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# Baseline time accounting: Considering global land use dynamics when estimating the climate impact of indirect land use change caused by biofuels

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**Abstract**
*Purpose* Current estimations of the climate impact from indirect land use change (ILUC) caused by biofuels are heavily influenced by assumptions regarding the biofuel production period. The purpose of this paper is to propose a new method (baseline time accounting) that takes global land use dynamics into account that is consistent with the global warming potential, that is applicable to any phenomenon causing land use change, and that is independent of production period assumptions.
*Methods* We consider ILUC in two forms. The first is called "accelerated expansion" and concerns ILUC in regions with an expanding agricultural area. The second is called "delayed reversion" and concerns ILUC in regions with a decreasing agricultural area. We use recent trends in international land use and projections of future land use change to assess how ILUC from biofuels will alter the development in global agricultural land use dynamics compared to the existing trend (i.e., the baseline development). We then use the definition of the global warming potential to determine the $CO_2$ equivalence of the change in land use dynamics.
*Results and discussion* We apply baseline time accounting to two existing ILUC studies in the literature. With current trends in global agricultural land use, the method significantly reduces the estimated climate impact in the previous ILUC studies (by more than half). Sensitivity analyses show that results are somewhat sensitive to assumptions regarding carbon sequestration and assumptions regarding postreversion ecosystems.
*Conclusions* The global dynamic development in land use has important implications for the time accounting step when estimating the climate impact of ILUC caused by biofuel production or other issues affecting land use. Ignoring this may lead to erroneous conclusions about the actual climate impact of ILUC. Several land use projections indicate that the global agricultural area will keep expanding up to and beyond 2050. We therefore recommend to apply the baseline time accounting concept as an integrated part of future ILUC studies and to update the results on a regular basis.

**Keywords** Biofuels · Bioethanol · Corn ethanol · ILUC · Indirect land use change · Time accounting

## 1 Introduction

Liquid biofuels provide a renewable alternative to fossil fuels in the transportation sector. For instance, corn-based ethanol can replace conventional gasoline, which causes average greenhouse gas (GHG) emissions of roughly 95 g $CO_2$ equivalents per megajoule of fuel (g $CO_2$e/MJ) when considering the entire life cycle from crude oil extraction through refining and combustion (Argonne National Laboratory 2010a). For comparison, Liska et al. (2009) estimated GHG emissions from US corn-based ethanol to be 38–48 g $CO_2$e/MJ. The

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corresponding number in the GREET Model version 1.8d (Argonne National Laboratory 2010b) is 53 g $CO_2$e/MJ (Argonne National Laboratory 2010a). This includes the energy efficiency improvements in ethanol production documented by Mueller (2010). Based on these numbers, substituting conventional gasoline with corn-based ethanol provides a significant potential for reduction of GHG emissions. However, emissions from so-called indirect land use change (ILUC) have not been considered in this comparison. ILUC may occur when existing agricultural land previously used for food or feed production is devoted to the production of biofuel feedstocks. Simply speaking, the resulting drop in the supply of feed or food can cause a relative increase in agricultural prices, which could provide incentives to increase production elsewhere (Kløverpris et al. 2008). To some extent, this production increase may come from conversion of new land to agricultural land, and this may result in GHG emissions, e.g. from forest clearing. To estimate the GHG emissions from ILUC and relate it to one unit of biofuels, it is necessary to estimate the *amount* of land indirectly affected, the *types* of land indirectly affected (grassland, forest, etc.), and the *greenhouse gas emissions* from these land types resulting from their conversion to agriculture. Finally, the GHG emissions from ILUC must be allocated to the volume of biofuels produced. This step is most often referred to as "time accounting" because the initial ILUC emissions must be ascribed to the subsequent biofuel production, which may take place during several decades. Searchinger et al. (2008) were the first to come up with a full analysis of ILUC emissions from biofuels. Since then, several other researchers have refined and improved ILUC modeling, e.g. Hertel et al. (2010). However, the time accounting approach applied by Searchinger et al. has somewhat set the standard for many other ILUC studies. Searchinger et al. simply distributed the ILUC emissions over 30 years of corn ethanol production. This is also known as the annualization method. The choice of a 30-year accounting period is clearly somewhat arbitrary and, at the same time, has significant implications for the results: If the accounting period is doubled, the ILUC emissions are halved and vice versa. Furthermore, the annualization method does not consider what would have happened to the land indirectly affected by biofuel production in a scenario without the biofuels. Instead, it is implicitly assumed that the global agricultural area would remain constant without biofuels and global land use dynamics are thereby ignored.[1] A more sophisticated approach to the time accounting issue is clearly a much needed addition to the scientific debate about ILUC. The purpose of this paper is to present a time accounting method that takes the shortcomings of the annualization method into consideration and to illustrate how this method would affect ILUC emissions calculated in other studies. We will refer to the concept as "baseline time accounting."

This paper will mainly focus on biofuels, but the philosophy behind baseline time accounting is applicable to any phenomenon resulting in ILUC such as highways and buildings on agricultural land, shifting from conventional to organic farming (in case of changed yields), political set-aside programs, and everyday dietary choices made by the consumer in the supermarket.

We will use the term "land use baseline" (or just baseline) to describe the constant development in land use taking place as a result of all other drivers than the specific subject under study.

