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Climate impacts of land use in LCA
– Elaboration of criteria for satisfactory methods

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Abstract

Introduction

LCA is a widely used tool for assessing the environmental impacts of products. However, despite the large importance of land use for atmospheric CO_2-levels there is still no consensus on how to include the climate impact of land use in LCA and results vary up to several hundred percent depending on method.

The purpose of this thesis is to contribute to a formation of consensus about how to handle the climate impact of land use in LCA by suggesting criteria for satisfactory methods to do this. The criteria are meant to limit the number of alternative methods and the variation in results.

Method

The criteria are elaborated through theoretical reasoning that takes its points of departure in the definitions of essential terms and in assumptions of desired properties for LCA such as internal consistency, comprehensiveness (the property of being all-inclusive) and comprehensibility (the property of being easy to understand).

Results

The analysis resulted in 11 criteria. One effect of the criteria is that when one makes assumptions of land use changes and use GWPs to aggregate emissions, then the impact of the change should be distributed over all the services that are derived during the new use up to the GWP time horizon. Other criteria concern the need to consider e.g. albedo, aerosol formation and impacts on the ability of the used land to provide services. Yet other criteria is about that an LCA should enable readers to understand the potential trade-offs between short and long term climate impacts.

Discussion

The criteria may be used to evaluate and improve suggested methods, as guidance in design of new methods and to point out research and development needs (e.g. concerning the inclusion of normally ignored climate forcers such as albedo and aerosol formation). Many used and suggested methods are inconsistent and adjustments according to the suggested criteria are likely to decrease the variation in results between methods. There is a need to evaluate the reliability of previous LCA studies and there could be a need to reconsider conclusions based on LCA that do not include climate impacts of land use in a satisfactory way. There is also a need to refine the suggested criteria and/or elaborate more specific standards for specific contexts.

Sammanfattning

Inledning
Livscykelanalyser (LCA) är analyser för att uppskatta miljöpåverkan av produkter. Trots att markanvändning har en stor påverkan på klimatet finns det fortfarande ingen konsensus kring hur markanvändning ska hanteras i LCA och variationen i resultat kan variera flera hundra procent beroende på metod.

Syftet med den här uppsatsen är att bidra till skapandet av konsensus kring hur markanvändning ska hanteras i LCA. Detta genom att föreslå kriterier för tillfredsställande metoder. Kriterierna är menade att begränsa både variationen i resultat beroende på val av metod och antalet alternativa metoder som används.

Metod
Kriterierna tas fram genom ett teoretiskt resonerande som tar sin utgångspunkt i definitionerna av centrala begrepp och i önskade egenskaper för LCA, som internt konsekventa antaganden, att de tar allt vikitgt i beaktande och att de är lätta att förstå.

Resultat
Analysen resulterade i 11 kriterier. En effekt av kriterierna är att när man gör antaganden om förändrad markanvändning och använder växthusgasernas GWP (vilka bygger på antaganden om permanenta pulsutsläpp) för att sammanväga växthusgasutsläppen i analysen, så måste utsläppen fördelas över alla produkter som erhålls från den nya markanvändningen fram till den tidshorisonten som GWP är definierad över. Andra kriterier berör behovet av att inkludera påverkan på t ex albedo, aerosoler och påverkan på markens bördighet. Ytterligare andra kriterier ställer krav på att en LCA ska möjliggöra för läsaren att föstå eventuella trade-offs mellan klimatpåverkan på kort och lång sikt.

Diskussion
Kriterierna kan användas för att utvärdera och förbättra föreslagna metoder, som guide i design av nya metoder och för att peka ut behov av forskning och utveckling (t ex vad gäller inkluderandet av faktorer som albedo och aerosoler). Många använda och föreslagna metoder är inkonsekventa och justeringar enligt kriterierna skulle sannolikt minska variationen i resultat beroende på metod. Det finns ett behov av att utvärdera tillförlitligheten i tidigare genomförda LCAer och man kan komma att behöva ompröva vissa slutsatser som är baserade på LCA som inte hanterat klimatpåverkan av markanvändning på ett tillfredsställande sätt. Det finns också ett behov av att utveckla kriterierna och/eller utveckla mer specifika standarder för specifika sammanhang som komplement till de här föreslagna generella kriterierna för tillfredsställande metoder för att hantera klimatpåverkan av markanvändning i LCA.

Popular summary

Estimates of the climate impact of products are often erroneous

Have you ever heard that a certain food has a larger climate impact than another? What you heard might have been misleading, as many methods used to estimate the climate impact of land use in life cycle assessments (LCA) are inconsistent, neglect important factors and focus on narrow time horizons.

One of the most common and grave inconsistencies is to attribute the full impact of a permanent land use change, for example from forest to cropland, to only the first 20, 30, or even first single year of land use following the change. As forests in most cases recover if the used land is abandoned, the largest impact of a permanent land use change is therefore caused by the continuous land use – the land occupation – and not the initial land transformation. If a studied production relies only on land use that occurs after the period to which the impact of a land use change is attributed, then no impacts of land use are attributed to the product. In many cases this means that the largest part – sometimes almost all – of the climate impact of the studied product is completely neglected.

The focus on narrow time horizons are problematic as the impacts of land use generally are transient (land tends to recover after usage), while fossil fuel derived CO_2-emissions are permanent. This means that the choice of time horizon will affect the comparison of products that to different extents rely on land use and fossil fuel use respectively. Normally LCAs are made only over a 100 year time horizon. Compared to longer time horizons, this overestimates the impacts of land use compared to fossil fuel use. Previously, many studies that compare biofuels and fossil fuels have shown that the choice of time horizon may alter which alternative that has the largest estimated climate impact. In a calculation example in this thesis it is also shown that the choice of time horizon determines the outcome of a comparison between field beans produced in Sweden and soybeans imported to Sweden from Brazil and there could be many more cases. There is also a similar problem when different products emit different proportions of greenhouse gases that have different atmospheric lifetimes.

An example of a factor that is often neglected is changes in albedo, i.e. the share of incoming radiation that is reflected from a surface. In an LCA that included impacts on albedo, it was shown to reduce the net climate impact of the product by half, over a 100 year time horizon. Another factor that may require more attention is different forms of land degradation, which can lead to larger areas being required in order to maintain the same level of production.

In the thesis I discuss different alternatives for how one could attribute impacts to land occupation in consistent ways and stress the importance of including also albedo and other often neglected climate forcers as well as effects of land degradation on the ability of the land to provide future products.

An interesting issue that is not addressed in the thesis is how inconsistencies that omit the largest part of the impact of a product can be possible. I see three important reasons:

- LCAs are traditionally performed through a compilation of the inputs and outputs of a production system in the studied scenario, while there is no relevant activities at all in the reference scenario, which therefore is implicit and more or less forgotten. This might work well for industrial processes, but not when handling land use that includes interventions with dynamic ecosystems.
- LCA are not empirically evaluated and the quality of LCA therefore completely depend on that the people involved in the making of an LCA has thought of all relevant processes and knows how they work.
- A pressure to make things fast and cheap means that there rarely is enough time to think things through and make a good work.

Raising the awareness of the reference scenario may be relatively easy. However, empirical evaluations of LCA are, as far as I can see, impossible and removing the pressure to make things fast and cheap also seems difficult. One should therefore be careful not to have overconfidence in LCA and I think there is reason to discuss when, and to what extent, it is suitable to rely on LCA as decision support. While I see no major problems with the use of LCA in research and development, I find it more dubious in marketing and public policy. Optimally, I think activities that cause environmental impacts, such as fossil fuel use and land use, should be regulated directly (through e.g. rationing of fossil fuels and taxes on land use) to such an extent that consumers and policy makers do not have to bother about the impacts of specific products.

Foreword

Concerning the personal language in this thesis

This thesis sometimes has a speculative character and a personal language that is unusual in the academic world. One reason for this is that many methodological choices that I have studied have not been fully motivated by the authors. I have therefore often had to guess and interpret the motives or reasons why the methods have been designed as they have. This reason could also be seen as a background to the second reason for the personal language; that I do not believe in objectivity. The questions asked and the interpretations of a study are always influenced by the previous experiences of the scientists performing a study, and I believe that it is healthy to be reminded of this.

Concerning the aim and scope of this work

My original intention was to suggest universally applicable criteria that could be used to classify any LCA-method as either satisfactory (i.e. useful as decision support) or not satisfactory. I have, however, realized that there is a limitation in the universality already in the usage of a single system of ideas and associated terminology. One could argue that the ideas and used terms refer to objects and processes in the world and that the terminology used, via the described objects and processes, could be "translated" to any other possible terminology. In a similar way, an object or process could be described in different levels of detail, and one could argue that it is possible to make translations between different levels of detail as well, though there in the cases of translations from a level of less to more details could be several possible translations.

Example: If one wants to increase the details in the description of an imagined chair, e.g. including the material it is made of, there are several materials to choose from. If one on the other hand want to decrease the detail in the description of a wooden chair, but keep enough level of detail to distinguish it from other types of furniture that are made to sit on, the only "translation" possible is that into "a chair" (presuming one want to keep using the same terminology).

There is a difference between more or less detailed and more or less specific. There is a correlation between the degree of details provided and the specificity of a description; the more details that are provided, the more specific is the description. However, one may refer to a specific object in more or less detail, though a less detailed description will allow an interpreter to, perhaps unconsciously, assume, perhaps erroneous, details about the specific object.

In order to maximize the universality of this work, I try to minimize the level of detail. However, it is desirable to also develop standards for specific contexts, in which one regulate also higher levels of detail.

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1. Introduction

Life cycle assessments, or life cycle analysis (LCA) is a widely used tool for assessing the environmental performance of products. It is used in many contexts and is the foundation of many other methods such as carbon footprinting. However, despite the widespread use of LCA and the large importance of land use for atmospheric CO_2-levels[1] there is still no consensus on how to include land use, and the climate impact of land use in LCA. Different methods have been proposed and results vary depending on which methods that are used. In a study of beef and milk by Flysjö et al. (2012) the climate impact of milk varies with up to 400% depending on which method that is used for including land use changes.

There are several differences between suggested methods, and some issues have been widely debated. A major controversy concern whether or not to include indirect land use changes (ILUC), i.e. land use changes that are caused by crop displacement, as have been proposed by for example Searchinger et al. (2008) and Schmidt et al. (2011). The suggestion of including ILUC stems from a notion that previous practices for estimating emissions of greenhouse gases (GHG) of products underestimate the impact of agricultural production because the impact of land use has not been included in a satisfactory way. However, there is also a resistance to the inclusion of ILUC. For example Zilberman et al. (2010) have argued that ILUC keeps individuals responsible for actions that they do not control, and there is still no consensus on how, or if and when, ILUC should be included in LCA.

Another unresolved issue is how to attribute the emissions from a land use change to the subsequent land use. The normal procedure is to amortize the emission from a land use change to the first 20 or 30 years of agricultural production following the change (Ahlgren and Börjesson 2011). However, in their report on ILUC in biofuel studies Ahlgren and Börjesson suggest that it would be more suitable to amortize the emissions over a period as long as one believe that the land will produce crops for biofuel production. The importance of the amortization period have been pointed out by Cederberg et al. (2011) in a study on Brazilian beef,

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[1] The contribution of land use to climate change is large in comparison to other factors, both when comparing the through history accumulated and the contemporary emissions.

Between 1850 and 2006 the cumulative emissions from land use change (158 GtC, gigatonne of carbon) is estimated to be roughly half of those from combustion of fossil fuels and cement production (330 GtC) (Canadell et al. 2007). Estimates of historical emissions from land use change up to 1850 are uncertain but range up to 360 GtC (Kaplan et al. 2012), which would make the cumulative emissions from land use change more than 50 % larger than those from fossil fuels up to 2006.

Though the carbon stocks remaining in vegetation and top one meter of soil in the world isn't as large as those in the fossil fuel reserves; 2 000 – 2 500 GtC compared to 5 000 – 10 000 GtC (Houghton 2003), land use still has the potential to make large contributions to further anthropogenic global warming.

where the emission per kg beef decreased with a factor 5 when changing the amortization period from 20 to 50 years.

There are different LCA-methodologies and I don't believe that there is one single correct method. I believe, however, that there are properties that LCA practitioners can agree are important for LCAs. Three such properties, I believe, are consistency, comprehensiveness (the property of being all-inclusive) and comprehensibility (the property of being easy to understand). In this thesis I formulate general guidelines for LCA based on these three properties and use the guidelines as points of departure in an analysis that aims at producing criteria for satisfactory methods to include the climate impact of land use in LCA.

1.1. Purpose and goal of study

The purpose of this thesis is to contribute to a formation of consensus about how to handle the climate impacts of land use in LCA, by suggesting criteria for satisfactory methods for handling the climate impact of land use in LCA. This should limit the number of alternative methods, and hopefully also the variation in results. The goal is to suggest criteria that are relevant for any LCA, regardless of the purpose and methodology of the LCA, while more specific criteria will have to be elaborated for specific purposes, in different regulations and standards.

The criteria are meant to serve as a tool in the evaluation and development of methods. In order to facilitate the understanding of how the criteria can be used it is provided examples of how they can be used in an evaluation of a few suggested methods.

1.2. Limitations of the scope

As the goal is to suggest criteria that are relevant for any LCA I keep this thesis on a general level. This means that I focus on fundamental principles that are independent of which precision or level of specificity/generality that is required in a study, and that could be supposed to apply in the same way to all climate forcers that are affected by land use. In the examples of the analysis I only discuss carbon stocks, but the principles discussed are supposed to be applicable for all climate forcers and the criteria are worded in climate forcing-neutral ways. The focus on general principles also means that the primary focus on land use aspects is on an ecosystem level[2] and on parameters that are necessary for the attribution of impacts on climate forcers of land use to products, including the development of climate forcers, the services that are derived from the land and the land use interventions/activities that link the two together. In this way the criteria can be applicable on any method, regardless of which levels of detail they apply in their modelling. However additional standards have to be elaborated to deal with demands on the higher levels of detail and on the quality of the modelling of individual parameters.

[2] With a focus on land use aspects on an ecosystem level, I mean a focus on parameters that describe the development of the ecosystem as one entity rather than on e.g. individual organisms and flows of energy and chemical substances in isolated processes within the ecosystem.

Though I wish I could formulate criteria that are universal, I realize that this is not possible. All aspects of the points of departure that I take will bring on a limitation in the universality of my reasoning. This is obvious for the general guidelines, but it also applies to the conceptual world and the terminology that I use, which also constitute parts of my points of departure. There are other possible terminologies, or conceptual worlds than mine, and I realize that the criteria I suggest could not be straight forwardly applied in any possible conceptual world or LCA methodology. I hope, and believe, however, that the conceptual worlds of the people in the LCA-community are similar enough to mine for my work to be understandable and applicable also in relation to their work. I believe therefore that the most critical limitations of the universality of the criteria are the definition and interpretation of the general guidelines.

2. Method

The general method of this thesis is theoretical reasoning, founded on a few points of departure. As points of departure I have set up definitions of essential terms and general guidelines for LCA. Based on these guidelines I elaborate criteria for satisfactory ways to handle the climate impacts of land use in LCA.

In support of the reasoning I use different types of examples requiring additional assumptions and usage of scientific theories, hypothesises and models. Many examples are also based on methods for handling the climate impacts of land use that have been suggested or used in the literature.

An overview of the structure of the thesis is provided in Figure 1

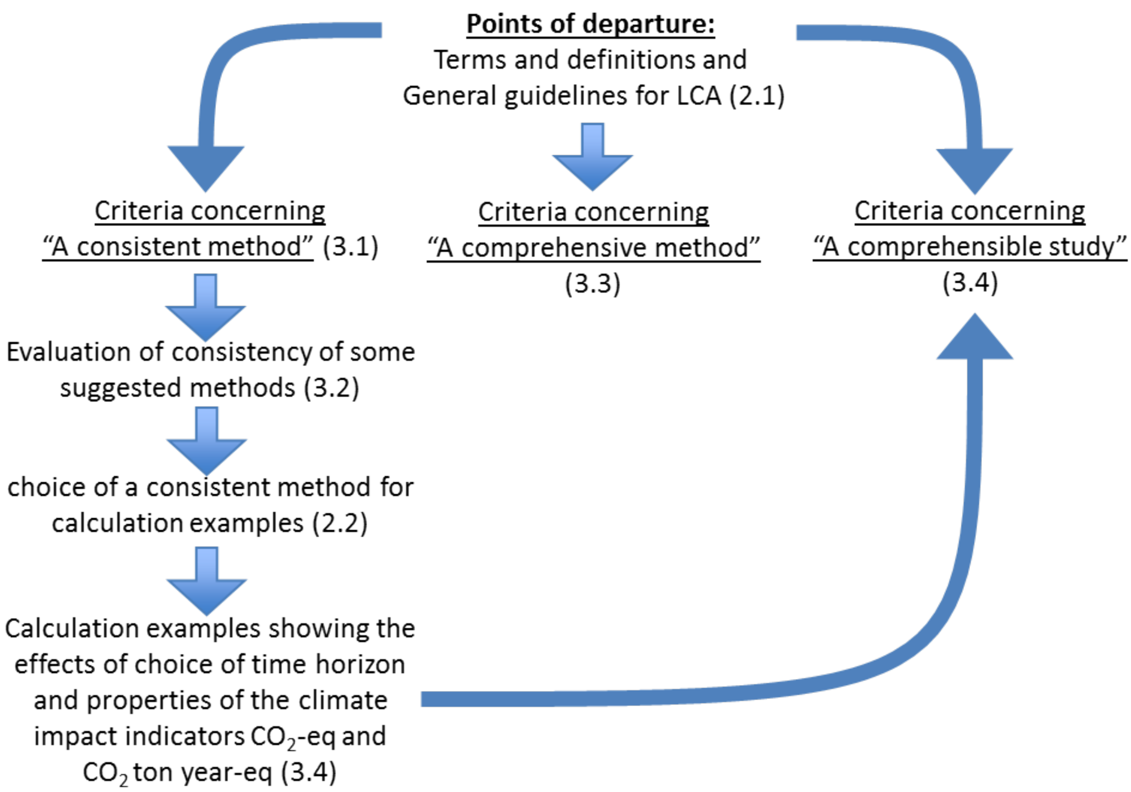

Figure 1 An illustration providing an overview of the thesis. The numbers in parenthesis indicates in which sections of the thesis the issues are addressed.

2.1. Points of departure

In order to elaborate on criteria for satisfactory methods to include climate impacts of land use in LCA I need some points of departure. I have to define the fundamental terms that are used in the thesis and what characterizes a "satisfactory method", i.e. the General Guidelines for LCA. These points of departure follow below.

2.1.1. Terms and definitions

In this section I define terms that are of particular importance for this thesis, may it be for the delimitation of, the reasoning in, or the understanding of the thesis. Many of the definitions might deviate somewhat from the conventional usages of the terms and some details in the definitions are important for the analysis in the thesis. In order to facilitate the understanding and interpretation of the definitions many of them are provided with comments.

2.1.1.1. A model

Definition: A model is any kind of representation, depiction, visualization, image or description.

2.1.1.2. To model

Definition: to create any kind of representation, depiction, visualization, image or description.

2.1.1.3. Environmental impact

Definition: An environmental impact is the consequences of an event, e.g. a human activity, for the world in which the event occurs. These consequences are defined as the difference between the development of the world with and without the occurrence of the studied event.

Comments: One can not observe the development of the world both with and without an event taking place. One can thus never observe the environmental impact of a specific event. One can, however, assess environmental impacts in different ways. For example:

- One can assess the likelihood of a specific effect of a specific type of events through e.g. controlled experiments

- If one has an observed scenario in which an event occurs one can model the environmental impact of the event by assuming a development of the world in which the event do not take place (i.e. a reference scenario).

- One can model an environmental impact by assuming both a development of the world in which the studied event occurs (a studied scenario), and a reference scenario. This is done if it is not feasible to observe any of the developments; the events studied might be hypothetical or generic, they may be too complicated and intertwined with other processes, or the effects may propagate far into the future while one want to know the impact now. An LCA is normally, if not always, of this third kind, and is often so for all mentioned reasons.

2.1.1.4. Scenario
Definition: A scenario is an observed or projected, imagined or in other ways assumed development of a situation, i.e. a sequence of events.

Comments: A scenario is often an assumed possible future, but one could also make hypothetical scenarios of an alternative past or a completely hypothetical situation. The essence of a scenario is that it is a situation that is developing over time. The description of a scenario is normally simplified, but the level of simplification can vary, for example in the delimitation of the processes included and in the level of included spatial and temporal detail. Though a scenario describes a development over time, all temporal detail may be omitted, perhaps only describing a shift from one steady state to another or the total flows of energy and matter passing a system boundary.

2.1.1.5. Life cycle assessment
Definition: A life cycle assessment (LCA) is an assessment that is conducted in order to provide information concerning the resource use and plausible environmental impact associated to *the fulfilment of the function of a product or service throughout the product's or service's full, or parts of it's full, life cycle* (hereafter referred to simply as *a product*). The life cycle of a product refers to the processes from extraction of raw materials, through production, distribution and usage to waste management.

Comments: As an LCA assesses the environmental impact of a product it does by necessity include a creation of two scenarios that define the impact, though the reference scenario may be completely implicit.

LCA is generally described as a compilation of the inputs and outputs of a production system, as is done e.g. in the ISO standards (ISO 2006). The definitions above, which demand a creation of two scenarios in LCA, might therefore seem unfamiliar or irrelevant to many in the LCA community. However, as described in the next paragraph, this view is compatible with the definitions above. The views on LCA as a compilation of in- and outputs to a production system and as an assessment of an impact that is defined by two scenarios are also combined in the theoretical foundation section of the handbook on LCA by Guineé et al. (2002).

When describing an LCA as a compilation of the inputs and outputs of a production system, one presumes that the only differences between the studied scenario and the reference scenario are the inputs and outputs that are related to the delivery of the product in the studied scenario. Though one explicitly only describes the relevant flows in the studied scenario, there is also an implicit reference scenario in which the product is not delivered and no relevant flows occur. The reference scenario is therefore not mentioned, or even thought of, in the assessment. I believe this focus on in- and outputs to and from the studied production generally works well when studying industrial processes. However, when it comes to land use, one intervenes with dynamic ecosystems, and though there are no relevant human interventions in the reference scenario, there could still be spontaneous ecosystem processes that have to be considered.

In an LCA with implicit scenarios defined only by the difference in flows crossing the boundaries of the studied production system, the modelled land development in the reference scenario could be introduced in the assessment as a system input, while the land development in the studied scenario could be introduced as a system output.

As it is not possible to observe the isolated impacts of a product, an LCA has to be constructed around assumed scenarios.

2.1.1.6. Ecosystem

Definition: An ecosystem is "A biological community of interacting organisms and their physical environment" (Oxford_dictionaries)

Comments: Also humans are organisms. Thus, also areas such as agricultural fields and cities are ecosystems where we interact with other living organisms and our physical environment.

2.1.1.7. Environmental impacts of land use

Definition: Environmental impacts of land use are the changes in the development of a piece of land and the subsequent consequences of these changes, caused by any action that derives services from that piece of land.

Comments: The definition refers to the environmental impacts caused by changes in land cover, such as changes in carbon stocks in soil and vegetation caused by anthropogenic interventions, while emissions from fossil fuel combustion associated to such interventions, such as e.g. ploughing, are not included but considered an impact of fossil fuel combustion.

Derived services from a piece of land could constitute such simple things as provision of solid ground to walk on.

2.1.1.8. Climate impacts of land use

Definition: Climate impacts of land use are the parts of an environmental impact of land use that affects the climate or are mediated by the climatic response.

Comments: Environmental impacts of land use that affect the climate includes e.g. impacts on the development of climate forcers such as carbon stocks, nitrous oxide (N_2O) emissions and aerosol formation, the contribution to elevated temperatures of the impacts on the land use related climate forcers and the subsequent effects on the biosphere and areas of protection. Climate impacts may be quantified by different climate impact indicators.

2.1.1.9. Impact indicator

Definition: An impact indicator is an aspect of an impact by which one chooses to quantify the impact.

Comments: The aspects of an impact that is of interest in an LCA are the areas of protection (i.e. the aspects that potential readers of the study values and want to keep from harm). The areas of protection could for example concern preservation of different aspects of biodiversity, ecosystem services, aesthetic values in the landscape or the wellbeing of humans or other organisms. The areas of protection are subjective (and therefore vary from reader to reader) and impacts on the areas of protection are normally very complex to model. Instead one often chooses impact indicators that are easier to model, such as the stratospheric adjusted cumulative radiative forcing, but are thought to be usable as proxies to the impacts on various areas of protection.

Impact indicators that quantify impacts on the areas of protection are often called endpoint (or damage) indicators, while indicators that quantify aspects of an impact higher upstream in the cause-effect chain (such as the CO_2-eq indicator that weigh emissions of GHGs based on their cumulative radiative forcing) are called midpoint indicators.

2.1.1.10. Areas of protection

Definition: Areas of protection are aspects of the world that someone cares about and which they want to keep from harm.

Comments: see comments to impact indicator.

2.1.1.11. Stratospheric adjusted radiative forcing

Definition: "the change in net (down minus up) irradiance (solar plus long-wave; in Wm^{-2}) at the tropopause AFTER allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values" (Ramaswamy et al. 2001).

Comments: The stratospheric adjusted radiative forcing can be integrated over time to render a stratospheric adjusted cumulative radiative forcing (in the remainder of this thesis referred to simply as radiative forcing respectively cumulative radiative forcing). The cumulative radiative forcing is a hypothetical quantity as it quantifies an energy accumulation under the hypothetical assumption that the temperatures at the earth surface and in the troposphere are not affected by the energy accumulation that is quantified. It could thus be seen as a gross energy accumulation while a net energy accumulation would require a subtraction of the increased energy loss caused by the increased radiation from earth due to the temperature rise caused by the energy accumulation.

