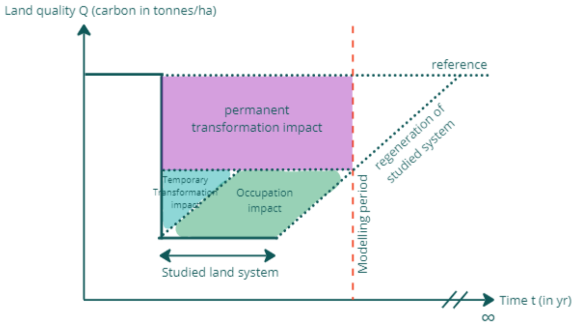

Figure 5.3b. A smaller modelling period leads to a smaller total impact and a relative smaller importance of temporary transformation and occupation impacts.

Next, these permanent impacts still must be amortized to a certain period (20 years recommended by Koellner et al., 2013), which creates inconsistency in the timeframes used within the framework. In the current framework it can happen that a very large permanent impact is quantified solemnly due to a very large modelling period, which subsequently needs to be amortized to a small amortization period, leading to a high LUC impact per year for a certain crop.

Above, it is shown that the modelling period has a large influence on the aggregated results. However, the authors mention that permanent impacts can also be expressed without choosing an (arbitrary) modelling period (Koellner et al., 2013). Even when one expresses permanent impacts in 'carbon tonnes' instead of 'carbon tonnes.year', the modelling period still influences the results. Due to the assigned modelling period, the temporary impacts can be smaller or larger (in carbon tonnes.year), simultaneously leading to larger or smaller permanent impacts (in carbon tonnes).

It can be debated whether one should make a distinction between temporary and permanent impacts at all. LCA currently does not make a distinction between temporary and permanent impacts. For example, the emissions coming from burning fossil fuels can be regarded as a permanent impact. However, in LCA these impacts are not 'flagged' as permanent and are not handled different than any other emissions. In the framework, the difference between permanent and temporary impacts is created by the assumption that impacts are temporary due to hypothetical regeneration. However, biological processes that remove the CO_2 molecules from the atmosphere and take them up into the ocean or the terrestrial biosphere (Archer et al., 2009), do not differentiate between a CO_2 molecule origination from a permanent carbon loss or a temporary carbon loss.

5.2.5 Aggregation of occupation and transformation

Koellner et al. (2013) perceive temporary transformation impacts and occupation impacts as the same type of impact, because they "describe actual, temporary (quality) impacts". Here, it is argued that transformation and occupation impacts are different. Transformation causes a measurable change in quality, which can be registered over the vertical quality axis of the UNEP-SETAC framework (Figure 5.4a). In contrast, the only measurable impact of occupation is a time delay (Chapter 5.2.1), which is a change over the horizontal time axis in the UNEP-SETAC framework (Figure 5.4b). In the context of GHG emissions, land transformation causes a measurable change in carbon content of the land. The quantified occupation impact in the UNEP-SETAC framework indicates the forgone sequestration, but occupation does not cause a measurable change in carbon content of the land (Chapter 5.2.1). Thus, it can be concluded that transformation and occupation impacts are not the same type of impact and they should not be aggregated.

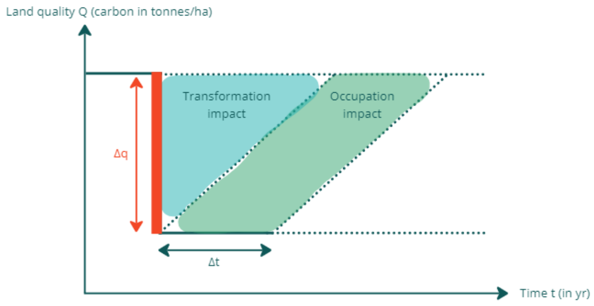

Figure 5.4a. The measurable transformation impact is a drastic change in quality at time t (in red), where a possible time dimension is neglected. The blue shaded area shows the quantified transformation impact according to the UNEP-SETAC framework.

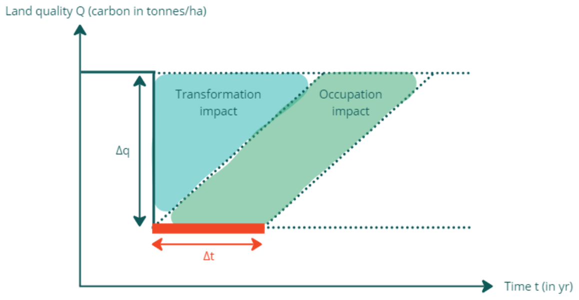

Figure 5.4b. The measurable occupation impact is a delay in time (in red) of regeneration. The green shaded area shows the quantified occupation impact according to the UNEP-SETAC framework.

5.3 Methodological choices within framework

5.3.1 Choice of reference situation

5.3.1.1 Differences between the first and second UNEP-SETAC paper

According to Milà i Canals et al. (2007), the reference situation should refer to a kind of 'non-use of the area', after which they recommended 'natural regeneration' for ALCA and an 'alternative system' for CLCA. Koellner et al. (2013) propose 3 options as reference situation (Potential Natural Vegetation (similar to natural regeneration); (quasi-) natural land cover; and current mix of land uses) and recommend using the second option, the (quasi-)natural land cover. According to Koellner et al. (2013), that is in accordance with the recommendations provided by Milà i Canals et al. (2007).

However, Milà i Canals et al. (2007) and Koellner et al. (2013) both have a different approach to the reference situation. Milà i Canals et al. (2007) base their reference situation on the chosen LCA mode (ALCA vs CLCA), where in both situations the reference situation should be focused on the 'non-use of the area'. Koellner et al. (2013) recommend the (quasi-)natural land cover and this is not influenced by the characteristics of the specific LCA study. For Koellner et al. (2013), the reference situation is independent of the type of impact, while for Milà i Canals et al. (2007) the reference situation is dependent on the type of impact. What they both have in common is that the reference situation is a hypothetical situation, and the future of the studied system is also based on a hypothesis. For both the natural regeneration (Milà i Canals et al., 2007) and the quasi-natural state (Koellner et al., 2013), it is unclear to researchers whether it refers to the historical land quality (pristine land) or the land quality of the regenerated state after the studied system (e.g., Cao et al., 2017; Liptow et al., 2018).

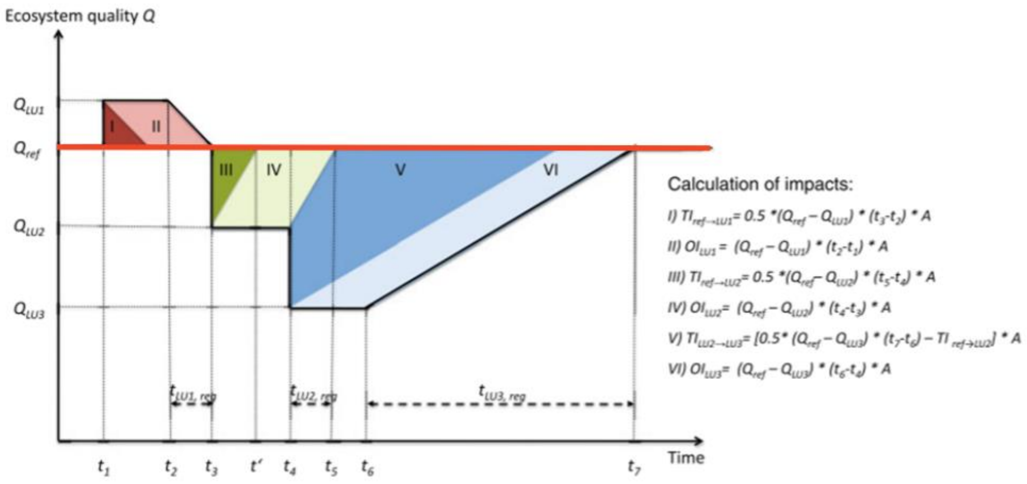

Figure 5.5. The reference 'quasi-natural land cover' is portrayed by horizontal red line (Modified from Koellner et al., 2013).

Figure 5.5 shows the reference scenario (the (quasi-)natural land cover) used by Koellner et al., (2013) in an example for the calculation of impacts. In this case, the (quasi-)natural land cover is the same throughout all transformation and occupation impacts (under the assumption that the quasi-natural land cover is constant over time). Koellner et al. (2013) recognize that a (quasi)-natural state identifies how far away the current system is from an idealistic state, and that might not be informative for policy makers that want to protect the current environment. A reference situation like quasi-natural state fails to address active restoration; any action on land will show loss of quality if it is not higher than the quasi-natural state. Active restoration is conducting an activity (e.g., reforestation) to restore the land, thereby increasing the restoration rate compared to natural restoration. In that case, even active restoration has a negative impact (Souza et al., 2015). Milà i Canals et al. (2013) also encountered issues with the same reference situation for both transformation and occupation impacts in a case study for margarine. They found that if occupation and transformation impacts have the same reference situation, the occupation impacts tend to dominate (unless very long regeneration times are considered).

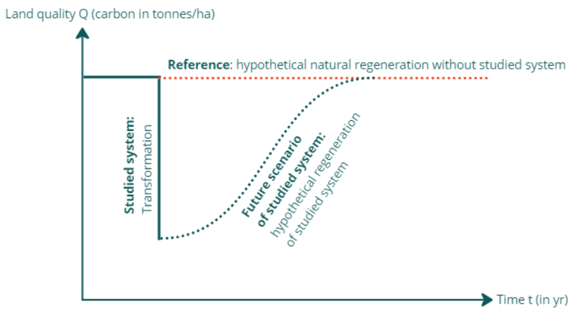

Figure 5.6a. Reference situation (in red) of transformation impacts, according to Milà i Canals et al. (2007).

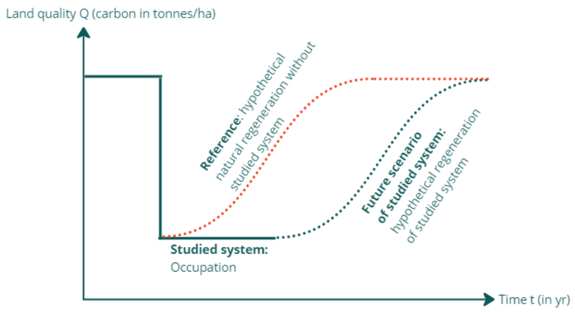

Figure 5.6b. Reference situation (in red) of occupation impacts, according to Milà i Canals et al. (2007).

Contrary to Koellner et al. (2013), the natural regeneration reference for ALCA by Milà i Canals et al. (2007) seems dependent on the impact type. The hypothetical future situation of the studied system is compared with the hypothetical future situation without the studied system. Both hypothetical situations are based on natural regeneration, which is unlikely (Chapter 5.2.2.1). For transformation impacts, the reference situation is the natural regeneration before the transformation impact (Figure 5.6a). For occupation impacts, the reference situation should be the natural regeneration of the state before the occupation impacts (Figure 5.6b). Applying the reference 'natural regeneration' of Milà i Canals et al. (2007) leads to different versions of the natural regeneration, depending on the characteristics of the studied system[2].

5.3.1.2 Debates in literature about choosing a reference situation

PNV and natural regeneration seem to be often confused with each other in literature and the differences between them are not clear, as the definitions seem to change over time and across literature. However, PNV and natural regeneration are similar and therefore the arguments provided in the paragraphs below are true for both natural regeneration and PNV.

There are two main reasons why natural regeneration and PNV are not suitable for an ALCA study. First, a baseline is needed in ALCA "in order to separate out anthropogenic activities (the technosphere) from natural or non-anthropogenic processes (the ecosphere)", thus the baseline in ALCA should not include anthropogenic activities (Brander, 2015; Soimakallio et al., 2015). However, natural regeneration (and thus sequestration) can only exist due to anthropogenic activity, because land-use change has decreased the carbon stocks below their natural equilibrium (Brander, 2015). Second, 'natural regeneration' double counts carbon emissions if results of several, independent, LCA studies are summed over time (Brander, 2015; Soimakallio et al., 2016). For example, if LCAs are conducted for consecutive periods of land

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[2] *Note: it is assumed that this is the correct interpretation of the reference situation by* Milà i Canals et al. (2007). Milà i Canals et al. (2007) *do not explicitly mention that the reference situation is different for occupation and transformation impacts, but in their separate examples of occupation and transformation, the reference situations are different.*

occupation, the sum of emissions found by these studies would be larger than the actual emissions[3]. However, ALCA should lead to additive results of all anthropogenic emissions (Chapter 5.1.1). Thus, natural regeneration is not consistent with ALCA.

There are also other reasons why the concept of natural relaxation or PNV can be challenged. Chiarucci et al. (2010) argue that "it is impossible to model PNV because of (i) the methodological problems associated to its definition and (ii) the issues related to the ecosystems dynamics". The PNV concept is challenged by multiple sciences: it is static, deterministic, relies on uncertain climate predictions and it does not include biological and vegetation dynamics (Chiarucci et al., 2010; Koponen et al., 2018). The authors argue that a change of paradigm is required to move from the unrealistic static concept of PNV to a more useful dynamic concept of vegetation. According to Othoniel et al. (2016), using PNV as a baseline leads to comparing the current situation with a hypothetical situation that may never happen. Thus, the obtained results with a PNV as reference situation represents how far the current state is from a natural state, instead of representing the measurable land use impact of the analysed system.

