International Journal of
Environmental Sciences & Natural Resources
ISSN: 2572-1119

Juniper Publishers
key to the Researchers

Research Article
Volume 18 Issue 1 - March 2019
DOI: 10.19080/IJESNR.2019.18.555979

Int J Environ Sci Nat Res


# Inter-Crops-Allocation (ICA) of $CO_2$ Emissions from Land Use Change

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**Submission:** March 11, 2019; **Published:** March 25, 2019

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**Abstract**

**Purpose:** The quantification of $CO_2$ emissions from indirect land use change (ILUC) is proposed by some stakeholders for the inclusion in carbon footprints (CF) of biofuels. The ILUC concept does not appropriately consider so far that each ILUC of a biofuel is direct land use change (DLUC) of another product. This leads to either double counting or free-rider incentives. The article's purpose is to introduce and test inter-crops-allocation (ICA); this new approach allocates $CO_2$ emissions from natural ecosystem conversion between all agricultural activities responsible for the land use change - be it directly or indirectly.

**Methods:** ICA was tested with a simplified model which covered two crops: one crop and its final products with an assumed indirect land use change (ILUC) effect and one crop and its final products with an assumed direct land use change (DLUC) effect. The model was applied on two case studies (sugarcane cultivation in Brazil, rapeseed production in Germany) while testing three different allocation procedures (energy, economic, cereal unit allocation).

**Results and discussion:** The ICA prove to be easily applicable and yields plausible results that avoid double counting and free rider incentives. The results of the first case study proves (sugarcane ethanol and beef) indicate that the significance of the ICA approach compared to the normal ILUC quantification is relatively small, especially taking into account the inherent uncertainties in ILUC quantification: 46g $CO_2$ $MJ^{-1}$ of sugarcane ethanol without ICA; 41 - 45g $CO_2$ $MJ^{-1}$ of sugarcane ethanol with ICA. However, the results of the second case study (rapeseed biodiesel and palm oil) prove that the approach can have a significant influence on ILUC quantification because the original value for rapeseed biodiesel production without ICA of 104g $CO_2$ $MJ^{-1}$ was reduced by up to 23% when ICA was applied (80-101g $CO_2$ $MJ^{-1}$).

**Conclusion:** ICA allows considering the direct as well as the indirect impact of agricultural activities on natural ecosystem conversion while avoiding double counting and free-rider incentives at the same time. If ILUC factors are considered in CF of biofuels, the application of ICA will lead to more scientific consistency and robustness. Further case studies and additional research are needed to expand the scope on the overall agricultural system.

**Keywords:** Indirect land use change, direct land use change, allocation, carbon footprint, biofuel

## Introduction

Since 2008 numerous scientific studies that deal with the quantification of $CO_2$ emissions from indirect land use change (ILUC) attributed to biofuel production have been published [1-9]. ILUC is a displacement effect defined as follows: If biofuel crops replace another agricultural production system the amount of this former product will decrease in the world market. If the demand for this product remains the same, the product's price will increase due to the reduced supply. These higher prices act as an incentive for farmers or companies to develop new agricultural area. The final land use change (LUC) that occurs in order to provide new agricultural land is in the studies indicated above attributed as ILUC of biofuel production. In case carbon rich natural ecosystems such as primary forest, peat bogs or land uses such as managed grassland are converted to arable land considerable amounts of greenhouse gas (GHG) emissions will be released [10]. These emissions will be significant for the carbon footprint (CF) if the related GHG emissions are included systematically in carbon footprinting; the application of ILUC on the CF has so far been mainly been performed for biofuels [1,9,10], even though the concept as such applies to all agricultural products [11,12].

Many of the scientific publications to date focus on which types of economic or deterministic models are suitable for ILUC quantification [1,2,4,9], on how high uncertainties about input parameters and results are [5,9,11] or on how the scientific knowledge could be used in policy making [11,13,14].

The quantification of GHG emissions caused by ILUC however also raises methodological questions about consistency with life cycle assessment (LCA) and carbon footprinting. As an example, the assessment of ILUC is up to now limited to the global warming potential only, even though other environmental impact categories are also affected. A comprehensive discussion of the scientific robustness and consistency of ILUC in the context of the international LCA standards can be found in Finkbeiner [11,12,15]. As of now, almost all studies focus on biofuels while not considering other agricultural products with the exception of by-products from biofuels production [16].