The global warming potential (GWP) of GHGs are calculated through a comparison of the cumulative radiative forcing of the gas in question and the reference gas carbon dioxide (CO_2).

2.1.1.12. CO_2-equivalents

Definition: The amount of carbon dioxide that, emitted as a pulse emission and over a given time horizon, is assumed to cause the same climate impact as the climate impact of a studied change in a climate forcer or combination of climate forcers.

Comments: The IPCC definition of CO_2-equivalents (or Equivalent CO_2 emission, CO_2-eqs) reads: "The amount of carbon dioxide emission that would cause the same integrated radiative forcing, over a given time horizon, as an emitted amount of a greenhouse gas or a mixture of greenhouse gases". This definition excludes other climate forcers than greenhouse gases (GHGs), such as albedo and aerosols. It is also dubious if the definition would allow a comparison of carbon dioxide from transient impacts on carbon stocks in soil and vegetation through a duration factor based on the integrated impact on carbon stocks (see discussion on the Müller-Wenk and Brandão method in section 3.1.2.7 and 3.2.3). I therefor define CO_2-eqs in a wider way.

2.1.1.13. CO_2 dissipation

CO_2 dissipation, or dissipation of CO_2, is a term for the different non-anthropogenic mechanisms by which emitted CO_2 leaves the atmosphere.

Comments: The term stems from Müller-Wenk and Brandão (2010) who denoted these processes "dissipative" carbon flows. I find the term partly contradictive, as a large part of the dissipation is mediated by photosynthesis, which is kind of the opposite to dissipation. However, for most other processes, such as diffusion into the oceans, it is consistent with the thermodynamical sense of the word.

The CO_2 that is sequestered during the relaxation of abandoned land is considered as an anthropogenic mechanism (and not part of CO_2 dissipation) as it would not take place unless the carbon stocks previously had been lowered by the human use of the land.

2.1.2. General guidelines for a satisfactory LCA-method

In the elaboration of the criteria for satisfactory methods to include climate impacts of land use in LCA I characterize a satisfactory LCA method by a set of general guidelines. The guidelines are divided into three principles around which the thesis is structured.

Principle 1. A consistent method

Environmental impacts should be attributed to products based on causality

- Guideline 1.1. The assumptions used should be in line with empirical data as well as fundamental theories and hypothesises of natural science
- Guideline 1.2. The methods should have a set of assumptions and value judgements that is internally consistent
- Guideline 1.3. The assumptions should reflect conditions and define impacts that are relevant with regard to the purpose of the LCA
- Guideline 1.4. Whenever it is possible, compared scenarios should be designed in order to avoid allocation

Principle 2. A comprehensive method

An LCA should be comprehensive

- Guideline 2.1. The method should be comprehensive and include all mechanisms by which the areas of protection are affected by the studied production

Principle 3. A transparent and comprehensible study

An LCA should be transparent and comprehensible

- Guideline 3.1. An LCA should enable the reader to understand the impacts of the studied product with regard to the reader's personal value system

The general guidelines are not strict demands on an LCA, but rather general aims, or guidance in development or evaluation of LCA methodology. Full compliance might not always be possible and strict minimum requirements have to be developed for different contexts.

2.2. Construction of examples used in the analyses

In the analyses and discussions I use illustrations of hypothetical developments of carbon stocks and their contribution to atmospheric CO_2 content and calculation examples of the climate impact of two different agricultural products: field beans cultivated in Sweden and soy bean meal cultivated in Brazil and imported to Sweden. Those illustrations and calculation examples have been constructed according to the principles described in the following sections.

2.2.1. Carbon stock modelling in illustrations and calculation examples

Since all examples are used to illustrate fundamental principles that can be discussed regardless of quality of the modelling of the carbon stock dynamics, I settle with a carbon stock modelling built on assumptions of constant carbon stock levels during alternative steady states which are connected by immediate losses and constant build up rates. And ignore potential storage of carbon in products.

In the calculation examples where impacts on carbon stocks are quantified the data is taken from Müller-Wenk and Brandão (2010), see Table 1.

Table 1. Data from Müller-Wenk and Brandão on Carbon Transfer from a land transformation to cropland (CT), Annual Carbon Storage during land relaxation after land has been abandoned (ACS) and the Relaxation Time for reaching steady state of potential natural vegetation (TR).

	CT (MgC/ha)	ACS (MgC/ha*year)	TR (year)
Tropical grassland	58	0.6	97
Tropical forest	151	2.5	62
Temperate forest	135	1.8	74
Boreal forest	150	0.6	238

2.2.2. Modelling of the contribution to atmospheric CO_2 content of impacts on carbon stocks

In this thesis, all modelling of the contribution of carbon stock changes to atmospheric CO_2 content is based on the Impulse Response Function (IRF) for CO_2, $CO_2(t)$, that is described in Forster et al. (2007) and is based on the Bern Carbon cycle Climate Model (BernCCM) version that is described in Joos et al. (2001):

$$\boldsymbol{C_{CO_2}(t) = 0.217 + 0.259 * e^{\left(\frac{-t}{172.9}\right)} + 0.338 * e^{\left(\frac{-t}{18.51}\right)} + 0.186 * e^{\left(\frac{-t}{1.186}\right)}} \qquad (1)$$

The IRF describes the response in atmospheric CO_2 levels following upon a pulse emission, assuming a constant reference level of 378 ppm and do not include the long term CO_2 dissipation mechanisms, which means that about a fifth (21.7%) of an emission is assumed to remain as a permanent addition to atmospheric CO_2[3].

[3] The IRF is also illustrated in Figure 3 on p. 24.

In cases where carbon stocks build up after abandonment of a piece of land, this build up is divided into yearly "pulses" of sequestrations, and the IRF is applied also on these sequestration pulses. Kirschbaum (2006) and Cherubini et al. (2011) have used the IRF of the BernCCM in principally the same way. The IRF is, however, not designed for sequestration flows and the accuracy of this procedure is discussed further in the section 4.11.1 "Modelling of the contribution to atmospheric CO_2 content of changes in carbon stocks" in the discussion.

2.2.3. Calculation example with field beans and soy bean meal

In order to illustrate how the choice of time horizon and climate impact indicator can affect the comparison of the impacts of different products I use a calculation example with field beans cultivated in Sweden and soy bean meal cultivated in Brazil and imported to Sweden. The example builds on the LCA of Flysjö et al. (2008). I have not prioritized to evaluate if the method that Flysjö et al. used to include the climate impacts of land use is satisfactory. Instead the climate impacts of land use is subtracted from the results of Flysjö et al. after which new climate impacts of land use, which are calculated according to a modified version of the method of Müller-Wenk and Brandão (2010), are added. See section 3.2.3 for a description of the original Müller-Wenk and Brandão method and section 3.2.3.2 and Annex I, Modifications of the method of Müller-Wenk and Brandão for a description of the modifications. In Flysjö et al. the results for field beans are reported for three different regions and in this thesis the data on field beans from region east is used.

The field beans are assumed to be cultivated in a temperate forest area and the soybeans are assumed to be cultivated in 60 % tropical forest and 40 % tropical grassland areas.

The calculation examples are reported both in CO_2-eqs and in CO_2 ton year-equivalents (CO_2 ton year-eqs) and over time-horizons up to 2500 years. The methods for calculation the GWP of N_20 used for the reporting in CO_2-eqs and for transforming the results into CO_2 ton year-eqs are described in the sections below.

Emissions of GHGs other than CO_2 and N_20 are small over a 100 yrs time horizon (1.1 % of total emissions for soy beans and 0.15 % of total emissions for field beans) and neglected for other time horizons and in the ton-year reporting.

2.2.3.1. GWP-calculation

The GWP of N_2O is calculated according to Forster et al. (2007), as the ratio of the Absolute Global Warming Potential (AGWP) of N_2O and the reference gas, CO_2:

$$GWP_{N_2O} = \frac{AGWP_{N_2O}}{AGWP_{CO_2}} = \frac{a_{N_2O} * \int_0^{TH} [C_{N_2O}(t)]dt}{a_{CO_2} * \int_0^{TH} [C_{CO_2}(t)]dt} \quad (2)$$

Where a_i is the radiative efficiency of the gases and $C_i(t)$ is the time dependent fraction that remains in the atmosphere of hypothetical one kg emissions that occur on a reference of constant concentrations,
$C_{CO_2}(t)$ is the same IRF function as described above in the section "Modelling of the contribution to atmospheric CO_2 " (equation 1),

$C_{N_2O}(t) = e^{\frac{-t}{114}}$,
$a_{N_2O} = 0.00303$ (W m^{-2} ppb^{-1}) and
$a_{CO_2} = 0.00001413$ (W m^{-2} ppb^{-1}).

2.2.3.2. Transformation of CO_2-eq to CO_2 ton year-eqs

In the discussion about a comprehensible reporting of LCA and the climate impact indicator I compare the CO_2-eq with a CO_2 ton year-eq climate impact indicator in an attempt to capture how different climate impact indicators might affect the readers focus on different time horizons.

Ton year units have been discussed in relation to carbon dioxide emission offsetting through carbon sequestration projects within the IPCC and the UN climate negotiations (IPCC 2000; Korhonen et al. 2002). Korhonen et al. discuss two varieties of carbon ton-years: “C tonne-years absent from atmosphere”, which measure the time-integrated impact on atmospheric CO_2 content, and “tonne-years in C stock”, which measure the time-integrated impacts on carbon stocks in soil and vegetation. In this thesis these measures are renamed atmospheric ton-years and carbon stock ton-years. The CO_2 ton year-eqs that I calculate are equivalents to the atmospheric ton-years (and measured in CO_2 tons, not tons of carbon). In the emission offsetting discussion, the focus has been on transforming the ton-years into CO_2-eqs for comparison with other emissions. Here, however, I transform the CO_2-eqs of other emissions into CO_2 ton year-eqs.

The CO_2 ton year-eqs exerted by an emission is calculated as the AGWP of the emission divided by the radiative efficiency of the reference gas CO_2. This could be described as a multiplication with “ton year-GWPs” that relate to the traditional GWPs as is described in equation 3:

$$GWP_i * \int_0^{TH} \left[C_{CO_2}(t)\right] dt = \frac{a_i * \int_0^{TH} [C_i(t)] dt}{a_{CO_2} * \int_0^{TH} [C_{CO_2}(t)] dt} * \int_0^{TH} \left[C_{CO_2}(t)\right] dt = \frac{AGWP_i}{a_{CO_2}} = ton\ year\ GWP_i \quad (3)$$

2.3. The evaluation of suggested methods

I interpret the evaluated methods based on the mathematical procedures in the methods and the definitions used in this thesis.

In some cases, the definitions and mathematical procedures are not enough to unambiguously interpret how the scenarios of a method look. I have tried to interpret the methods so that the scenarios are in accordance with the criteria. When a method can be interpreted in different ways so that each interpretation contradicts different criteria, I discuss the reasonable alternative interpretations I can see.

This method for interpreting the evaluated methods leads to that my interpretation sometimes contradicts statements in the original descriptions of the evaluated methods.

3. Analysis and results
The analysis and results is divided in four main sections:

In section 3.1 I elaborate criteria based on the guidelines pertaining to the principle "**A consistent method**".

In section 3.2 I apply the criteria from section one in an evaluation of the consistency of a few suggested methods. This evaluation serves several functions: to exemplify how the criteria may be interpreted and used, to guide me in the choice of a method to use in the examples in the latter sections of the thesis and to analyse the usefulness of the evaluated methods. (It has also been a part in the method of elaborating the criteria, which have existed in several preliminary versions that has been abandoned as I have not found them to function well enough in the evaluation. This iterative trial and error analysis has been left out from the report for enhanced readability.)

In section 3.3 I elaborate criteria based on the guideline pertaining to the principle "**A comprehensive method**"

In section 3.4 I elaborate criteria based on the guideline pertaining to the principle "**A transparent and comprehensible study**"

There is no evaluation of suggested methods with regard to the second and third principle. This is because I think that the criteria that are based on these principles is easier to interpret and/or are exemplified in the examples I use in the elaboration of the criteria.

3.1. Principle 1: A consistent method
In this section I elaborate criteria for satisfactory methods to include climate impacts of land use based on the guidelines pertaining to the principle "**A consistent method**". I first identify which assumptions that have to be made in the assessment of climate impacts of land use in LCA. Then I discuss and elaborate criteria based on each of the guidelines pertaining to the principle, guideline by guideline.

3.1.1. Identification of necessary assumptions
When land use is considered in an LCA it is because a part of the studied product depends on land use. The impact of this land use is an environmental impact that should be assessed according to the definition of an environmental impact, as the difference between a scenario in which the land use interventions required to derive the studied product occur (a studied scenario), and a scenario in which these land use interventions do not occur (a reference scenario).

The design of the compared scenarios will often depend on a number of assumptions, e.g. concerning which land that is assumed to be used/affected and concerning the carbon dynamics on the used land. All those assumptions could vary largely depending e.g. on which level of simplification that is used or which generality that is desired.

Though one can design the compared scenarios in different ways, there are some aspects related to the land use that will have to be considered. First and foremost there are the functions provided by the land (for example agricultural yields) and the environmental aspects considered. As the impacts on the studied environmental aspects are mediated through the land use interventions (e.g. ploughing and harvesting) used to derive the studied product, the land use interventions are at least indirectly considered.

All of the aspects mentioned above depend on each other, but also on the properties of the land that is assumed to be used. The study could concern the use of any land area, from a specific field or farm to global land use patterns. There are many ways to decide which land, or type of land in hypothetical/general cases, that should be assumed to be used. Which way to choose could be more or less clearly guided by the purpose of the study, but can also be a matter of arbitrary choices[4]. As I aim at developing criteria that are relevant for any LCA I do not go into assumptions needed to design the details in the compared scenarios but focus on the most fundamental assumptions and how one should make sure to stick to the assumed scenarios in a consistent way.

In summary, one has to assume a reference and a studied scenario, each describing the services derived from the affected land and the development of the considered environmental aspects. These assumptions require assumptions of the land use interventions needed to derive the services and of the properties of the used land that one has to know in order to model the development of the relevant environmental aspects and e.g. yield levels in the case of agricultural production.

3.1.2. Analysis of the implications of the guidelines

3.1.2.1. Guideline 1.1: The assumptions used should be in line with empirical data as well as fundamental theories and hypothesises of natural science

There is one scientific theory that is relevant for all assumptions concerning the alternative developments of a piece of land: ecological succession. If land is not managed it will develop on its own according to theories about ecological succession. In many cases this means that land that is abandoned with time would approach a state that is similar to what was the state before the land was used. This is however not always the case, and for example increased erosion during land use could cause the climax following the ecological succession to deviate from the state that preceded the use.

3.1.2.2. Suggestion of criteria 1

1. All scenario design should be consistent with theories of ecological succession.

[4] I believe, however, that even when there is no consistent guidance from the purpose and choices are arbitrary, many LCA practitioners will construct some arguments (based on implicit and subconscious points of departure) that imply that the chosen assumptions are the one and only right combination of assumptions anyway. Probably I haven't managed to completely eliminate such elements in this thesis either.

3.1.2.3. Guideline 1.2: The methods should have a set of assumptions and value judgements that is internally consistent

The elaboration of criteria based on Guideline 1.2 builds in large part on the definitions of LCA and of environmental impacts. According to these definitions an LCA is made to assess a plausible environmental impact of a product, and an environmental impact is defined as the difference between two scenarios. Thus, an LCA is made to describe the difference in the environmental parameters of two compared scenarios. As it is the difference between the scenarios that is of interest, the compared scenarios may be implicit, any absolute value of specific parameters in the scenarios may be unknown and there could be an unlimited number of combinations of possible scenarios that could render the specified environmental impact of the product in a particular LCA. However, all assumptions in an LCA say something about a scenario and/or of the relation between the compared scenarios. In this way all assumptions are connected and may be consistent or inconsistent with each other (see Figure 2). Thus, all assumptions in an LCA are pieces in the puzzle that defines the difference between the two compared scenarios and, according to the guideline, all pieces should fit together and define a consistent picture.

The assumptions concerning land use and development of used land in the compared scenarios are connected to the assumptions about other activities that are assessed in the LCA through the aggregation of impacts (see Figure 2). In LCA the climate forcers considered are normally only emissions of GHGs (the need to include also other climate forcers are addressed in section 3.3 "Principle 2: A comprehensive method"), which are aggregated through their respective GWPs into carbon dioxide equivalents. As described in section 2.2.3.1, the GWP builds on a comparison of the AGWP of pulse-emissions on constant reference levels of the atmospheric concentrations[5] up to a specified time-horizon, normally 100 years, after which further impacts of the emitted gases are ignored (see Figure 3). As the assumptions in an LCA should be internally consistent, the assumption of a permanent pulse emission in the GWP calculation require that the CO_2-implications of land use are caused by an instant and permanent decrease in carbon stocks in the studied scenario in relation to the reference scenario, which normally is achieved through an assumption of a permanent land use change. Through the assumed permanency of the decrease in carbon stocks emerges a connection between the development of the land in the compared scenarios and the GWP time-horizon. For as long the studied land use is assumed to have an impact on carbon stocks and atmospheric CO_2 content, i.e. up to the GWP time-horizon, the scenarios must be designed to match this with a permanent decrease in carbon stocks. If one do not assume e.g. a desertification process that prevent a recovery of vegetation and carbon stocks, this means that the land use in the studied scenario will have to continue up to the time-horizon, while no land use occurs in the reference scenario. As all aspects (derived services, carbon stocks and other environmental aspects and land use interventions) within a scenario

[5] It could be hard to construct a completely consistent set of assumptions including these constant reference levels of the atmospheric concentrations of GHGs, but I believe it is of minor importance for the results of an LCA and think that it is a deviation from the guideline that is acceptable.

should be consistent, this also means that one have to consider a permanent continuous difference in derived services from the land between the two scenarios. These connections are generalized and condensed into criteria 3 and 4 below.

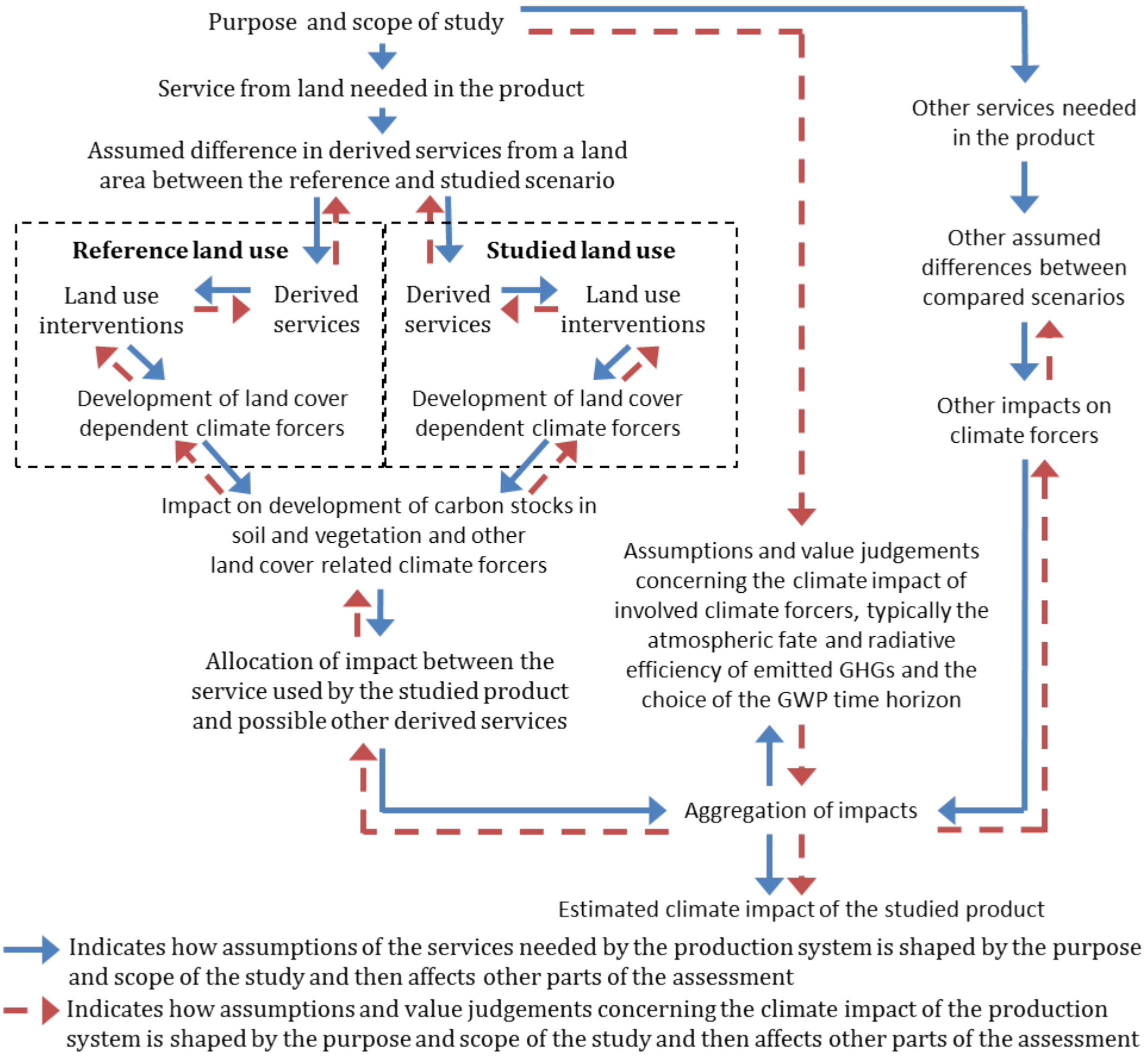

Figure 2. The figure illustrates the connections between different assumptions that are made in an LCA involving land use. The aggregation of impacts connects the assumed land use in the compared scenarios with the assumptions in other parts of the assessment. Important to notice is how the assumptions and value judgements concerning the involved climate forcers and the difference in derived services from land use are interdependent. This interdependency means that if GWPs are used to aggregate CO_2-emissions from land use with other emissions, then this requires that the compared scenarios are designed in order to render a comparable emission (i.e. an instant and permanent decrease in carbon stocks in the studied scenario relative to the reference scenario), which normally is achieved through an assumption of a land use change. As the scenarios should be internally consistent, such an assumed permanent difference in land use has to be matched by a permanent difference in derived services. Furthermore, all of the services derived up to the GWP time horizon should be acknowledged in the allocation of the emission caused by the land use change.

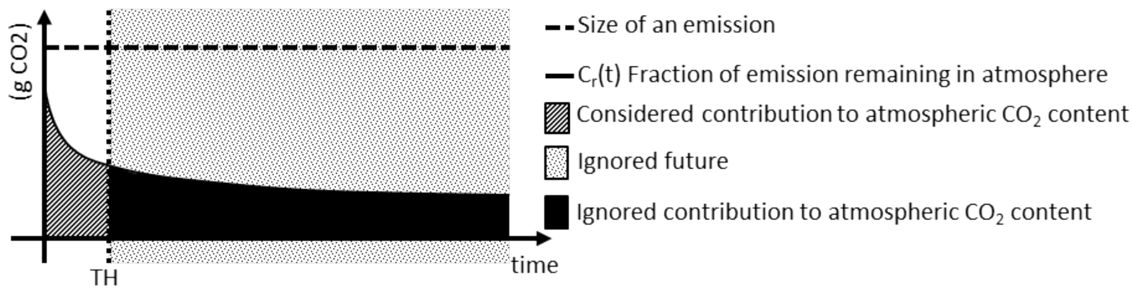

Figure 3 An illustration of the impulse response function of the Bern carbon-cycle climate model used in the GWP-calculation and a time horizon of 100 years. A 100 year time horizon means that most of the impact of a CO_2 emission on atmospheric composition is ignored.

If two connected aspects of a scenario are not modelled over the same time horizon it is not possible to know whether they are consistent over the time period that only one of them is modelled. This leads to criteria 2 below.

One does not have to assume permanent emissions from land use changes. It is also possible to assess the impacts of delimited land use periods and interventions that cause temporary emissions (i.e. emissions that are reversed as the land is assumed to recover after the land use) as is done by Müller-Wenk and Brandão (2010). Though the elaboration of the criteria is based on the example of the assumptions of permanent emissions, the criteria is applicable to both cases.

3.1.2.4. Suggestion of criteria 2-4

2. All aspects of the scenarios and impacts that are part of the method should be modelled over the same time horizon.

3. The assumed development of carbon stocks and other climate forcing aspects of the land, the land use interventions, and the derived services from the land should be consistent throughout the whole time horizon in all scenarios in the assessment.

4. The assumed difference in the development of carbon stocks and other climate forcing aspects of used land between two compared scenarios should be consistent with the climate impact that this difference is assumed to cause.

Comment to criterion 4: When impacts (emissions) are aggregated with the use of their GWPs the assumptions concerning the climate impacts are the sizes of the emissions, the radiative efficiency and the development of the atmospheric fraction of emitted gases. The latter two are used in the calculation of the GWP and entail a specific development of the gross cumulative radiative forcing exerted by the emitted GHGs, which could be considered to be the climate impact that is referred to in criterion 4. All these aspects should be consistent with the assumed difference in the development of carbon stocks and other climate forcing aspects of used land between two compared scenarios. In section 3.2 it is provided examples of how the criterion can be applied in the evaluation of some suggested methods.