Several alternative reference situations are proposed in literature. Brander (2015) argues that a natural baseline is most suitable for ALCA. "A natural regeneration baseline represents the amount of sequestration that would occur if anthropogenic land occupation ceased, e.g. through the abandonment of agricultural land", whereas "a natural baseline represents the amount of sequestration that would occur if there had been no anthropogenic activities at all" (Brander, 2016). Othoniel et al. (2016) advocate to further explore the 'most recent available mix of land use', because it would "allow highlighting improvement strategies"; "avoid the consideration of ecosystems' regeneration", which is a source of sensible uncertainties (Brandão & Canals, 2013; De Baan et al., 2013; Saad et al., 2013); and it may be more interesting for decision makers to obtain information "based on a realistic situation than on a theoretical one" (Chaplin-Kramer et al., 2017; Koellner et al., 2013; Souza et al., 2015).

5.3.1.3 Current application of reference situations in literature

Soimakallio et al. (2015) have performed a literature review and found four different types of baselines used by ALCA studies: 1) zero baseline; 2) business as usual; 3) natural or quasi-natural steady state; 4) natural regeneration or PNV. The vast majority of studies have not explicitly applied or proposed a baseline (Soimakallio et al., 2015). Soimakallio et al. (2015) found that while many methodological studies have adopted the guideline for natural regeneration by Milà i Canals et al. (2007) in their recommendations, only few studies have actually applied the natural regeneration as a reference (e.g., Milà i Canals et al., 2013). Of all possible reference scenarios mentioned by UNEP-SETAC, so far only the PNV has been used in LCA research (Cao et al., 2017; Souza et al., 2015), while this is not always the most relevant reference situation based on the LCA scope (Chiarucci et al., 2010; Othoniel et al., 2016; Souza et al., 2015; Teixeira, 2014). Thus, there is a discrepancy between methodological recommendations and practical applications of a reference situation.

Even though the conclusions made by Soimakallio et al. (2015) about the suitability of certain reference situations for ALCA do not necessarily match the conclusions made within this thesis, their findings are beneficial because they show that the majority of the studies in their literature review do not use the recommended natural regeneration reference situation and most studies do not even explicitly mention which reference situation they used. These findings are important, because the choice of reference situation highly influences the result of a comparative LCA study. Cao et al. (2017) found that the choice of reference can invert rankings and conclusions in comparative LCA studies. Koponen et al. (2018) has created a visual representation of the effect that the choice of a different reference situation has on the

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[3] *Note: the emissions found in the UNEP-SETAC framework would always be larger than the actual emissions, because factually emissions are zero under the assumption that land quality remains constant over time during occupation (Chapter 5.2.1).*

quantification of impacts (Figure 5.7). This shows how important it is that there is consensus in choosing a reference situation and that the used reference situation is explicitly mentioned and substantiated.

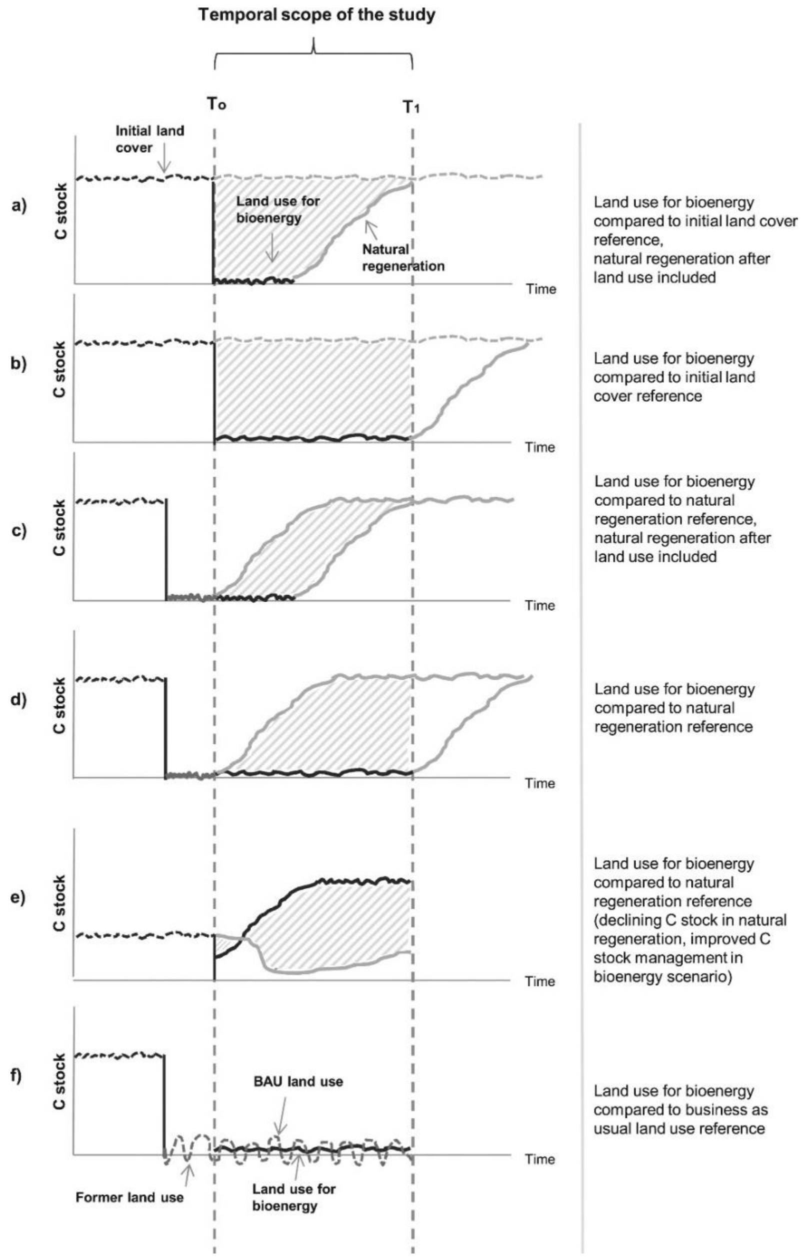

Figure 5.7. The effect of various reference situations in different bioenergy cases (reproduced from Koponen et al., 2018).

After the literature review by Soimakallio et al. (2015) showed that there was no consensus in application and guidelines for reference situations, new studies (e.g., Cao et al., 2017; Koponen et al., 2018) were published that proposed new types of reference situations and/or decision trees to unify the decision process for choosing a reference situation. It can be debated whether these kinds of decision trees that propose to use many different kinds of reference situations in different types of LCA studies (by means of complicated decision trees) are beneficial in creating consistency among LCA practitioners regarding the chosen reference situation. Koponen et al. (2018) reason that "because large uncertainties surround reference situations, and these counterfactual scenarios have a decisive influence on the calculation of climate effects of a bioenergy system, several alternative reference scenarios may be considered".

However, this is a contradictory conclusion: instead, because the choice of reference situation highly influences the results in (comparative) LCA studies (Cao et al., 2017), the community should aim for fewer choices and more consistency. Therefore, we argue for a simplification of the reference situation, instead of expanding on suitable options and decisions.

5.3.2 Amortization period and method

An amortization period is needed to attribute the total impact of transformation to an agricultural product that was produced on that land after the transformation happened. Thus, amortization is an accounting solution that is needed to attribute transformation impacts to products that have been cultivated in the years after transformation. However, it is impossible to know for how long in the future the land will be used for cropland cultivation. Therefore, it needs to be determined over which period (until which year of production after transformation) emissions will be attributed, and this is a difficult debate.

An example is presented here to elucidate the difficult debate regarding the amortization period and method. A Brazilian rainforest was transformed to cropland in 1990, to cultivate soybean. Thus, one can argue that the soybean cultivation in 1991 should be attributed some of the emissions due to the transformation in 1990. However, it can be debated how long a product should be held accountable for the emissions that happened in the past. Is soybean cultivation in 2005 still responsible for the transformation in 1990, and what about soybean cultivation in 2024?

Currently, a 20-year amortization period is standardized, this means that soybean cultivation in 1991 and 2005 are attributed emissions of the land transformation in 1990, but soybean cultivation in 2024 is not. A 20-year amortization period is the standard amortization period in both the UNEP-SETAC framework and other international carbon footprinting (CFP) methods for LULUC GHG emissions (Appendix I). The scientific basis for choosing 20 years is that 20 years corresponds to the time it takes for the carbon stock achieve a new balance after an impact (also called the transition period) (IPCC, 2006) (Figure 5.8a). However, in the UNEP-SETAC framework, the transition period is neglected, because they make the simplified assumption that land transformation impacts do not have a time component, but instantly reach their final state after the transformation (Figure 5.8b).

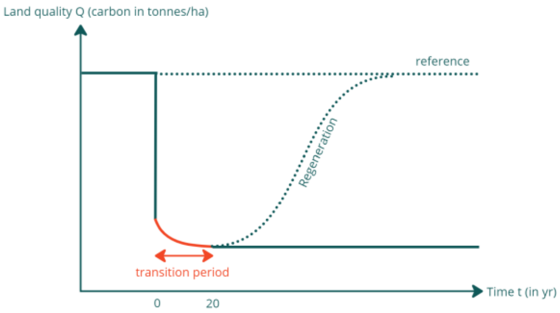

Figure 5.8a. The transition period is highlighted in read, which is currently not included in the UNEP-SETAC framework.

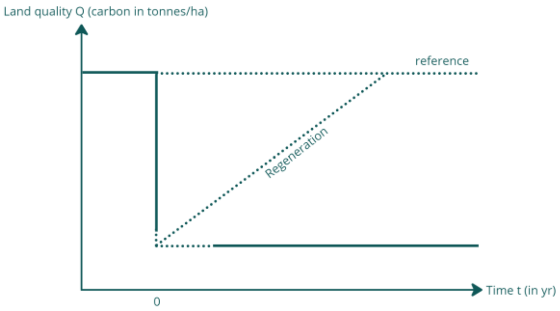

Figure 5.8b. The transition period is neglected in the UNEP-SETAC framework, because it is assumed that the quality reaches its final state instantly, without a time component.

Another way of choosing an amortization period would be to amortize the impacts based on the time that the land transformation had an impact on the environment. According to Koellner et al. (2013), setting the amortization period equal to the regeneration time would be a suitable alternative of the 20-year amortization time. By means of consequential reasoning, one could argue that if the land was left abandoned after the transformation, the environmental impact would be restored after the regeneration time (Figure 5.9). However, this is an 'what-if' scenario because the carbon would only be in the air for the regeneration time if the land was left to regenerate, which is an unlikely alternative scenario.

Additionally, regeneration times are highly uncertain (Chapter 5.2.3) and using the regeneration time as the amortization period would create differences in amortization periods between products from different LUC types. If these differences are based on highly uncertain values, it affects the robustness of the analysis. Therefore, it can be argued that the regeneration time is not a suitable amortization period for an ALCA study.

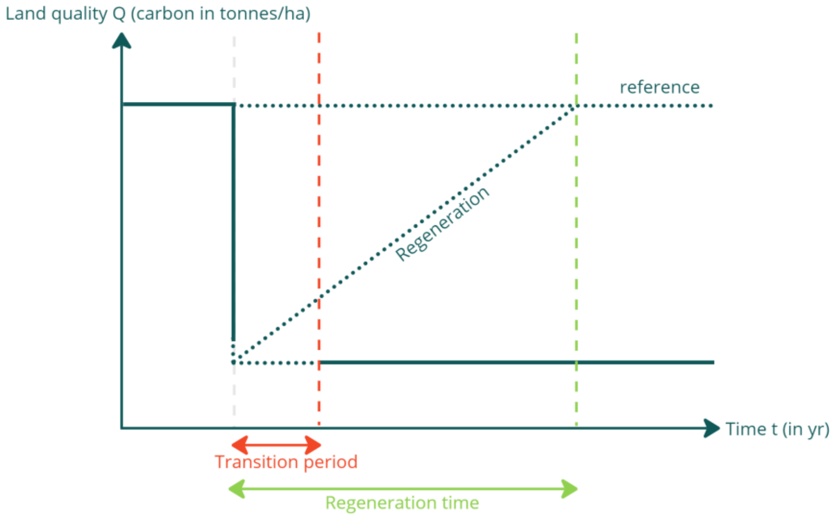

Figure 5.9. Amortization period equal to the regeneration time (green), instead of an amortization period equal to the transition period (red).

Milà i Canals et al. (2007) and Koellner et al. (2013) did not mention it explicitly, but they apply an equal amortization method, which means that the impacts are equally distributed over the production within the amortization period. Consequently, there is a large difference between the emissions attributed to the cultivated product in year 20 after the transformation (5% of transformation emissions attributed) versus the cultivated product in year 20 after the transformation (0%) (Appendix I).

5.4 The Climate Regulation Potential (CRP) by Müller-Wenk & Brandão (2010)

5.4.1 Confusion about the definition of CRP

It seems that there is no clarity in scientific literature about the definition of CRP. Koellner et al. (2013) define the CRP as the capacity of ecosystems to uptake carbon from air (in the topsoil and land cover), where the indicator is the carbon flow (in tonnes.year/m^2) change due to land use. However, Koellner et al. (2013) also refer to the framework by Müller-Wenk & Brandão (2010) as the carbon sequestration potential (CSP). In contrast, Milà i Canals et al. (2013) define the CRP as forgone sequestration in above and below ground biomass, expressed in 'kg C transferred to air'. Thus, there is a lot of confusion about what the CRP is. In the next paragraphs, only the original content of Müller-Wenk & Brandão (2010) has been evaluated.