ILUC caused by biofuel feedstock expansion is however always direct land use change (DLUC) of another agricultural production "incentivized by the cross-price effects of an increased production of biofuel feedstock which then translates into an additional demand for so far unused land areas" [17]. The same LUC thus can be defined as DLUC of a specific agricultural activity that displaces a natural ecosystem as well as ILUC of an elsewhere expanding agricultural activity. About the quantification of ILUC factors the currently common practice is to debit all $CO_2$ emissions from the final LUC to the expanding biofuel feedstock while disburdening the crops that directly displace natural ecosystems at the same time. However, the same ILUC could be also just accounted for as DLUC of the crop that is displaced.

GHG emissions arising from DLUC are to be included in CF calculations according to the PAS 2050 [18], may be included according to the GHG Protocol [19] and are consistent to be included according to ISO 14044 [20] on LCA [11]. As emissions from DLUC are even obligatorily to be included in the CF of biofuels according the Renewable Energy Directive (RED) it should be a logical consequence to do the same for all other agricultural products. However, if the scope of CF is extended to all agricultural products, i.e. if all LUC is accounted for as DLUC, there is no more ILUC. If the assessment intends to share the LUC burdens between the direct and indirect drivers, the question arises how the $CO_2$ emissions from the final LUC should be allocated between the expanding biofuel feedstock and the crop that directly displaces the natural ecosystem. Assuming that both agricultural activities share the responsibility by either indirectly or directly contributing to natural ecosystems conversion, it seems reasonable that all products resulting from both agricultural activities should share the burden of the $CO_2$ emissions caused by the associated LUC [15]. Thus, we propose a methodology that allows considering the impact of both agricultural activities, the expanding agricultural activity as well as the one that directly displaces natural ecosystems; this is a typical situation for allocation.

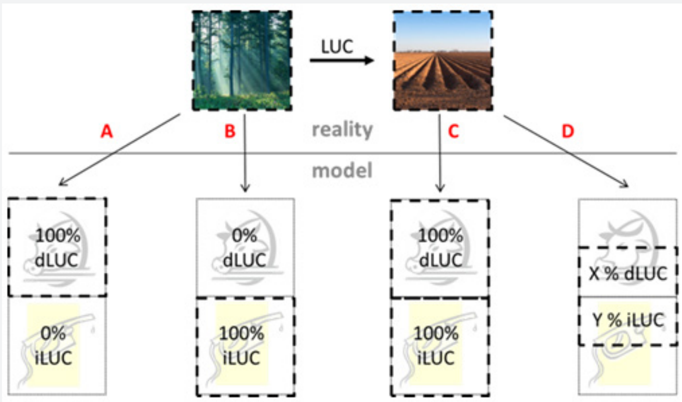


**Figure 1:** Schematic options for allocating land use change.

Figure 1 schematically shows different modeling options. What happens in reality is presented in the upper part of the figure. In the real world only LUC can be observed, shown here exemplary for conversion of forest to agricultural land. Several possibilities exist to model this process in LCA - depending on the allocation choices of the burden generated by the LUC. The LUC burden can be either allocated to the direct process responsible for physically cutting down the forest. This would be DLUC shown here for the example of cattle farming. The LUC burden could also be allocated indirectly to a process that is assumed to be responsible for the cattle farmer's action to cut the forest. This would be ILUC shown here for the example of biofuel production.

The physical reality and the physical allocation are shown in case A in Figure 1: The direct physical action takes 100% of the burden; therefore, there is 0% of ILUC. Option A would be the standard modeling approach in attributional LCA or CF. The second case B shows the allocation choice of the proponents of the ILUC concept, even though they do not present it as an allocation choice. If all the burden of the DLUC of the displaced crop (here feed for cattle) is accounted for as ILUC of the displacing crop (here: biofuel producer), the resulting net DLUC of the displaced crop will be zero. This can only be done based on economic assumptions and is inconsistent with attributional LCA. This case obviously provides wrong incentives because the one who is cutting the natural forest (physical reality) gets a free-rider ticket to do so. Case C represents the case of double-counting. In this case the emissions are allocated to both cattle and biofuels. As a result, there is 100% DLUC and 100% ILUC, which is obviously not consistent with the ISO standard´s requirement to avoid double-counting. The last case D represents the proposed 'inter-crops-allocation'. Transparency requires making an explicit allocation choice for the LUC burden. If ILUC is supposed to be considered at all, this ICA


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allocation will be required to avoid double-counting and wrong free-rider incentives.