3.1.2.5. *Guideline 1.3 The assumptions should reflect conditions and define impacts that are relevant with regard to the purpose of the LCA*

When one assesses land use that takes place on land that already has been used for some time, one could assume different reference scenarios. Either one assumes a reference scenario that deviates from the land use in the studied scenario at the time of the first use of the land (a reference for a historical decision as is used e.g. in PAS2050 (BSI 2011)), or a reference scenario in which the land is used as in the studied scenario up to the first land use involved in the studied product, but then is abandoned (a reference for a contemporary decision, as is used by e.g. Müller-Wenk and Brandão (2010) and Schmidinger and Stehfest (2012)). Figure 4 illustrates an example of the two types of scenarios.

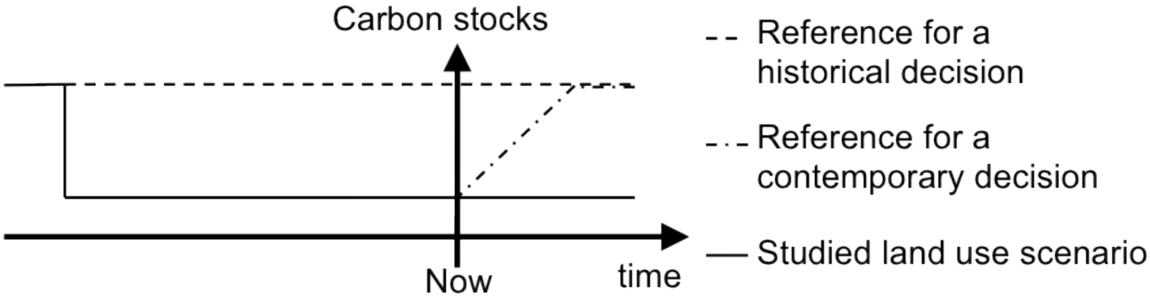

Figure 4. For the same studied scenario of a land use that has been going on for some time, one could assume different reference scenarios (in which the land use do not take place). In this figure is shown one reference scenario in which the studied land use never begun (a reference scenario that describes the impact of the historical decision of starting the land use) and one scenario in which the land use stops (a reference scenario that describes the impact of the contemporary decision to continue the land use). In general the relevant scenarios in LCA are scenarios that describe the impact of contemporary decisions.

What is relevant in an LCA are impacts of decisions that are made in association to the studied product. These decisions may be between taking new pristine land into use or leaving it pristine, a change from one land use to another, between continuing a land use or abandoning the land, between two different uses of the same derived service from the land or any combination of the above. In any case, the relevant impacts are impacts of decisions in which the studied product, or a service that is used in the studied product, is a governing factor.

3.1.2.6. *Suggestion of criteria 5*

5. The land use in the compared scenarios should be identical up to the first land use intervention that would not have been carried out, had it not been for either the demand for the studied product or a decision to derive a service that is used in the studied product from a piece of land.

Comments:
In LCAs of generalized or in other ways hypothetical products, there is a hypothetical history of the used land, but this hypothetical history could be whatever one assume it to be. The criterion does thus not provide a general guidance on what state the land should be assumed to be in at the time of the divergence of the compared scenarios, as this is dependent on the purpose of the study, and in some cases may be a more or less arbitrary decision.

3.1.2.7. Guideline 1.4 Whenever it is possible, compared scenarios should be designed in order to avoid allocation

In this section I discuss the general guideline "Whenever it is possible, compared scenarios should be designed in order to avoid allocation" and how it relates to the handling of land use in LCA.

I see two types of situations where this guideline is relevant:

- When one could, but do not have to, derive more than one kind of service from a piece of land during the same land use period
- When one assesses land use in the form of land use changes instead of separate land use interventions or delimited land use periods

The first type of situation could e.g. concern allocation between grains and straw. As straw doesn't have to be, and often is not harvested, the impacts of the grain and straw harvest could be assessed separately as in Figure 5, where the impact on carbon stocks of the cultivation and harvest of grain is defined by a scenario in which only grain is harvested (scenario B) and a scenario where the land is abandoned (scenario C), while the impact of the harvest of straw is defined by a scenario in which both grain and straw is harvested (scenario A) and the scenario in which only grain is harvested (scenario B). Another example is the harvest and allocation between timber, slash and stumps. In both of these cases the guideline implies that the harvest of the different parts should be assessed separately. There could be cases, however, when the by-harvest is necessary in order to create profitability or in other ways is essential for the land use required for the primary harvest. In such cases it could be motivated to allocate also a part of the impacts from the land use interventions required for of the primary harvest to the by-harvest.

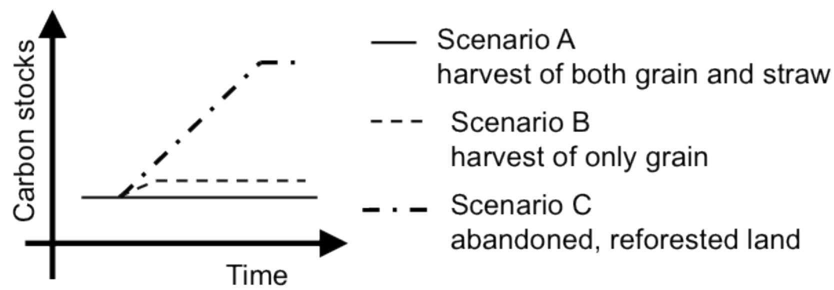

Figure 5. An illustration of scenarios that could be used to assess the climate impact of the land use in the cultivation of grain and associated harvest of straw. The starting point in all scenarios is land where straw has been harvested every time there has been grain cultivation in the crop rotation. In scenario A this land use continues. In scenario B the same crop rotation continues, but with the cease of harvest of straw and a subsequent small increase in carbon stocks. In scenario C the land is abandoned followed by reforestation and a large increase in carbon stocks. The impact of the cultivation of grain is assessed with scenario C as the reference scenario and scenario B as the studied scenario. In the assessment of the impact of the harvest of straw, scenario B turns into the reference scenario and scenario A is the studied scenario.

In contrast, allocation procedures that are independent of the land use interventions such as allocation between soybean meal and soy oil, which are separated in processes taking place after the harvest, is not possible to assess separately and is thus not concerned by the guideline.

The other type of situation where the guideline is relevant is when one assesses land use as land use changes instead of separate land use interventions or limited land use periods. A land use change is generally assumed to be a process that causes a single initial emission, but over time continuously derives services from the used land. The attribution of parts of an emission from a land use change to a product is thus a form of allocation procedure. An amortization of an emission from a land use change could thus also be described as an allocation procedure performed with the usage of allocation factors, as in the following interpretation of the British standard PAS2050: According to PAS2050 a CO_2 emission from a land use change should be amortized over the first 20 years of land use following the land use change; the first 20 years of land use is in this case attributed an impact by an allocation factor of 0.05 $(1/20 = 0.05)$ while subsequent years of land use is attributed an impact by an allocation factor of 0.

However, there are also ways to compare the transient impacts on carbon stocks in soil and vegetation with permanent emissions without the detour of the assumption and allocation of a permanent emission of a land use change to the specific land use period of interest. One alternative could be taken from the discussion on reforestation and afforestation in the Clean Development Mechanisms (CDM) of the Kyoto protocol and other emission offsetting where it has been suggested to measure the CO_2-implications of land use in the time integrated unit ton-years (IPCC 2000; Korhonen et al. 2002). In an LCA context Müller-Wenk and Brandão (2010) have suggested a method in which they translate the temporary impacts on carbon stocks in soil and vegetation into "fossil-combustion-equivalent tons of carbon" (fCeq) via a duration factor that is calculated as the ratio of the carbon stock ton-years of the land use impact and the atmospheric ton-years of a fossil fuel reference emission[6].

According to the guideline "Whenever it is possible, compared scenarios should be designed in order to avoid allocation" one could argue that one should avoid any assumptions of land use changes and always make assessments of delimited land use periods or interventions by methods similar to that of Müller-Wenk and Brandão. However, if one wants to enable the handling of CO_2-implications of land use as permanent pulse emissions, one have to allow assessments of the impacts of land use as parts of impacts of land use changes. I therefore suggest that one may make assumption of land use changes if one base the allocation on estimates of the impact of the delimited land use periods or interventions studied, as this will render results that are similar to if one assess the impacts of the delimited land use periods or interventions directly.

[6] As discussed further in the evaluation of the Müller Wenk and Brandão method (p. 37) this is a skewed comparison; a consistent comparison would be to compare either the carbon stock ton-years of both land use and reference emission, or the atmospheric ton-years of both.

3.1.2.8. Suggestion of criteria 6

6. If one allocates impacts of a land use period that provides services of which the land use impacts could be assessed separately by dividing the land use period into separate sub-periods and/or interventions, then one should use allocation factors that are based on a comparison of the impacts of the separate sub-periods and/or interventions.

Comments:
The impact of delimited land use periods can be calculated in different ways. Basing allocation factors on the impact of delimited land use periods can be done in even more ways. The simplest way to define an allocation factor to one year of land occupation would be to state that the impact of each year of occupation will be the same. This render an allocation factor of 1/TH (where TH is the time horizon of the assessment) for each year of occupation, which in practice is the method applied by Schmidinger and Stehfest (2012). One could argue against this procedure as it is somewhat inconsistent with regard to the time-horizon, which I will discuss further under section 3.2.2 Schmidinger and Stehfest.

An allocation factor for a studied land transformation or a land occupation period could be calculated as the impact of the transformation or occupation period divided by the impact of the land use change. This is a procedure that in practice is the same as the calculation of the duration factor of the Müller-Wenk and Brandão method, if it is adjusted to consistently use either the atmospheric or the carbon stock ton-years.

3.2. Examples of how the criteria can be used to evaluate the consistency of some suggested methods

3.2.1. The British standard PAS2050

PAS2050 (BSI 2011) is a specification from the British Standards Institute on how to assess the carbon footprint of goods and services. According to the specification, carbon footprinting should include assessments of direct land use changes and amortize emissions from land use changes over the first 20 years of the subsequent land use following the change. The climate impact indicator is CO_2-eqs using GWP_{100} characterization factors.

In the specification a land use change is defined as a “change in the purpose for which land is used by humans (e.g. between crop land, grass land, forest land, wetland, industrial land).” There are no remarks about the transient character of impacts of land use in the specification. I therefore interpret the term as including an assumption of a permanent shift from one use to another, rendering a permanent shift in the properties of the land, from one steady state of carbon stocks to another and from one continuous provision of services (e.g. crops, timber, biodiversity and aesthetic values) to another. An example of how a land use change from unused forest to agricultural land would be assessed according to the specification is illustrated in Figure 6.

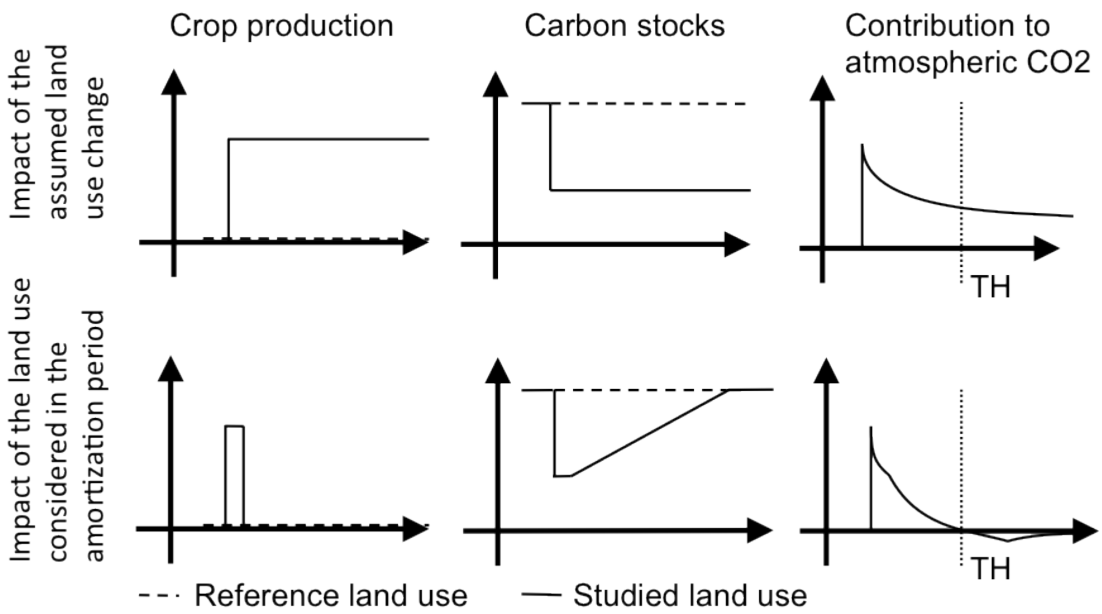

Figure 6. Illustration of the assessment of land use changes according to PAS2050. The top row shows the assumed development of crop production and carbon stocks in the reference and studied land use and the contribution to atmospheric CO_2 content that is associated to a land use change. The bottom row shows how the same parameters would develop (presuming ecological succession is able to restore the carbon stocks to the state preceding the initial land use change) if the new land use lasted only for the first 20 years to which the impact is allocated according to the standard. The difference between the rows shows that an attribution of the full impact of an assumed land use change to only 20 years of production is inconsistent with the principle "A consistent method".

3.2.1.1. Accordance of the method with the criteria

1) All scenario design should be consistent with theories of ecological succession.
   - One could perhaps interpret the specification in different ways, but I interpret it as assuming a permanent land use in the studied scenario, which permanently prevent the typical ecological succession towards a "natural" climax. The criterion is thus fulfilled.

2) All aspects of the scenarios and impacts that are part of the method should be modelled over the same time horizon.
   - As I interpret the specification's definition of a land use change, the carbon stock changes and the provision of services by the land are both assumed to be permanent, lasting at least up to the GWP_{100} time horizon. According to this interpretation the criterion is fulfilled. As emissions are amortized only over 20 years of land use following the land use change, one could possibly also interpret the method as assessing only 20 years of provision of services. However, when considering cases in which the land use change occurred more than 20 years before the studied production, the land still produces services after those 20 years. Thus, I think the reasonable interpretation is that also the provision of services is assumed to be permanent, and the criterion is fulfilled.

3) The assumed development of carbon stocks and other climate forcing aspects of the land, the land use interventions, and the derived services from the land should be consistent throughout the whole time horizon in all scenarios in the assessment.

- I interpret the land use change as a permanent change. Thus, the derived services and carbon stock development during the following 80 years up to the GWP time horizon are also modelled though those services are not attributed any part of the impact. The land use interventions could also be said to be implicitly modelled during all 100 years, while only the ones belonging to one cropping season are mentioned, as that is all that is needed to allocate the proper impact to one unit of the studied product. I consider the criterion fulfilled.

4) The assumed difference in the development of carbon stocks and other climate forcing aspects of used land between two compared scenarios should be consistent with the climate impact that this difference is assumed to cause.
   - In cases when the land from which the services used by the studied product is derived underwent the land use change before the studied production takes place, I can not see how the time-horizons over which the impacts are assessed should be defined. I can therefore not judge if the criterion is fulfilled in these cases (see also criterion 5 below). However, for assessments of contemporary land use changes the criterion is fulfilled.

     According to the standard one should aggregate climate impacts by the GWP_{100} of the emitted GHG. This means that the assumed climate impact of the difference in carbon stock development between compared scenarios includes the cumulative radiative forcing exerted over 100 years by permanent pulse emissions of CO_2 from the studied land use changes. One could make two interpretations of the carbon stock modelling that are consistent with this impact, either that temporal detail is omitted[7], or that carbon stocks are assumed to drop instantly at the land use changes. Either way, the method could be criticized for the simplifications concerning the carbon stock modelling, but the criterion is fulfilled for assessments of contemporary land use changes.

5) The land use in the compared scenarios should be identical up to the first land use intervention that would not have been carried out, had it not been for either the demand for the studied product or a decision to derive a service that is used in the studied product from a piece of land.
   - The only types of land use changes that are described in the specification are land use changes from land not in use to land in different types of use. Thus, the criterion is only fulfilled in cases when the studied product relies exclusively on land that has not been used before the land use that provides services to the studied product is initiated.

6) If one allocates impacts of a land use period that provides services of which the land use impacts could be assessed separately by dividing the land use period into separate sub-periods and/or interventions, then one should use allocation

[7] Though if one omit temporal detail throughout the assessment one couldn't distinguish crop production that takes place before and after the 20 year amortization period, which is an argument for that the latter interpretation is the valid one.

factors that are based on a comparison of the impacts of the separate sub-periods and/or interventions.

- The land use change could be divided into shorter periods of land use that could be assessed separately, and attributing the full impact of a land use change that is assessed over a 100 year time horizon, to only 20 years of land use is not an allocation that is based on the proportion of the separate impacts (compare with Figure 6). The criterion is not fulfilled.

3.2.1.2. Possible adjustments to make the method satisfactory

As I interpret the method and the criteria, the method would be in accordance with the criteria if it coordinates the time horizon and the allocation of emissions from land use changes (e.g. by changing the amortization period to 100 years) and if it is used only in cases where it is suitable to assume that land use takes place on previously pristine land, while continuous land use should be assessed with assumptions of abandonment of used land in the reference scenario, as in the method of Schmidinger and Stehfest (2012).

3.2.2. Schmidinger and Stehfest

Schmidinger and Stehfest (2012) suggest a set of assumptions in which there is a decrease in production in the reference scenario, while the production continues at the same rate in the studied scenario. This means that there is a continuous land use in the studied scenario, while the used land is abandoned in the reference scenario. As vegetation recovers on the abandoned land in the reference scenario it sequesters carbon, and the lack of this sequestration in the studied scenario – the "missed potential carbon sink" – is considered equivalent to a CO_2 emission.

Schmidinger and Stehfest model the carbon stock development over three time horizons; 30, 50 and 100 years, and amortize the impact over the same periods. Schmidinger and Sthefest motivate the 100 year time horizon with that regrowing vegetation approaches a new equilibrium in about this time period, the 30 year time horizon with that it is a convention in biofuel studies and that the development over the coming 30 years are crucial for climate stabilization and the 50 year time horizon with that it is an intermediate between 30 and 100.

The climate impact indicator is CO_2-eqs using a GWP_{100} characterization factor, though this is explicit only in Blonk et al. (2008), from which Schmidinger and Stehfest adopt all data that do not concern the "missed potential carbon sink".

The study includes a complex modelling of land use patterns and carbon stock development, but I focus only on the fundamental assumptions; how land use is assumed to stop in the reference scenario and continue in the studied scenario, the time perspectives and the principles for allocating the impact of the studied land use to the services that are derived during the use. An illustration of the method is provided in Figure 7.

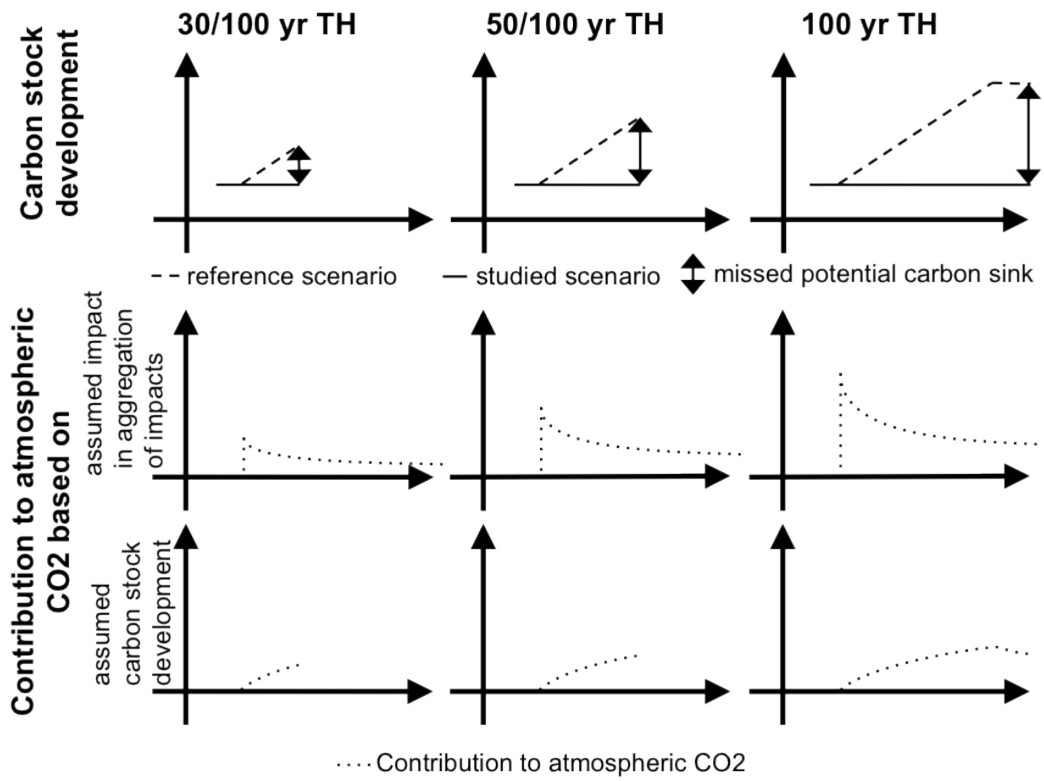

Figure 7 An illustration of the Schmidinger and Stehfest method applied in a hypothetical context. The top row shows the assumed carbon stock development in the studied and reference scenario and the missed potential carbon sink that is defined as the difference in carbon stocks between the two scenarios at the end of respective modelling period. The second row shows how the missed potential carbon sink is assumed to contribute to atmospheric CO_2 content in the aggregation with other GHG emissions into CO_2-eqs using the GWP_{100} characterisation factor. The bottom row shows the contribution to atmospheric CO_2 levels taking into account the timing of the carbon sequestration and stretching only as far into the future as the carbon stocks are modelled. The 30 and 50 year time horizons for the modelling of carbon stocks (and, though not included in the figure, yields) in row one are inconsistent with the 100 year GWP time horizon in row two, this inconsistency violates criterion 2 and makes it impossible to assess the accordance with criterion 4 for these inconsistent time horizons. There is also an inconsistency between the gradual carbon sequestration in the reference scenario (row one and three) and the assumption of a single pulse emission in the GWP-calculation (row two). This exaggerates the impact of the missed potential carbon sink, which is shown by a comparison of the single pulse emission in row 2 with row 3 in which the contribution to atmospheric CO_2 content is modelled with a temporal resolution of yearly pulses.

3.2.2.1. Accordance of the method with the criteria

1) All scenario design should be consistent with theories of ecological succession.
    - In the studied scenario there is a permanent land use and in the reference scenario, where land use ceases, the land is assumed to develop on its own. The criterion is fulfilled.

2) All aspects of the scenarios and impacts that are part of the method should be modelled over the same time horizon.
    - Schmidinger and Stehfest model carbon stocks over three different time horizons; 30, 50 and 100 years, and amortize the missed potential carbon sink over the same three time horizons, while in all cases the GWP is calculated using a 100 year time horizon. The inconsistent 30/100 and 50/100 year time horizons are in conflict with the criterion.

As the land is assumed to be used over the full time horizons in the studied scenario, one must assume that all land use interventions also occur throughout the time horizons. The land use interventions are, however, not explicitly modelled throughout the time horizon but related to a specific amount (a reference flow) of the studied products (e.g. a kg, or ton). I interpret the method so that the land use interventions are implicitly modelled during all 100 years, while only the interventions allocated to the reference flow of the studied products are explicitly modelled. In this aspect, I consider the criterion fulfilled for the consistent 100 year time horizon.

It is also worth noting that there is a problem concerning the determination of the allocation factors used to allocate the impact of the land use to yield of each year. The 1/TH allocation factors build on the assumption that each year of land use has approximately the same impact. This assumption requires that the impacts of each year of land use that follow upon the first year is assessed over periods that stretches further into the future than the time horizon of the main assessment (see Figure 8 A). One could thus object that the 1/TH allocation factors (or 20/TH as in the case of the 20 year occupation periods in Figure 8) apply different time horizons for every sub-period of land use and therefore contradict criterion 2. However, as the impacts of the sub-periods are assessed separately they all have their separate pair of compared scenarios, and one could argue that each sub-period in this case could be assessed by their own time horizon, from the point in time when the compared scenarios diverge for respective sub-period (Figure 8 B). And these time horizons are all the same in the sense that they are of the same length as the time horizon of the main assessment.

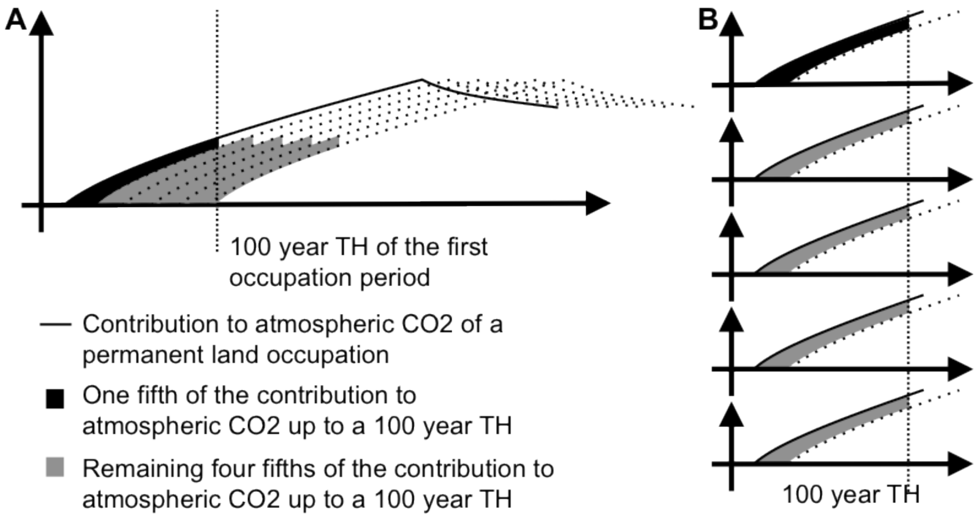

Figure 8. The figure shows the contribution to atmospheric CO_2 content of a permanent land occupation as a function of time (full line), taking the timing of carbon sequestration into account, and the impacts of five 20 year land occupation periods (delimited by dotted lines and the impact of the first period is indicated by the black area and the remainder of the periods are indicated by the grey area), each assessed over their own 100 year time horizon. One could argue both that the periods are assessed over the same time horizon (Illustrated in figure B), and by different time horizons (illustrated in figure A).