## 2 Methods

### 2.1 Current land use baseline trends

We begin by looking at the most recent trends in the land use baseline. From 1998 to 2007,[2] the cropland area in the developed world (loosely defined as Europe, North America, and Oceania) decreased steadily by a total of 4 % or roughly 2.2 million ha (Mha) per year on average (FAOSTAT 2010). When comparing to data in Roques et al. (2011), it appears these cropland changes were inversely correlated with changes in idle cropland, but Europe and the USA also saw an increase in forest cover during the period described (FAO 2010; Smith et al. 2010).

The recent trends in cropland areas in the developed world indicate that neither direct nor indirect effects from biofuels have caused any (gross) expansion of the cropland area in this part of the world from 1998 to 2007. Instead, biofuel production has likely slowed down the rate at which land has gone out of production due to idling or other causes. We will later refer to this effect as "delayed reversion".

From 1998 to 2007, the developing world (loosely defined as Africa, Asia, and Latin America) has seen a 5 % increase in cropland area or roughly 4.9 Mha/year on average. This has mainly been driven by changes in Africa and Latin America (FAOSTAT 2010). See Electronic Supplementary Material 1 (Section 1) for further details.

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[1] Interestingly, the baseline dynamics are often considered in the estimation of the amount of land indirectly affected, which is explicitly modeled as a net change, i.e., a change in relation to a baseline (see e.g., Hertel et al. 2010).

[2] The latest 10-year period for which global land use data were available in the FAOSTAT database (FAOSTAT 2010) at the time of writing.

## 2.2 Baseline implications for time accounting

As shown in the previous section, the land use baseline is not static as implicitly assumed in the annualization method (used for time accounting in most existing studies of ILUC emissions from biofuels). The fact that the baseline is dynamic is actually what allows us to discard the annualization method (and its dependency on a fixed biofuel production period) and instead estimate global warming from ILUC emissions specific to the year in which a given volume of biofuels is produced. The issue of a dynamic baseline has previously been addressed by Kløverpris et al. (2010). However, this was in relation to land quality, not GHG emissions (graphically illustrated in Fig. 3 in the previous paper). The baseline time accounting concept builds on the approach discussed by Kløverpris et al. (2010) and the implications for the modeling of GHG emissions from ILUC are discussed below. Whereas Kløverpris et al. (2010) only dealt with marginal changes in agricultural land use (typically adequate for product life cycle assessment), we will show how baseline time accounting can also cover larger changes in land use, which may occur as result of biofuel policies or other policies affecting agricultural land use, e.g. the EU set-aside policy.

### *2.2.1 Accelerated expansion*

We begin by explaining ILUC in the form of accelerated expansion. When biofuels cause ILUC in a region where arable land use is already increasing, the additional (indirect) land use effect will be to speed up the expansion of the agricultural area. New land will thereby be taken into production earlier than it otherwise would have been in the baseline. If an existing crop field is used for biofuel feedstock production during 1 year, another area of new land will come into production somewhere else 1 year earlier compared to the baseline. If the production of feedstock is maintained in the next year (on the same existing agricultural land), yet another area of remote new land will come into production 1 year earlier than it otherwise would have had and so forth. This is illustrated in Fig. 1, which shows how two consecutive years of biofuel production each has the same ILUC impact, namely to bring a given area (indicated by a star) into production 1 year sooner than in the baseline. Note that this yearly impact is independent of the assumed production period as long as the baseline is expanding.

Figure 1 illustrates a situation in which the subject under study (in this case biofuel production) causes indirect land use change, which does not exceed the annual baseline expansion of the agricultural area. In that sense, Fig. 1 is relevant to all marginal changes but also changes of a significant size (seen in relation to baseline changes).

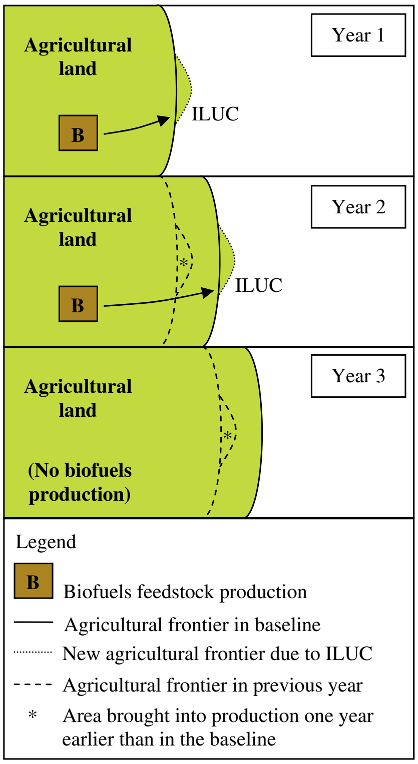

**Fig. 1** Accelerated expansion. In a region with an expanding agricultural area, the indirect land use effect of biofuels produced elsewhere will bring new land into production earlier (in this case 1 year earlier) than in a baseline situation without the biofuels. This is illustrated with 2 years of biofuel production in the figure above. Note that each year has the same ILUC impact (*asterisk*)

In case of a larger biofuel program, the accelerated expansion (the area coming into production sooner than in the baseline) may exceed the next year's baseline expansion whereby some land comes into production not just 1 year but two or more years earlier than in the baseline. We will later show how the baseline time accounting methodology can address this situation. Furthermore, ILUC could potentially go beyond the expansion that would anyway have occurred in the baseline, at some point. This situation is discussed in Section 4.3.