5.4.2 Differentiating between fossil and biogenic carbon

The basis of the CRP framework is the differentiation that the authors make between fossil carbon and biogenic carbon. According to Müller-Wenk & Brandão (2010), fossil carbon follows the Bern carbon cycle, and has an average residence time of 157 years in the atmosphere. In contrast, they assume that biogenic carbon does not follow the Bern carbon cycle. They reason that a particular biogenic CO_2 molecule that enters the atmosphere due to transformation, stays in the atmosphere for the average regeneration time, and subsequently that particular biogenic CO_2 molecule is sequestered again in the land. The residence time of a biogenic CO_2 molecule originating from land transformation is equal to the average regeneration time. They argue that one year of occupation is responsible for a biogenic CO_2 molecule to be one year longer in the atmosphere, and therefore they argue that the residence time of a biogenic CO_2 originating from occupation is equal to one year.

The authors argue that due to the difference in residence time of fossil carbon (157 year), biogenic transformation carbon (0.5*regeneration time) and biogenic occupation carbon (1 year), "1 ton of carbon from any case of land use may cause a different global warming effect than 1 ton of carbon from fossil combustion". They reason that it is hence justified to discount a biogenic carbon emission based on the lower climatic impact of biogenic carbon compared to fossil carbon (Müller-Wenk & Brandão, 2010).

There are multiple reasons why it cannot be argued that biogenic and fossil carbon have a different residence time in the atmosphere. First, natural processes do not make a distinction between fossil CO_2 and biogenic CO_2. Both CO_2 molecules are sequestered completely equally, because they are the exactly the same molecule. Thus, biogenic CO_2 is not sequestered faster by biological processes than fossil CO_2. Second, it cannot be said that biogenic carbon does not follow the Bern carbon cycle and that biogenic carbon sequestration happens faster than the Bern carbon cycle. The terrestrial carbon cycle is part of the Bern carbon cycle, thus sequestering biogenic carbon happens through the terrestrial carbon cycle of the Bern carbon cycle. The authors also argue that biogenic carbon should never have a duration factor higher than 1, "because carbon from destruction of vegetation with slow regeneration can always leave the atmosphere through the 'dissipative' outflow path towards the oceans and the continents". According to the authors, "carbon from land use can be less damaging, but not worse than carbon from fossil combustion". These statements are not correct, because both biogenic CO_2 and fossil CO_2 are the same molecule, thus one is not worse for the environment than the other and both leave the atmosphere through the biologic processes on the earth that are incorporated in the Bern carbon cycle. Further, the assumption that the residence time for CO_2 originating from transformation is dependent on the regeneration time of the transformation type (e.g., from tropical forest to cropland, or from grassland to cropland) is also faulty. This is not true because biological processes are not dependent on where the CO_2 molecule originates from. Thus, the distinction that Müller-Wenk & Brandão (2010) make between fossil and biogenic carbon, is currently purely made based on value choices and not based on science.

5.4.3 Cut-off at 500 years

Müller-Wenk & Brandão (2010) propose 500 years, because a cut-off at 100 years would lead to an average residence time in the atmosphere of 47.5 years, which would "be too short, unduly favouring carbon from fossil combustion". "Favouring" is a value judgement, which is not a good foundation for choosing a cut-off. Thus, choosing 500 years is a rather arbitrary value choice (Liptow et al., 2018). Additionally, it is inconsistent with the global warming indicator, where GWP100 uses a 100-year time horizon.

5.4.4 Calculating CRP based on the carbon transfer

Müller-Wenk & Brandão (2010) multiply the duration factor with the carbon transfer. The carbon transfer is the measurable carbon that was transferred from the land to the atmosphere due to the land transformation. There are two main issues with calculating the CRP based on the carbon transfer.

The carbon transfer is inconsistent with the UNEP-SETAC framework (Figure 5.10). In the UNEP-SETAC framework, the impact of transformation is the difference between the quality after transformation and the quality of the reference situation: the quasi-natural land cover (Koellner et al., 2013). In contrast, in the CRP framework, the carbon transfer is the measurable impact which is calculated as the difference between the quality after transformation and the quality before transformation.

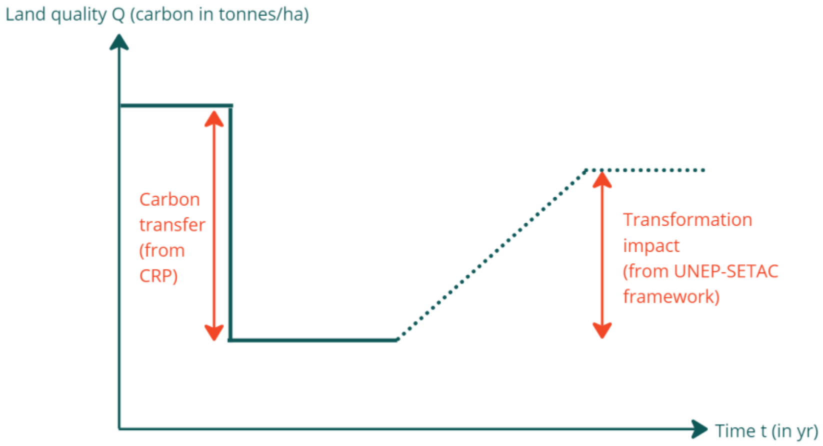

Figure 5.10. The difference in quantifying the transformation impact of the CRP framework versus the UNEP-SETAC framework.

Type of land use (biome of tropical forests)	t C per hectare transferred to air by the transformation	Duration factor (df)	Fossil-combustion-equivalent ton C per hectare transferred to air (Ceq)
Transformation forest to cropland	150.75	31/157=0.20	30.2
Occupation as cropland 1 year	150.75	1/157=0.0064	0.96
Transformation forest to pastureland	120	32.5/157=0.21	25.2
Occupation as pastureland 1 year	120	1/157=0.0064	0.77
Transformation forest to artificial land	150.75	56/157=0.36	54.3
Occupation as artificial land 1 year	150.75	1/157=0.0064	0.96

Table 5.1. Example calculation by Müller-Wenk & Brandão (2010) for the biome of tropical forests.

The CRP framework uses the same carbon transfer (due to transformation) to calculate both the CRP for land transformation and occupation. For example, in Table 5.1, the carbon transfer from transformation from tropical forest to cropland equals 150.75 tonnes carbon per hectare and the occupation carbon transfer thus also equals 150.75 tonnes carbon per hectare. However, it is counterintuitive that they multiple the duration factor of ‘1/157’ for 1 year of occupation with the total transformation impact. This means that one year of occupation is responsible for the delay of the regeneration of the complete regeneration impact. However, during that 1 occupation year, only 1 year could have been used to sequester carbon during regeneration. It would make more sense if the carbon transfer of occupation would be quantified as one year of occupation, divided by the relaxation time, and multiplied with the carbon transfer.

5.4.5 Converting kg CO_2.year to kg CO_2-eq via the Bern carbon cycle

Instead of using the CRP framework to convert carbon in the unit ‘kg.year’ to kg CO_2-eq, it is also possible to directly convert the unit by using the Bern carbon cycle. In Chapter 4.11 was explained that the average residence time of a CO2 unit pulse is 157 years, at a cut-off of 500 years. This means, that at a cut-off of 500 years, the surface under the graph in the Bern carbon cycle is 157 years (yellow surface in Figure 5.11). This is similar to 1 unit of CO2 that is in the air for 157 years and disappears afterwards (blue surface in Figure 5.11). It can be assumed that weight and time are substitutable, i.e., 1 kg of CO_2 for 2 years is equal to 2 kg CO_2 for 1 year. Thus, 1 kg CO_2 for 157 years is equal to 157 kg CO_2 for 1 year (red surface in Figure 5.11). Thus, to convert ‘kg CO_2.year’ to ‘kg CO_2-eq’, the carbon amount in ‘kg.year’ can be divided by 157. In Chapter 7, it is shown that using this method versus the CRP method both lead to the same outcome (if the same transformation impact value is used).

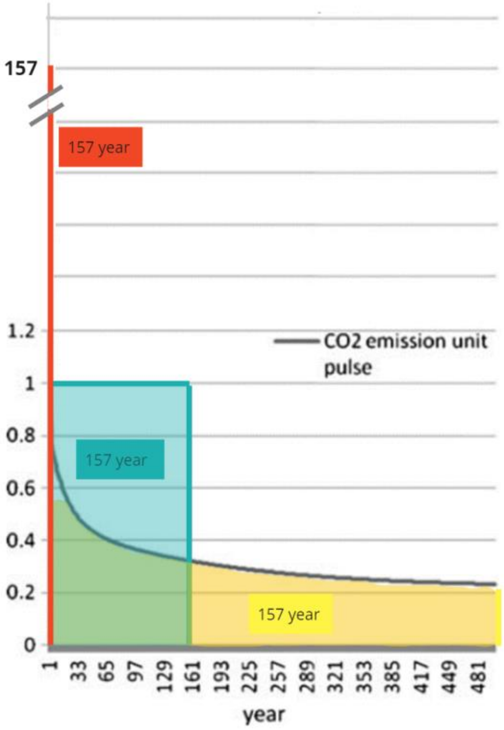

Figure 5.11. Residence time of 1 pulse CO_2 is 157 years for a cut-off at 500 years for the Bern carbon cycle.

6. Proposal for an improved conceptual framework

In this chapter, an improved conceptual framework for quantifying LULUC GHG impacts in LCA is proposed.

6.1 Improving the weaknesses of the UNEP-SETAC framework

It can be concluded from Chapter 5 that there are multiple weaknesses of the framework that need to be resolved. The main weakness of the UNEP-SETAC framework is the mix between ALCA and CLCA. If a framework can be used for both ALCA and CLCA, it should be in line with both modes separately, and not mix the characteristics of the two methods. ALCA should lead to additive results of all anthropogenic emissions, relative to a pre-anthropogenic baseline. There should be no double counting or discounting of emissions, which can be achieved by only including measurable emissions relative to a pre-anthropogenic baseline. In CLCA, emissions could be double counted due to overlapping system boundaries and because emissions are quantified relative to an alternative system.

There are also areas of improvements that are independent of the CLCA vs ALCA mode discussion. First, the impact of GHG emissions is not dependent on the origin of the CO_2 molecule, because the atmosphere does not make a distinction between CO_2 originating from fossil carbon, temporary biogenic carbon or permanent biogenic carbon. Second, time and quality impacts are different and should not be aggregated. Third, arbitrary value choices (e.g., modelling period, amortization period and method, reference situation) should be limited, standardized, and based on science. Fourth, quantifying impacts in carbon tonnes.year adds unnecessary complexity.

6.2 The improved conceptual framework for ALCA

In this subchapter, the improved conceptual framework will be explained for an ALCA study. The framework is improved based on the weaknesses that were found in the UNEP-SETAC framework. The framework is explained step by step in the next paragraphs, by means of a hypothetical land use situation.

6.2.1 Step 1: categorization of land use in periods

The first step to quantify LULUC GHG emissions is to divide the use of land in periods (Figure 6.1). Periods are divided based on the function and/or the owner of the land. Every period has a start and end. Both the start and end have a quality (Q) and a time (t), thus each period has a ΔQ and a Δt.

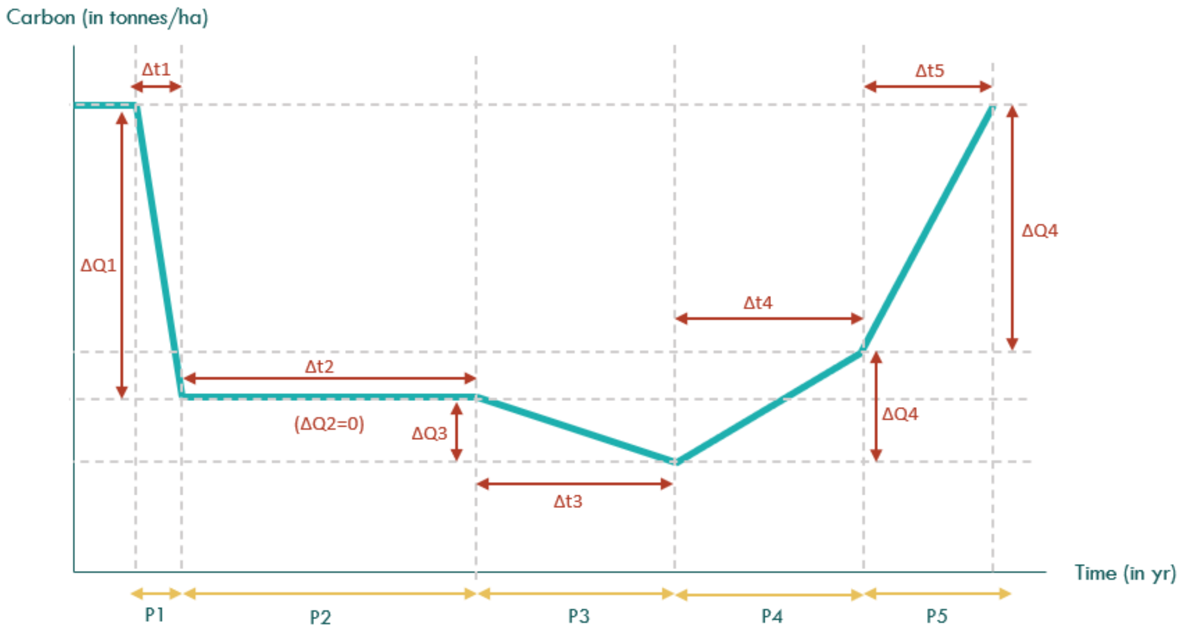

Figure 6.1. Dividing the land use in periods.

For each period, the type of land use should be determined: transformation, occupation, or land abandonment. In a transformation period, the main goal of the period is to change the land use type, e.g., deforestation or reforestation. In an occupation period, the main goal of the period is to use the land for the cultivation of a product that is related to the FU of the LCA study. In a land abandonment period, the land is not used for any purpose. Figure 6.2 shows an example of categorizing land use periods.