The objection against the 1/TH factor discussed above is based on the perspective on carbon stocks with a gradual build up in the reference scenario (see Figure 7 and discussion concerning criterion 4 below). If one switch perspective to the simplified view of the missed potential carbon sink as a single, cumulated and one-dimensional, mass of lost carbon sequestration, one loose the temporal detail on carbon stock development. If this loss of temporal detail also is applied on all production that takes place up to the time horizon, one can no longer discriminate between productions taking place at different times. From this perspective I find the 1/TH allocation factors to be the only reasonable allocation procedure, and I would rather illustrate the allocation of the impact as in Figure 9. I consider the criterion fulfilled.

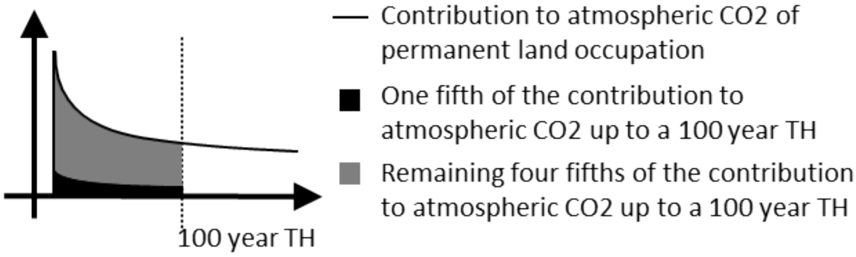

Figure 9. The figure shows the contribution to atmospheric CO_2 content of a pulse emission of CO_2, a 100 year time horizon, and how one fifth of the impact of the pulse emission up to the time horizon may be attributed/allocated to a 20 year sub-period of the time horizon.

3) The assumed development of carbon stocks and other climate forcing aspects of the land, the land use interventions, and the derived services from the land should be consistent throughout the whole time horizon in all scenarios in the assessment.
    - The criterion is only applicable on the consistent 100 year time horizon that passed criterion 2. Carbon stocks are assumed to be kept constant by a continuous land use in the studied scenario and to develop as vegetation regrow on abandoned land in the reference scenario. With the same reservations concerning the land use interventions as in criterion 2, I consider the criterion fulfilled.

4) The assumed difference in the development of carbon stocks and other climate forcing aspects of used land between two compared scenarios should be consistent with the climate impact that this difference is assumed to cause.
    - The carbon stock modelling is comprised of a constant level of carbon stocks in the studied scenario, in which the land use continues, and a build-up of carbon stocks in the reference scenario, where used land has been abandoned. While the carbon stock modelling is two-dimensional (including both a time and mass dimension), describing a gradual build-up of carbon stocks in the reference scenario, the impacts on carbon stocks are reported as one-dimensional masses of carbon (one for each studied time horizon), which is treated as single pulse emissions in the aggregation with other GHG emissions.

In the comparison with other greenhouse gases, the time dimension of the impact is both reintroduced and re-removed through the GWP-factors. If one compare what the contribution to atmospheric CO_2 content of the land use in the studied scenario would be if the time dimension was kept consistently with the contribution to atmospheric CO_2 content that is assumed in GWP-comparison, one can see that the removal and reintroduction of the time dimension has caused an inconsistency that exaggerate the impact of the land use in the studied scenario (Figure 7). The method is thus in conflict with the criterion.

5) The land use in the compared scenarios should be identical up to the first land use intervention that would not have been carried out, had it not been for either the demand for the studied product or a decision to derive a service that is used in the studied product from a piece of land.
   - Up to the point when the compared scenarios diverge in response to a decreased demand for the studied product in the reference scenario, the land is used in the same way in the two scenarios. The criterion is fulfilled.

6) If one allocates impacts of a land use period that provides services of which the land use impacts could be assessed separately by dividing the land use period into separate sub-periods and/or interventions, then one should use allocation factors that are based on a comparison of the impacts of the separate sub-periods and/or interventions.
   - Schmidinger and Stehfest amortize the missed potential carbon sink over all years of land use up to the time horizon. This is equivalent to a 1/TH allocation factor, which is in accordance with the criteria, presuming that each year of land use may be assumed to cause approximately the same impact (see evaluation concerning criterion 2 above).

3.2.2.2. Possible adjustments to make the method satisfactory
Criterion 2 is met by adjusting the GWPs according to each time horizon used in the assessment.

Concerning criterion 4, the inconsistency is due to that temporal detail (the time-dimension) first is lost when the impact is calculated as a one-dimensional missed potential carbon sink from the two-dimensional carbon stock modelling of the compared scenarios and then is reintroduced with a different assumption of the temporal profile of carbon sequestration in the GWP-calculation. The solution could be to either omit the temporal dimension from the beginning, or to maintain it throughout the assessment. This could be done either by consistently handle the measured parameters as functions of time (fully keep the temporal detail), or measure the impact in units that contain the time dimension, such as a ton-year unit (acknowledge the temporal dimension. However, both strategies have drawbacks.

Drawbacks with the strategy to maintain the temporal dimension:

1. It might make the 1/TH allocation factor inconsistent with criterion 2 (see the evaluation above) and regardless of interpretation, the 1/TH allocation factor will underestimate the impact of the first year of land use after the scenarios diverge. With this strategy it is therefore preferable to develop also the allocation factors.
2. It might induce new inconsistencies in relation to the assumed radiative efficiency and IRF of the BernCCM (which are both based on fixed conditions), which might be hard to make consistent with the changes assumed to occur in the reference scenario. However, if these potential new inconsistencies cannot be (or are not) solved, their effects on the result are probably negligible and they are not concerned by any of the criteria.
3. The CO_2-implications of land occupation can no longer be handled as emissions with the GWP 1 (this could be described as that one abandon the land use change concept (see section 4.5.2 The land use change concept). This entail a more complex modelling procedure.

Drawbacks with the strategy to omit the temporal dimension:

1. If one omits temporal detail, I don't think it would be consistent to distinguish different levels of carbon sequestration for the different time horizons, but only the change from the original to final steady state. If that is so, the loss of information concerning the gradual build-up of carbon stocks is worse, with regard to the consequences for the relevance of the result, than the original inconsistency was for time horizons shorter than the time it takes for the land to reach a new steady state after abandonment in the reference scenario (see Figure 10).
2. In cases when it is not reasonable to assume that carbon stocks reach a stable steady state (See section 3.3.2 Underlying processes that affect any of the climate forcing aspects of land), it could be difficult, or impossible, to model the carbon stocks in an appropriate way without inclusion of temporal detail.
3. GWP calculations are based on modelling of contribution to atmospheric content of emitted GHGs including temporal detail. Though this might not be concerned by the criteria, it is an inconsistent inclusion of temporal detail.

I find that the strategy to maintain the temporal dimension throughout the assessment is to prefer. However, if one wants to stick to the land use change concept, drawback number one of the complete omission of temporal detail (that it renders a result that is less relevant than an acceptance of the inconsistencies of the original method) raises the question of if the criterion should be rewritten, e.g. in order to focus only on the impact that is attributed to the studied product, rather than on the total impact that is defined by the compared scenarios. This is discussed further in section 4.5.2 "The land use change concept".

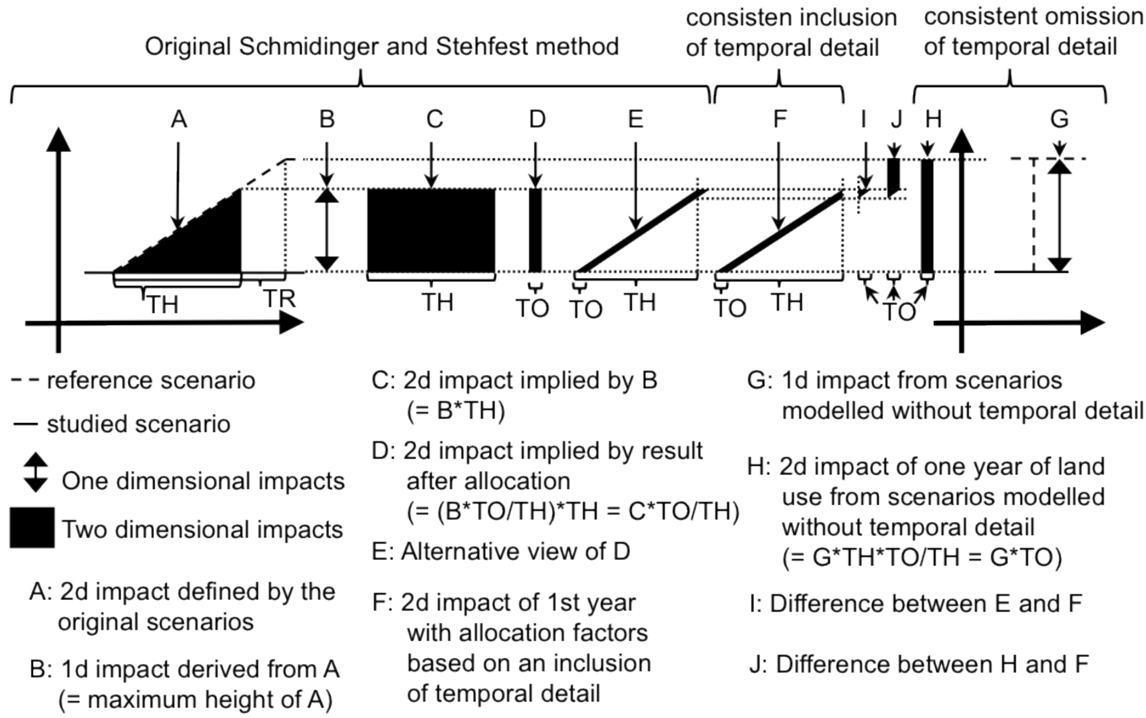

Figure 10. A graphical comparison of the original and suggested adjusted versions of the Schmidinger and Stehfest method, based on a simplified carbon stock modelling. The version with a consistent inclusion of temporal detail is assumed to provide the most accurate result (F), and the results rendered by the other versions (E and H) are compared to F (I and J). As I ≤ J for all TH, the original version of the method is assumed to provide more relevant results than the version that is adjusted with a consistent omission of temporal detail. In the right graph, the omission of temporal detail is illustrated by that the change from the state during the initial land use and the final state after abandonment of the land overlap along the time axis. This is drawn with inspiration from Figure 1.2.2.3.1 in the section "Main model simplifications" in Guineé et al. (2002).

3.2.3. Müller-Wenk and Brandão

Müller-Wenk and Brandão (2010) assess the impact of delimited land use periods and land transformation activities, instead of the common approach to assume permanent land use changes. The method builds on the UNEP-Setac framework described by Milà i Canals et al. (2007) and is made to assess the impacts of two standard types of land use activities: land transformation and land occupation. Assessments of impacts of delimited land use periods are enabled by assuming studied scenarios in which the land is abandoned and start to relax as soon as the studied land use (e.g. one cropping season) ends, see Figure 11.

By avoiding assumptions of permanent land use in the studied scenario, Müller-Wenk and Brandão avoid the delicate matter of deciding how to allocate the emission of a land use change to the land use period used for the studied production. However, the absences of the assumption of permanency of carbon stock changes also means that the CO_2-emissions of land transformations and missed potential carbon sinks caused by land occupation can not simply be summed with CO_2 emissions from fossil fuels. Therefore the CO_2 implications of land use is weighted with a duration factor (df) that compares the longevity of the impact on the carbon stocks on the used land with the time integrated contribution to atmospheric CO_2 of a reference CO_2 emission from fossil fuel combustion. The longevity of the impact on carbon stocks is calculated as TR/2 for land transformations and is equal to the occupation period for land occupation (see Figure 11 for definition of TR and occupation period). The contribution to atmospheric CO_2 of the reference emission is calculated as $\int_0^{500} C_r(t)dt$, where $C_r(t)$ is the impulse response function of the BCCM. The longevity of the land use impacts could also be expressed as $\int_0^{500} CD(t)dt$, where CD(t) is the carbon debt as a function of time and the carbon debt = carbon stocks in reference scenario - carbon stocks in studied scenario.

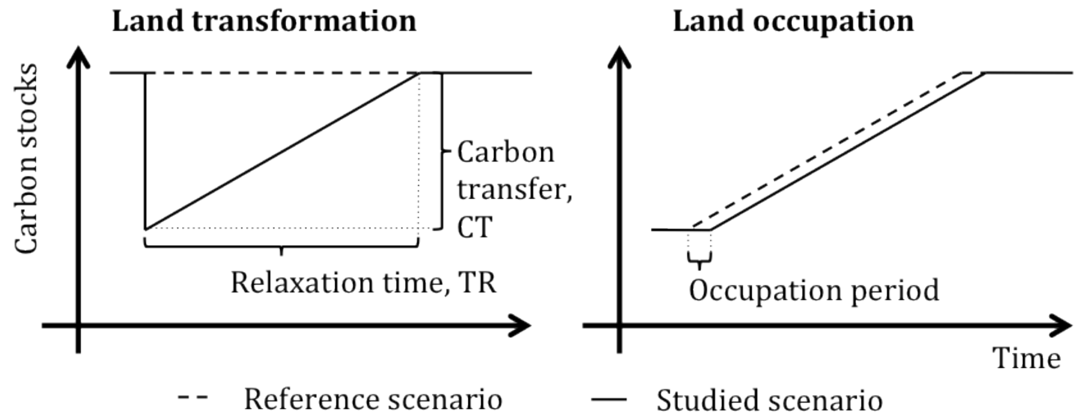

Figure 11. An illustration of the carbon stock development in the reference and studied scenarios that define the land transformation and land occupation impacts in the Müller-Wenk and Brandão method.

Müller-Wenk and Brandão express the impact of land use in "'fossil-combustion-equivalent' tons of carbon". The 'fossil-combustion-equivalent' tons of carbon may then be transformed into fossil-combustion-equivalent tons of CO_2 through a multiplication with the molar mass of CO_2 (44 g/mol) and division with the molar mass of C (12 g/mol).

3.2.3.1. Accordance of the method with the criteria

1) All scenario design should be consistent with theories of ecological succession
   - Fulfilled

2) All aspects of the scenarios and impacts that are part of the method should be modelled over the same time horizon.
   - Müller-Wenk and Brandão apply a 500 yr time horizon in the calculation of the df. The method is described on its own and not applied in an LCA. For the criterion to be fulfilled the method may only be used in combination with GWPs calculated with a 500 year time horizon.

3) The assumed development of carbon stocks and other climate forcing aspects of the land, the land use interventions, and the derived services from the land should be consistent throughout the whole time horizon in all scenarios in the assessment.
   - Fulfilled

4) The assumed difference in the development of carbon stocks and other climate forcing aspects of used land between two compared scenarios should be consistent with the climate impact that this difference is assumed to cause.

- The climate impact that the assumed difference in carbon stocks is assumed to cause could be represented by the cumulative radiative forcing or contribution to atmospheric CO_2 that the fossil-combustion-equivalent tons of CO_2 is assumed to cause in comparison to other GHGs with the use of their respective GWP.

  The duration factor is based on an inconsistent comparison of the time integrated carbon debt (that do not regard the dissipation of emitted CO_2) of the land use and the time integrated contribution to atmospheric CO_2 (that regards the dissipation of emitted CO_2) of the reference CO_2 emission (see example in Figure 12). This means that the assumed climate impact of land use is exaggerated (i.e. larger than what the assumed difference in carbon stocks could cause). The criterion is not fulfilled.

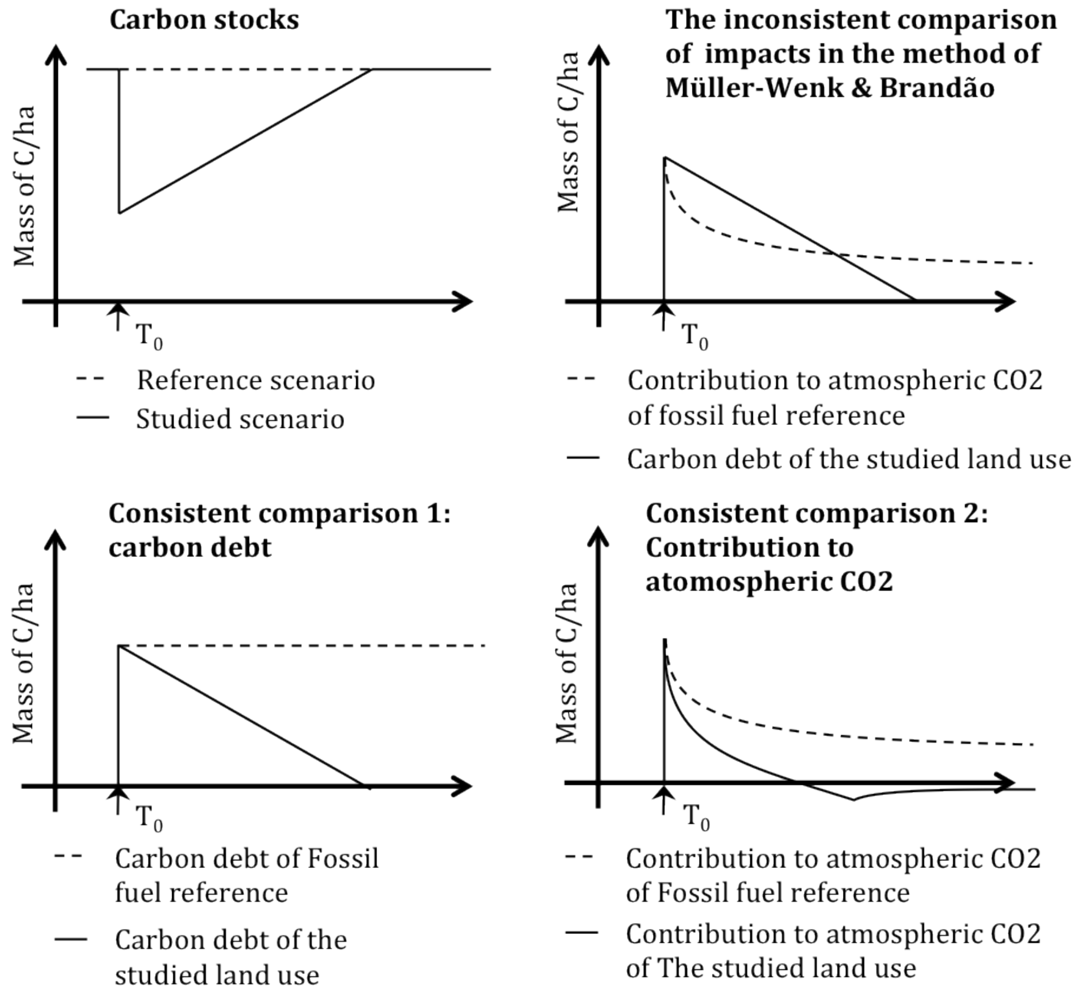

Figure 12. An example of a land transformation impact according to the Müller-Wenk and Brandão method and two ways to adjust the method for a consistent comparison of land use and fossil fuel derived CO_2. T_0 marks the timing of the land transformation.

5) The land use in the compared scenarios should be identical up to the first land use intervention that would not have been carried out, had it not been for either the demand for the studied product or a decision to derive a service that is used in the studied product from a piece of land.
   - The method assess the impacts of land transformations and delimited land occupation periods separately. The criterion is fulfilled for both kinds of

activities, and they can be combined in different proportion in order to reflect the extent to which a studied production is assumed to contribute to an expansion of land use (a land transformation is typically a preparation of land for a new use in association to an increase in production capacity, while land occupation typically is the land use during which services are derived from the land).

6) If one allocates impacts of a land use period that provides services of which the land use impacts could be assessed separately by dividing the land use period into separate sub-periods and/or interventions, then one should use allocation factors that are based on a comparison of the impacts of the separate sub-periods and/or interventions.
   - As the method assesses the impact of delimited land use periods no allocation is needed. The criterion is fulfilled.

3.2.3.2. Possible adjustments to make the method satisfactory

The inconsistent comparison of the time integrated carbon debt of the land use and the time integrated contribution to atmospheric CO_2 of the reference CO_2 emission in the calculation of the df can be adjusted in two ways (see also the example of a land transformation in Figure 12):

1. Compare the carbon debt of both the reference CO_2 emission and land use
2. Compare the contribution to atmospheric CO_2 of both the reference CO_2 emission and land use

Comparing the carbon debt is mathematically easier, but comparisons of the contribution to atmospheric CO_2 can be done e.g. according to the principles described in section 2.2.2. However, due to the precarious assumptions of this approach there is no guarantee that it increases the accuracy compared to the comparison of carbon debt.

Formulas for calculating the carbon stock ton-years based on the variables Carbon transfer, Relaxation time, Occupation period and Time horizon are given in Annex I, Modifications of the method of Müller-Wenk and Brandão. These formulas also enable the use of any time horizon.

3.2.4. ILUC-principles of Searchinger et al

Searchinger et al. (2008) assessed the climate benefits of substituting fossil fuels with ethanol produced from corn grown in the USA. The study includes a complex modelling of land use patterns, while I focus only on the fundamental principles, which are illustrated in Figure 13.

In addition to the results reported as emissions per functional unit (grams of CO_2 equivalents per MJ of energy in fuel) it is also reported payback times (i.e. the time it would take for produced fuel to offset the initial carbon release from land use changes through replacement of fossil fuels) under different scenarios. In the evaluation of the accordance of the method with the criteria below, I only consider the part of the study that reports emissions per functional unit.

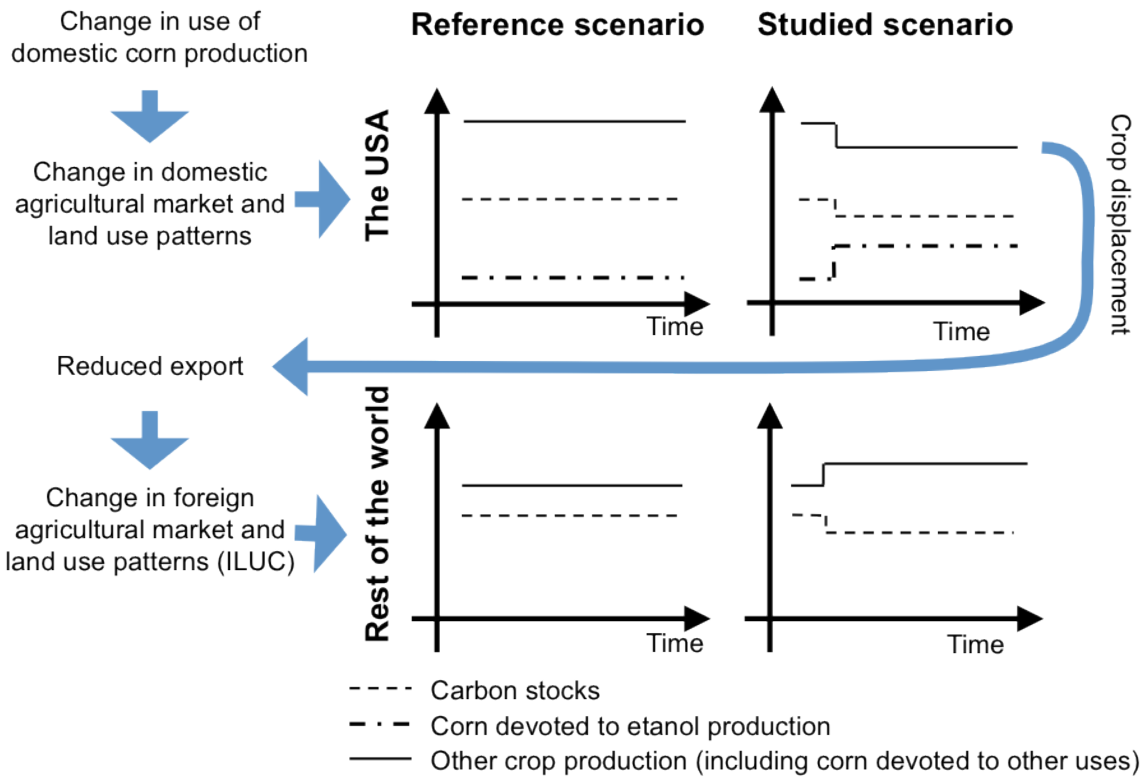

Figure 13. An illustration of the fundamental principles in the study of Searchinger et al. (2008), in which they assessed the climate benefits of replacing fossil fuels with corn ethanol in the USA. Some of the corn diverted to ethanol production is projected to be replaced by an increase in agricultural land in the USA, which leads to the decrease in carbon stocks in the upper right figure, and increased prices on fodder are projected to slightly decrease meat and dairy consumption, which somewhat reduces the need to replace the corn diverted to ethanol, but most of the diversion of corn to ethanol production leads to reduced exports, which in turn leads to an expansion of agricultural land and subsequent carbon losses in the rest of the world (graphs in bottom row).