### *2.2.2 Delayed reversion*

The other form of ILUC is delayed reversion. In regions where agricultural land use is declining, ILUC will slow this process down. If an existing crop field is occupied for biofuel feedstock production during 1 year, it will indirectly postpone (by 1 year) the time by which a corresponding area of agricultural land is going out of production (analogous to “accelerated expansion”). Another year of biofuel feedstock production (on the same existing agricultural land) would have the same effect although it would now be another area of agricultural land, which was delayed in its “retirement” from agriculture. This is graphically illustrated in Fig. 2. Based on Section 2.1, we find it likely that the "retired" land will go idle and start the early reversion to a natural state. We therefore designate this type of ILUC delayed reversion. Also in this case, the ILUC impact of several years of biofuel production would be the same and assumptions about the production period are unnecessary (assuming yields and other parameters stay the same). Note that under the assumption of a static baseline, delayed reversion would not be a possibility because there would be no reversion (in the baseline) to delay. This again shows why the baseline is important.

## 2.3 Estimating an ILUC factor

As discussed above, ILUC will change the timing of land use changes in the baseline. This means that these changes would occur anyway, but they must still be accounted for.

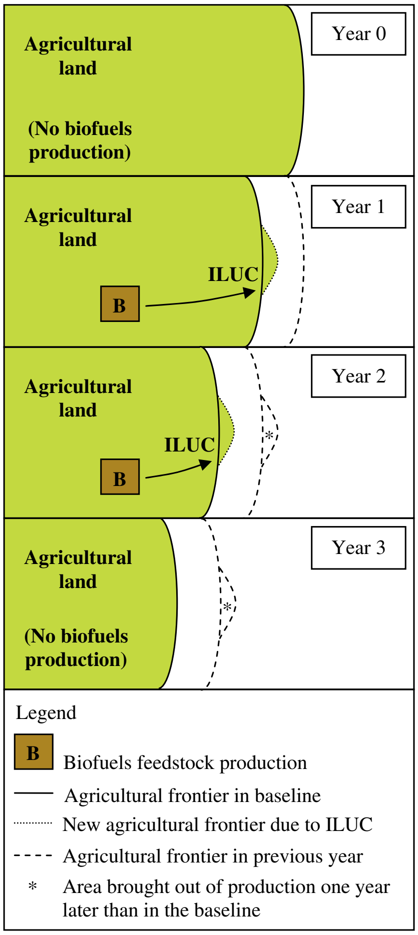

**Fig. 2** Delayed reversion. In a region with a decreasing agricultural area, the indirect land use effect of biofuels produced elsewhere will delay the reversion of land going out of production (in this case by 1 year) compared to a baseline situation without the biofuels. This is illustrated with 2 years of biofuel production in the figure above. Note that each year of production has the same ILUC impact (*asterisk*)

We now move on to the global warming implications of the time shift in GHG emissions caused by ILUC seen in relation to a dynamic baseline. The earlier GHG emissions in the case of accelerated expansion and the postponed carbon sequestration in the case of delayed reversion cause GHGs to be present in the atmosphere for a longer time than in the baseline. During this additional time, they will cause warming, which must be considered.

The GHG emissions from indirect land use change attributed to one unit of biofuels is often referred to as "the ILUC factor" (although it is in fact an addend, not a factor). Since the ILUC factor is added to the direct emissions from biofuel production, the unit of the ILUC factor must be consistent with the direct emissions. These are typically measured by their global warming potential seen over 100 years (here referred to as GWP100). The GWP100 expresses the $CO_2$ emission, which would cause the same cumulative radiative forcing (CRF) as a given radiative effect during the accounting period of 100 years. There has been some debate over the GWP concept (see e.g., Fuglestvedt et al. 2003; Shine 2009; Levasseur et al. 2010). For instance, while a variety of arguments support 100 years as a reasonable accounting period (Fearnside 2002), this time period is basically arbitrary. It is, however, beyond the scope of this paper to enter these discussions. We will simply accept that the GWP100 is the common choice of metric for global warming impacts and describe how an ILUC factor for accelerated expansion and delayed reversion can be derived accordingly. Note that we are not exchanging one arbitrary choice (the assumed biofuel production period) for another (the accounting period in the GWP concept). We are simply ensuring consistency between the ILUC factor estimation and the GWP concept.

The GWP100 is defined as the CRF of a radiative effect during 100 years divided by the CRF of a pulse emission of one unit of $CO_2$ during the same period of time (Ramaswamy et al. 2001). The GWP can be derived for GHG emissions but also for other radiative effects, e.g., changes in albedo (Muñoz et al. 2010). In accordance with the GWP100 definition, we will define the ILUC factor under dynamic baseline conditions as the difference between the CRF of the ILUC emissions and the CRF of the baseline emissions[3] during the same 100-year period seen relative to the CRF of a pulse emission of one unit of $CO_2$. This can also be expressed as in the equation below:

$$\text{ILUC factor} = \frac{\text{CRF}_{\text{ILUC}} - \text{CRF}_{\text{Baseline}}}{\text{CRF}_{\text{CO}_2}}$$

where CRF designates the cumulative radiative forcing over the same period of 100 years. For a conceptual illustration of

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[3] The baseline emissions being equal to the ILUC emissions but occurring 1 year later or more (see Table 1).

$CRF_{ILUC}$ and $CRF_{Baseline}$, see Fig. 3. The method proposed here for handling temporal shifts in GHG emissions is not novel. A similar approach (the Lashof method) has previously been published by Fearnside et al. (2000). For further discussion, see Electronic Supplementary Material 1 (Section 2).