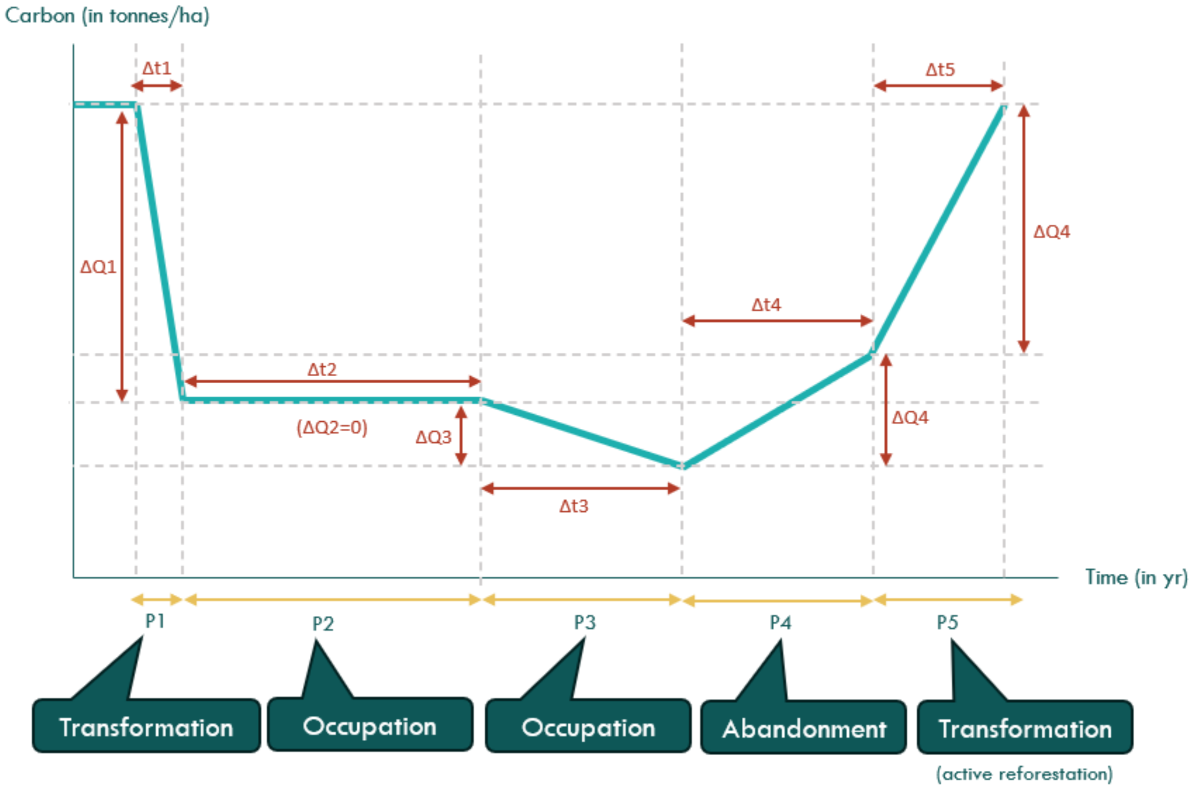

Figure 6.2. Categorizing the land use periods.

6.2.2 Step 2: quantify transformation impacts

In step 2, the transformation impacts should be quantified. First, it should be determined whether the year of cultivation of the agricultural product under study falls within the amortization period.

An amortization period is needed to attribute the total impact of transformation to an agricultural product that was produced on that land after the transformation happened. Thus, amortization is an accounting solution that is needed to attribute transformation impacts to products that have been cultivated in the years after transformation. However, it is impossible to know for how long in the future the land will be used for cropland cultivation. Therefore, it needs to be determined over which period (until which year of production after transformation) emissions will be attributed. In this framework, it has been chosen to base the amortization period on the time that the land transformation had an impact on the environment. In the context of GHG emissions, it can be argued that the impact of land transformation lasts for the average residence time of a CO_2 molecule in the atmosphere. The average residence time of a CO_2 pulse in the atmosphere can be determined based on the Bern carbon cycle (Chapter 4.11). It has been chosen to use a cut-off of 100 years for the Bern carbon cycle, because that is also the cut-off that is used for the GWP100. A cut-off of 100 years, results in an average residence time of 47.5 year (Chapter 5.4.3). For practical implementation, 47.5 year is rounded up above to a 50-year amortization period.

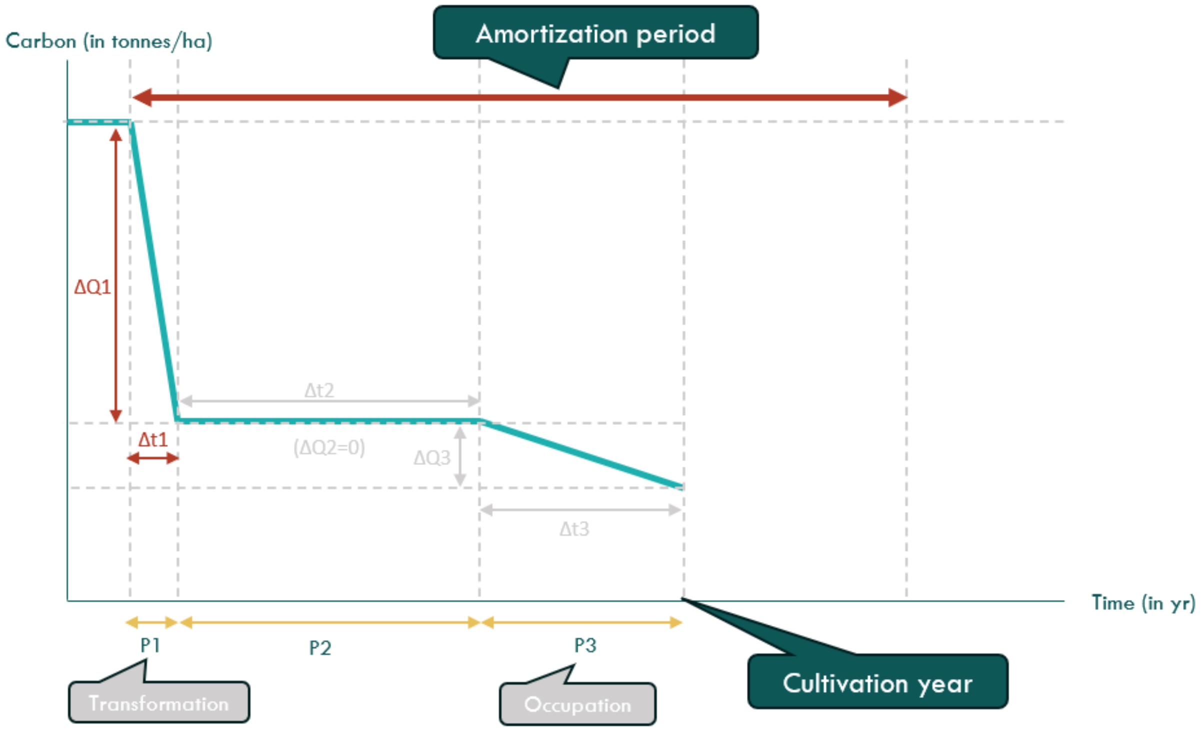

Figure 6.3. Determining if the year of cultivation (at the end of period 3) falls within the amortization period.

The year of cultivation is the end of period 3 (P3) (Figure 6.3). In this example, the year of cultivation falls within the amortization period (Figure 6.3). This means that a part of the transformation impact of period 1 should be attributed to the studied product in period 3. The transformation quality impact is calculated by: $\Delta Q = Q_{end.period} - Q_{begin.period}$. The transformation time impact is calculated by $\Delta t = t_{end.period} - t_{begin.period}$. Thus the transformation impact of period 1 is $\Delta Q1$ and $\Delta t1$ (Figure 6.3).

As amortization method, it has been chosen to use linear amortization, because it allows for a smoother transition (compared to equal amortization) of allocated emissions of the last year within the amortization period compared the first year outside of the amortization period.

The quality and time impacts of period 1 are linearly attributed to the studied product in the cultivation year in period 3. Linear amortization starts at the start of the first occupation period after the transformation period and ends at the end of the amortization period. The reader is referred to ESM sheet 6 for the attributed percentages of land transformation for each year within the amortization period of 50 years for a linear amortization method.

In this framework, sequestration activities are calculated as transformation impacts ('ΔQ=Qend.period – Qbegin.period') and they are equally allocated to the owner of the land during the transformation period. One can debate whether sequestration should be claimed by humans. It can be argued that regeneration is a natural process that should not belong in ALCA. However, Brander (2015) argues that sequestration only exists because anthropogenic LUC has reduced terrestrial carbon stocks below their equilibrium level. Therefore, we argue that sequestration activities should be included in ALCA, relative to a pre-anthropogenic baseline, to enable a complete mass balance of carbon.

6.2.3 Step 3: quantifying the occupation impact

The year of cultivation falls within an occupation period. Like a land transformation impact, an occupation quality impact is calculated by 'ΔQ=Qend.period – Qbegin.period' and an occupation time impact is calculated by 'Δt=tend.period – tbegin.period'. Thus the total occupation impact of period 3 is ΔQ3 and Δt3 (Figure 6.4). The occupation impacts are equally amortized over the occupation time, thus the occupation time impact is 1 year (Δt/Δt) and the occupation quality impact is ΔQ/Δt.

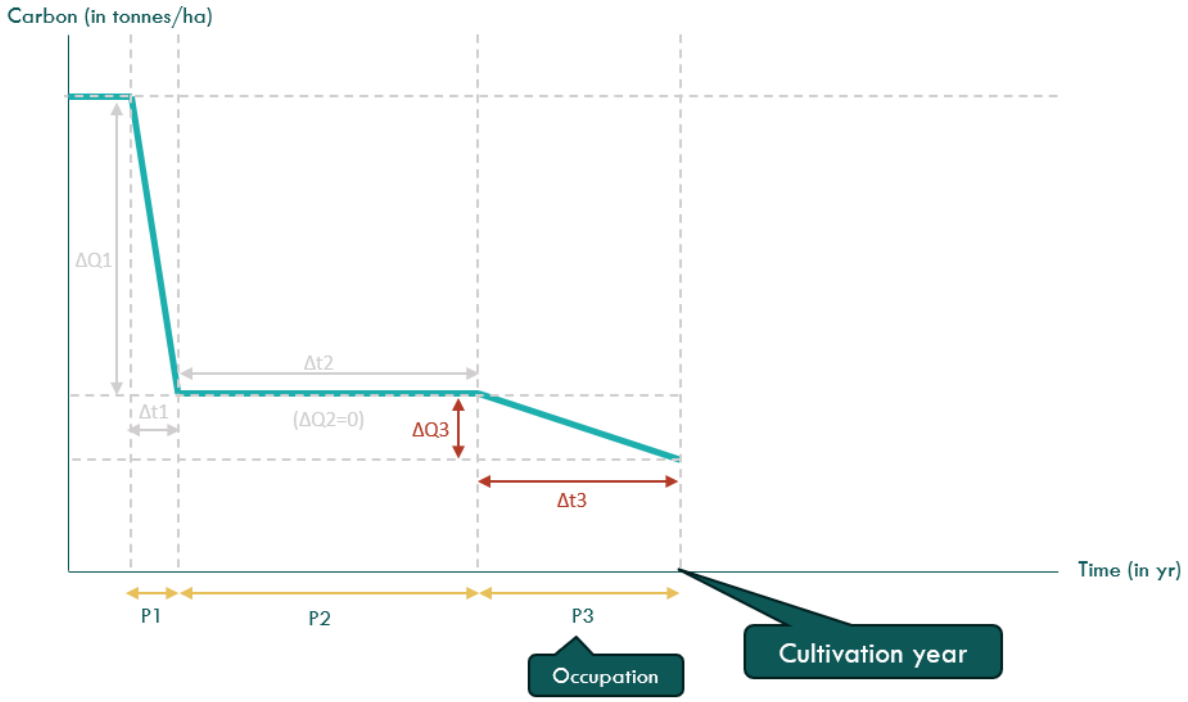

Figure 6.4. Determining the occupation impacts of period 3.

6.2.4 Optional Step 3b for CLCA: forgone sequestration

In this framework, the option to include forgone sequestration has been added, which is only suitable for application within a CLCA study. The forgone sequestration quantifies the impact of using the land for the FU, relative to abandoning the land and letting it regenerate.

In literature, definitions and calculations of forgone sequestration vary (e.g., Koponen & Soimakallio, 2015; Schmidinger & Stehfest, 2012), but for this framework the definition and calculation of Brander (2016) will be followed. Brander (2016) argues that forgone sequestration is calculated by subtracting the level of sequestration in the reference situation from the amount of sequestration in the studied system. This method is explained in Textbox 6.1.

Textbox 6.1

Brander (2016) has explained the concept of foregone sequestration by means of the following example. Before transformation, 1 ha of land sequesters 1 tCO_2/year indefinitely. Due to transformation, the land loses 100 tCO_2. The studied system is occupation, thus it does not sequester CO_2. If land was abandoned, it would sequester 5 tCO_2/year for 20 years (until it regenerates the lost 100 tCO_2). After those 20 years, it would sequester 1 tCO_2/year indefinitely again. Brander (2016) quantifies the forgone sequestration by subtracting the level of sequestration in the reference situation from the amount of sequestration in the studied system:

Forgone sequestration = sequestration in studied system – sequestration in reference situation

If the chosen reference situation is natural relaxation (land abandonment), the studied system is occupation, and the time horizon is 20 years, then the forgone sequestration is:

$0\ tCO_2/yr * 20\ yr - 5\ tCO_2/yr * 20\ yr = -100\ tCO_2$

and if the chosen reference situation is natural baseline (before transformation), the studied system is occupation, and the time horizon is 20 years, then the forgone sequestration is:

$0\ tCO_2/yr * 20\ yr - 1\ tCO_2/yr * 20\ yr = -20\ tCO_2$

where sequestration is represented as a positive number, and so foregone sequestration is represented by a negative number, which means a loss of sequestration.