3.2.4.1. Accordance of the method with the criteria

1) All scenario design should be consistent with theories of ecological succession.
    - No abandonment of land is assumed to take place in any of the scenarios, so there is no need to account for ecological succession on abandoned land. Some of the assumed expansion of agricultural land is assumed to take place in areas with growing forests. In these areas the missed potential carbon sink is accounted for as an emission. The criterion is fulfilled

2) All aspects of the scenarios and impacts that are part of the method should be modelled over the same time horizon.
    - I am not sure about how to interpret the method on all aspects. The results include emissions also of GHGs other than CO_2, but it is not stated which characterization factor that is used to aggregate them. I assume, however, that it is the GWP_{100} that is used, meaning that the presence of emitted GHG in the atmosphere is modelled over 100 years.

      In general most land use changes seem to be assumed to be permanent. However, they also state "For growing forests, we attributed emissions to biofuels equal to the carbon those lost forests would no longer sequester over 30 years". This could either be interpreted as an assumption that forests will reach a steady state in on average 30 years, or that carbon stocks are modelled over only 30 years[8]. 30 years are also the period over which emissions from the land use changes are amortized.

According to the interpretation that carbon stocks are modelled over 30 years, this is inconsistent with the 100 year time horizons and the criterion is not fulfilled. According to the interpretation that carbon stocks reach a steady state in 30 years there could be a consistent 100 year time horizon that fulfils the criterion, but in that case the allocation of emissions would not be allocated in accordance with criterion 6 as the impacts of 100 years of land use is allocated to only 30 years of land use.

3) The assumed development of carbon stocks and other climate forcing aspects of the land, the land use interventions, and the derived services from the land should be consistent throughout the whole time horizon in all scenarios in the assessment.
   - As discussed in association to criterion 2 there is no unambiguous time horizon and I have not looked into the details of the modelling of the land use patterns. Regarding the fundamental principles the criterion is fulfilled at least for the first 30 years, over which carbon stocks are explicitly modelled.

4) The assumed difference in the development of carbon stocks and other climate forcing aspects of used land between two compared scenarios should be consistent with the climate impact that this difference is assumed to cause.
   - Concerning the loss of growing forests, Searchinger et al. writes about the "rate of growth of vegetation", which indicate a gradual build-up of carbon stocks while the impact is accounted for as a pulse emission. Thus, regarding the loss of growing forests, there is the same problem with temporal detail on carbon sequestration as in the Schmidinger and Stehfest method. Except for this inconsistency, the criterion is fulfilled for the first 30 years, over which carbon stocks are explicitly modelled. For year 30-100 it depends on if one interpret the method as implicitly modelling carbon stocks also for this period (see discussion regarding criterion 2 above). If carbon stocks are implicitly modelled over the full 100 year time horizon, then the criterion is fulfilled, otherwise it is assumed 70 years of climate impacts for which there is no basis in the carbon stock modelling.

5) The land use in the compared scenarios should be identical up to the first land use intervention that would not have been carried out, had it not been for either the demand for the studied product or a decision to derive a service that is used in the studied product from a piece of land.

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[8] In the supporting material they state that "…the GHG cost would be the loss of the carbon that would be sequestered on these lands over 30 years. This carbon gain is calculated as regaining 75% of the original 25% of carbon lost from the original conversion to agriculture, i.e., 18.5% of carbon in undisturbed lands of the ecosystem type, plus a rate of growth of vegetation equal to regrowing ecosystems of that type", which is not enough for me to determine which interpretation that is correct.

- All differences between the compared scenarios are responses to an increase in demand for the studied product in the studied scenario. The criterion is fulfilled.

6) If one allocates impacts of a land use period that provides services of which the land use impacts could be assessed separately by dividing the land use period into separate sub-periods and/or interventions, then one should use allocation factors that are based on a comparison of the impacts of the separate sub-periods and/or interventions.
   - I assume Searchinger et al. uses a 100 year GWP time horizon. According to criteria 1-4 this require 100 years of land use for the assumed climate impact to be consistent with the assumed land use and carbon stock development. Thus, the emission should be allocated over 100 years of derived services. The criterion is not fulfilled (unless they use GWPs with a 30 year time horizon).

3.2.4.2. Adjustments to make the method satisfactory

Concerning criterion 4 and the problems related to the temporal detail on carbon sequestration in growing forests, see the evaluation of the Schmidinger and Stehfest method above. Otherwise, the method would be in accordance with the criteria if it coordinates the GWP time horizon and amortization period and make sure that carbon stocks also are modelled over the full time horizon.

3.2.5. Schmidt et al

The Schmidt et al. (2011) method is based on the assumption that all land use is intertwined on four global land tenure markets, one market to handle the demand for land suitable for each of the four uses Extensive forest land, Intensive forest land, Rangeland, and Arable land. For each market they calculate the impact of demanding one kg C of potential net primary production (NPP_0), which also is converted into an average impact of demanding one hectare for one year (a hectare-year).

The impact of demanding one kg C of NPP_0 (or a hectare-year) on one of the markets may then be multiplied by the NPP_0 (or hectare-years) that are appropriated by the studied land use, in order to calculate the total impact of this land use. See Figure 14 for an overview of the method. To estimate the NPP_0 that is appropriated by the studied land use, data on the NPP_0/ha in different biomes can be retrieved from Haberl et al (2007). The consequences of basing an LCA on the demand for land measured in NPP_0 or hectare-years are discussed further in section 4.5.4.1.

3.2.5.1. Estimation of the impact per kg C of demanded NPP_0 from the market

There are three supplies that are assumed to contribute with NPP_0 to the markets: Land already in use, Expansion and Intensification. Land already in use and Expansion is further divided into sub-supplies for land in different regions. The estimation of the impact per demanded kg C of NPP_0 could be divided into two main steps: an estimation of the share of the different supplies of NPP_0 and the impact per kg C of NPP_0 from each supply.

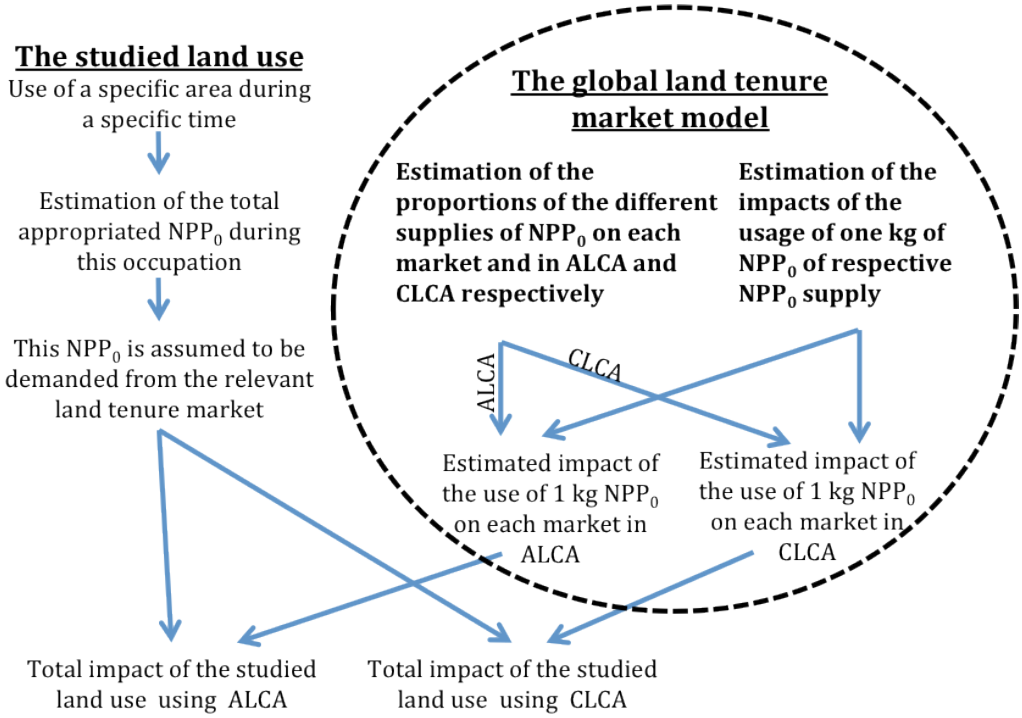

Figure 14. An overview of the Schmidt et al. (2011) method. Note that the global land tenure market model is independent of the studied land use. The impacts of the studied land use thus occurs on an implicit market, while the land tenure market model is a tool that is not part of the compared scenarios, but is used as guidance in the design of the compared scenarios. The ALCA and CLCA versions of the method are described in section 3.2.5.3 below. Omitted in the figure is that Schmidt et al. also provide a result based on the demand for land measured in hectare-years as an alternative to NPP_0.

3.2.5.2. Estimation of the proportions of the different supplies

The proportions between the different supplies are determined by an estimate of the total NPP_0 that is provided by the different supplies. The estimates of the total NPP_0 that is provided by “existing land” and “land use changes” are based on an inventory of the total areas that was used in the world in 2010 and the average area of land in different regions that underwent land use changes during the years 2000-2010. The estimated areas are then converted into supply of NPP_0.

The only method considered to contribute to intensification is nitrogen fertilizer application (N application) and intensification is assumed to take place only on the market for agricultural land. It is assumed that the NPP_0 provided by intensification is constituted by the increase in NPP_0 that is rendered by the global increase in nitrogen fertilizer at the reference year (the reference year is represented by the average increase from 1999 to 2008) and that all intensification can be represented by the NPP_0 increase achieved by a 5 % increase in N-application on Canadian barley.

It is only the increase in N-application at the reference year that is assumed to contribute to the supply of NPP_0, while the N-application up to the previous year is not assumed to contribute to the supply of NPP_0. The NPP_0 that is provided by intensification is thus assumed to be constant, even though N-application is assumed to increase every year (see Figure 15). No explanation is given to why the N-application level that is assumed to provide NPP_0 in one year not is assumed to provide NPP_0 in the subsequent year, and I interpret it as an inconsistency in the method. One could draw a parallel to the handling of the area-based NPP_0 supplies (land already in use and expansion) and say that there should be an additional NPP_0 supply: “Intensification already in use”.

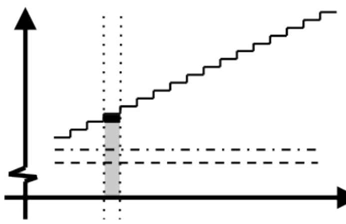

Figure 15. It is only the increase in N-application during the current year that is assumed to provide NPP_0 to the market. Thus, though there is an increase in fertilizer use every year, the provision of NPP_0 and associated emissions by intensification is assumed to be constant from year to year. I find this inconsistent; if the N-application level applied during the year preceding the reference year is assumed to provide NPP_0 during the preceding year, it should be assumed to provide NPP_0 during the reference year as well (if one do not make explicit assumptions that explain why it doesn’t). The NPP_0 supplied by N-application up to the level applied during the preceding year could be handled by introducing an additional NPP_0 supply: Intensification already in use.

3.2.5.3. Two varieties of the model

The model comes in two varieties, one for each of the two LCA-types Consequential LCA (CLCA) and Attributional LCA (ALCA). Schmidt et al distinguish CLCA and ALCA based on one characteristic that is relevant for their land use modelling, namely which supplies that should be included. In CLCA the “Actual affected/unconstrained supply” should be used, while in ALCA the market average should be used. Schmidt et al state that the supply of “land already in use” is constrained. Therefore CLCA is assumed to derive NPP_0 only from Expansion and Intensification, while ALCA is assumed to derive NPP_0 from all three supplies. The assumption that “land already in use” is constrained is discussed further in section 3.2.5.7.2 and 4.5.3.

3.2.5.4. The impact per kg C of NPP_0 from Land already in use and Expansion

NPP_0 from the supply Land already in use is supplied by an activity that Schmidt et al. call “existing land” and NPP_0 from Expansion is supplied by the activity “land use changes”. For the activity “existing land” Schmidt et al state that “There are no inputs of products or exchanges with the environment taking place in this activity” (p. 13), while for the activity “land use changes” the exchanges with the environment includes “transformation from land not in use to land in use /…/ as well as the associated emissions with deforestation”.

Schmidt et al describe “land use changes” and “existing land” as separate activities. However, they are connected, as Schmidt et al. write that “Changes in the production volume of ‘land already in use’ are determined by the previous year’s expansion” and the emissions from deforestations associated to “land use changes” are, as far as I can see, assumed to be permanent. This indicates that the scenarios that define the impacts of “land use changes” also include the impacts of a following permanent land use (i.e. continuous “existing land”-activities). Thus, though Schmidt et al describe “land use changes” and “existing land” as separate activities, all “existing land”-activities must be part of a preceding “land use change" and the scenarios that describe the impact of "existing land"-activities must be extensions of scenarios that describe the impacts of previous "land use changes". This means that Schmidt et al use the term "land use changes" to refer to two different things: on one hand a permanent land use change, and on the other hand an activity that appropriates the NPP_0 of the land during the first year of land use after a land use change. From here on, I use citation marks to distinguish the "land use changes" that refers to the NPP_0-supplying activity that constitutes the first year of land use after a land use change from the permanent land use changes that also includes subsequent "existing land"-activities.

As the differences between the scenarios that define the impact of a land use change includes both the "land use change" and subsequent "existing land"-activities, there is an implicit allocation procedure which allocates the full impact (an allocation factor of 1) of a land use change to the "land use change" and none (an allocation factor of 0) to the following "existing land"-activities (Figure 16).

3.2.5.5. The impact per kg C of NPP_0 from Intensification

As described above, it is assumed that all intensification can be represented by a 5 % increase in N-application on Canadian barley. The estimate of the impact is based on a comparison of the yields and impacts of cultivation of barley on 1 ha in Canada under current and intensified (5 % increase) N-application. The impacts are then converted from the hectare to NPP_0 basis by a comparison of the average yield and NPP_0 in North America.

3.2.5.6. Accordance of the method with the criteria

In order to evaluate the method with regard to the criteria, one must identify the scenarios involved in the method. In the method one can find the following scenarios:

1) The observed development of the global land use, described by the land already in use in 2010, the yearly expansion of land use between 2000-2010, and the yearly increase in N-application use 1999-2008.
2) The scenarios defined by the assumptions in the land tenure market model:
   a) The assumed development of land use in the global land tenure market model (described by the graphs to the left in Figure 16).
   b) A pair of scenarios that defines the impacts of each land use change involved in providing NPP_0 to the land tenure market, including both contemporary land use changes that provides NPP_0 through "land use changes" and historic land use changes that provides NPP_0 through "existing land"-activities.
   c) The pairs of scenarios that define the impacts of intensification at any year.
   d) The eight pairs of scenarios that define the impacts of demanding one kg C of NPP_0 from any of the four NPP_0 markets in CLCA an ALCA respectively.
3) The scenarios that define the impacts of the studied production in an LCA that uses the method.

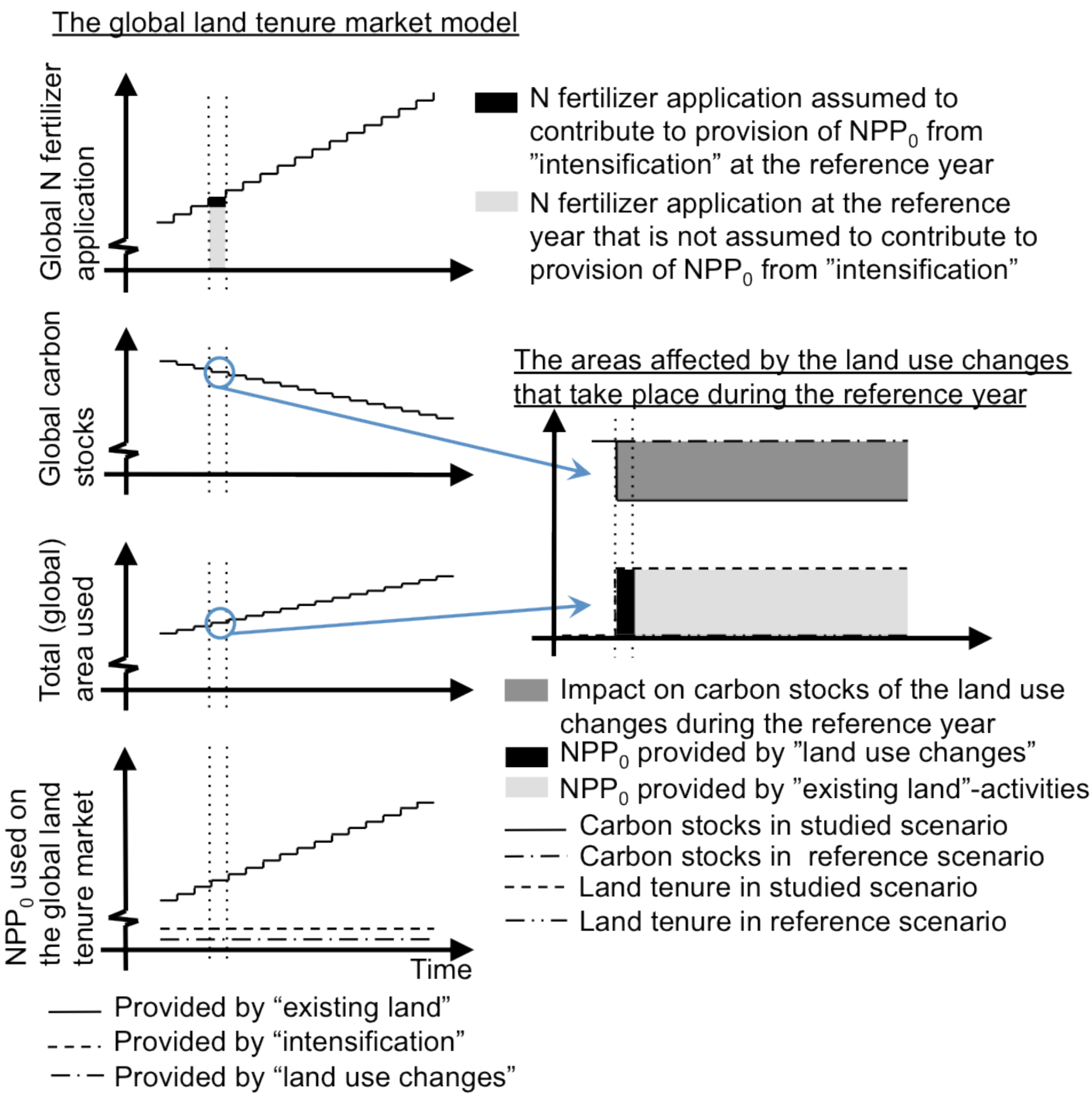

Figure 16. The graphs to the left show the assumed development in the global land tenure market model (the scenario that is described in paragraph 2a in the list of scenarios above). The graph to the right shows the NPP_0 supply and carbon stock development on the areas that are affected by the land use changes that the "land use changes" that take place during the reference year are part of (the scenarios that are described in paragraph 2b in the list of scenarios above). Note the distinction between land use changes and "land use changes" (described in section 3.2.5.4). The allocation of the full impact of the land use changes that take place during the reference year (dark grey area in the right graph), to the NPP_0 provided by the "land use changes"-activities (black area in the right graph) and no part allocated to the NPP_0 provided by the subsequent existing land-activities (light grey area in the right graph), is in conflict with criterion 6.

Scenario 2a) is an extrapolation of the observed scenario described in 1). It assumes the same areas of land already in use in 2010 as in the observed scenario, and that land use will continue to expand and intensify with the average rate of the observed scenario. This is a single scenario that is not used to define an impact, but is used to determine the proportions of the contribution of NPP_0 from the different supplies

The scenarios in 1) and 2) are not part of the LCAs that use the model. The LCAs have their own scenarios, and the global land tenure market model can be seen as a tool in the design of the scenarios that define the impacts in the LCAs. As I understand it, however, the assumed development of land use in the global land tenure market model (2a, above) could, but does not have to, be the same scenario as either the studied or the reference scenario of an LCA that use the model.

The scenarios in 2b) and 2c) do not have to be identified as separate scenarios but could be seen as different aspects of the same pairs of scenarios: one pair for each year, describing both the intensification and the land use changes in all regions in the same pair of scenarios. Also, the scenarios described in 2d) are not necessary to identify as separate scenarios; the impacts per demanded kg C of NPP_0 could be seen as the result of an allocation procedure that attributes a part of the impacts defined in 2b) and 2c) to the demand of a single kg C of NPP_0.

For the method to be satisfactory, all scenarios and pairs of compared scenarios that are part of the method should fulfil the criteria.

1) All scenario design should be consistent with theories of ecological succession.
    - As I interpret the method, it only handles permanent land use changes from land not in use to land in use, so there is no need to account for any ecological succession on abandoned land in any of the scenarios. The criterion is fulfilled.

2) All aspects of the scenarios and impacts that are part of the method should be modelled over the same time horizon.
    - The method uses the GWP_{100}. Land use changes are assumed to be permanent and thus stretching over the full 100 year time horizon. As in previous methods, I think the method should be interpreted in such a way that the land use interventions and derived services are modelled over the full time horizon, though only the ones that are part of the studied product are explicit. I consider the criterion fulfilled.

3) The assumed development of carbon stocks and other climate forcing aspects of the land, the land use interventions, and the derived services from the land should be consistent throughout the whole time horizon in all scenarios in the assessment.
    - With the interpretation of the method described in the second paragraph of section 3.2.5.4, the method fulfils the criterion if one considers only isolated land use changes and their consequences for carbon stocks. However, the handling of intensification is in conflict with the criterion, as described below.

      Consider two subsequent years in the scenario that describe the development in the land tenure market model. In year 1 the N-application (a land use intervention) is x ton N, which is assumed to contribute with y kg C of NPP_0 (a derived service). In year 2 the N-application is 1,05*x ton N, which is assumed to still only contribute with y kg C of NPP_0. No explanation for this is given and I think the N-application and the NPP_0 it is assumed to provide cannot be consistent in both year 1 and year 2. Also, as the demand for land is based on (the NPP_0 of) the used area and N-application reduces area requirements, the primary production increasing effects of N-application is accounted for in two ways; both as reduced demand for land exerted by products, and as provision of NPP_0 to the market through intensification. This means that every time there is N-application that contributes to intensification in the direct land use of a studied product, too much NPP_0 is assumed to be supplied by intensification (of which parts is implicit and provided by the direct land use) and too little NPP_0 supplied by land already in use and expansion.

As indicated in Figure 2.1 of the Schmidt et al. report, the impacts of N-application are also handled outside the intensification-activity of the land tenure market. The report did not include information on how the N-application within and outside the land tenure market model should be coordinated. This means that there could arise additional inconsistencies.

4) The assumed difference in the development of carbon stocks and other climate forcing aspects of used land between two compared scenarios should be consistent with the climate impact that this difference is assumed to cause.
    - As the CO_2 emissions from the land use changes that provide NPP_0 from the supply land already in use has occurred in the past (often several hundred years ago), I can not see how the time-horizons over which the impacts are assessed should be defined and I can therefore not judge if the criterion is fulfilled. However, this problem will be solved if the method is adjusted to meet criterion 5 (see the paragraph below and section 0).

5) The land use in the compared scenarios should be identical up to the first land use intervention that would not have been carried out, had it not been for either the demand for the studied product or a decision to derive a service that is used in the studied product from a piece of land.
    - The impacts of “land use changes” and “existing land”-activities are both defined by pairs of compared scenarios that define the impact of land use changes, and the scenarios in each pair diverge at the time of the land use change. When it comes to “land use changes”, they coincide with the starting points of the land use changes that they are part of and the criterion is thus fulfilled for the “land use changes”. When it comes to “existing land”-activities, they take place after the starting points of the land use changes that they are part of. The scenarios that define the impacts of an “existing land”-activity thus diverge before the “existing land”-activity takes place (Figure 17). One could argue that also the land use changes preceding these “existing land”-activities are relevant with regard to the purpose of the LCA, but in that case parts of the emissions of these changes should be allocated to the studied product, which is not the case in the method. The method is thus in conflict with the criterion.

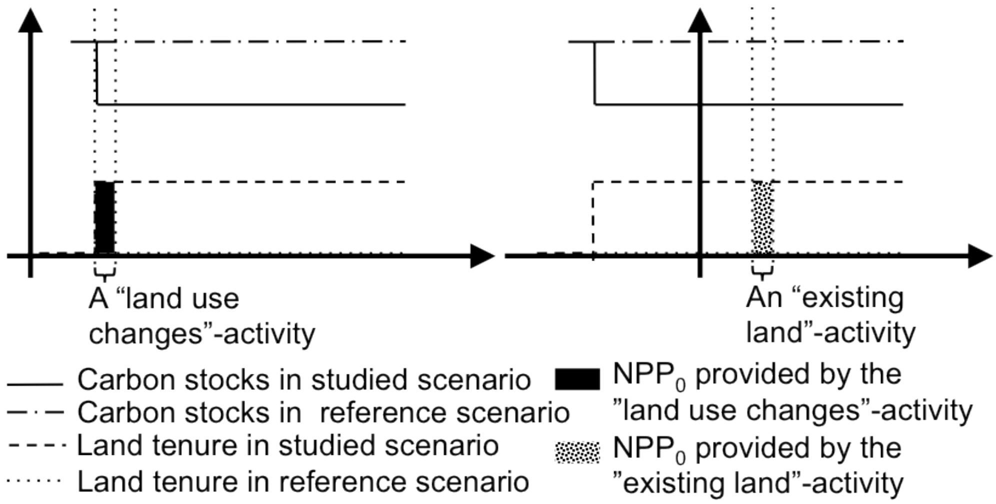

Figure 17. An illustration of a “land use changes-activity and an “existing land”-activity. In the case of the “land use changes”-activity the compared scenarios diverge when the activity takes place, which is in accordance with criterion 5. In the case of the “existing land”-activity, the compared scenarios diverge before the activity takes place, which is in conflict with the criterion.