There are – as usual – different allocation procedures available, but the condition they have to fulfill is clearly that the total allocated burden has to be 100% according to formula (1).

DLUCnet (displaced crop) =

DLUCgross (displaced crop) – ILUC (displacing crop) (1)

Allocation represents a regularly applied methodology in LCA whenever it comes to multi-output processes. Agriculture is a multi-output process so that we suggest allocation as a suitable approach to consider direct as well as indirect drivers on natural ecosystem conversion; we call this specific field of application inter-crops-allocation (ICA). According to the ISO standards on LCA [21] and CF [22] allocation is preferably done based on the physical properties of all accruing products [20]. The lower heating value (LHV) and the mass represent suitable properties for physical allocation. Brankatschk and Finkbeiner [23] additionally introduced the cereal unit (CU) allocation as a method particularly suitable for agricultural products. Economic allocation based on market values is another approach that can be used, if there are no clear physical relationships applicable [20].

In this article we present a simplified two-crops-model used to investigate how different allocation procedures would affect the CF of specific agricultural products when applying ICA. The objective is not to present the most realistic values on ILUC or DLUC but to test the applicability and suitability of this method and to assess the relevance of the topic.

## Methodology

Agriculture worldwide can be considered as a multi-output production system, in which one is able to identify an expansion of the overall agricultural land, of specific agricultural activities and of specific end products resulting from agricultural activities. GHG emissions related to LUC caused by the agricultural area expansion could theoretically be debited to all end products; one has to quantify the expansion of the agricultural area used for specific agricultural activities and the increase in the resulting end products. A huge amount of data is however required in order to conduct this overall ICA. As we first want to investigate the relevance of the topic, we use a simplified and idealized model calculation in order to investigate how different ICA approaches would affect the CF of agricultural products, and particularly biofuels.

As a simplification the model only considers two crops: one expanding agricultural activity, one displacing agricultural activity and all end products resulting from both activities. We furthermore assume a direct displacement without any other agricultural activities being involved. This model has been applied to two case studies. Both case studies deal with the end product biofuels as biofuels have been the driver for the ILUC debate. As shown by Bauen et al. [24] an increase of biofuel production can lead to several market reactions; all of them have an influence on the amount of ILUC. These market reactions are expansion of the cultivation area, yield increase and substitution. The first case study conducted here deals with the market reactions area expansion and yield increase while the second case study addresses the case of substitution.

As a *first example* we chose sugarcane cultivation as the expanding agricultural activity; the end product is sugarcane ethanol. Sugarcane area expansion was assumed to take place on pasture land. As a result, a cattle farming with the purpose of beef production is assumed to be displaced. The final natural ecosystem conversion is assumed to be a conversion of tropical rain forest to pasture land. This situation is plausible for the situation in Brazil where sugarcane ethanol production is supposed to be partly responsible for deforestation by displacing cattle farming from the South-Central Region to the Amazon Legal [4].

As a *second example* we chose rapeseed oil that is used to produce biodiesel in Germany. Studies on ILUC indicate that if less rapeseed oil is available as a vegetable oil in the EU food market because of its usage as a feedstock for biodiesel production it will probably be substituted by rapeseed oil from Ukraine and by palm oil produced in Indonesia or Malaysia [24]. We assume that 50% of the “loss” of rapeseed oil will be substituted by rapeseed oil produced in Ukraine where enough agricultural land is available [24]. The remaining 50% of rapeseed oil are assumed to be substituted by palm oil from Malaysia where new oil palm plantations are assumed to be generated on peat bogs. Thus, the usage of rapeseed oil supposed for biodiesel production in the EU is assumed to partly lead to a transformation of peat bogs in Malaysia in order to cultivate oil palms.