Thus, in the example, sequestration of the studied system is '$-\Delta Q3$' and the sequestration of the reference situation is '$\Delta Q3.ref$'. Thus, the forgone sequestration is '$-\Delta Q3 - \Delta Q3.ref$' (Figure 6.5). Like normal occupation impacts, the forgone is equally amortized over the occupation period: 'forgone sequestration period 3 / $\Delta t3$'.

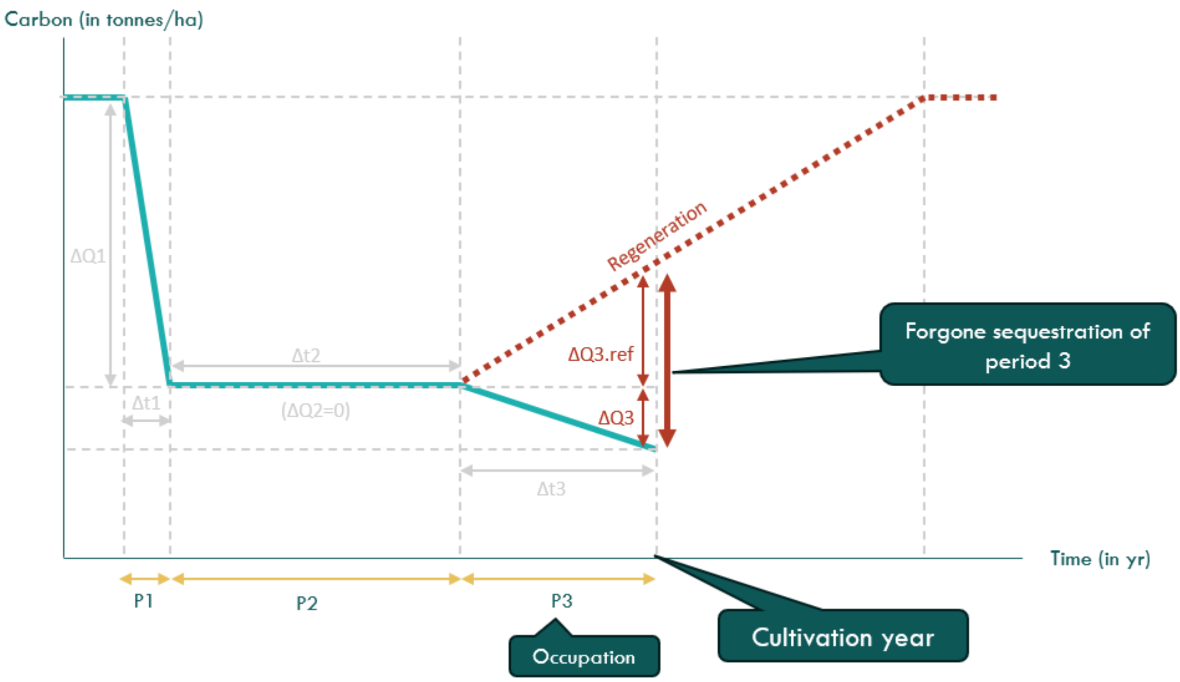

Figure 6.5. Determining the forgone sequestration in CLCA for period 3.

6.3 Benefits of the improved conceptual framework

The improved conceptual framework offers several benefits compared to the UNEP-SETAC framework:

- Only (and all) measurable impacts are included in the inventory;
- No predictions of future land use are necessary to calculate impacts;
- There is no discussion anymore about the reference situation, because impacts are calculated based on the characteristics at the end of the period relative to the characteristics at the start of the period;
- Transformation impacts are not discounted based on hypothetical future land regeneration;
- Modelling periods have become obsolete, because there is no distinction between permanent and temporary land use impacts;
- For CLCA, it is still possible to quantify the impact of the studied system compared to an alternative situation to indicate the indirect effects of occupation.

7. LULUC case study

In this chapter, the improved conceptual framework will be demonstrated in a comparative case study about palm oil production in Indonesia and sunflower oil production in France. The results of the improved conceptual framework will be compared with the UNEP-SETAC framework and other carbon footprinting (CFP) standards.

7.1.1 Scenarios and data collection

The goal of the hypothetical case study is to illustrate how the improved conceptual framework (proposed in Chapter 6) performs in a comparative case study, compared to the UNEP-SETAC framework and CFP standards.

In the case study, the LULUC GHG emissions of sunflower seed cultivation in France were compared with the LULUC GHG emissions of palm oil fruit cultivation in Indonesia. Palm oil is the most consumed oil worldwide and Indonesia is its largest producer (Absalome et al., 2020). However, palm oil is subject of controversy because it is associated with declining biodiversity and deforestation (Absalome et al., 2020). Sunflower oil is regarded as a healthy and more sustainable alternative of palm oil (Anushree et al., 2017). France is one of the leading countries for the production and development of sunflower oil as an alternative for palm oil (Anushree et al., 2017).

In terms of LULUC characteristics, both cases are very different. Forests in Europe were mostly deforested before the industrial revolution (Kaplan et al., 2009), while deforestation for palm oil production in Indonesia peaked in 2009 (Austin et al., 2019). While sunflower oil might be perceived more sustainable because it does not add to recent deforestation, palm oil has a much higher yield per hectare (FAOSTAT, 2020) and because it is a perennial crop, the vegetation adds an additional 60 tonnes C/ha to the land. Additionally, the carbon content of the potential natural vegetation in France is believed to be much lower than in Indonesia (Searchinger et al., 2018). The different characteristics of the two crops and the fact that they are used as alternatives, make it an interesting case study to test the outcomes of different frameworks.

The functional unit for which the two alternatives were compared is ‘1 kg of crude oil cultivated in 2020’. It is assumed that 1 kg of palm oil can be substituted by 1 kg of sunflower oil in food products. Details of the data collection can be found in the ESM sheet 2. Data for the carbon in vegetation and in soil have been collected from the FAO Global Forest Resource Assessment (FRA) 2020 and from the IPCC. Data for the cultivation of the crops have been collected from FAOSTAT.

This case study aims to illustrate the main findings of this thesis. This case study is not conducted to obtain an accurate measure of LUC GHG, but rather demonstrating how different frameworks work, so simplifications have been made. It has been chosen to not include the impact of management activities on LULUC emissions, as management activities are not within the scope of this thesis.

7.1.2 Modelling

The two alternatives are compared with each other by means of 5 different frameworks for calculating LULUC GHG emissions.

The first framework is the UNEP-SETAC framework (Koellner et al., 2013) combined with the Bern carbon cycle. The results of the UNEP-SETAC framework in carbon tonnes.year are converted to tonnes CO_2-eq by means of the Bern carbon cycle (Chapter 5.4.5). The second framework is the CRP method by Müller-Wenk & Brandão (2010), which is based on the UNEP-SETAC framework (Chapter 4.11). The third framework is the improved conceptual framework proposed in this thesis.

The fourth and the fifth framework are two CFP standards: the PAS 2050 and the Forest Land use and Agriculture Guidance (FLAG). CFP is defined as calculating the “sum of greenhouse gas emissions and removals in a product system expressed as CO_2-eq (ISO TS 14067). CFP is based on LCA, but only calculates impacts for the climate change impact category (Finkbeiner, 2014). It has been chosen to compare the UNEP-SETAC framework, the CRP framework and the improved conceptual method with these CFP standards, because these CFP methods seem to be much more frequently used by LCA practitioners and companies than the UNEP-SETAC framework. The PAS 2050 is widely used in Europe and the FLAG is required for companies that follow the Science Based Target initiative (SBTi). More information regarding these CFP standards and a textual comparison of the frameworks can be found in Appendix I.

Table 7.1 provides an overview of the methodological choices in each of the abovementioned frameworks. The formulas that are followed for each framework to calculate the LULUC GHG emissions per alternative can be found in the ESM sheet 4.

Table 7.1. Overview of methodological choices in the five frameworks used for the illustrative case study.

Methodological choices	UNEP-SETAC	CRP	Improved conceptual framework	PAS 2050	FLAG
LUC Amortization method	Equal	Equal	Linear	Equal	Linear
LUC amortization period	20 years	20 years	50 years	20 years	20 years
Assuming future land regeneration	Yes	Yes	No	No	No
Transformation impacts calculated relative to	PNV	Previous land quality (measurable carbon transfer)	Previous land quality (measurable carbon transfer)	Previous land quality (measurable carbon transfer)	Previous land quality (measurable carbon transfer)
Measurable occupation impacts	No	No	Yes, calculated relative to previous quality	No	No
Forgone sequestration due to occupation	Yes, calculated relative to PNV	Yes, calculated relative to previous land quality (measurable carbon transfer)	Yes, calculated relative to PNV	No	No

7.1.3 Results

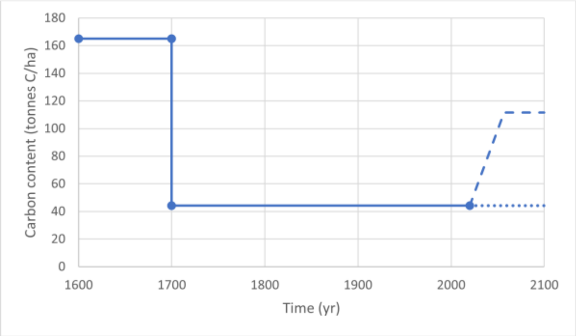

Figure 7.1a. The carbon content on a parcel of land for sunflower cultivation in France.

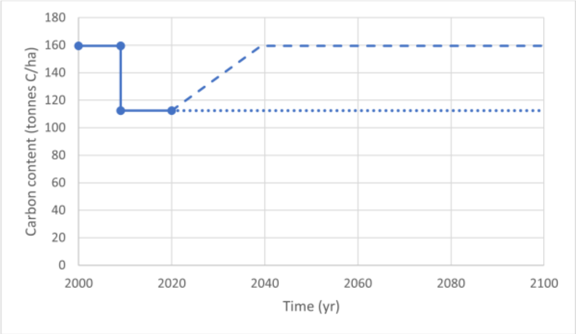

Figure 7.1b. The carbon content on a parcel of land for palm oil fruit cultivation in Indonesia.

The solid line represents the factual carbon content over time. The dashed line represents the hypothetical future assumed by Koellner et al (2013), while the dotted line represents the assumed future by the improved conceptual framework.

Figure 7.1a and 7.1b show the carbon content of the land (in tonnes C/ha) over time for each scenario. For sunflower cultivation in France, the carbon content of the land was 163 tonnes C/ha, which decreased due to deforestation in 1700 to 44 tonnes C/ha. For palm oil fruit cultivation in Indonesia, the carbon content of the land was 160 tonnes C/ha, which decreased to 113 tonnes C/ha due to deforestation in 2009.

Figure 7.2 shows the LULUC GHG emissions for both alternatives calculated for the 5 LULUC frameworks. When using the UNEP-SETAC framework, 1 kg of sunflower oil causes 3.46 kg CO_2-eq emissions (from occupation) and 1 kg of palm oil causes 0.472 kg CO_2-eq emissions (0.153 kg CO_2-eq from transformation and 0.319 kg CO_2-eq from occupation). When using the CRP framework, 1 kg of sunflower oil causes 6.20 kg CO_2-eq emissions (from occupation) and 1 kg of palm oil causes 0.472 kg CO_2-eq emissions (0.153 kg CO_2-eq from transformation and 0.319 kg CO_2-eq from occupation). When using the improved conceptual framework, 1 kg of sunflower oil causes 0 kg CO_2-eq emissions and has a forgone sequestration -14.7 kg CO_2 emissions and 1 kg of palm oil causes 1.57 kg CO_2-eq emissions (from transformation) and has a forgone sequestration of -2.61 kg CO_2-eq emissions. When using the PAS 2050, 1 kg of sunflower oil causes 0 kg of CO_2 emissions and 1 kg of palm oil causes 2.50 kg CO_2 emissions (from transformation). When using the FLAG, 1 kg of sunflower oil causes 0 kg of CO_2 emissions and 1 kg of palm oil causes 2.38 kg CO_2 emissions (from transformation).