In order to calculate the CRF values for the land use emissions in the ILUC and baseline scenario, we rely on a spreadsheet-based climate model based on Forster et al. (2007). The model provides yearly increased radiative forcing based on emission data determined by the user. The GHG emissions can be inserted in different years so a temporal emissions profile for land use change can be established. The model takes into account the atmospheric GHG residence time.[4] The CRF of ILUC emissions seen over a 100-year period can thereby be established as well as the CRF of baseline emissions seen over the same period of time. It is thus possible to calculate the ILUC factor relevant for dynamic baseline conditions. In the following, we explain how the GHG emissions from ILUC are inserted into the spreadsheet model. The model itself is provided as an electronic appendix in two versions (see Electronic Supplementary Materials 2 and 3) illustrating the two case studies described in Section 3.1.

ILUC from biofuel production (or other phenomena affecting the demand for land) will typically be seen in both the developed and the developing world (Searchinger et al. 2008; Hertel et al. 2010; Kløverpris et al. 2010). When the ILUC occurring in the developing world is smaller than the annual baseline expansion (E) and ILUC in the developed world is smaller than the annual baseline reversion (R), the emission profiles to be inserted in the spreadsheet climate model can be expressed as in Table 1. The ILUC emissions are assumed to take place instantaneously after the production of the triggering biofuel production (year 1), whereas in the baseline, the same emissions (from the same land) would not have taken place until 1 year later (year 2), following the logic explained in Section 2.2.1. For the developing world, ILUC emissions are modeled as accelerated expansion with GHG emissions from conversion of above- and below-ground biomass (a) and the same emissions in the baseline, only happening 1 year later (see Section 2.2.2). For simplicity, above- and below-ground carbon emissions are assumed to occur instantaneously. Distributing these emissions more realistically over several years would only have a minor influence on results since the time shift in the emissions profile would still be the same. Carbon sequestration could be included during the first year of the baseline emissions profile (see Table 1), but, as the carbon sequestered during this year is released as part of the subsequent years' emissions from above- and below-ground biomass, the baseline carbon sequestration in year 1 has been omitted for the developing world.[5] For the developed world, ILUC emissions are modeled as delayed reversion, which means that the land in the baseline will sequester carbon for an additional year compared to the biofuel (ILUC) scenario (see Table 1). In principle, carbon sequestration in both the ILUC and the baseline situation could be included from year 2 and onwards. However, these emissions would simply cancel out each other and thereby not influence the result.

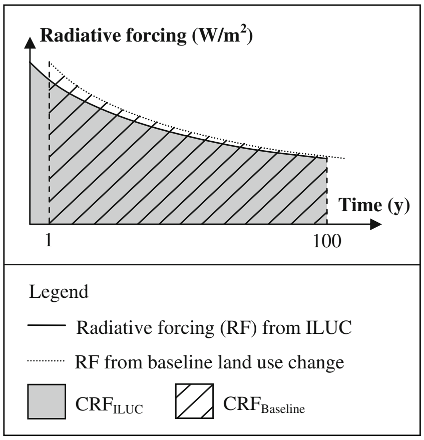

**Fig. 3** Radiative forcing from land use emissions. Conceptual illustration (not to scale) of radiative forcing from land use change in a situation where ILUC causes land to come into production 1 year earlier than in the baseline. The radiative forcing decreases after the land use change because of GHG removal from the atmosphere caused by different mechanisms

So far, we have only considered a situation in which the studied change (biofuel production) does not cause ILUC, which exceeds the annual rate of land use change in the baseline (cf. Fig. 1). This will always be the case when studying marginal changes in land use. When looking at larger changes where ILUC in the developing world does exceed annual baseline expansion (E), some of the accelerated expansion will happen *more* than 1 year in advance of the baseline expansion. In that case, the emission profiles in Table 2 should be used in the climate model (see Electronic Supplementary Material 1, Section 3.1 for details).

If ILUC exceeds the annual baseline reversion in the developing world, 1 year of reversion will be delayed, and the net land use change exceeding the annual baseline reversion will consist of expansion into an area that recently “reverted.” However, that is only in the first year of biofuel production. In the next year, biofuel production will delay the reversion of the area that was “reconverted” due to the first year of biofuel production. The emissions profiles for the developed world in Table 1 are therefore relevant for all

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[4] The significance of this was also discussed by O'Hare et al. (2009).

[5] An alternative approach could be to include baseline carbon sequestration in year 1. and then subtract it from the above- and below-ground emissions in year 2. However, this would only have a negligible influence on results and therefore we chose the other simpler approach.

**Table 1** Land use emission profiles

| Region | Year → | 1 | 2 | 3 | 4 | 5 | … |
|---|---|---|---|---|---|---|---|
| Developing | ILUC | a | – | – | – | – | – |
| | Baseline | –* | a | – | – | – | – |
| Developed | ILUC | – | – | – | – | – | – |
| | Baseline | −c | – | – | – | – | – |

The general form of ILUC and baseline emission profiles for the developing world (accelerated expansion) and the developed world (delayed reversion) when ILUC does not exceed annual baseline expansion and reversion, respectively. The unit of a and c is mass of $CO_2e$ per functional unit, for biofuels typically grams of $CO_2e$/megajoule

*a* total above- and below- ground C emissions, *c* average annual carbon sequestration

* See discussion in text about carbon sequestration

years of production except the first, which has been given further consideration in Electronic Supplementary Material 1 (Section 3.2).