Average $CO_2$ emissions from the conversion of natural ecosystems were calculated based on the IPCC methodology [25]. In addition, several data on biomass and energy yields is required in order to run our simplified model and to derive the allocation factors (see Table 1 & 2) [26-40]. Overall, three different allocation procedures have been used for ICA: energy allocation based on the LHV, CU allocation and economic allocation based on the market value. Emissions from ILUC and DLUC are calculated and related to the agricultural products, respectively, based on the following formulae (2), (3), and (4). Our starting point is the production of a biofuel feedstock on one hectare of already existing agricultural area ($A_B$). We then calculate the area that is additionally needed in order to produce the displaced agricultural product. The finally resulting area expansion on natural ecosystems $A_{LUC}$ is usually less than one hectare as a part of the displaced product can be regained by an increase in yields (see formula (2)). $CO_2$ emissions from natural ecosystem conversion can then be allocated to all products produced on the overall area ($A_B$ + $A_{LUC}$). The allocation factor included in formulae (3) and (4) is not considered in current models; it is proposed here as part of the ICA approach.

$$A_{LUC} = A_B - A_Y \quad (2)$$



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$A_{LUC}$: Agricultural area expansion on natural ecosystems [ha].

$A_B$: Area used for additional biofuel production [ha].

$A_Y$: Area saved because of yield increase over time and/or higher yields of the substituting crop [ha].

$$ILUC_{GHG} = \frac{(A_{LUC}) * \Delta CO_2}{A_B * Y_1} * AF \qquad (3)$$

$ILUC_{GHG}$: ILUC induced $CO_2$ emissions related to the amount of end product gained on $A_B$ [g $CO_2$ kg$^{-1}$].

$\Delta CO_2$: $CO_2$ emissions resulting from natural ecosystem conversion [g $CO_2$ ha$^{-1}$].

$Y_1$: Yield for product 1 (expanding agricultural activity) [kg ha$^{-1}$].

AF: allocation factor.

$$DLUC_{GHG} = \frac{(A_{LUC}) * \Delta CO_2}{(A_{LUC}) * Y_2} * (AF - 1) = \frac{\Delta CO_2}{Y_2} * (AF - 1) \qquad (4)$$

$DLUC_{GHG}$: DLUC induced $CO_2$ emissions related to the amount of end product gained on $A_{LUC}$ [g $CO_2$ kg$^{-1}$] $Y_2$: Yield for product 2 (directly displacing agricultural activity) [kg ha$^{-1}$]

If the ICA allocation factor is not being considered this practice will obviously cause double counting as the same $CO_2$ emissions are included in the CF of both products. Thus, we suggest including an allocation factor into ILUC and DLUC calculations. The following formulae show how to calculate the allocation factors.

$$A_B * Y_1 * p_1 = P_1 \qquad (5)$$

$$A_{LUC} * Y_2 * p_2 = P_2 \qquad (6)$$

$$P_1 + P_2 = P_{total} \qquad (7)$$

$$\frac{P_1}{P_{total}} = AF \qquad (8)$$

$p_1$: lower heating value, cereal unit or market price of product 1.

$P_1$: overall lower heating value, cereal unit or market price of product 1 gained on $A_B$.

$p_2$: lower heating value, cereal unit or market price of product 2.

$P_2$: overall lower heating value, cereal unit or market price of product 2 gained on $A_{LUC}$.

These formulae assume that one product accrues on a specific area; however, if more than one product is produced on $A_B$ and $A_{LUC}$ additional products can easily be included in the calculation.

## Results and Discussion

### Case study 1: sugarcane ethanol and beef production in Brazil

The first case study refers to the expansion of sugarcane area in Brazil for the purpose of ethanol production. Expansion takes place on pasture land so that a cattle farming with the purpose of beef production is displaced. The final natural ecosystem conversion is tropical rain forest conversion to pasture land in the North of Brazil. Results of ILUC modeling show that one hectare of sugarcane expansion on pasture land will not lead to a generation of one hectare of pasture land in the Amazon Legal but will only lead to a minor displacement. The reason is that the loss in beef production is not only compensated by generating new pasture land but also by increasing the cattle stocking rate and the average slaughter weight. Nassar et al. [41] claimed that only 0.08 ha new land would be necessary for one additional ha of sugarcane. De Souza Ferreira Filho [42] ascertained a value of 0.14 ha for one ha of sugarcane and Dunkelberg [43] a value of 0.22 ha. The latter value is chosen as this study used the same input parameter values as they were used in the calculation presented here.