6) If one allocates impacts of a land use period that provides services of which the land use impacts could be assessed separately by dividing the land use period into separate sub-periods and/or interventions, then one should use allocation factors that are based on a comparison of the impacts of the separate sub-periods and/or interventions.
   - Schmidt et al allocates 100% of land use changes to the “land use changes”, i.e to the first year of land use following a land use change, and 0% to the following “existing land”-activities, i.e. any land use that takes place more than one year after the land use change. The impacts of “land use changes” and “existing land”-activities could be assessed separately using principles from the Müller-Wenk and Brandão (2010) method. The impacts of “existing land”-activities would then be larger than zero, and part of the impacts from land use changes should thus be allocated to the “existing land”-activities. The criterion is not fulfilled.

3.2.5.7. Possible adjustments to make the method satisfactory

3.2.5.7.1. Intensification

All intensification should be accounted for, not only the increase in intensification during the reference year. However, I think that intensification should be handled separately from the land tenure market model. If a farmer increases NPP_0 by N-application, this renders higher yields and reduces the area requirements of the production. This reduction in area requirement entails a reduced demand for NPP_0 on the land tenure market. Effects of intensification on the market are thus already accounted for in the estimate of the NPP_0 (or hectare-year) demand and should therefore not be included in the land tenure market model.

Alternatively one could estimate the NPP_0 demand of the studied product based on the average NPP_0 required by that type of product (estimated with data on yield levels on land that is not intensified), instead of based on the NPP_0 that is obtained from the area used by the studied product under intensified conditions. With this approach one could keep intensification in the land tenure market model, but one would still have to develop the method in order to include "intensification already in use".

3.2.5.7.2. The proportions of land already in use and expansion

Though I find no conflict between the criteria and the methods for estimating the proportions of land already in use and expansion, I think that they deserve further attention.

In the market average approach (the ALCA version of the method) the proportions of land already in use and expansion is dependent only on the expansion rate of global land use. The global expansion of land use depends on multiple factors, including population increase, which is about twice as big as the expansion of agricultural land[9]. Also, if an increase in production of a particular kind of products, say for example biofuels, contributes to the expansion rate of total global land use, then the impact of this expansion will be attributed as much to other kinds of products (for example foods) as to the biofuel production. The market average approach for estimating the proportions of the different supplies thus has little, if any, causal relation to the studied product.

I also find the assumption that "land already in use" is a constrained supply (used in the CLCA version of the method) dubious. Though the demand of agricultural products is increasing, people already eat. A studied product might even replace a product that would have required more land than the studied one. To assume that basic food products are an additional production that does not replace another food product therefore, to me, seems like an unreasonable foundation for the attribution of impacts of expansion. Similar reasoning could be applicable also on many forestry products. Therefore, I think that whether "land already in use" should be considered constrained or not depends on the context, and it would be preferable to differentiate the contribution to expansion of land use between different products.

The handling of the expansion of land use is discussed further in section 4.5.3.

3.2.5.7.3. "Land use changes" and "existing land"-activities

A consequence of criterion 5 is that "land use changes" and "existing land"-activities should be assessed by different pairs of compared scenarios. I see two alternative strategies to do this: to continue to make assumptions of permanent land use changes, or to start assess "land use changes" and "existing land" as delimited land use periods, as in the Müller-Wenk and Brandão (2010) method.

With the strategy to continue to make assumptions of permanent land use changes, "Land use changes" would be assessed with the same scenarios as in the original Schmidt et al method, while "existing land"-activities would be assessed with a continuous land use in the studied scenario and an abandonment of the land in the reference scenario, as in the Schmidinger and Stehfest (2012) method. For a

[9] According to Schmidt et al (2011) the market for arable land expand with less than 0,5 % per year and the expansion rate of the other land tenure markets are even smaller, while population increase is 1.14 % (Worldometers 2015)

discussion on how to allocate the impact of the land use changes to the services derived in the studied scenario, see the evaluations of the PAS2050 and Schmidinger and Stehfest methods.

With the strategy to assess "land use changes" and "existing land" as delimited land use periods, the most straight forward comparison with the Müller-Wenk and Brandão (2010) method would be that an "existing land"-activity corresponds to one year of land occupation, and a "land use change" corresponds to a land transformation plus one year of land occupation. However, I find it arbitrary to merge a land transformation with one year of land occupation and suggest a more comprehensive change: that the "land use changes" should be divided into a "land use change"/land transformation activity and an "existing land"/land occupation activity and that it only is the "existing land"/land occupation activity that should be assumed to provide NPP_0, while the "land use change"/land transformation activity should be assumed to provide potential net primary production available for occupation (NPP_0AO), measured in kg C of NPP_0/year. This also gives a new perspective on the estimation of the proportions of the different supplies: all NPP_0 should be assumed to be supplied by "existing land"/land occupation activities. It remains, however, to figure out when, and to what extent the provision of NPP_0AO also should be included. This is discussed further in section 4.5.3 When to include the impacts of expansion of land use.

3.2.5.8. Schmidt and Brandão - A revised version of the Schmidt et al version

The Schmidt et al. (2011) method has been updated since 2011, and a newer version is described in Schmidt and Brandão (2013). In the 2013 version they only work with the CLCA version of the method and assess expansion (the NPP_0 supplied by the activity "land use changes") through a delimited land use period, as described in Figure 18, and the following citation:

> If only expansion is considered, occupation of 1 ha in 1 year will cause 1 ha deforestation. After the duration of 1 yr, the land is released to the market for land, i.e. to other crops, which can then be grown without deforestation. Hence, the occupation of 1 ha-yr is modelled as 1 ha deforestation in year 0 and -1 ha deforestation in year 1. (p. 15)

The associated impact is calculated as the time integrated contribution to atmospheric CO_2-content of a pulse emission from deforestation at year t_0 from t_0 to t_0+TH minus the time integrated contribution to atmospheric CO_2-content of a pulse emission from deforestation at year t_0+1 from t_0+1 to t_0+TH (see equation 4).

$$impact = e * \frac{a_r * \left(\int_0^{TH}[C_r(t)]dt - \int_0^{TH-1}[C_r(t)]dt\right)}{a_r * \int_0^{TH}[C_r(t)]dt} \quad (CO_2 - eqs) \qquad (4)$$

where e is the magnitude of the impacts on carbon stocks of the studied land use change, $C_r(t)$ is the impulse response function of the BernCCM and a_r is the radiative efficiency of CO_2.

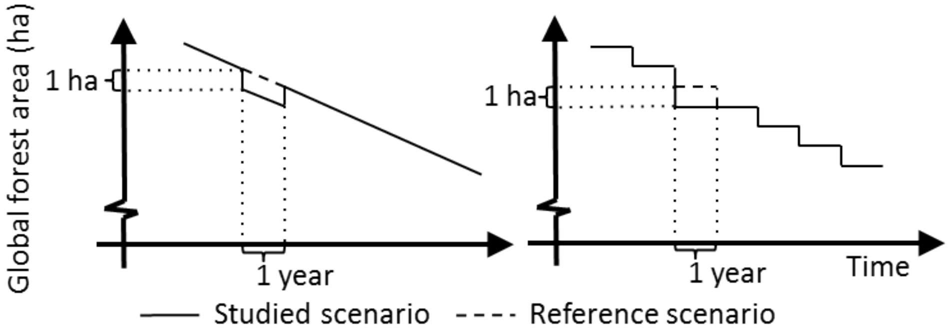

Figure 18. Two alternative illustrations of the scenarios that describe the impact of expansion in the Schmidt and Brandão (2013) method. The left graph shows how Schmidt and Brandão illustrates the scenarios (they do not denote them scenarios, and the reference scenario is not mentioned in the text, though it is displayed as a dashed line), with a constant background rate of deforestation in both scenarios and, in the studied scenario, an additional decrease in forest cover in the beginning of the studied year followed by an increase in the end of the year. However, in the text of the report, I do not find any assumptions about that forest cover is assumed to increase at any time. I would therefore prefer an alternative illustration, e.g. as the one to the right. Regardless of if one look at the original or the revised illustration, the forest area is the same in the compared scenarios before and after the studied year of land occupation. Thus, there is a background expansion that takes place independently of the land occupation, but the studied land occupation does not contribute to it. I therefore find it confusing that Schmidt and Brandão denote this supply of NPP_0 "expansion". See main text below for further discussion on the topic.

The expansion-impact that Schmidt and Brandão assess is that of making a land use change happen one year earlier than what would otherwise be the case, and they attribute it to the crop production of 1 year of land occupation. Also, if one compares the forest area in the compared scenarios before and after the studied year of land occupation, the forest area is the same in the compared scenarios (Figure 18). This means that there is a background expansion of land use that takes place independently of the studied land occupation, but the studied land occupation does not contribute to the expansion. Therefore, I find it unsuitable to use the terms "expansion" and "land use changes" to denote the supply and activity of which Schmidt and Brandão calculates an impact in this method. One could perhaps argue that "land use changes" in this case is short for "an activity that includes an initial expansion and subsequent contraction of land use". However, if this was the case, the inputs to the activity, which according to Schmidt and Brandão include "land transformation from…" and "land transformation to…", should also include a "land transformation back again".

I would denote the activity that Schmidt and Brandão denote "expansion" as being 1 year of land occupation. Schmidt and Brandão also use the term land occupation in parallel to "expansion" and "land use changes", though the term is not used to denote a specified concept in the method. In order to distinguish the impact of land occupation that is calculated by Schmidt and Brandão from the impact of land occupation that is calculated by Müller-Wenk and Brandão, I would denote it land occupation on an expanding market whereas the impact calculated by Müller-Wenk and Brandão is the impact of land occupation on a stable, or shrinking, market.

Going back to the citation above, the wording "After the duration of 1 yr, the land is released to the market for land, i.e. to other crops, which can then be grown without deforestation" indicates that there is an assumed permanent expansion of land use in the studied scenario as compared to the reference scenario. This is, however, not acknowledged in the calculated impact. The calculated impact is a reasonable impact of the first year of land occupation following a land transformation, but the impact of the following years of land occupation could be calculated in the same way. Therefore, I think that the method Schmidt and Brandão use to calculate the impact of "expansion" actually fits better to the supply of "land already in use" than to "expansion".

As in relation to the 2011 version of the method, I would recommend the division of different land use activities according to the Müller-Wenk and Brandão method, i.e. into land occupation and land transformation, and that all NPP_0 should be assumed to be provided by the land occupation activities, while the land transformation activity should be assumed to provide NPP_0AO. However, the impact of land occupation could also be calculated in the way that Schmidt and Brandão calculate the impact of "expansion".

Intensification is described only shallowly in Schmidt and Brandão (2013), and I have not identified any differences concerning Intensification as compared to the Schmidt et al. (2011) method. In the discussion of the original method I described how the handling of intensification could become consistent either by totally lifting intensification out of the land tenure market model, or by changing the way in how one estimate the demanded NPP_0 of the studied product.

As I think that the method Schmidt and Brandão use to calculate the impact of "expansion" actually fits better to the supply of "land already in use" than to "expansion" and that all NPP_0 should be assumed to be provided by the land occupation activities, I think it is enough to change the description of the method and exclude the intensification supply, while keeping the procedures for calculating the impact of the expansion activity (though now use it as the impact of the "land already in use" activity), in order to make the method consistent concerning the supply of NPP_0. It remains, however, to determine if, and to what extent, the supply of NPP_0AO should be accounted for in an LCA.

3.3. Principle 2: A comprehensive method

In this section I discuss the principle "**A comprehensive method**" and its guideline: "The method should be comprehensive and include all mechanisms by which the areas of protection are affected by the studied production".

The guideline suggests that methods should be comprehensive, i.e. include all known processes and environmental aspects that are relevant to the studied impact categories. This is also the case when the inclusion of an aspect introduces large uncertainties into the assessment, but the uncertainties should also be reported[10]. No increase in precision, no matter how large, is worth any loss in accuracy, no matter how small. I believe, however, that one normally must compromise in accuracy, e.g. while making cut-offs in upstream processes, in order to enable feasible studies, though one could make estimates/guesses of the impacts of these upstream processes as well.

In the following sections I will discuss mechanisms that could be concerned by the guideline and are specific for land use:

- Mechanisms that affect the climate forcing of land areas, including:
    - Different climate forcing aspects of land, e.g. nitrous oxide emissions, mineral dust aerosols and albedo
    - Underlying mechanisms that affect any of the climate forcing aspects
- Mechanisms that affect the potential of land to deliver services (as e.g. yield levels affect area requirements)

There are also other mechanisms that could be concerned by the guideline but that are not specific for land use, and left to be discussed further elsewhere, such as:

- (Upstream) processes around the technical system boundaries that an LCA practitioner might consider to cut off.
- Mechanisms through which the climate forcing aspects affect the areas of protection
- Mechanisms that are at work over long time periods.

3.3.1. Different climate forcing aspects of land

Both Helin et al. (2013) and Müller-Wenk & Brandão (2010) mention that there are other climate impacts of land use than the impact on carbon stocks, which is the only aspect that they discuss. I have not made a thorough review, but the climate forcing aspects of land that I have come across are the development of:

- Carbon stocks
- Methane emissions
- Nitrous oxide emissions
- Aerosol formation from biogenic volatile organic carbon (Tunved et al. 2006; Spracklen et al. 2008)
- Mineral dust aerosol formation (Forster et al. 2007)
- Albedo, surface roughness, evapotranspiration and transmitted heat (Bonan 2008; Jackson et al. 2008)

[10] I do not go further into demands on reporting of uncertainties in this thesis, but it could be motivated by principle Principle 3 "A transparent and comprehensible study". Handling of uncertainties is a subject that deserves further attention.

While aerosols and biophysical mechanisms often are overlooked, Bright et al. (2012) show that in a 100 year perspective albedo could offset around 50 % of the emissions from biofuel production sourced with biomass from managed boreal forest in northern Europe.

The usefulness of assessments that leave out whole climate forcers is dubious and all climate forcers should be considered even though uncertainties are large. When uncertainties are large, they should, however, also be reported.

3.3.1.1. Suggestion of criteria 7

7. All types of affected climate forcers should be considered.

3.3.2. Underlying processes that affect any of the climate forcing aspects of land

What demand on complexity and level of detail in LCA modelling does the guideline entail? As I see it, the empirical features of a model (i.e. features that build on correlation of empirical data[11]) could be said to indirectly consider also underlying mechanisms that could affect the modelled parameters. Therefore I do not think the guideline entail any demands of neither an explicit nor direct inclusion of particular underlying processes that affect the climate forcing aspects of land.

However, the empirical features of used models should, according to guideline 1.1, be in line with empirical data as well as fundamental theories and hypotheses of natural science, and principle 3 has implications for the handling of uncertainties. Thus, while I do not suggest a criterion concerning the general handling of underlying processes that affect any of the climate forcing aspects of land with regard to principle 2, there could be many issues regarding such underlying processes that deserve to be regulated by criteria based on guideline 1.1 and 3.1. It could be, however, that those issues would have to be elaborated with regard to specific climate forcers. An example of an issue that could deserve attention is the common assumptions of steady states of carbon stocks in mature ecosystems.

Though it often is assumed that ecosystems and carbon stocks reach a steady state, some ecosystems continuously build up carbon stocks; most conspicuous is probably peat-accumulating ecosystems, but several studies has also shown continuous increases also in old growth forests (Wardle et al. 2003; Luyssaert et al. 2008). Wardle et al. (2003) found a build-up of 0.5 kg of carbon per square meter and century on islands with continuous boreal forest without major fire events for about 3000 years in northern Sweden. This sequestration of 0.05 tC ha^{-1} yr^{-1} could perhaps be considered negligible but the estimates of Luyssaert et al. (2008) of an average carbon sequestration of 2.4 ± 0.8 tC ha^{-1} yr^{-1} in forests older than 200 years is an indication that the steady state assumptions not should be used by default. Especially over long time horizons seemingly low rates of emissions or sequestrations can make large contributions to the total impacts.

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[11] Further information concerning the division into, or continuum between, empirical and process-based models can be found e.g. in Adams et al. (2013)

3.3.3. Processes that affect the potential of land to provide services

When land use causes soil degradation the impacts take different forms depending on context. If the land is used continuously for cropping even though the soil is degraded, the effects could be lowered yields or the requirement of additional inputs of e.g. micronutrients and/or pesticides to compensate for weaker crops. In other cases the degradation could lead to a slash and burn based agriculture, or a complete abandonment of the land. In assessments of delimited land use periods, where the land in the studied scenario is abandoned when the studied land use period is over, soil degradation could affect both the relaxation time and the climax steady state of the land (illustrated in Figure 19).

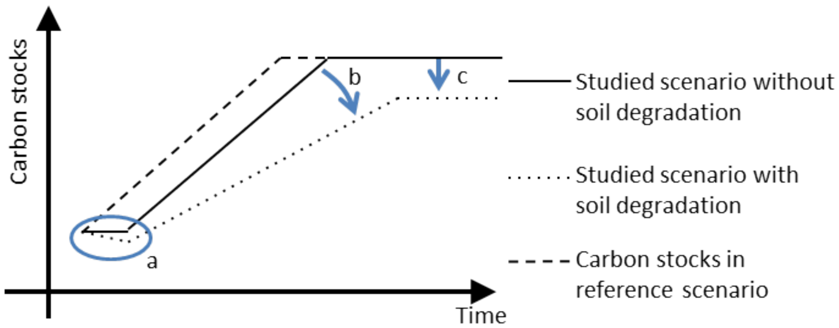

Figure 19. Three different ways in which soil degradation could impact carbon stocks: through lowering carbon stocks during the use (a), by slowing down relaxation (b) and through altering the climax (final steady state) after relaxation (c). Other possible impacts of soil degradation are yield losses or the need for periods of fallow during which fertility may recover.

The situation in the Amazon is an example on how soil degradation prevents land from being used for continuous cropping. Cederberg et al. (2011) handles this situation through assuming a shift from pristine forest to a heterogeneous and ever shifting landscape that over time reaches an equilibrium with settled proportions of cropland, pasture and secondary forest. The emissions from this shift is then allocated to all the kinds of products that are derived from the shift and the following land use; timber, crops and livestock products.

I see two alternative strategies for handling the implications of potential soil degradation. Either one assess the consequences of the potential soil degradation, or one perform a system expansion and include (hypothetical) measures that prevent or compensate for any soil degradation, i.e. a replacement of all matter (mineral particles, soil carbon, macro- and micro nutrients) that is lost through erosion or removal of yields.

3.3.3.1. Suggestion of criteria 8

8. Possible effects of impacts of land use on the ability of the land to provide services should be considered.

Comment: Such effects could be lowered yields, which could be compensated by an expansion of agricultural area, perhaps in combination with a slash and burn regime. Another service that is provided of land is carbon storage. Effects on the properties of the land that could affect carbon dynamics after an assumed abandonment of used land should also be considered.

3.4. Principle 3: A transparent and comprehensible study

In this section I discuss the implications for LCA practices of the general guideline "An LCA should enable the reader to understand the impacts of the studied product with regard to the reader's personal value system". As I see it, there are two aspects of the guideline:

- the reporting should provide enough information, and
- the information should be presented in ways that are easy to interpret.

Ideally, all LCA practices should be shaped with regard to the interactions between the general guideline, different value issues (aspects of personal value systems[12]) and our knowledge of the world. Some LCA practices that concern the climate impact of land use are listed in Annex II together with lists of potentially relevant value issues and aspects of global warming and a figure that illustrates a few interactions between them.

If one focuses only on the first aspect of the guideline – that the reporting should provide enough information – and make the strictest possible interpretation, this would require an LCA, in all its aspects, to suite any possible value system. That is an interpretation that would require an unfeasible adaptation of the LCA to cover the variation in results of a multitude, if not any possible, purpose and scope of an LCA on the studied product.

However, there is a trade-off between the two aspects, as a complex LCA could complicate the interpretation. Also, as written in the general guidelines section, the guidelines are not strict demands on an LCA, but rather general aims and one has to weigh the advantages of enhanced compliance with the guidelines with the necessity to keep LCA practises feasible – not only to interpret, but also to perform.

To sort out most of the LCA practices listed in Annex II requires a lot of background information and analyses of the consistency with other parts of the methodology. In this thesis I will therefore only address the common practice to report climate impacts in emissions of CO_2-eqs using a single time horizon, and the problems of this approach with regard to the guideline[13]. As for the other issues listed in Annex II it would be desirable with a thorough examination of them in order to provide general information about the potential variations in results depending on practices used and to explore the trade-off between the two aspects of the guideline.

[12] May they be the value systems of the LCA practitioner, the people who have ordered the LCA, the people who make up the organisation who ordered the LCA, the people who have provided information to the LCA or any other person who have had an influence on the LCA.

[13] The choice of climate impact indicator and time horizon might not seem to concern land use, but as shown later, they affect the comparison between climate impacts of land use in different areas and between climate impacts of land use and fossil fuel use.

In the first section below I'll discuss the choice of time horizon. Thereafter I discuss what the second aspect of the guideline, that reporting should be easy to interpret, entails for the choice of climate impact indicator.

3.4.1. Choice of time horizon

In this section I discuss what the principle "**A transparent and comprehensible study**" entails for the choice of time horizon in an LCA. First I provide examples of how the choice of time horizon can affect the result of an LCA and discuss the relevance of long time horizons before I discuss how the choice of time horizon should be handled with regard to the general guideline.

3.4.1.1. The effect of the choice of time horizon on the relative contribution of fossil fuel combustion and land use impacts.

A calculation example, using the three different time horizons 100, 500 and 2500 years, of the climate impact of soybean meal imported to Sweden from Brazil and of field beans grown in Sweden is shown in Figure 20. For the 100 year time horizon the field beans has an impact that is roughly 50 % larger than that of soybeans, but for the longer time horizon it is the soy beans that cause the larger impacts; at the 2500 year time horizon more than twice the impact of the field beans. This difference in relative impact depending on time horizon is mainly due to that the impact of the field beans to a larger extent is caused by land use, while the soybeans cause larger emissions from fossil fuel combustion. As the emissions from land use are temporary (and/or distributed over a longer period of crop production at longer time horizons), the importance of those impacts decrease relative to the impacts from fossil fuel combustion with the increasing time horizon.

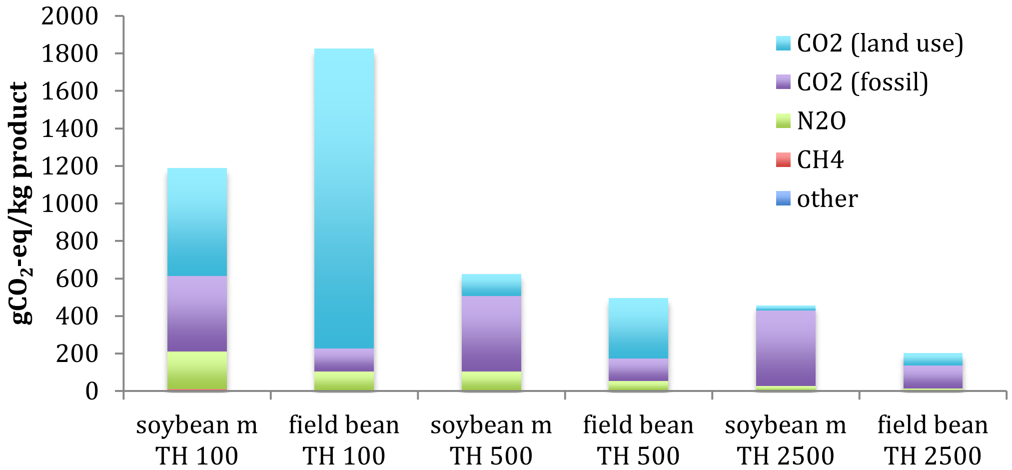

Figure 20. The figure shows the GHG emissions (in CO_2-eq) caused by field beans grown in a temperate forest areas in Sweden and soybeans grown in Brazil in a mixture of 40% of tropical forest areas and 60% of tropical grassland areas and imported to Sweden. Neither mechanisms that affect the potential of land to deliver services nor all land use related climate forcers are considered, and the example does thus not meat criteria 7 and 8. It is therefore not suitable as an assessment of the climate impact of the two products, but serves as an illustration of the effect of the choice of time horizon. The result is based on the LCA of Flysjö et al. (2008), to which the climate impact of land use is added (after subtraction of the land use impact of the soybean cultivation that are included with the method of ecoinvent in Flysjö et al.) The land use impacts are calculated according to the methods described in section 2.2.3. Emission of methane is excluded for the TH 2500 and "other" is excluded in both TH 500 and 2500. There could be gases with long atmospheric lifetimes in "other", but Flysjö et al do not provide such data, the impacts would probably still be negligible and it is irrelevant to the purpose of the example.

3.4.1.2. The influence of choice of time horizon on comparisons of land use in different biomes

The choice of time horizon does not only affect the relation between the CO_2 implications of land use and emissions of CO_2 of fossil origin and other GHGs, but also the relation between land use in different biomes, both for land occupation (Figure 21) and transformation. For example, changing time horizon from 50 to 250 years makes the impact of occupation of tropical forest as cropland for one growing season (1/2 year) to turn from twice as large to half as large as the occupation of boreal forest as cropland for one growing season (1 year).