## 2.4 Additional methodological elaboration

The method proposed in this paper has been discussed extensively prior to publication (at conferences, in working groups, during the review process, and in other academic forums). Particularly one key question has always been at the center of the debate: What if biofuel production continues or, in other words, will biofuels not, at some point, lead to land use expansion on top of maximum baseline expansion? Since this question is key to understanding the baseline time accounting concept, it will receive special attention in this section. First of all, we stress that the baseline time accounting concept is not directly applicable when/if the object of study (in this case biofuels) leads to agricultural expansion beyond what would have occurred anyway in the baseline. We will later refer to such expansion as "additional expansion" (as opposed to accelerated expansion). Secondly, whether biofuels lead to additional expansion depends on the duration of their production and the baseline. Thirdly, if biofuel production should not stop, it is certainly wrong to assume a production period of 30 years. Interestingly, Searchinger et al. (2008) chose a 30-year production period partly because they found that "ethanol is typically viewed as a bridge to more transformative energy technologies." If Searchinger and colleagues are right, all (or at least a substantial part) of the agricultural expansion possibly caused (indirectly) by biofuel production would most likely have occurred at some point anyway. This illustrates the shortcomings of the annualization method and the need for consideration of the baseline.

The fundamental basis for the thinking behind the baseline time accounting concept is the typical product-oriented approach in consequential life cycle assessment. We ask the question: What is the environmental impact, in this case the climate impact specifically, of producing and using a given product at a given time under the given circumstances *relevant at that time*. It is well known that the circumstances surrounding a system under study, e.g., market trends, may have important implications for the LCA of a given product. For a general discussion, see e.g., Ekvall and Weidema (2004). The present paper basically considers how trends in agricultural land markets influence the climate effect of ILUC caused by a given product. When land use baseline trends change, this will affect the estimation of the ILUC factor, especially when looking at larger land use changes (cf. Table 2). Note that the baseline time accounting method does not rely on an a priori assumption about biofuel production stopping sometime in the future (if biofuels is the object of study). What the method does is to allow for an estimation of the GWP100 from ILUC caused by the production of a "land-consuming" product at a given point in time—as long as the estimated ILUC does not lead to a greater agricultural area than the baseline peak. For further discussion of "additional expansion", see Section 4.3.

**Table 2** Land use emission profiles

| Year | 1 | 2 | 3 | n |
|---|---|---|---|---|
| ILUC | a | – | – | – |
| Baseline | – | If $I_a \le E$: a<br>If $I_a > E$: $E/I_a \times a$ | If $I_a \le E$: 0<br>If $E < I_a \le 2E$: $(I_a - E)/I_a \times a$<br>If $I_a > 2E$: $E/I_a \times a$ | If $I_a \le (n-1)E$: 0<br>If $(n-2)E < I_a \le (n-1)E$: $(I_a - (n-2)E)/I_a \times a$<br>If $I_a > (n-1)E$: $E/I_a \times a$ |

The general form of ILUC and baseline emission profiles for the developing world (accelerated expansion) when ILUC exceeds annual baseline expansion

*a* total above- and below-ground carbon emissions (mass of $CO_2e$ per functional unit, for biofuels typically 'g $CO_2e$/MJ'); $I_a$ ILUC in the form of accelerated expansion in the developing world (in million hectares); *E* annual baseline expansion in the developing world (assumed to currently be 4.9 Mha, based on Section 2.1)

## 3 Results

### 3.1 Baseline time accounting applied to existing studies

To illustrate the influence of baseline time accounting on existing ILUC factor results, we apply the concept on the studies by Searchinger et al. (2008) and Hertel et al. (2010), both relating to corn-based ethanol. We derive emissions data directly from these studies. Above- and below-ground emissions in the developing world (a) are estimated at 2,240 and 110 g $CO_2$e/MJ for the Searchinger and Hertel study, respectively (see detailed calculations in Electronic Supplementary Material 1, Section 4). As for the carbon sequestration values to be used for the delayed reversion calculations, it is less straight forward to use the data in the original studies. The reason is that the authors use foregone sequestration values for mature ecosystems, which only sequester relatively small amounts of carbon. To avoid underestimation of the carbon sequestration delayed by ILUC in the developed world, and, in order to consistently use the data from the original studies, we exploit that these studies estimate above- and below-ground carbon emissions (a) from land conversion in the developed world. Based on the assumption that the carbon lost upon conversion of land will be resequestered within 100 years, we estimate the annual average carbon sequestration delayed in the developed world by dividing the above- and below-ground emissions (a) with 100 (i.e., $c = a/100$, for the developed world). This gives delayed carbon sequestration of 5.9 and 10.1 g $CO_2$e/MJ for the Searchinger and Hertel study, respectively. There are two important reasons for dividing by 100 years. First, it is consistent with GWP100. Second, it is generally considered reasonable to assume that land reverting to a natural state will have reached maximum carbon stock or close-to-maximum carbon stock within 100 years. If this is not the case, the baseline time accounting concept will slightly underestimate the climate impact of delayed reversion. On the other hand, if carbon sequestration is continuously offset by management activities (e.g., plowing of idle land to avoid full renaturalization) or not taking place at all (e.g., due to development on the land), the concept will, to some extent, overestimate the climate impact of delayed reversion. Note that only the average sequestration rate for 1 year is required (c in Table 1), but, to estimate this number, assumptions about future carbon sequestration over the GWP100 accounting period are necessary. Further discussion and detailed calculations are available in Electronic Supplementary Material 1 (Section 4). See also sensitivity analyses in Section 3.2.