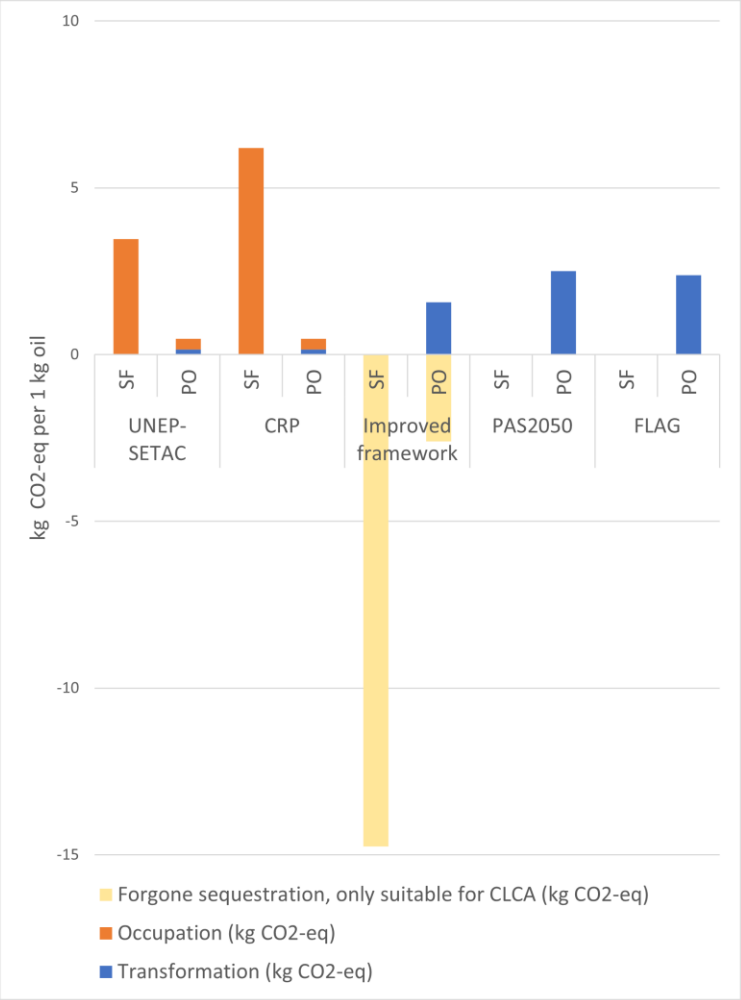

Figure 7.2. The impact of LULUC activities for 1 kg of sunflower oil (SF) or palm oil (PO), expressed in kg CO_2-eq, calculated by 5 different methods.

7.1.4 Discussion

Both the UNEP-SETAC framework and the CRP framework have resulted in the same transformation impacts for sunflower oil (0 kg CO_2-eq, because LUC happened more than 20 years ago) and palm oil (0.153 kg CO_2-eq). However, the frameworks calculate LUC transformation impact differently because the UNEP-SETAC framework the PNV as reference situation (difference between the PNV and the quality after LUC), while the CRP framework takes the quality before LUC as a reference situation (the difference between the quality before LUC and the quality after LUC) (Chapter 5.4). However, for palm oil the quality before LUC and the PNV quality are assumed to be the same and hence the methods lead to the same results for palm oil. For occupation impact, the frameworks lead to different results for sunflower oil, but the same result for palm oil. The difference is again caused by the difference in reference situation: the UNEP-SETAC framework uses the PNV as reference and the CRP framework the quality before LUC. For palm oil, both references are assumed to be the same, but for sunflower oil they are different. This is because it is believed that the ecosystems in Europe will never be able to return to their original state from centuries ago.

Both PAS 2050 and FLAG only quantify the measurable carbon transfer (from the quality before LUC to the quality after LUC), and do not quantity occupation impacts. Both only account for transformation impacts if the land use change happened within an amortization window of 20 years. The difference between them is that PAS 2050 requires equal amortization while FLAG requires linear amortization. However, in this situation the land use change for 1 kg of palm oil happened 11 years ago (2009, with reference to the yield in 2020), thus the difference in emission allocation is only small (0.05% for PAS 2050 and 0.0475% for FLAG). Differences in results would have been bigger if the LUC happened recently (more emission allocation with linear amortization) or later (more emission allocation with equal amortization).

In the basis, the improved conceptual framework is similar to the PAS 2050 and the FLAG, because they only inventory measurable impacts for ALCA studies. However, for the improved conceptual framework, a linear amortization period of 50 years. In this case, this leads to lower attributable emissions, because for palm oil the transformation happened only 11 years ago. The biggest difference between the CFP methods and the improved conceptual framework, is that the improved conceptual framework adds the possibility for CLCA to add forgone sequestration to the impact categories.

It is visible that the emissions for sunflower oil are much higher than palm oil in the UNEP-SETAC and the CRP framework. On the contrary, the improved conceptual framework, the PAS 2050 and the FLAG framework led to higher emissions for palm oil. This is mainly caused by the inclusion of occupation impacts in the UNEP-SETAC and the CRP framework. The occupation impacts of sunflower oil are higher than palm oil because the yield (kg/ha) is much lower for sunflower seeds and the difference between the carbon content of occupation compared to the reference situation is larger for sunflower oil. The improved conceptual framework, the PAS 2050 and the FLAG framework do not account for occupation impacts as factual emissions. Additionally, the UNEP-SETAC framework and the CRP framework discount the measurable transformation emissions based on hypothetical regeneration, thus the transformation impacts are quite small compared to the other frameworks.

The improved conceptual framework indicates that 1 kg of sunflower oil has the largest forgone sequestration. First, palm oil fruit (perennial crop) cultivation adds 60 tonnes C/ha to the land, while sunflower oil does not. The forgone sequestration is -47 tonnes C/ha for palm oil fruit while the forgone sequestration for sunflower seeds is -68 tonnes C/ha. Second, there is more land needed for 1 kg of sunflower oil. As a result, 1 kg of sunflower oil has a 566% larger forgone sequestration than 1 kg of palm oil.

7.1.5 Conclusion

The results of the case study illustrate the earlier findings in this thesis. The UNEP-SETAC and the CRP framework discount the transformation impacts based on hypothetical future regeneration, which results in a much lower transformation impact than other frameworks. The UNEP-SETAC and the CRP framework assign a large CO_2-eq impact to occupation impacts, even though they are not measurable, based on hypothesis that the land would have regenerated without the occupation. As a result, the UNEP-SETAC and the CRP framework lower impacts to the factual transformation impacts (thus LUC) and higher impacts to the hypothetical occupation impacts. Thus, when using the UNEP-SETAC and CRP framework, it can be concluded that the use of land for 1 kg of palm oil is more sustainable in terms of GHG emissions.

The CFP methods (PAS 2050 and FLAG framework) only assign transformation impacts to 1 kg of palm oil. Thus, when using the CFP methods, it can be concluded that the use of land for 1 kg of sunflower oil is more sustainable in terms of GHG emissions.

When using the improved conceptual framework, it can be concluded that the measurable impact of using 1 kg palm oil is higher than using 1 kg of sunflower oil. However, the forgone sequestration showed that if there is more production than demand, it is better to use palm oil and to regenerate the land that is used for sunflower seed cultivation.

The conclusions regarding the sustainability of the alternatives in each framework differ greatly. The results of this comparative case study illustrate that the choice of LULUC framework can invert the conclusions of LULUC GHG emissions between two alternatives. This shows that it is highly important that the academic community reaches consensus in using one type of framework and also determines which framework is suitable for LCA and creates most valid and reliable results.

8. Discussion & Recommendations

In the UNEP-SETAC framework, the LCA practitioner is provided with various methodological choices that should be taken based on the chosen LCA mode: ALCA or CLCA. However, this analysis showed that the UNEP-SETAC framework is largely based on consequential thinking, because emissions are calculated relative to alternative scenarios. A sum of all land transformation and occupation impacts, calculated by means of the UNEP-SETAC framework, does not equal to a sum of all measurable anthropogenic land transformation and occupation impacts in the world. Therefore, this analysis concluded that the UNEP-SETAC framework is not suitable in its current form for an ALCA study.

To advance method development, weaknesses of the UNEP-SETAC framework were resolved in an improved conceptual framework for LULUC impacts. The results of the comparative LCA case study, in which both the UNEP-SETAC framework and the improved framework were used, illustrated that the choice of LULUC framework can invert the conclusions of LULUC GHG emissions between two alternatives. The results of this study therefore indicate that the use of the UNEP-SETAC framework in a comparative ALCA study could lead to inverted results.

These results are the key findings of this study. However, there are several points that need to be discussed. In the following paragraphs, the implications, limitations and recommendations of the research will be elaborated.

8.1 Implications of the research

8.1.1 Implications for science

The goal of this master thesis was to advance the method development of LULUC frameworks that quantify LULUC GHG emissions of agricultural products in LCA studies. It was found that the most well-known framework in the scientific community for LULUC GHG emissions in LCA, the UNEP-SETAC framework, is not widely used in practice. One of the research objectives was to identify and evaluate the weaknesses of the UNEP-SETAC framework that might prevent it from being widely accepted and used in LCA studies. Existing literature had discussed several limitations of the UNEP-SETAC framework in relation to ecosystem services (Othoniel et al., 2016), however this is the first study that has evaluated the UNEP-SETAC framework in the context of GHG emissions. Brander (2015, 2016) had made some interesting observations about the confusion between CLCA and ALCA in choosing a land use baseline, however the criticism was not directed towards the UNEP-SETAC framework. This is the first study to recognize that the UNEP-SETAC framework is not suitable for an ALCA study in its current form. Based on these findings, it is highly recommended that the scientific community of LULUC in LCA looks beyond the UNEP-SETAC framework and further researches the possibilities for a new framework.

Another research objective was to propose an improved generalized LULUC GHG framework in LCA. The improved conceptual framework is novel, because it is the first LULUC GHG framework in LCA that can be used for both ALCA and CLCA. The improved framework is in line with both modes separately and does not mix the characteristics of the two methods. The basis of the framework is aligned with ALCA, and optionally, the forgone sequestration can be calculated for a CLCA study. Using this improved framework for ALCA studies leads to additive results of all measurable anthropogenic emissions, relative to a pre-anthropogenic baseline. And for CLCA, forgone sequestration can be quantified relative to the alternative system of land abandonment (if the agricultural product was not cultivated). In LULUC LCA literature, methodological choices for LCA practitioners within LULUC frameworks are abundant. The work within this thesis resists this trend, by arguing that more methodological choices lead to inconsistency and a lack of standardization. In the proposed framework, certain value choices have been made obsolete, such as the modelling period. Other arbitrary value choices (e.g., amortization period and method, and reference situation) have been standardized and based on science (where possible). It is hoped that this simplified LULUC GHG framework for LCA forms the starting point for further development of new frameworks that are aligned with the chosen LCA mode.

Despite the criticism regarding the UNEP-SETAC framework, it is acknowledged that great effort has been made by the UNEP-SETAC group to put LUC in LCA on the agenda. Since the call for papers by Milà I Canals (2007) regarding land use in LCA, a lot has changed. With the number of papers that have been published, and the ongoing activity of the co-authors to publish papers regarding this topic, the group has succeeded in putting this societally important topic on the research agenda.

8.1.2 Societal relevance

Several standards and methodologies for land use change carbon accounting have been developed over the past decade(s) by public bodies, private entities, and the scientific community. The European Commission (EC) is currently working on a protocol for (LCA-based) carbon modelling within the EC's Environmental Footprint Method, as a standardized methodology for carbon accounting in Europe. The Joint Research Centre (JRC) has published a draft Technical Report regarding this topic. The JRC is the EC's science and knowledge service and aims to provide evidence-based scientific support to the European policymaking process. In this draft, the JRC considered modelling land occupation impacts based on the UNEP-SETAC framework. The JRC considered to calculate the land occupation as the carbon sequestration that would have happened if that land was left to regenerate during that year. As advocated in this thesis, we consider that not in line with ALCA because it does not quantify the measurable emissions of land occupation. By means of the work that was conducted for this thesis, it was argued in a meeting with the JRC that occupation impacts should not be quantified by means of the UNEP-SETAC framework for an ALCA study. If the framework is used in an ALCA study, there will be high potential for misinterpretation of results as it combines the two modes of LCA within a single study. For mitigation strategies to be successful, it is highly essential that governmental and international bodies are aware of that.

8.1.3 Industrial Ecology relevance

This study was conducted in partial fulfilment of the requirements for the degree of Master of Science in Industrial Ecology at Leiden University and Delft University of Technology. Industrial ecology is "the study of systemic relationships between society, the economy, and the natural environment" (International Society for Industrial Ecology, n.d.). Methods used within the field of industrial ecology include material flow analysis, environmental input-output analysis and LCA. The aim of industrial ecology is to address sustainability challenges, by taking an interdisciplinary approach in identifying, designing, and critically evaluating sustainability solutions.

This thesis is relevant to the LCA community within industrial ecology, because it focused on method development and identified issues within the UNEP-SETAC LUC framework for LCA. In this thesis, both the causes and the consequences of using the UNEP-SETAC framework were evaluated, and a new method for quantifying LUC in LCA was proposed. In this thesis, an improved conceptual framework was designed to inspire other researchers within the industrial ecology community to collaborate in further developing a new LUC framework for LCA. The results of this thesis can be used to improve scientific research that guides society in making strategic decisions to redesign and minimize the impact of the global food system.

8.2 Limitations and recommendations

8.2.1 Terminology

In this research, it was decided to mainly follow the terminology of Milà i Canals et al. (2007) and Koellner et al. (2013). The UNEP-SETAC framework is already rather difficult for the reader to understand. Using different concepts than what the authors have originally used might have caused additional confusion. However, the terminology in the UNEP-SETAC framework does not necessarily align with the terminology that is used in different research fields. Use of different terms to describe the same concept in different research fields creates a divergence within different research fields, while it is important that these research groups collaborate.

During this research, issues with terminology in the field of LUC in LCA were encountered. First, many different terms are used for the same concept within the field of LUC in LCA. For example, the reference situation is also called reference system, reference scenario, or baseline (Koponen et al., 2018). The modelling period is also called temporal scope (Koponen et al., 2018), time frame (Milà i Canals et al., 2007), modelling time (Koellner et al., 2013), or time horizon (Koellner et al., 2013). Amortization is also called allocation, and the amortization period is also called amortization window (e.g. in PAS 2050), temporal scope (e.g., Koponen et al. (2018) or allocation period (Koellner et al., 2013). Second, terms are used interchangeably, because it is believed that they describe (roughly) the same concept, but they actually describe different concepts. For example, according to Soimakallio et al. (2016), 'land occupation' in LCA literature means 'land use'. However, land use is "the total of arrangements, activities and inputs applied to a parcel of land" (IPCC, 2019). That is different than land occupation, which is "the use of a land area for a certain human-controlled purpose (e.g., agriculture) assuming no intended transformation of the land properties during this use" (Milà i Canals et al., 2007). In UNEP-SETAC, land occupation is treated as land use in the narrow sense (Müller-Wenk & Brandão, 2010), excluding flows from activities, in- and outputs or products. Land use is included as an environmental flow, but not as an economic process. Third, terms were used inconsistently with other research fields. For example, to describe the residence time or atmospheric lifetime (Archer et al., 2009), Müller-Wenk & Brandão (2010) invented the term 'stay in the air'. Where literature outside the LCA community uses LUC, the LCA community uses land transformation (Koellner et al., 2013). Fourth, some terminology has also changed over time. For example, Milà i Canals et al. (2007) uses the term relaxation, while six years later Koellner et al. (2013) uses regeneration.