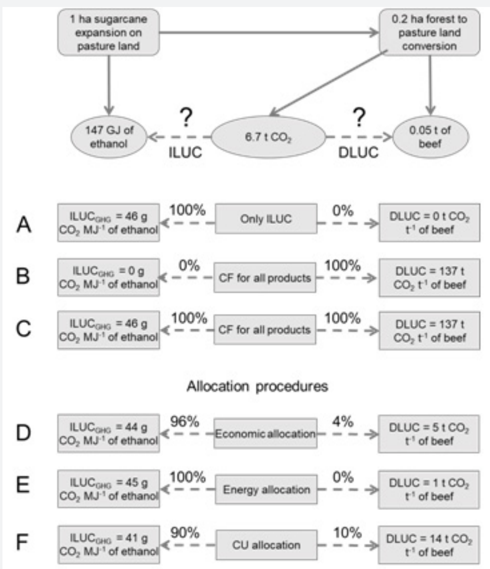


**Figure 2:** Options for inter-crop allocation and their results for the sugarcane ethanol / beef example.



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$CO_2$ emissions resulting from the conversion of Amazonian rain forest to pasture land are calculated to be 30.5t $CO_2$ $ha^{-1}$ $yr^{-1}$ for a period of 20yr based on IPCC [25]. Overall only 6.7t $CO_2$ $yr^{-1}$ will be released as only 0.22 ha of new pasture land have to be generated in order to compensate the loss of one ha pasture land in the South-Central Region. These emissions must be allocated to all products gained on 0.22ha of pasture land and on one hectare of sugarcane. The main products are sugarcane ethanol (147GJ) and beef (50kg); other products such as fibers have not been considered. Figure 2 visualizes the displacement effect caused by sugarcane area expansion and demonstrates the results of ILUC and DLUC quantification when conducting ILUC quantification as currently common (A), when applying the concept of carbon foot printing on ethanol and beef (B, C) and when applying various ICA procedures (D-F).

According to the approach of ILUC quantification as discussed within the scope of the European biofuel policy, all $CO_2$ emissions from the final LUC are charged to the expanding sugarcane ethanol production (see case A in Figure 2). Based on an average ethanol yield of 147GJ $ha^{-1}$ of sugarcane, $CO_2$ emissions from ILUC amount to 46g $CO_2$ $MJ^{-1}$ of ethanol. This approach, however, has the effect of disburdening cattle farming that directly displaces forested land from responsibility for any LUC-induced $CO_2$ emissions; although DLUC caused by a new generation of pasture land would occur, in the CF calculation of beef emissions from DLUC would be set to zero. This, however, can lead to a free-rider effect, as the party directly profiting from the final LUC is not held accountable for these LUC-induced $CO_2$ emissions - not even in a scenario in which the product CF is used as a market incentive to reduce carbon emissions in the economy. Thus, such an approach, in which all LUC $CO_2$ emissions are allocated to the expanding biofuel feedstock, fails to provide a market incentive for LUC reduction that specifically addresses those directly benefitting from deforestation.

If the scope of the CF were broadened and applied to all agricultural products as it is now applied to biofuels, ILUC would no longer exist, as DLUC would be completely charged to the respective agricultural activity directly displacing the natural ecosystem (case B). Thus, in our example all $CO_2$ emissions from LUC are debited to beef while disburdening sugarcane ethanol at the same time. This option would however not consider the potential indirect effect of expanding crops, which has been proposed as a relevant concern in the case of biofuel production [4,44,45]. Case C addresses ILUC as it is currently done while allowing the inclusion of $CO_2$ emissions from DLUC into the CF of beef at the same time. This would cause double counting of the LUC-induced $CO_2$ emissions. As double counting shall be avoided [19], this does not represent an appropriate and ISO conformant approach for handling LUC-induced $CO_2$ emissions.