The emission figures described in the previous paragraph (above- and below-ground emissions in the developing world and carbon sequestration emissions for the developed world) are to be used in the climate model. In order to do so, it is necessary to consider whether the changes in cropland modeled by Searchinger et al. (2008) and Hertel et al. (2010) exceed the changes in the baseline (cf. Section 2.3). We do so by comparing to the ongoing changes in cropland area described in Section 2.1 (−2.2 Mha/year in the developed world and +4.9 Mha/year in the developing world). For the Searchinger study, we find that ILUC in the developing world exceeds ongoing expansion by roughly 70 %, and we therefore apply Table 2 for establishing of emissions profiles. These are shown in Table 3. For the Hertel study, we find that ILUC in the developed world exceeds baseline reversion by roughly 15 %, and we therefore consider the special case of the first year of production. Further discussion and detailed calculations are available in Electronic Supplementary Material 1 (Section 4).

Table 4 summarizes the results from applying the baseline time accounting concept to existing ILUC studies (spreadsheet calculations available in Electronic Supplementary Materials 2 and 3). For the special case of the first year of biofuel production (see last part of Section 2.3), an ILUC factor of 31 g $CO_2$e/MJ is estimated for the Hertel study (because delayed reversion in the developed world exceeds annual baseline reversion).

As shown in Table 4, the ILUC factors based on the baseline time accounting concept (under current baseline development in global agricultural land use) are significantly lower (60–70 %) than the ILUC factors based on the 30-year annualization method. The main reason is that the baseline time accounting method is based on the additional radiative forcing from a temporal shift in land conversion caused by the production of a given quantity of biofuels under the baseline conditions relevant at the time of production. The background situation (baseline) is important because it predicts the “alternative fate” of the land that is allegedly brought into production as an indirect result of biofuel production in a given year. By comparing ILUC emissions from conversion of land at the agricultural frontier with the emissions resulting from the baseline conversion of the same land, the climate impact (ILUC factor) is estimated. As implied by the equations in Table 2, the rate of baseline expansion in the developing world (E) can have a substantial impact on results. If baseline expansion is slow, a large indirect land conversion ($I_a$ in Table 2) may push land into production more than 1 year in advance of the baseline conversion (cf. Searchinger case in Table 3), which will increase the ILUC factor.

### 3.2 Sensitivity analyses

Two main aspects of uncertainty could potentially influence the results derived with the baseline time accounting concept, both relating to delayed reversion. One is the uncertainty relating to the average carbon sequestration per year,

**Table 3** Land use emissions (in grams of $CO_2e$/megajoule) as modeled with the baseline time accounting concept

| Original study | Region | Year → | 1 | 2 | 3 | 4 | … |
|---|---|---|---|---|---|---|---|
| Searchinger et al. (2008) | Developing | ILUC | 2,240 | – | – | – | – |
| | | Baseline | – | 1,322 | 918 | – | – |
| | Developed | ILUC | – | – | – | – | – |
| | | Baseline | −5.9 | – | – | – | – |
| Hertel et al. (2010) | Developing | ILUC | 110 | – | – | – | – |
| | | Baseline | – | 110 | – | – | – |
| | Developed | ILUC | – | – | – | – | – |
| | | Baseline | −10.1 | – | – | – | – |

the other is the uncertainty relating to postreversion ecosystems (whether retired cropland turns into forest, grassland, or parking lots).

For the Searchinger study, we used the spreadsheet climate model to investigate the sensitivity to the emissions profile for carbon sequestration. We assumed that the same amount of carbon was sequestered within the GWP accounting period but at different speeds (within 1, 20, and 99 years). We found that this could change the result (the contribution to the ILUC factor from delayed reversion) within a range of +2 to −20 %. Thus, the shape of the emissions profile for carbon sequestration has a significant influence on the result but does not change it by orders of magnitude. See Electronic Supplementary Material 1 for details (Section 4).

For the Hertel study, our average annual (delayed) carbon sequestration was based on an average of conversion to forest and grassland (see Electronic Supplementary Material 1, Section 4.2.2). Assuming reversion only to forest gave a total ILUC factor of 18 g $CO_2e$/MJ, whereas reversion only to grassland gave a total ILUC factor of 4 g $CO_2e$/MJ (i.e. plus/minus two-thirds compared to the result in Table 4). These numbers are both below the original ILUC factor estimate (27 g $CO_2e$/MJ) from Hertel et al. (2010) but show that results are sensitive to postreversion ecosystem assumptions. More details are available in Electronic Supplementary Material 1 (Section 4.2.4).

**Table 4** Estimated ILUC factors

| | 30 years annualization (g $CO_2e$/MJ) | Baseline time accounting (g $CO_2e$/MJ) |
|---|---|---|
| Searchinger et al. (2008) | | |
| Developing world | 78 | 24 |
| Developed world | 26 | 6 |
| Total | 104 | 30 |
| Hertel et al. (2010) | | |
| Developing world | 3 | 1 |
| Developed world | 24 | 10 |
| Total | 27 | 11 |

## 4 Discussion

### 4.1 Future changes in the land use baseline

As implied by the baseline time accounting concept, it is the dynamics of the land use baseline *at the time of the biofuel production*, which determines the climate impact of indirect land use change. The reason is that the baseline indicates what would have happened to the land indirectly affected by biofuels if the fuels had not been produced. The analysis of current baseline trends in Section 2.1 justifies our approach for current biofuel production but does not describe the future conditions for baseline time accounting. We therefore looked at several projections of future changes in global agricultural land use (Fischer et al. 2002; Bruinsma 2003; Alder et al. 2005; Bakkes and Bosch 2008; Stehfest et al. 2009; Bruinsma 2009; Fischer 2009) to assess the future validity of the baseline time accounting concept.