It is recommended for researchers of LUC in LCA to reach consensus on the use of terminology. The use of different terms (with sometimes slightly different meanings) creates confusion both within and across different fields of research. Without consistency of terms, it is unclear which impacts are quantified in a study, because different terms include different impacts. An attempt has been made to be consistent with the use of terminology within this thesis. Efforts have been made to include a glossary that explains the different terms used within this thesis and to mention possible synonyms that are used in literature.

8.2.2 Modes of LCA

In this thesis, two modes of LCA have been discussed: ALCA and CLCA. However, multiple other modes of LCA exist. Guinée et al. (2018) found a non-exclusive list of 6 additional modes, next to ALCA and CLCA. Guinée et al. (2018) found that "ALCA is the only mode focusing on modeling a situation as it is, either in the past, present, or future, but without any changes", while the other modes "all aim at estimating the effects of changed situations, where the change and/or the background state are based on a scenario" and "aim to assess the environmental life-cycle performance of a future system on the short, mid, or long term". Thus, it can be concluded that CLCA is "just one mode out of at least six other modes to model life-cycle impacts of possible consequences of changes to existing product systems, or of introducing novel technology or product systems" (Guinée et al., 2018).

Within this research, these other LCA modes have not been researched. It is unknown what the suitability is of the UNEP-SETAC framework and the improved conceptual framework for other modes of LCA besides ALCA and CLCA, or what kind of changes should be made to make it suitable for other future-oriented modes of LCA. We agree with Guinée et al. (2018) and Suh & Yang (2014) that "dividing the LCA world into CLCAs and ALCAs overlooks the studies not fitting this divide and hampers a constructive dialog about the creative use of modelling frameworks". Therefore, it is recommended that further research takes into account the multiple modes of LCA that exist when further developing LULUC frameworks (including the improved conceptual framework).

8.2.3 Regeneration time

Both the UNEP-SETAC framework and the improved conceptual framework use the regeneration time to calculate impacts. In the UNEP-SETAC framework, the regeneration time is used to calculate both the land transformation and occupation impact. In the improved conceptual framework, the regeneration time is used to quantify the forgone sequestration for a CLCA study.

It is important to note that regeneration time data is hardly available. The little data that is available often lacks a scientific foundation and is outdated or hypothetical (e.g., Müller-Wenk & Brandão, 2010), and therefore regeneration time data is highly uncertain (Koellner et al., 2013). This research gap was already identified in 2010 (Müller-Wenk & Brandão, 2010), but since then not much has been improved. The regeneration time values in both the UNEP-SETAC framework and in the improved conceptual framework are a source of uncertainty. In the improved conceptual framework, the forgone sequestration can be calculated if the annual sequestration after land abandonment is known. The annual sequestration can either be a directly collected data point, or it can be calculated by dividing the regeneration time by the amount of sequestered carbon during the regeneration time. However, for both methods, data is hard to find. Thus, if it is desired (for future oriented LCA modes) that LULUC frameworks provide information based on a regeneration baseline, it is essential that the data quality of regeneration times is improved in further research.

8.2.4 Rewarding passive and active sequestration

In the improved conceptual framework, it is argued that both passive (natural regeneration) and active (e.g., reforestation) sequestration activities should be accounted for in ALCA. We argue (in line with Brander, 2015) that sequestration only exists because anthropogenic LUC has reduced terrestrial carbon stocks below their equilibrium level. Therefore, sequestration activities should be included in ALCA, relative to a pre-anthropogenic baseline, to enable a complete mass balance of carbon. However, including passive sequestration in LCA as an anthropogenic impact, also leads to double counting of sequestration: once as sequestration in the inventory, and once included in the Bern carbon cycle in the climate impact category. If we want to include sequestration in LCA as an anthropogenic impact, the Bern carbon cycle should be corrected for that. If we account for passive sequestration as 'human-induced', the slope of the Bern carbon cycle should be made flatter, resulting in longer average lifetime of CO_2 in atmosphere, which would increase the impact of CO_2 on climate change.

Including passive sequestration activities in ALCA is a topic of debate. Helin et al. (2013) advocate that it is essential that the environmental impacts attributed to the studied system would not have occurred without the existence of the activity. According to the ILCD Handbook (European Commission Joint Research Centre, 2010), "only the net interventions related to human land management activities shall be inventoried. Interventions that would occur also if the site was unused shall not be inventoried". Following this line of reasoning, only credits should be given to active restoration activities. But it cannot be known for sure whether regeneration would also have happened without the activity. If the owner of the land did not actively decide to protect it and to leave it abandoned, it might have been bought by another entity and used for cropland. Thus, the choice to include passive sequestration in the improved conceptual framework can be a point of debate, which could be investigated in further research.

8.2.5 Forgone sequestration

In the improved conceptual framework, it was chosen to use the method of Brander (2016) for the quantification of the forgone sequestration. However, there are also alternative method available, for example the carbon opportunity cost by Searchinger et al. (2018) or the missed potential carbon sink by Schmidinger & Stehfest (2012). Due to limited resources, the carbon opportunity cost method has not been further researched. The missed potential carbon sink by Schmidinger & Stehfest (2012) was further researched but had several limitations.

According to Schmidinger & Stehfest (2012), "if less production occurs, agricultural land will be abandoned, leading to a carbon sink when vegetation is regrowing. This carbon sink, which does not occur if the product would still be consumed, can be attributed to the product as missed potential carbon sink". They argue that "the total GHG effect of a product is calculated as the sum of the emissions along the product chain according to conventional LCA (not including direct emissions from land-use change) plus the missed potential carbon uptake due to land-use occupation". The formula that Schmidinger & Stehfest (2012) use to quantify the missed potential carbon sink is shown in Eq. 8.1:

(Eq. 8.1) $$Missed\ potential\ carbon\ sink = \frac{occupation\ time}{time\ horizon} \times A\ \times carbon\ sink$$

where the *occupation time* (in yr) is the time for which the missed potential carbon sink is calculated (for 1 year of occupation it is 1), the *time horizon* (in yr) is the time over which the potential CO_2 uptake is annualized, *A* (in ha) is the area that is needed per kg of product, and *carbon sink* (in tonnes CO_2/ha) is the sink that would occur if the land is able to regenerate over the time horizon. Schmidinger & Stehfest (2012) calculate the results for two time horizons: 30 years (supposedly in line with biofuel studies) and 100 years (in line with Milà i Canals et al., 2007).

Quantifying a missed potential carbon sink by means of this equation has two main implications. First, the missed potential carbon sink is highly dependent on the chosen time horizon. This can be explained by the following example, where the regeneration time is 60 years and the total carbon sink is 50 tonnes carbon per hectare (Textbox 8.1). Choosing a time horizon of 30 years, leads to a potential sink of only 25 tonnes carbon per hectare, which results in a missed potential carbon sink of 0.83 tonnes carbon per hectare for 1 year of occupation. Choosing a time horizon of 60 years, leads to a potential sink of 50 tonnes carbon per hectare, which results in a missed potential carbon sink of 0.83 tonnes carbon per hectare for 1 year of occupation. Choosing a time horizon of 100 years, leads to a potential sink of 60 tonnes per hectare, which results in a missed potential carbon sink of 0.5 tonnes carbon per hectare for 1 year of occupation. Thus, the potential carbon sink becomes lower once the time horizon is longer than the regeneration time, because the sink is already saturated (Koponen & Soimakallio, 2015). Second, the choice of time horizon is a value choice. This shows that the value choice of a time horizon in the equation of Schmidinger & Stehfest (2012) highly influences the quantified potential carbon sink, which is undesirable.

Textbox 8.1

In this example, the regeneration time is 60 years and the total carbon sink is 50 tonnes carbon per hectare, and the area is 1 ha.

In case of a 30 year time horizon, only 25 tonnes of carbon can be regenerated. Thus, the calculation is as follows:

$$Missed\ carbon\ sink = \frac{1}{30} \times 1 \times 25 = 0.83\ tonnes\ carbon$$

In case of a 60 year time horizon, 50 tonnes of carbon can be regenerated. Thus, the calculation is as follows:

$$Missed\ carbon\ sink = \frac{1}{60} \times 1 \times 50 = 0.83\ tonnes\ carbon$$

In case of a 100 year time horizon, 50 tonnes of carbon can be regenerated (because after 60 years, the carbon content is in a steady state). Thus, the calculation is as follows:

$$Missed\ carbon\ sink = \frac{1}{100} \times 1 \times 50 = 0.5\ tonnes\ carbon$$

To conclude, multiple ways exist to quantify forgone sequestration. However, some methods have several limitations, such as the 'missed potential carbon sink' by that Schmidinger & Stehfest (2012). It is recommended that further research investigates alternative forgone sequestration methods, to ensure that the best available option is included in a LULUC framework.

8.2.6 Bern carbon cycle

The Bern carbon cycle is based on the dissipation of CO_2 molecules in the carbon pools, which includes the passive sequestration of carbon on land. In the improved conceptual framework, an amortization period of 50 years is proposed, in line with the average residence time of a CO_2 molecule in the atmosphere according to the Bern carbon cycle (cut-off 100 year). However, the more land transformations, the longer the CO_2 resides in the atmosphere, because the capability of the terrestrial carbon cycle to sequester CO_2 will decrease. However, this change in capacity of the terrestrial pools to sequester CO2 due to LULUC activities, is not included in the Bern carbon cycle. Thus, the amortization period is not corrected for the marginal residence time of a CO_2 molecule in the atmosphere due to that specific LULUC activity. The LULUC LCA community should be mindful of this limitation of the proposed framework.

8.2.7 Improved conceptual framework

The improved conceptual framework is only one idea how the weaknesses of the UNEP-SETAC framework could be improved. It is important that the current weaknesses of the UNEP-SETAC framework are recognized and resolved, but the proposed conceptual framework is not necessarily the optimum framework that is achievable. Most resources within this study have been directed at understanding the UNEP-SETAC framework and identifying the weaknesses of the framework. Only limited resources were left to develop an improved conceptual framework. It is not argued that the improved conceptual framework is the best framework to quantify LULUC GHG emissions in LCA, but instead it is argued that the improved conceptual framework is an improved framework compared to the existing UNEP-SETAC framework and is more consistent with the ALCA and CLCA modes. Therefore, we encourage the development of new LULUC frameworks to stimulate the method development in the scientific community, as long as a newly developed frameworks improve on the identified weaknesses of the UNEP-SETAC framework and are consistent with the aim of the LCA study.

8.2.8 Development of characterisation factors

To increase the use of LULUC frameworks in LCA studies and to increase standardization, one of the enablers is to create ready-to-use CFs. For the improved conceptual framework, CFs have not been yet developed. Currently, an LCA practitioner could only use the improved conceptual framework in an LCA study by calculating the LULUC emissions by hand. In an LCA study, the LCA practitioner would have to add these emissions to the corresponding process as emissions to air. Without CFs, the framework is not going to be implemented by the average LCA practitioner, because it is very time consuming to collect LULUC data and calculate emissions by hand. Thus it is highly essential that CFs are developed for the improved conceptual framework. With CFs, the LCA practitioner could (for example) select the environmental intervention 'LUC, from rainforest to annual cropland, in Brazil, in 18 years ago', and insert the desired amount for the unit 'ha'. The impact assessment model would contain the CF for the environmental intervention, thus the LCA practitioner does not have to quantify the LULUC emissions that belong to 'LUC, from rainforest to annual cropland, in Brazil, in 18 years ago'. As a result of the CF, the GHG impact of 1 ha of 'LUC, from rainforest to annual cropland, in Brazil, in 18 years ago' would automatically appear in the impact category 'climate change (GWP100)'. This would limit the efforts needed by LCA practitioners to collect data and to conduct calculations for the various LULUC types that can exist within their LCA studies. Therefore, the impact of this thesis would be enlarged if further research develops CFs based on the improved conceptual framework.

9. Conclusion

This study attempts to answer the following main research question: '*How can the UNEP-SETAC framework be improved to better quantify LULUC impacts of agricultural products in LCA?*' This main research question can be answered by means of the sub research questions.

- *How are LULUC impacts quantified in the UNEP-SETAC framework?*

The UNEP-SETAC framework distinguishes two types of impacts: land transformation and land occupation. Essential in the framework is the concept of regeneration; it is assumed that nature will restore land quality to a new steady state if occupation is absent (fallow land). Land transformation and occupation impacts are quantified by calculating the difference in quality over time between the studied system and the reference situation. The reference situation is the quality of land without human activity, which is dependent on studied system and the mode of LCA. The difference in quality is calculated until the studied system has reached a new steady state after regeneration. In the context of GHG emissions, the metric 'land quality' is expressed as carbon in the unit 'tonnes.year', which resembles the carbon content of the land that has been lost due to the studied system.