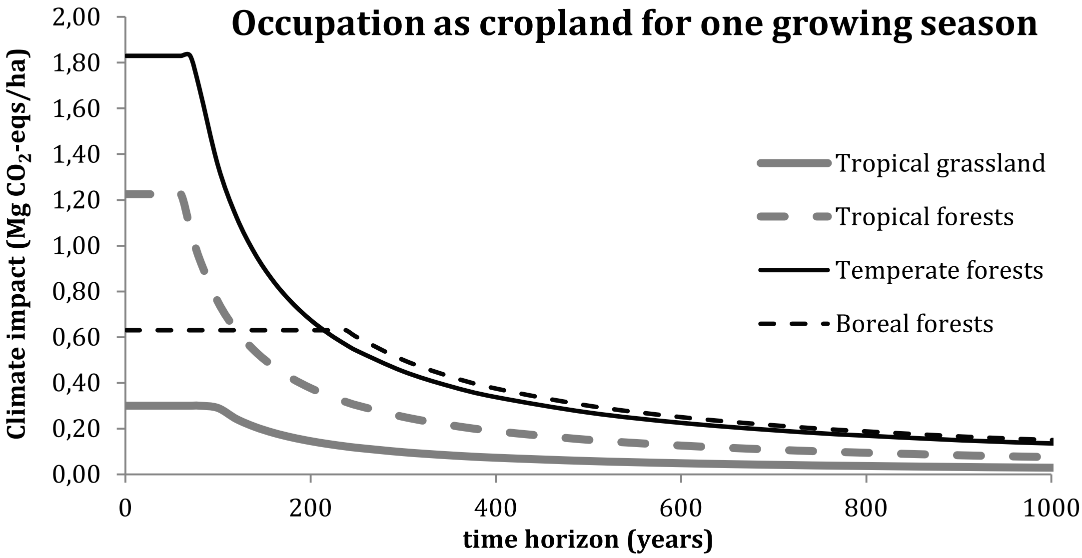

Figure 21. The climate impact of the land occupation as cropland during one growing season (1/2 years for the tropical biomes and 1 year for the temperate and boreal forest biomes) from the biomes listed in Table 1. Changing time perspective may alter the conclusion of a study. For example, changing time horizon from 50 to 250 years makes the impact of occupation of tropical forest as cropland for one growing season to turn from twice as large to half as large as the occupation of boreal forest as cropland for one growing season.

3.4.1.3. The relevance of long time horizons

Many GHGs affect the climate for several thousand years. The IRF used to describe CO_2 dissipation in the fourth assessment report of the IPCC do not include the long term processes that are part in removing CO_2 from the atmosphere, leading to a model in which over a fifth of CO_2 emissions remain in the atmosphere indefinitely. Archer et al. (2009), who examined the long term CO_2 dissipation mechanisms, conclude that "Generally accepted modern understanding of the global carbon cycle indicates that climate effects of CO_2 releases to the atmosphere will persist for tens, if not hundreds, of thousands of years into the future." There are also other GHGs (mostly perfluorinated compounds) that have atmospheric lifetimes of a few – in one case fifty – thousand years (Forster et al. 2007).

It could be argued that the normally used climate impact indicator CO_2-eqs and other indicators that are based on cumulative radiative forcings are invalid over long time horizons due to large uncertainties in e.g. future atmospheric composition and rates of CO_2 dissipation, or because the radiative forcings that are used as constants in reality do not exist as constants as the radiative forcing successively gets more and more offset by an increased heat radiation into space as soon as temperatures start to increase as a response to the radiative forcing.

Criticism of the use of radiative forcings as constants are correct in the sense that an increase in the atmospheric concentration of a GHG do not cause an ever-increasing temperature as the dimensional analysis of the cumulative radiative forcing imply. However, adding a "gross" to the cumulative radiative forcing term could solve the denotation problem and, though temperatures do not increase indefinitely after an increase in the concentration of a GHG, the increase still exerts a warming by withholding the new temperature, which, if concentrations fell to original levels, would fall back to the pre-perturbation temperature. Therefore I still find the (gross) cumulative radiative forcing concept useful as a climate impact indicator also over long time-horizons, though it could be given a unit that clarify its role as an indicator that have only a hypothetical physical counterpart, such as for example Climate Impact Units (CIU).

3.4.1.4. Elaboration of Criteria

The calculation examples above, as well as a multitude of biofuel studies such as e.g. Levasseur et al. (2010), illustrates that in the choice between two ways to fulfil a function, one way may have the smallest impact in a short time perspective, while the other have the smallest impact in a longer time perspective. Presuming that an estimated impact perfectly reflects the impacts on the areas of protection, the only reason to choose a time horizon shorter than eternity is a pure time preference – i.e. that one values future generations less than the present generations. There seems to be a wide agreement among ethicists that all generations deserve equal treatment (Hellweg et al. 2003), but according to the guideline readers should be enabled to make their own value judgments. Also, presuming that an estimated impact perfectly reflects the impacts on the areas of protection is questionable. There are plenty of uncertainties in how well chosen climate impact indicators and estimated impacts represent the impacts on the areas of protection. There are for example uncertainties in how well a climate impact indicator represents the impacts on the areas of protection related to

- the risks associated to the different aspects of warming[14],
- the possible feedback and threshold effects in the climate system,
- the possibilities for mankind to develop methods to reverse climate forcing (for example through carbon sequestration in soils),
- the possibilities for mankind to prepare for and adapt to different rates of global warming,
- the ability of other species to adapt
- and how the ecosystems, ecosystem services and life support systems are affected by global warming.

Also in relation to the risk management connected to these uncertainties, readers should be enabled to make their own value judgments. Regarding climate impact indicators based on the gross cumulative radiative forcing, such as the CO_2-eqs, the risks of positive feedback mechanisms, such as increased releases of CO_2 and methane from arctic regions (O'Connor et al. 2010) and tipping points in the climate system (Lenton 2011) in combination with the prospects of further development of carbon sequestration technologies, such as biochar production

[14] See e.g. Kirschbaum (2006) for a discussion on how the instantaneous effect of elevated temperature, the rate of temperature increase and the cumulative impact of increased temperatures have different implications.

(Lenton 2010; Sohi et al. 2010), makes me think that not only the gross cumulative radiative forcing, but also the timing of the exerted radiative forcing is likely to affect the areas of protection. When two ways to fulfil a function exerts the same long term gross cumulative radiative forcing, I would prefer the way that exerts a larger share of this forcing further into the future, as there in such a case is a larger chance to prevent parts of the impacts.

For a reader to be able to make their own value judgement, they have to be aware, or be made aware, that a trade-off exist, and be provided information about the size of the impacts at different times. Informing the reader on the existence and sizes of potential trade-offs could be done in different ways.

It is a common practice to report results as CO_2-eqs by a single time-horizon and specify how large proportion of the total emission that is constituted by the different GHGs. This practice enable a reader who has a notion about how the GWPs of the gases change depending on time horizon to make an approximation of the trade-offs between short and long term impacts. Such approximations are, however, complicated by that land use in different areas causes different emissions/contributions to atmospheric CO_2, (unless one uses an ILUC-method in line with Schmidt et al). It is further complicated if one includes albedo and other previously disregarded climate forcers. Though it is possible to comprehend the trade-offs by the provision of such information, it requires that the reader is aware of the possibility of the existence of such trade-offs and possess sufficient knowledge and skills to convert the results to different time-horizons.

Given the amount of information that has to be given, including details on which land that is used and in which way it is used, and the requirements on the reader's abilities to interpret the results, alternative reporting practices are desirable.

One alternative that has been used by e.g. Levasseur et al. (2010) and several of the references in the review of Helin et al. (2013) is to report the results over several time horizons, or as a function of time horizon. One could also report by a combination of indicators, e.g. a combination of one indicator that reflect the supposed long term impacts on e.g. sea level rise and one indicator reflecting how soon and with which rate the impacts are supposed to set in. Such a combination of indicators does, however, still require the use of a time horizon for the long term impact (if there is no limit value for the integral of the long term impact as $t \to \infty$) and entail large uncertainties and delicate value judgements concerning the construction of the timing and rate reflecting indicator or indicators. When reporting the results as a function of time horizon the reader is given the full picture and the opportunity to intuitively extrapolate the results over longer time horizons.

I believe that the easiest way to inform on the existence and size of potential trade-offs is to report the results for a few different time horizons, or as a function of time horizon. In studies where the results is meant to enable comparisons with other studies one have to assume that there may be trade-offs and that information have to be provided for the readers to comprehend them.

3.4.1.5. Suggestion of criteria 9 and 10

9. The assessment should inform about the influence of the choice of time horizon on the results of the study.

10. The reporting should indicate how the impact develops as $t \to \infty$

Comments:
This could for example be achieved by reporting the climate impact as a function of time horizon (without discounting within the time horizon, which I believe will be automatically/intuitively done by most readers according to their own preferences when they interpret the graph), and over a time interval that is sufficiently long for a stable relationship between the estimated impact of different products to appear or at least be implied. Deeming from the example in this thesis, I think intervals reaching up to about 2000 years seem appropriate, but examples with products causing emissions of other long lived GHGs such as various perfluorinated compounds should also be examined. Over such long timespans one might have to include the long term CO_2 dissipation processes in order not to distort the comparison of fossil CO_2 with other climate forcers.

3.4.2. Choice of climate impact indicator

The predominant climate impact indicator is the CO_2-equivalent, which compares the emissions of GHGs by a GWP-factor, which is described in the method section.

As the denominator, i.e. the cumulative radiative forcing exerted by the reference emission, in the GWP-calculations (see equation 2) is growing with a growing time-horizon, the warming exerted by one unit of CO_2-eq will increase with time. This means that viewed over a longer time horizon, one unit of CO_2-eqs will have a larger climate impact than it has over a shorter time horizon.

Failure to understand the long-term consequences of carbon dioxide emissions are likely to delay actions that mitigate climate change (Dutt and Gonzalez 2012) and when there is a trade-off between impacts in the short and long term, as in the calculation example in Figure 20, I believe that the above described property of CO2-eqs could be confounding for decision makers who use an LCA. How different a comparison of two products can appear depending only on choice of climate impact indicator is illustrated in Figure 22. In Figure 22 the reporting in CO_2-eqs of the calculation example from Figure 20 is complemented with a reporting in the climate impact indicator CO_2 ton year-equivalents. The CO_2 ton year-equivalents, and how they in this thesis are derived from the already calculated CO_2-eqs, is described in section 2.2.3.2 Transformation of CO_2-eq to CO_2 ton year-eqs.

Though the relative difference between soybean meal and field beans are the same at each time horizon, regardless of which indicator that is used in Figure 22, the two indicators could give different impressions of which product that has the largest climate impact. With the CO_2-eq unit (left) one might put a larger weight on the short time horizon since it seem like the impact is larger there and this might give the impression that soybean meal is to prefer from a climatic point of view. However, with the CO_2-kg-year-eq unit (right), the large long-term effect of fossil combustion is more explicitly displayed, which I believe makes the results more comprehensible for a general audience.

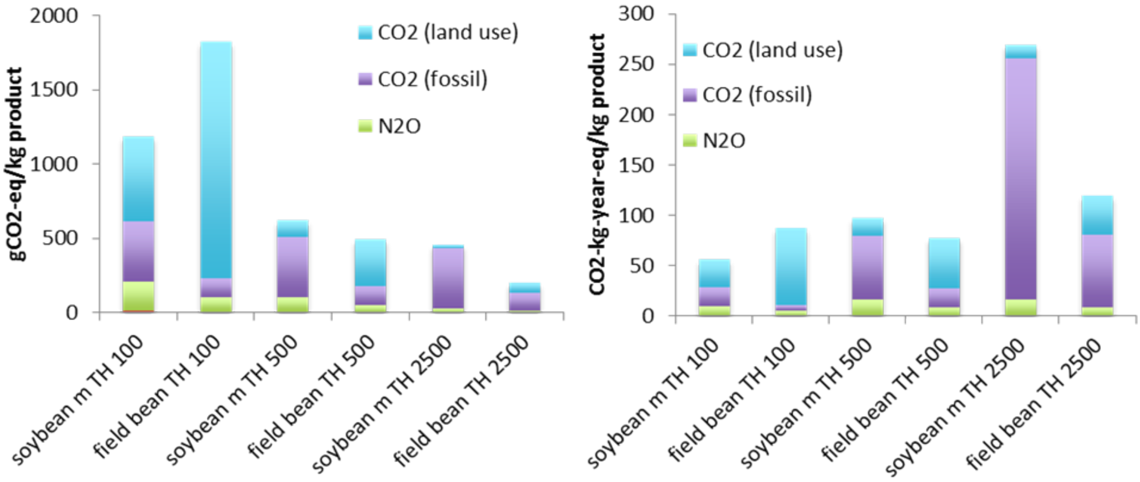

Figure 22. The climate impact of 1 kg of soybean meal imported to and 1 kg of field beans grown in Sweden for three different time horizons and reported as CO_2-equivalents (left) and CO_2-equivalent ton years (right). The CO_2-equivalents results are the same as in (Figure 20) and transformed into CO_2 ton year-equivalents according to the methods described in section 2.2.3.2.

3.4.2.1. Elaboration of criteria

As the CO_2-eq in the LCA context is an ***impact-***indicator, it should reflect the size of the impacts on the areas of protection. For example emissions of CO_2 are in themselves not something that would concern the human population. What is of concern is how emissions, other environmental impacts, and exhaustion of natural resources affect current and future human generations, and the ecosystems in which they (will) live. As emissions of GHGs exert warming for as long as there are remnants of the emissions left in the atmosphere, the impacts of an emission will grow with time.

Though the temperature response of a pulse emission eventually will return to zero, the cumulative impact (measured in e.g. degree-days, mega joule-years, and likely also cumulative economic costs or human years lived) will increase until it start to level out as the temperatures start returning downwards. As the impacts will increase with time, that should be indicated by the impact indicator.

3.4.2.2. Suggestion of criteria 11

11. A climate impact indicator should be designed so that it is reasonable to assume that one unit of the indicator represent an impact of a constant (but possibly unknown) size on the areas of protection, regardless of time horizon

Comment:
Examples of potentially suitable units are gross cumulative radiative forcing (J/m^2), gross energy accumulation (J), surface temperature degree-days (degrees*s), global sea-level rise (m), number of lived years lost (s), and/or cumulative economic cost.

4. Discussion

4.1. Fullfillment of the goal and purpose of the thesis

The purpose of the thesis was to contribute to a formation of consensus about how to handle the climate impacts of land use in LCA and limit the number of alternative methods as well as the variation in results depending on method used. The goal was to suggest criteria for satisfactory methods for handling the climate impacts of land use in LCA that could serve as a tool in the evaluation and development of methods.

The goal of the thesis is, at least partly, achieved; criteria for satisfactory methods are suggested and it is shown how they may be used to evaluate and develop methods. However, there are issues, such as when to include the impacts of expansion of land use and not only land occupation, where it is desirable to examine the need and possibility to elaborate further criteria. It could be, however, that the handling of these remaining issues is dependent on purpose and methodology to the extent that generally applicable criteria will be too complex or vague to be interpretable and useful.

Whether the purpose will be achieved depends on the extent to which the thesis is spread and has an impact on the LCA community. However, if the criteria based on principle 1 "A consistent method" are applied, they will limit the variation in results between different methods by making sure that the direct impacts of land occupation on traditionally used land is not lost in an implicit and misguiding allocation procedure.

The potential of the criteria to limit the number of used methods is unclear. On a theoretical level, the number of possible methods that fulfill the criteria must be smaller than the number of all (i.e. whether they fulfill the criteria or not) possible methods. This theoretical limitation has, however, probably little practical significance, as all the evaluated methods may be adjusted in order to comply with the criteria and in some cases even in different ways. It could be, however, that the limitations in the variation of results could facilitate a formation of consensus around a standard method, as less is at stake when the variation depending on method is smaller.

4.2. Principle 1: A consistent method

From principle 1, criteria are elaborated that are meant to ensure that impacts are defined and attributed to products in a consistent way and based on causality.

Criterion 1 states that all scenarios should be consistent with theories of ecological succession. Criteria 2-4 identify the connections between, and demand an internal consistency among, the most fundamental assumptions concerning the impacts of land use. Together, criteria 1-4 make sure that when a land use change is assumed to cause a CO_2-emission that is aggregated with other emissions into CO_2-equivalents using the gases respective GWP, then the assumed permanency of the CO_2-emission in the GWP calculation is matched by a permanent difference in derived services between the compared scenarios. Criterion 5 prevents that estimated impacts are affected by historic factors that no longer affect the impacts of present or future land use interventions. Finally, criterion 6 ensures that the allocation of the impacts of a land use period to the different services derived during this period is based on causality.

It is possible to use the criteria concerning Principle 1 "A consistent method" in evaluations of suggested methods. It is, however, often difficult to deduce which implicit assumptions that are made in a suggested method, which complicates the evaluation. In these situations the criteria can function as guidance in the interpretation of a method by giving a hint about what the implicit assumptions should be. For criterion 1, which was fulfilled by all the evaluated methods, this was its only function in the evaluations. It is, though, a fundamental assumption that has implications for the interpretation of the methods with regard to the following criteria, and an insufficient consciousness of the possibility that land might be abandoned followed by subsequent ecological succession might have contributed to the common failure to base the allocation of impacts of land use changes on causality.

4.2.1. Allocation of the impact of a crop rotation to the involved crops according to criterion 6

Concerning criterion 6, I have mostly discussed the 1/TH allocation factors that can be used in order to allocate an impact to the crops produced during a 1 year cropping season, a procedure based on the assumption that all years of land use (1 year is considered as 1 of the "sub-periods" mentioned in criterion 6) has the same impact. However, different crops often have different functions and effects in a crop rotation. How should one, in this context, interpret the condition "[if] impacts could be assessed separately" in criterion 6? If a studied crop is integrated into a crop rotation where it affects e.g. the fertilizer need of subsequent crops, and these effects differ depending on which crops that are involved, could one then assess the crops separately? The issues of if and how a crop should be handled in the context of a crop rotation is a question that could deserve attention.

4.3. Principle 2: A comprehensive method

Through principle 2 I stress the importance of considering all mechanisms through which land use affects climate. Criterion 7 demands a consideration of all climate forcers, including e.g. aerosol formation and albedo. Criterion 8 demands that secondary effects of soil degradation, which could include climate impacts of expansion of agricultural area due to lowered yields, are considered.

4.4. Principle 3: A transparent and comprehensible study

In relation to principle 3 I discuss how an LCA should enable readers to interpret the study with regard to their personal value systems. This requires both that the LCA provides sufficient information, and that it is presented in an understandable way. Criterion 9 and 10 ensures that enough information is given concerning trade-offs between impacts in the short and long term, while criterion 11 demands that this information is provided through a consistent climate impact indicator that do not change value depending on time horizon.

4.4.1. Limited target groups of LCA and the enabling of readers to interpret an LCA with regard to the reader's personal value system (Criteria 9 and 10)

There could be cases where it is known on beforehand which readers there will be and what their interests are. One could argue that one in those cases may adapt the scope of the study after their interests and do not have to perform an analysis that is adapted to any reader and all their possible different personal value systems, and that criteria 9 and 10 thus not are universally applicable. One way to solve this could be to add "If it is not known on beforehand that all potential readers/stakeholders have a more limited interest," in the beginning of these criteria. Nevertheless, it may be hard to guarantee that a predicted group of readers will be contained and that no one will be added or exchanged. Also, personal value systems are dynamic and may be affected e.g. by questions raised by information provided in an LCA. Information on the long term impacts may increase a reader's interest in these long term impacts. As there is a chance that an LCA may help to develop a reader's personal value system, I think that the original criteria should be universally applied.

4.4.2. Climate impact indicator and time horizon

A conclusion in the review of Helin et al. (2013) is that cumulative radiative forcing as a function of time is a well motivated climate impact indicator. This is consistent with criteria 9-11, and with the CO_2 ton year-eq unit, which is proportional to the cumulative radiative forcing of a climate impact.

Korhonen et al. (2002) criticize the application of the ton year indicator on transient carbon storage in forestry projects and argues that it is misleading as it "can indicate that carbon sequestration helps in the mitigation of climate change even when the impact of the project on the CO_2 concentration is that concentration increases". This is due to that the transient carbon storage reduces the CO_2 uptake of, or causes a release from, oceanic and terrestrial sinks. When the transient carbon storage comes to an end, only the effect on the oceanic and terrestrial sinks remain. The reversed phenomenon is illustrated in the bottom right graph of Figure 12, where a transient release of CO_2 eventually leads to a decrease in atmospheric CO_2 concentration. However, all this can be captured also with the CO_2 ton-year indicator; in the short term a transient carbon sequestration will decrease CO_2 concentrations and if one reports the results over a large enough time interval, the increase in atmospheric CO_2 that may occur over longer time horizons will be reflected by a decrease in cumulative sequestered ton years. The problem is thus not the ton year indicator, but the exclusion of the longer time horizons.

4.5. Reflections from the evaluation of some suggested methods

4.5.1. Utility of the evaluated methods

The evaluation of suggested methods shows that inconsistencies are common. One can imagine situations where some of these inconsistencies may heavily distort the results. One such situation is when an inconsistent allocation of emissions from assumed land use changes (as in PAS2050) are used in comparisons of crops that are grown on already established crop land and crops that to a large extent is grown on recently deforested land. There is reason to be very careful with drawing conclusions from methods that do not fulfil criteria 1-6.

4.5.2. The land use change concept and the suggestion to adjust criterion 4

Most of the evaluated methods handle the transient character of impacts on carbon stocks in soil and vegetation by putting the studied production in the context of a permanent land use change in order to enable the handling of CO_2-implications of land use as a single pulse emission (or as a missed potential carbon sink that is equivalent to a single pulse emission). Then they allocate a part of this emission to the studied production. I call this strategy the land use change concept (LUCC).

With a strict interpretation of Guideline 1.4 "Whenever it is possible, compared scenarios should be designed in order to avoid allocation", the LUCC would not be allowed. However, it is a strong tradition to handle CO_2-implications as pulse emissions and the handling of transient impacts on carbon stocks require that LCA practitioners and readers learn new conceptual models. In the elaboration of criteria, I therefore chose a looser interpretation of the guideline, but instead regulated the allocation of the impact of a land use change to the products produced during the new land use with criterion 6.

A major drawback with the LUCC is that when it is not suitable to assume that the studied production will cause a land use change, but relies on an established land use (i.e. usage of land that was used already before the studied land use took place), all of the evaluated methods that could be categorized as a LUCC method is in conflict with either criterion 4 or 5. Below, I will discuss the different strategies the evaluated methods use for handling established land use within the LUCC, and the possibilities to make them consistent with the criteria.

4.5.2.1. Three strategies for handling established land use within the LUCC

Among the evaluated methods, there are three different strategies for handling established land use within the LUCC.

- *The historic land use change strategy* used in the PAS2050 and Schmidt et al. methods assess the impact of the preceding land use change.
- *The continuing land use strategy* of the Schmidinger and Stehfest method, in which one assumes an abandonment of the used land in the reference scenario.
- *The crop displacement strategy* used by Searchinger et al, in which the impact is assessed through assumptions of an alternative land use in the reference scenario and a displacement of this use in the studied scenario.

4.5.2.2. The historic land use change strategy

With *The historical land use change strategy* one gets in conflict with criterion 5. I do not see any possible adjustments of the methods belonging to the strategy in order to meet criterion 5 that do not make them leave the strategy. Except for adjustments that would make the methods belong to one of the other two strategies, one could avoid the problem by assuming that all land use takes place in pristine areas. This could be seen as a fourth strategy, denoted e.g. *The always compare with pristine land strategy* or *The avoiding established land use strategy*. This strategy would have the same influence on the results as the possibility to make *The continuing land use strategy* compatible with criterion 4 through an omission of temporal detail, but I find it conceptually simpler to understand.

4.5.2.3. The continuing land use strategy

Of the evaluated methods, *The continuing land use strategy* is only represented by the Schmidinger and Stehfest method, which is in conflict with criterion 4 (see section 3.2.2). I suggested two adjustments of the Schmidinger and Stehfest method in order to meet criterion 4: a consistent inclusion of temporal detail or a complete omission of temporal detail. As a consistent inclusion of temporal detail will make the method leave the LUCC and a consistent omission of temporal detail exaggerate the estimated impacts of land use for short time-horizons more than the original inconsistency do (see Figure 10), I lifted the possibility to adjust criterion 4 in order to allow the inconsistent inclusion of the time dimension by focusing the criteria only on the impact that is attributed to the studied product, rather than on the total impact that is defined by the compared scenarios. I'll get back to the different possibilities after the discussion about *The crop displacement strategy*.

4.5.2.4. The crop displacement strategy

Of the evaluated methods, *The crop displacement strategy* is only represented by the Searchinger et al. method. The Searchinger et al. method runs into the same conflict with criterion 4 as the Schmidinger and Stehfest method does, due to the assumption that some of the ILUC caused by the crop displacement are assumed to take place in areas with growing forests. One could make methods that assume that all effects of crop displacement are compatible with both the LUCC and criterion 4, e.g. by assuming that all crop displacement causes ILUC that takes place in unused areas that are in steady states. The influence on the result of such a limitation in the assumed possible effects of crop displacement would be of a similar character as that of the possibility to make *The continuing land use strategy* compatible with criterion 4 through an omission of temporal detail, but be of a smaller magnitude, as it would only concern parts of the affected land and not the full relaxation time.