These projections are highly driven by changes in world population and consumers' dietary choices, but they differ in several aspects such as yield assumptions, modeling framework, considered land use types, etc. (see Electronic Supplementary Material 1, Section 5). Some of them include future biofuel production, whereas none of them consider future production of biomaterials, which may increase considerably in the future (King et al. 2010).

In some of the land use projections, the future trend in agricultural land use in the developed world is negative while positive in others. However, all of the studies agree that the total agricultural area will increase up to 2030. Furthermore, all of the studies, except one (Stehfest et al. 2009), agree that total agricultural land use will increase up to and beyond 2050. This shows that baseline time accounting can be applied for many years to come. It will, however, be necessary to update ILUC factor calculations in the future as baseline conditions and other aspects change. This is not unique to the ILUC issue. Many carbon intensity values (e.g., for fossil fuels) change over time.

### 4.2 Isolating the subject of study from the baseline

The purpose of the baseline time accounting concept is to describe the climate impact of a change seen relative to a dynamic baseline or, in other words, a change on top of all other changes. In order to do so, it is necessary to develop a reasonable estimate of the rate of change in the baseline (E in Table 2 and C in Electronic Supplementary Material 1, Section 3). If studying larger changes (e.g., US corn ethanol production or the EU set-aside program), it is necessary to make sure that the change itself is not counted when estimating the underlying baseline changes.

This introduces some challenges in the case studies used in the present paper. The baseline trends are estimated based on changes in the global agricultural area from 1998 to 2007, but, during this period, the production of corn ethanol had already begun. In 1998, US annual ethanol production had slowly reached 5.3 gigaliters (Gl) or 9 % of the total mandate of 56 Gl (RFA 2012). Potentially, this production had already had an indirect effect on the global agricultural area. In 2001, annual corn ethanol production in the US reached 6.7 Gl and then increased more swiftly to 24.6 Gl in 2007 (RFA 2012). Due to the inertia of the global economy and especially land markets, it is unlikely that the increased production of ethanol in the last part of the period from 1998 to 2007 had any influence on the global agricultural area by the end of the period. We did, however, consider the implications of a "worst-case scenario" assuming an instantaneous (indirect) effect on the global agricultural area from the increase in annual US corn ethanol production up to 2007. This adjustment increased the ILUC factor for the Searchinger study (estimated by use of the baseline time accounting concept) from 30 to 50 g $CO_2$e/MJ. Despite the substantial increase in the result, it is still more than 50 % lower than the ILUC factor estimated by Searchinger et al. (2008) with 30-year annualization. For the Hertel study (estimating a much lower cropland increase in the developing world), the adjustment of annual baseline expansion in the developing world had no influence on results. For details, see Electronic Supplementary Material 1, Sections 4.1.5 and 4.2.5.

### 4.3 Additional expansion

At some point, the global agricultural area will stop expanding and potentially start to gradually contract. This is, however, not foreseen within the temporal scope of the land use projections mentioned in Section 4.1, with the exception of Stehfest et al. (2009) who indicate that global agricultural land use contraction might occur already around 2030. When approaching such a tipping point, biofuel production could (indirectly) cause expansion that otherwise would not have occurred. We designate this additional expansion (as opposed to accelerated expansion). When considering a marginal change, additional expansion would only occur in the exact moment when the baseline shifts from expansion to contraction (the tipping point) and therefore additional expansion would not be of relevance in practice (consider a marginal change in relation to the dotted line in Fig. 4). Additional expansion might, however, become relevant when studying larger changes extending many years into the future. This is because a large change (maintained continuously) will cause additional expansion when approaching the time of the tipping point (see full line in Fig. 4).

Note that only at the exact time of the tipping point the indirect land use change would consist fully of additional expansion. The annualization method implicitly assumes this stage as being permanent (by implicitly assuming a flat, nondynamic baseline). As indicated in Fig. 4, the indirect land use change will, in fact, consist of a mix of accelerated and additional expansion when approaching the baseline tipping point from the left. On the immediate right of the tipping point, indirect land use change will consist of a mix of additional expansion and delayed reversion.

In the case of biofuels causing additional expansion, there is no longer any baseline land use conversion to compare to, and baseline time accounting can no longer be applied directly as described above. Based on the review of land use projections in Section 4.1, additional expansion seems unlikely in the near future. We will, however, add some additional considerations to how the baseline time accounting concept could potentially be extended to also address additional expansion (in combination with accelerated expansion and delayed reversion). The climate model in Electronic Supplementary Materials 1 and 2 could be used to model a multiyear production scenario for biofuels. This obviously means that production period assumptions become unavoidable (as in the annualization method), but this approach would allow for a rigorous and consistent

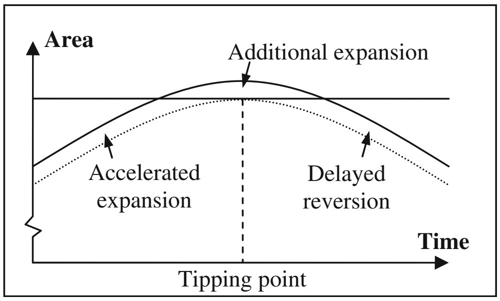

**Fig. 4** Additional expansion. Conceptual illustration of how a larger change in land use (*full curve*) may cause "additional expansion" around the tipping point of the land use baseline (*dotted line*)

incorporation of baseline implications (as opposed to the annualization method). Note that in case of additional expansion, land indirectly affected by biofuels (or another subject of study) would not have come into production in the baseline and must therefore be assumed to go out of production and start reversion after termination of its (indirect) cause of conversion. Note also that the approach outlined above would, conceptually, be in consistence with the method proposed by Levasseur et al. (2010) in which a dynamic inventory of GHG emissions is computed (further info given in Section 4.5). We will leave further considerations for future research.