- *What are the weaknesses of the UNEP-SETAC framework?*

In the UNEP-SETAC framework, the LCA practitioner is provided with various methodological choices that should be taken based on the chosen LCA mode: ALCA or CLCA. However, the analysis showed that the UNEP-SETAC framework is largely based on consequential thinking, because emissions are calculated relative to alternative scenarios and based on future assumptions. Due to the design of the framework, a sum of all land transformation and occupation impacts calculated by means of the UNEP-SETAC framework does not equal to a sum of all measurable anthropogenic land transformation and occupation impacts in the world. Therefore, the analysis concluded that the UNEP-SETAC framework is not suitable in its current form for an ALCA study. Moreover, calculations are influenced by arbitrary value choices and a distinction is made between CO_2 originating from fossil carbon, temporary biogenic carbon or permanent biogenic carbon, while there is no scientific basis for this claim.

- *How can the weaknesses of the UNEP-SETAC framework be resolved to achieve an improved conceptual framework?*

In this thesis, an improved conceptual framework is proposed that improves several weaknesses of the UNEP-SETAC framework. The improved framework is in line with both ALCA and CLCA separately and does not mix the characteristics of the two methods. The basis of the framework is aligned with ALCA, and optionally, the forgone sequestration can be calculated for a CLCA study. Using this framework for ALCA studies leads to additive results of all measurable anthropogenic emissions, relative to a pre-anthropogenic baseline. For CLCA, the forgone sequestration can be quantified to indicate the impact of using the land for the FU, relative to abandoning the land and letting it regenerate. In the proposed framework, certain value choices have been made obsolete, such as the modelling period. Other arbitrary value choices (e.g., amortization period and method, and reference situation) have been standardized and (where possible) made based on science.

- *How do the UNEP-SETAC framework and the improved conceptual framework compare in a comparative LCA case study of an agricultural product?*

The comparative LCA case study comparing the LULUC GHG emissions of sunflower oil cultivated in France and palm oil cultivated in Indonesia showed different results using the UNEP-SETAC framework and the improved conceptual framework. It was assumed that the land in France was transformed centuries ago and the land in Indonesia was transformed in 2009. The functional unit for which the two alternatives were compared was '1 kg of crude oil cultivated in 2020'. When applying the UNEP-SETAC framework, 1 kg of sunflower oil caused 3.46 kg CO_2-eq emissions (from occupation) and 1 kg of palm oil caused 0.472 kg CO_2-eq emissions (0.153 kg CO_2-eq from transformation and 0.319 kg CO_2-eq from occupation). When using the improved conceptual framework, 1 kg of sunflower oil caused 0 kg

CO_2-eq emissions and had a forgone sequestration -14.7 kg CO_2 emissions and 1 kg of palm oil caused 1.57 kg CO_2-eq emissions (from transformation) and had a forgone sequestration of -2.61 kg CO_2-eq emissions. Thus, when using the UNEP-SETAC framework, it could be concluded that that the use of land for 1 kg of sunflower oil caused more GHG emissions, while when using the improved conceptual framework, it could be concluded the use of land for 1 kg of palm oil caused more GHG emissions. In the improved framework, forgone sequestration (in CLCA) showed that if there is more oil production than demand, it is better to use palm oil and to regenerate the land that is used for sunflower seed cultivation. The results of the case study illustrated that the choice of LULUC framework can invert the conclusions of LULUC GHG emissions between two alternatives. This showed that it is highly important that the academic community reaches consensus on using one type of framework.

To ensure the effectiveness of mitigation strategies for LULUC GHG emissions, it is crucial for governmental and international entities to recognize that the combination of LCA modes within the UNEP-SETAC framework can potentially lead to conclusions being inverted or results being misinterpreted. Therefore, it is highly recommended for the LULUC community within LCA to explore alternatives beyond the UNEP-SETAC framework and to delve into researching new possibilities. Within this study, an improved conceptual framework has been proposed as an advancement over the existing UNEP-SETAC approach. This proposal is favoured because it aligns with ALCA and CLCA methodologies and minimizes arbitrary value choices. Further research is advised to assess the applicability of this proposed framework for other future oriented LCA modes. Furthermore, it is essential that further research focusses on developing CFs for the improved conceptual framework. This is crucial to facilitate widespread adoption of the proposed improved conceptual framework among LCA practitioners.

10. References

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Appendix I. International standards for LUC CFP

In this Appendix, the characteristics of the UNEP-STEAC framework are compared to the most important international standards for LUC CFP.

For the quantification of LUC GHG emission in LCA, three international standards for CFP are most frequently used: the Publicly Available Specification (PAS) 2050; the Forest Land use and Agriculture Guidance (FLAG); and the Greenhouse Gas (GHG) Protocol. These three standards require LUC emissions to be included in the CFP and require LUC emissions to be reported separately.

About the CFP standards

In this section, background information regarding the three CFP standards is be provided.

About the PAS 2050

The European Commission has developed the Product Environmental Footprint (PEF), which is a standardized LCA based method for quantifying the environmental impact of products (European Commission, n.d.). Its aim is to create more consistency and transparency on the sustainability of products and organization, by creating a European harmonized environmental calculation rules based on the LCA method. Specific calculation rules have been created for different product groups, named Product Environmental Category Rules (PEFCRs), and also for organisations (OEFCRs). The PEF was in its pilot phase from 2013 to 2018 and has now gone into a transition phase (where changes are made) before the policy implementation (European Commission, n.d.).

The PEF recommends the PAS 2050 for LUC: “For land use change: all carbon emissions and removals shall be modelled following the modelling guidelines of PAS 2050:2011 (BSI 2011) and the supplementary document PAS 2050-1:2012 (BSI 2012) for horticultural products” (European Commission, 2021)

The development of the Publicly Available Specification (PAS) has been facilitated by The British Standards Institution (SBI) Standards Limited. The main aim of PAS 2050 is to establish a common basis for quantifying GHG emissions that informs and enables GHG reduction programs (British Standards Institution, 2011). The PAS builds on ISO14040 and ISO 14044 by providing specific guidelines for assessing GHG emissions in LCA, including “treatment of emissions and removals from land use change and biogenic and fossil carbon sources” and “treatment of the impact of carbon storage in products and offsetting” (British Standards Institution, 2011). Additionally, the PAS 2050-1:2012 has been created to provide supplementary requirements (to PAS 2050) for the cradle to gate stages of GHG assessments of horticultural products (British Standards Institution, 2012).

About the FLAG

The Forest Land use and Agriculture Guidance (FLAG) is developed by Science Based Target initiative (SBTi). SBTi is a partnership between the Carbon Disclosure Project (CDP), the United Nations Global Compact, World Resources Institute (WRI) and the World Wide Fund for Nature (WWF) (Science Based Targets, n.d.-a). SBTi offers businesses a predefined roadmap to reduce their GHG emissions, thereby mitigating climate change impacts, while also helping business grow more sustainably.

FLAG is the first standard that addresses the inclusion of land-based emissions and emission removals, so business can set targets to reduce their LUC impact. However, FLAG refers to the GHG protocol for details on emission calculations. Businesses with SBTi targets and emissions within FLAG sectors, must set targets and report on FLAG emissions according to this guideline (Science Based Targets, n.d.-b).

FLAG has announced that an updated version will be published after the GHG Protocol Land Sector and Removals Guidance is completed, to ensure it aligns.

About the GHG Protocol

The Greenhouse Gas (GHG) Protocol establishes global frameworks to quantify GHG emissions from private and public sector operations and mitigation efforts (Greenhouse Gas Protocol, n.d.-a). The GHG Protocol was established in 1998 through collaboration the World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD) (GHG Protocol, n.d.-b).

Companies reporting a corporate GHG inventory in conformance with the Greenhouse Gas Protocol shall follow the Land Sector and Removals Guidance if the company has land sector activities in its operations or value chain or if the company is reporting removals. The GHG Protocol Land Sector and Removals Guidance clarifies the procedures for companies to account for and report GHG emissions and removals originating from land management, LUC, biogenic products, carbon dioxide removal technologies, and associated activities within GHG inventories (Greenhouse Gas Protocol, n.d.-c). This builds upon the foundation of the Corporate Standard and Scope 3 Standard.

This guidance is under development since 2020 (Greenhouse Gas Protocol, n.d.-c). The Draft for Pilot Testing and Review is currently accessible, and the final version of the Guidance is expected to be completed and released in 2024. Therefore, the GHG Protocol is not included in the case study in Chapter 7.

Comparing the CFP frameworks with UNEP-SETAC

Main differences regarding the fundaments of the frameworks

There are two main differences that can be found between the UNEP-SETAC framework and the CFP standards.

First, the CFP frameworks assume that LUC emissions are lost “forever”. This can be perceived similar as assuming that the future of land use is continued occupation in the framework of UNEP-SETAC (Figure I.1a). However, instead of assuming that occupation is the future scenario, UNEP-SETAC assumes as a default that land will be abandoned after the studied land use, thus they assume that LUC emissions are taken up from the atmosphere during regeneration of the land (Figure I.1b).

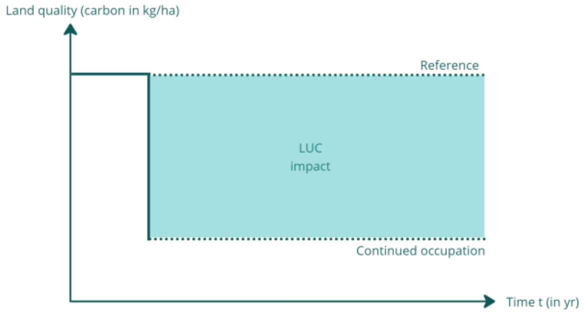

Figure I.1a. CFP methods assume that LUC emissions are permanent.

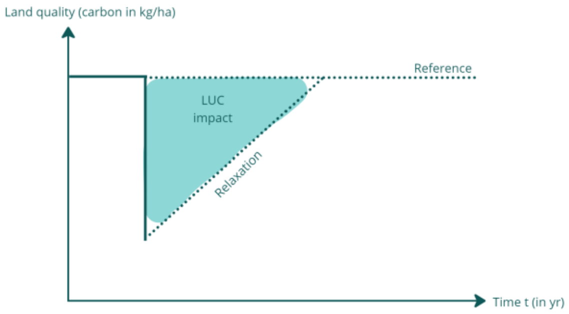

Figure I.1b. UNEP-SETAC assumes LUC emissions are temporary.

Second, most CFP standards do not include the impacts caused by occupation. CFP standards include the measurable impacts and if it is assumed that quality remains stable during occupation, there is no measurable occupation impact. On the contrary, UNEP-SETAC assumes that the impact of occupation is the difference between the land quality of the studied occupation and a hypothetical land quality in a more ideal scenario.

Differences in amortization period and method

Table I.1 shows the differences in amortization period and method for the CFP methods compared to the UNEP-SETAC framework.

Table I.1. Amortization period and method of CFP standards and the UNEP-STAC framework.

	FLAG	GHG Protocol	PAS 2050	UNEP-SETAC framework
Amortization period	20 years	20 years	20 years	20 years
Amortization method	Linear	Linear or equal	Equal	Equal

The CFP standards and UNEP-SETAC framework all recommend an amortization period of 20 years. This means that LUC emissions are attributed to the crops that are grown in 0 up to 20 years after the LUC event. Thus, no LUC emissions are attributed to the crops that are grown after 21 or more years after the LUC event. It is believed that 20 years corresponds to the time it takes for carbon stock to reach a new equilibrium after transformation, thus equal to the duration of the transition period (IPCC, 2006).

The amortization (or discounting) method determines how the calculated GHG emissions within the amortization period are assigned to crops, i.e. how much responsibility is assigned to the crops of a particular year within the amortization period.

With equal amortization, LUC emissions are equally distributed among the years within the amortization period. Thus, in case of the PAS 2050, 5% of the LUC emissions is assigned to each year within the 20-year amortization period (Figure I.2). Figure I.2 also shows that after those 20 years, there is a very big difference in LUC emissions for year 21 (0%) compared to year 20 (5%).

With linear amortization, the highest percentage of emissions is assigned to the production within first year after LUC and the lowest percentage of emissions is assigned to the production within the last year of the amortization period. Thus, in the case of a 20-year amortization period and linear amortization (e.g., FLAG), it results in a smoother transition of assigned LUC emissions between year 20 (0.25%) and 21 (0%) (Figure I.2).

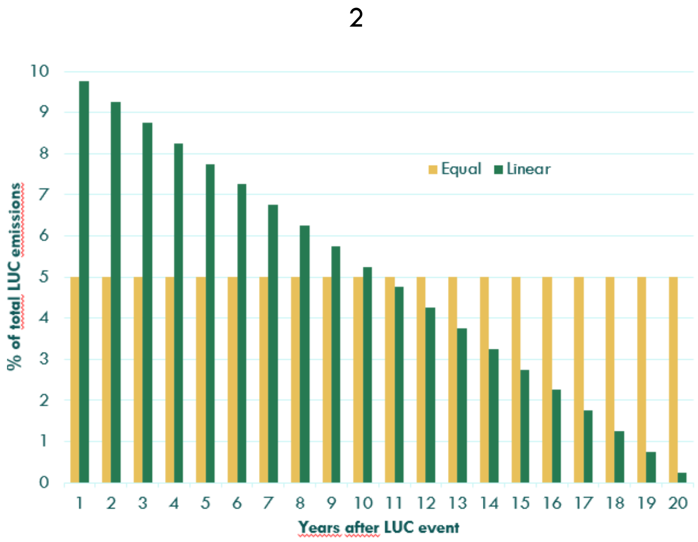

Figure I.2. Equal and linear amortization in % per year of total LUC emissions for an amortization period of 20 years.