4.5.2.5. Abandonment of the LUCC

As discussed above, there are several acceptable alternatives that can make the LUCC and the criteria compatible:

- to adjust criterion 4 in order to allow the inconsistent treatment of the temporal detail in the Schmidinger and Stehfest and Searchinger et al. methods, which will produce the most relevant results.
- making the cop displacement strategy consistent with criterion 4 by assuming that all effects of crop displacement causes ILUC that takes place in unused areas that are in steady states.
- *The avoiding established land use strategy*, which is simple and produce results that are as relevant as the omission of temporal detail within *The continuing land use strategy*
- to adjust the Schmidinger and Stehfest and Searchinger et al. methods through omission of temporal detail

However, criteria 9-11 entail an abandonment of the CO2-eq climate impact indicator and other changes that, in turn, entail diminished, or a complete loss of the benefits of the simplifications of the LUCC. Also, it might not always be reasonable to assume that unused ecosystems are at steady states (see section

3.3.2). Therefore, I think that an abandonment of the LUCC in favour of assessments of delimited land use periods and/or an inclusion of temporal detail is to prefer.

4.5.3. When to include the impacts of expansion of land use

The two varieties of the LUCC that is given in PAS2050 and the Schmidinger and Stehfest methods, the distinction between the ”land transformation” and ”land occupation” activities in the Müller-Wenk and Brandão method, and the distinction between the activities ”land use changes” and ”existing land” in the Schmidt et al. method are all different versions of the same division. They are divisions between activities that include an expansion of land use (i.e. an increase in production capacity) and activities that rely on land that is already prepared for use.

In the Müller-Wenk and Brandão (2010) method there is a distinction between the two types of activities land occupation and land transformation and Müller-Wenk and Brandão are criticised by Schmidinger and Stehfest (2012) for not providing guidance on when the two activities should be used. However, if one compares the Schmidinger and Stehfest (2012) and PAS2050 methods with the Müller-Wenk and Brandão method, one can see that the difference in land use activities between the two compared scenarios in the Schmidinger and Stehfest method only includes land occupation activities, while the difference between the compared scenarios in the PAS2050 method also includes a land transformation. The Schmidinger and Stehfest method thus only offer the land occupation alternative, while one have to turn to other methods if one want to include land transformation impacts, and Schmidinger and Stehfest do not either give guidance on if, or when, that should be done.

In the Schmidt et al. (2011) method, the distinction between the two activities “existing land” and “land use changes”, is similar to the distinction between land occupation and land transformation activities in the Müller-Wenk and Brandão method. In the evaluation of the Schmidt et al. method I compared the two distinctions and suggested that the “land use changes”-activities should be divided into a “land use change”/land transformation activity and an ”existing land”/land occupation activity and that it only is the ”existing land”/land occupation activity that should be assumed to provide NPP_0, while the “land use change”/land transformation activity should be assumed to provide potential net primary production available for occupation (NPP_0AO), i.e. a capacity to deliver a certain amount of NPP_0/year, to a certain land tenure market.

With the suggestion that the different activities should be assumed to provide different services it becomes apparent that land transformations normally are associated to the impacts of establishing or increasing production capacity[15]. These impacts should reasonably be included when the studied product is additional, or replaces a product that demanded less land, and should therefore be

[15] There are cases, however, when reoccurring land transformations are part of land occupation regimes, as is the case in slash and burn (see Cederberg et al. (2011)) and other land use regimes with periods of fallow that are broken with land transformations.

differentiated depending on product and context. For example, most food production is part of already existing production and consumption patterns and could therefore be assumed to rely only on land occupation. However, some foods require more land than others; according to Peters et al. (2007) diets including large amounts of meat and large percentage of calories from fat require larger areas than other diets and for example meat and fats could thus be attributed larger shares of expansion than beans, cereals and other more land-efficient foods. The details of such a differentiation are a topic for further method development.

4.5.4. How should land use be assumed to be affected by the studied production?

The evaluated methods have different strategies for choosing which land that is assumed to have been used or will be affected by a studied product. These different strategies will affect the estimated impact of the use of different products in different ways. To the extent an LCA creates incentives for what land that is used, the choice of method can therefore direct land use towards different types of land. Below, I'll exemplify by first discussing the NPP_0- and hectare-based versions of the Schmidt et al. (2011) method and then the Müller-Wenk and Brandão method. Finally I discus some possible implications of the general guidelines.

4.5.4.1. The two versions of the Schmidt et al. (2011) method

In the Schmidt et al. (2011) method, all used land in different parts of the world are assumed to be part of one of the four global land tenure markets for extensive forest land, intensive forest land, range land, or arable land. Therefore, the only properties of the used land that affect the estimated impact of the use of land from a specific market are properties that affect how much land that is demanded from the market. When demand is measured in hectares, the use of land with a high fertility will decrease the area requirements of primary production dependent services, and thus also decrease the measured exerted demand. When demand is measured in the NPP_0 of the used land, on the other hand, the use of land with a high fertility do not affect the exerted demand, as the decreased area requirements are cancelled by the higher NPP_0 per area used. Thus, when land is used for primary production-dependent purposes, the hectare-based version of the method creates an incentive to use fertile land, while the NPP_0-based version does not create such an incentive.

When land is used for purposes that are not dependent on primary production, such as providing ground for buildings, the fertility of the used land is not affecting the area requirements. In these cases, the exerted demand is not affected by which type of land that is used and there is no incentive to use land with any particular properties in the hectare based version of the method, while the exerted demand is increasing with an increasing fertility of the land and there is an incentive to use infertile land in the NPP_0-based version.

In different contexts one might want to create different incentives: When it comes to agricultural production, one might want to create incentives to use fertile land, as this decrease area requirements. On the other hand, when it comes to land use that is not depending on biomass production, like land occupation of buildings, one might want to create incentives to use infertile land, in order to minimize the displacement of agricultural production and ILUC. However, if one discriminate between usage of land with different fertility without taking into account that also the impacts on local carbon stocks and other climate forcing aspects of the used land vary between different areas (as in the hectare-based version of the Schmidt et al. method) there is a risk that results get skewed and that the incentives will cause changes in land use patterns that increase impacts, as some areas with high fertility also might be areas where land use has particularly large climate impacts per hectare used. Therefore, if one discriminates between land use in different areas, I think it is best to consider both the capacity of the land to provide services and the circumstances concerning the local climate forcing aspects of the land, as e.g. in the Müller-Wenk and Brandão method.

4.5.4.2. The Müller-Wenk and Brandão method

In the Müller-Wenk and Brandão method, the impacts are assessed as compared to if the used land was left untouched or abandoned, and they differentiate between land in 7 different biomes[16]. Therefore, the estimated impact is not only proportional to the exerted demand of land (i.e. the area used), but also depend on how the development of carbon stocks is assumed to be affected by the land use in the biome where the land use takes place. Thus, for primary production dependent services, it is created an incentive to use land that is both fertile and situated in a biome where the land use is assumed to cause as small impact as possible on the climate forcing related aspects of the used land per hectare used[17].

The point of LCA is to discriminate between products with different environmental performance. Whether which type of land that is used is a relevant aspect of a studied product, as well as how specific this discrimination should be, depend on the purpose of the study; when studying a generalized product, the discrimination between usage of different types of land may be low, or absent. However, also in some cases where the studied product is specific enough to motivate a differentiation between land use in different regions, such a differentiation could have undesirable effects if the incentives created do not affect all land users on the same premises, as in the case of sector specific environmental performance based subsidies. In such cases, producers with a high motivation to lower the estimated impacts of their own production (e.g. biofuel producers that get subsidies if their production have estimated impacts that are low enough) could locate their production to areas where impacts are lower, while other producers with less motivation to keep their estimated impacts low could move their production to areas where the direct impacts are higher. Thus, as long as there are subsidies or taxes/fees related to land use that are differentiated based on the category of the product, there could be a reason to assess the impact of land use without differentiation between land use in different regions also in assessments of specific products. I also see this as a reason to stop subsidising biofuels and instead reduce fossil fuel use through taxation, rationing and/or other restrictions.

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[16] Note that one also could make assumptions of separate land tenure markets for usage of land in different biomes, or calculate the global average impact of cropland without describing it through a land tenure market.

[17] In cases where the usage contribute to a negative radiative forcing, as little impact as possible means as large negative impact as possible.

4.5.5. Should there be additional criteria?

There are inconsistencies that are not captured by the suggested criteria. For example, in the evaluation of Schmidt et al. (2011) I have not found a way to use the criteria to show that the NPP_0-supply "land already in use" not on default should be considered a constrained supply. This, as well as the questions of when to include the impacts of expansion (section 4.5.3), which land that should be assumed to be affected by the studied land use (section 4.5.4), and those of the LCA practices listed in Annex II that are not addressed in this thesis show that there are issues that need to be examined further and possibly be regulated by additional criteria before the "criteria for satisfactory methods" are complete. However, in some methodological choices, different alternatives might be suitable in different contexts. In order to be generally applicable in such cases, criteria would either have to be vague, so that they risk becoming meaningless, or cover all special cases so they become too complex and ungraspable. Such issues might be better to regulate in in standards or criteria that are applicable in specific contexts.

4.6. Implications of the results for the controversies mentioned in the introduction

In the introduction I mentioned two land use related controversies in LCA methodology: amortization period and ILUC, which I discuss below.

4.6.1. Amortization period

In a report about ILUC in assessments of the climate impacts of biofuel production, Ahlgren and Börjesson (2011) suggest that one should amortize ILUC emissions over a period as long as one believe that the land will produce crops for biofuel production, rather than over a fixed period of 20 or 30 years. I would in the light of criteria 1-6 draw their reasoning one step further and suggest that one should amortize the impact over a period as long as there is a difference in derived services between the compared scenarios. Or expressed more generally, that one should allocate the impact over all the services that are derived from the land in the studied scenario but not in the reference scenario.

4.6.2. ILUC

As I see it, the general guidelines and criteria do not have any general implications for the choice between methods that include impacts of ILUC and other methods. However, as long as the impact of land use is assessed in a consistent way (in accordance with criteria 1-6), I believe that the difference between different methods will be relatively small in comparison to the difference between ILUC-methods and inconsistent methods like the PAS2050 method, in which no impact at all have been allocated to usage of land that has already been in use for some time. Also, both assessments of direct and of indirect land use could be varied to a large extent and have a large overlap in function (see also footnote 16). However, if one has a context where the studied production is specified in such a way that one must assume that it uses since long used land and/or land at a specific location with known properties, then assumptions of indirect land use through e.g. a land tenure market or crop displacement are useful if one want to include impacts of expansion and/or usage of some kind of average land, rather than the type of land at the specified location (see also section 4.5.3 and 4.5.4).

4.7. Other land uses and climate forcers than cropland and carbon stocks

Most examples in this thesis have concerned carbon stocks on land that is used continuously as cropland. In these examples the variations in carbon stocks are small and neglected. During other land uses, such as clear-cutting based forestry, there are large fluctuations in carbon stocks during a single harvest rotation. Also, on any type of land use, impacts on climate forcers other than carbon stocks could undergo large fluctuations during a single year. These fluctuations could probably be handled by considering the average values of the parameters during the studied land use regime, though one have to make sure that the assumptions concerning the studied land use regimes are consistent and that e.g. assumed average productivity would not be affected by any kind of soil degradation that would result from the assumed land use. However, there could be additional challenges and more work on how the criteria should be interpreted and applied in different contexts is needed.

4.8. Carbon stocks in products

As mentioned in the method (section 2.2.1) I ignore carbon stocks in products in all examples in this thesis. Carbon stocks in products could, however, have a significant impact on the results of an LCA and should be included.

When temporal detail is included one may simply add the ton-years of the carbon stored in the products produced during the studied land use to the carbon stocks of the used land (or subtract it from the impact). When temporal detail is omitted and CO_2-implications are handled as permanent emissions through the land use change concept, one could probably in most cases, if not all, identify a steady state level of carbon stocks in products, based on the average production rate and lifetime of the produced products. This level could then be added to the average carbon stock level on the used land.

4.9. Possible further implications of the guidelines

There could be many further implications of the guidelines. One is that Guideline 1.2 "The methods should have a set of assumptions and value judgements that is internally consistent" could be used to link the assumptions concerning climate impacts to other impacts of land use such as eutrophication and one could e.g. formulate criteria requiring that the same scenarios should be used for reference development of both climate forcers and nutrient leakage.

4.10. Handling trade-offs between short and long term impacts

As discussed in section 3.4.1 Choice of time horizon there are sometimes trade-offs between protecting the climate in the short and long term connected to land use. This trade off will be especially pronounced when it comes to deforestation for biofuel production. If one now uses a short time horizon, with the effect that biofuels seem to have a larger climate impact than fossil fuels, and therefore clear less forest for agricultural production and produce less biofuels, without reducing energy consumption, then more fossil fuels will be combusted. This additional fossil fuel combustion, due to the short time-horizons used, means that there will be less options for future generations to start biofuel production when the climate crisis is intensifying or peak oil is intensifying. If we are to make a transition from fossil fuels to biofuels on behalf of forest cover it is better to do it as soon as possible, since the additional fossil fuels combusted while we wait are irreversible emissions. As the climate crisis already is quite urgent, efforts to reduce energy and fuel consumption should be of a high priority.

4.11. Other research and development needs

My analysis has been biased by that I've had thoughts about correcting specific inconsistencies I have spotted in LCA literature. Had someone who lacked the knowledge of these inconsistencies performed the analysis with the points of departure I set and then tried to make a systematic analysis of what they entail for the handling of climate impacts of land use in LCA, they could have concluded in other criteria. The set of criteria I suggest could most probably be improved. However, I'm not sure that it is worth prioritizing improving criteria that should be applicable in any context. It is perhaps more fruitful to develop and improve standards for handling climate impacts of land use in LCA in specific contexts, based on more specified theoretical foundations and/or are adapted for specific purposes.

4.11.1. Modelling of the contribution to atmospheric CO_2 content of changes in carbon stocks

When modelling the contribution of impacts on carbon stocks to atmospheric CO_2 levels I use the IRF of the BernCCM (see section 2.2.2 Modelling of the contribution to atmospheric CO_2 content of impacts on carbon stocks). The IRF is designed to describe the response to an emission, i.e. CO_2 uptake of oceans and terrestrial sinks, not for the potential release of CO_2 from these sinks after sequestration flows. Since some of the processes that are part in withdrawing CO_2 from the atmosphere are not equilibrium processes, see e.g. Denman (2007), using the BernCCM IRF on sequestration flows is not correct. I suppose one can get around this by counting the effects of the studied sequestrations as cancelling of emissions occurring elsewhere. However, I find this solution reasonable only as long as CO_2 levels are rising. Considering the 350 ppm target set by Hansen et al. (2008), this will hopefully not be very long. It is therefore desirable to develop IRFs for CO_2 sequestration flows or other enhanced modelling procedures for handling the atmospheric response to CO_2 sequestration.

5. Conclusion

A set of criteria for satisfactory methods that can serve as a tool in the evaluation and development of methods for handling climate impacts of land use in LCA is suggested and the goal of the thesis is thus achieved, though the criteria could be elaborated further.

Inconsistencies in the handling of the CO2-implications are common in the evaluated methods and some inconsistencies could heavily distort comparisons between different products. It is, however, relatively easy to correct these inconsistencies with the suggestions given in this thesis.

It is urgent to develop methods to include the impacts of radiative forcers other than GHGs, such as albedo and aerosol formation, and to improve the reporting of LCAs in order to facilitate for readers to make their own value judgement in relation to trade-offs between short and long term impacts.

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7. Annex I, Modifications of the method of Müller-Wenk and Brandão

Modifications of the method of Müller-Wenk and Brandão (2010) to allow the use of any time horizon and a consistent use of carbon stock ton-years in the comparison of temporary carbon stock changes and permanent CO_2-emissions.

The formulas are only usable in contexts where one settles with the simplifications of carbon stock modelling that I've adopted from Müller-Wenk and Brandão: constant carbon stock levels during steady states, connected by immediate losses and constant build up rates.

7.1. Ton years exerted by a land use change

Impact (e) in carbon stock ton-years of the reference emission, i.e. a permanent emission from fossil origin or from a land use change:

$$\boldsymbol{e\ (ton\ years) = CT\ (tons) * \ TH\ (years)} \quad \textbf{(AI 1)}$$

where CT is the carbon transfer (i.e. the size of the emission) and TH is the time horizon of the assessment.

7.2. Ton years exerted by a land use transformations

For a land transformation the impact in carbon stock ton-years is in this thesis approximated as

$$\boldsymbol{e = CT * \frac{TR}{2}\ \ for\ TH > TR} \quad \textbf{(AI 2)}$$

$$\boldsymbol{e = \left(\frac{CT}{TR} * TH\right) * \frac{TH}{2} + \left(CT - \frac{CT}{TR} * TH\right) * TH = CT\left(TH - \frac{TH^2}{2TR}\right)\ for\ TH < TR} \quad \textbf{(AI 3)}$$

where TR is the relaxation time (the time it takes for carbon stocks to return to a state similar to that prevailing before the transformation, se Figure 11). A graphical explanation of the equation is found in Figure 23.

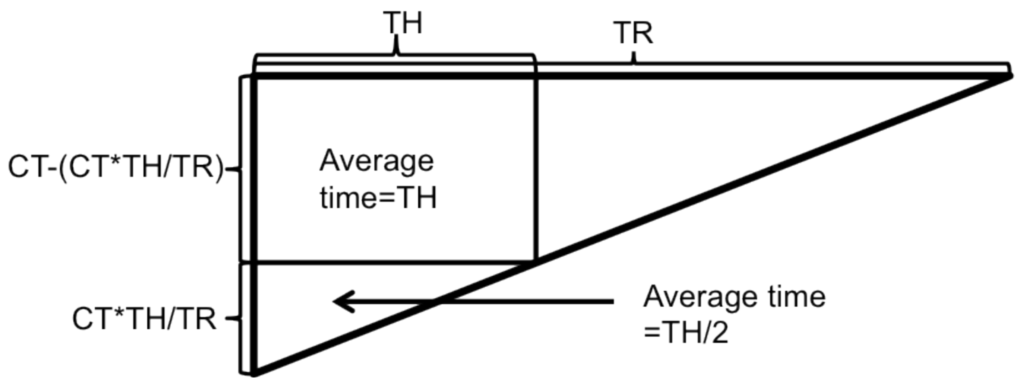

Figure 23 Graphical explanation of the calculation of the impact of a land transformation in carbon stock ton-years.

7.3. Ton years exerted by a period of land occuation

For land occupation the impact in carbon stock ton-years can be approximated as:

$$e = CT * TO \; for \; TH > TR \qquad \text{(AI 4)}$$

$$e = \left(\frac{CT}{TR} * TH\right) * TO = CT * TO * \frac{TH}{TR} \; for \; TH < TR \qquad \text{(AI 5)}$$

Where TO is the occupation period (see Figure 11). This procedure includes also a small part of the impact that takes place after the time horizon (see Figure 24). If one wants to eliminate this error the impact should instead be calculated as

$$e = \left(\frac{CT}{TR} * TH\right) * TO - \frac{TO * \left(\frac{CT}{TR} * TO\right)}{2} = TO * CT * \frac{\left(TH - \frac{TO}{2}\right)}{TR} \; for \; TH < TR \qquad \text{(AI 6)}$$

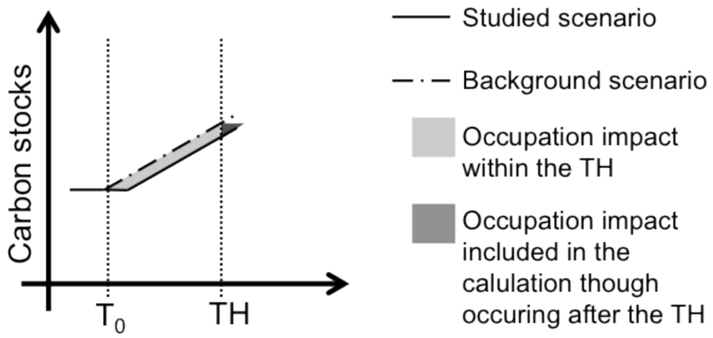

Figure 24. T_0 is the starting point of the occupation period, not the occupation period (TO).

8. Annex II, Lists of scientific input, value issues and LCA practices to consider in an LCA, and an illustration of how they are intertwined.

Scientific input

- Different temporal aspects of climate change and their effects
    - Timing of temp change or exerted radiative forcing
        - Affects possibility for human civilisation to compensate for emissions through carbon sequestration and to prepare for adaptation
    - Rate of temp change
        - Affects possibility for both human civilisation and other species to adapt
    - The new temp at any new moment
        - Affects e.g. storms, floodings heat waves, fires, agricultural yields (climate feedbacks and thresholds)
    - Cumulative warming (degree-days)
        - Sea level rise
        - Desertification
        - Climate feedbacks and thresholds
- Different geographical aspects of climate change e.g.
    - Warming of atmosphere at ground level
    - Warming of the oceans
        - Affects e.g. sea level, intensity of storms, feadbacks (sea ice, release of methane from seabed)
    - Warming of soil
        - Affects e.g. ecosystem function (including agriculture) feedbacks (decomposition of organic matter and release of methane from permafrost)
- Impacts of different climate forcers and products have different time profiles
- Feedbacks and threshold effects in the carbon-climate system

Value issues

- Choice of areas of protection, e.g.
    - Different aspects of human health
    - Different aspects of human culture (e.g. solidarity, peace, knowledge and a specialized society)
    - Health of other organisms
    - Different aspects of biodiversity (e.g. genetic, species, ecological function and ecosystem level; preservation of present diversity and on-going evolution)
    - Aesthetic Wilderness
- Presencism/generationism [18]
- Values concerning management of uncertainties and risks
    - Focus on minimizing harm (choosing actions that avoid the scenarios with the worst outcomes), maximizing potential gain or maximizing expected value.
    - level of precaution; worst case or most probable scenarios[19]
- Preference between marginal and average effects
- Preference between generic and specific information
- Prioritizing meeting the basic needs of all of mankind, or the wants of the people with the highest purchasing power in the market economy

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[18] Presencism: The idea that the present is more important/has a higher value than the future
Generationism: The idea that present (and near term) generations are more important/has a higher value than future generation

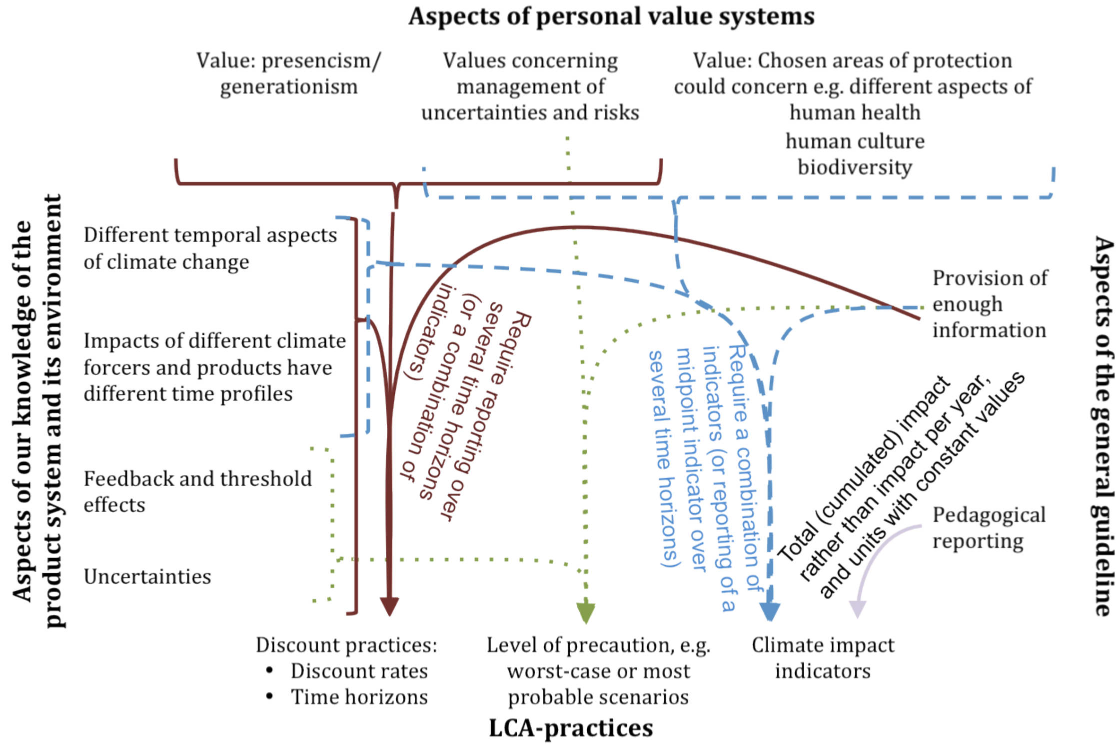
[19] E.g. concerning soil degradation during agricultural activites. Precaution concerning technology development in e.g. renewable energy and CCS are also relevant with regard to trade-offs between short and long term impacts. Development of future emissions, climate sensitivity, feedbacks in the carbon cycle and ability of humanity and other organisms to adapt/evolve.

LCA-practices

- the choice of climate impact indicator
- the GWP time-horizon and other discounting practices
- which land that is assumed to be used
- what is assumed as reference land use
- how the effects of crop displacement are handled in cases where the land is used in the reference land use
- how land transformation impacts are handled in methods that distinguish between land transformation and land occupation impacts (such as the Müller-Wenk and Brandão method)
- how one handle uncertainties in modelling of the effect of the land use on carbon stocks and other climate forcing aspects associated to the land
- how one handle uncertainties in modelling of the effect of the land use on soil fertility
- how one handle uncertainties in the climate modelling, e.g. concerning feedback effects

Requirements of a comprehensive reporting

- Provision of enough information
- Pedagogical reporting



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