### 4.4 Flat baselines

In some parts of the world, little change in the agricultural area is observed, and little change is projected despite the increasing pressure on global land resources caused by population growth, changing diets, etc. If biofuel production indirectly leads to expansion of agricultural land use in a region with a flat baseline, it could be considered additional expansion to which the baseline time accounting does not apply (see previous section). Meanwhile, it is unlikely that biofuels will cause ILUC in a region which is otherwise unaffected by the increasing pressure from the global market. It is therefore important to be critical towards ILUC modeling predicting land use changes in regions with flat land use baselines. For instance, the GTAP Model applied by Hertel et al. (2010) predicts a 0.4-Mha increase in the Canadian croplands as a result of US corn ethanol production (more than 10 % of the estimated ILUC), but the Canadian cropland area has been relatively constant since 1980.

### 4.5 Comparison to other time accounting methodologies

The present paper has compared the baseline time accounting concept to the annualization method as applied by Searchinger et al. (2008) and Hertel et al. (2010). Other studies have also addressed the challenges of properly accounting for time in GHG analyses of systems with carbon stock changes. In this section, key studies in the literature are briefly compared to the baseline time accounting concept.

O'Hare et al. (2009) looked at ILUC emissions from US corn ethanol production. They also developed a spreadsheet model, which could take the atmospheric residence time of carbon emissions into account. This allowed them to consider the warming impact of early emissions (from land use change) compared to that of later emissions (from biofuel production and avoided fossil fuel combustion). They concluded that this would lead to a higher relative impact of the ILUC emissions. Just as the annualization method, the method presented by O'Hare et al. (2009) relies on an assumed biofuel production period with significant influence on results.

Kendall et al. (2009) also criticized the time accounting method applied by Searchinger et al. (2008) for some of the same reasons mentioned by O'Hare et al. (2009) and in the present paper. Kendall et al. (2009) developed a time correcting factor (TCF) to characterize the impact of a pulse $CO_2$ emission annualized over a given time horizon. The TCF was also based on the residence time of GHG emissions, and results were highly dependent on assumptions regarding the production period of biofuels.

Levasseur et al. (2010) took a different approach and developed time-dependent characterization factors to take into account the timing of GHG emissions in LCA in order to ensure consistent time frames. By using a biofuel case, Levasseur et al. (2010) demonstrated how different analytic time horizons had a big impact on the results. The authors did not explore the impact of the biofuel production period, but, if this had been changed, it would also have affected results considerably with the method suggested by Levasseur et al. (2010).

Cherubini et al. (2011) also studied emissions from bioenergy. However, their focus was not on ILUC but on the temporary release of biogenic carbon between feedstock harvesting/combustion and feedstock regrowth. They argued that the warming effect of the temporary release should be accounted for, and, just as in the present study, the authors took their point of departure in the GWP methodology and developed global warming potentials for biogenic GHG emissions from different crop and forestry rotation systems.

Müller-Wenk and Brandão (2010) also studied the release of biogenic carbon emissions suggesting a slightly different approach than Cherubini et al. (2011). The authors derived "fossil combustion-equivalent" amounts of biogenic carbon transferred to the air from different biomes as a result of land transformation and land occupation. As in the present paper and several other studies mentioned herein, Müller-Wenk and Brandão (2010) build on the atmospheric residence time of $CO_2$, but they recommend an accounting period of 500 years to be used in their analysis.

All of the studies mentioned above build on radiative forcing of GHG emissions, just as the concept presented in the present paper. When converting GHG emissions at different points in time to impacts, the different studies (including the present study) have a lot of similarities. Seen in this perspective, the suggested approach in the present paper for estimating an ILUC factor is not the real novelty of the paper. It is the findings in Section 2.2 on the implications of a dynamic baseline that add new insights to the analysis of ILUC.

## 5 Conclusions

The global dynamic development in land use has important implications for the time accounting step when estimating the climate impact of ILUC caused by biofuel production or other issues affecting land use. The key element of the baseline time accounting concept is to consider what would happen to the land indirectly affected by biofuel production in a baseline situation without the specific subject under study. If the land indirectly affected would have been affected anyway at a later stage, the omission of this aspect may lead to erroneous conclusions about the actual climate impact of ILUC. When applying the baseline time accounting concept to existing biofuel studies, we find that the estimated ILUC impact is significantly reduced under current baseline conditions. The baseline time accounting concept does not rely on an arbitrary choice of biofuel production period. On the other hand, it requires an understanding of the trend in baseline land use at the time during which the biofuels are produced. Several land use projections indicate that the global agricultural area will keep expanding up to and beyond 2050. Our recommendation is therefore to apply the baseline time accounting concept as an integrated part of future ILUC studies and to update the results on a regular basis just as other estimations of carbon intensities are being updated.

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