ICA of LUC-induced $CO_2$ emissions was tested in order to avoid both double counting and free rider incentives. Several allocation procedures are available, including energy, economic, and CU allocation methods, each with its respective allocation factor (see Table 1, Figure 2). Depending on the allocation procedure the percentage of the overall LUC $CO_2$ emissions allocated to ethanol varies between 90 and 100%. The resulting ILUC $CO_2$ emissions were in the range between 41 and 45g CO $MJ^{-1}$ of ethanol and DLUC $CO_2$ emissions were between 1 and 14g $CO_2$ $t^{-1}$ of beef. The results prove that the choice of the allocation procedure influences the CF of ethanol and beef. The values for ILUC however are in a similar range compared to the situation without ICA in which the allocation factor is either 0 or 100% (100% ILUC: 46g CO $MJ^{-1}$ of ethanol; 100% DLUC: 137g CO $t^{-1}$ of beef). The choice of the allocation procedure thus influences the assessment of both beef and ethanol albeit not to the same degree as the general decision on how to consider DLUC and ILUC. The difference between ICA and "normal" ILUC quantification is the highest in the case of CU allocation when ILUC emissions debited to ethanol are 10% lower than without ICA.

**Table 1:** Data used to derive the allocation factors; case study sugarcane ethanol.

| | Yield[a] [kg $ha^{-1}$] | CU[b] [kg $ha^{-1}$] | CU ($A_{LUC}$) [kg] | Allocation Factor [%] |
|---|---|---|---|---|
| **CU Allocation** | | | | |
| Ethanol | 5,510 | 2,672 | 2,672 | 89.7 |
| Beef | 223 | 1,395 | 307 | 10.3 |
| **Economic Allocation** | | **Monetary Value[c] [R$ $ha^{-1}$]** | **Monetary Value ($A_{LUC}$) [R$]** | |
| Ethanol | 5,510 | 7,324 | 7,324 | 96.2 |
| Beef | 223 | 1,312 | 289 | 3.8 |
| **Energy Allocation** | | **LHV[d] [MJ $ha^{-1}$]** | **LHV ($A_{LUC}$) [MJ]** | |
| Ethanol | 5,510 | 147,124 | 147,124 | 99.6 |
| Beef | 223 | 2,752 | 605 | 0.4 |

[a] Calculated using an average sugarcane yield of 75 t ha [26]; average ethanol yields 93 L $t^{-1}$ of sugarcane [27]; stocking rate 1.027 [28]; average slaughter weight of bovine animals 217kg [29].
[b] Calculated using 47.5kg melasse $t^{-1}$ of sugarcane, 0.75dt CU $dt^{-1}$ of sugarcane, average ethanol yields 93 L $t^{-1}$ of sugarcane (0.48 dt CU $dt^{-1}$ for ethanol); 6.26dt CU $dt^{-1}$ of beef [30].
[c] Calculated using the average producer prices of 5.89 R$ $L^{-1}$ for beef and 1.05 R$ $L^{-1}$ of ethanol [31].
[d] Calculated with an LHV of 26.7MJ $kg^{-1}$ of ethanol [32] an LHV of 25.2MJ $kg^{-1}$ of dry beef [33] (water content: 51% [34]).

## Case study 2: rapeseed biodiesel produced in Germany and palm oil produced in Indonesia

The second case study refers to biodiesel production from rapeseed oil in Germany. As already mentioned, 50% of the "loss" of rapeseed oil is assumed to be substituted by rapeseed oil from Ukraine where enough abandoned agricultural land is available. The remaining 50% of rapeseed oil are assumed to be substituted by palm oil from Malaysia. We furthermore assume that one liter of rapeseed oil is substituted by one liter of palm oil. As the yield


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per hectare of palm oil is much higher than that of rapeseed oil (4.2t $ha^{-1}$ vs. 1.4t $ha^{-1}$) only 0.17 ha of oil palms are required in order to substitute one hectare of rape.

**Table 2:** Data used to derive the allocation factor; case study rapeseed biodiesel.

| | Yield[a) [kg $ha^{-1}$] | CU[b) [t $ha^{-1}$] | CU ($A_{LUC}$) [t] | Allocation Factor[%] |
|---|---|---|---|---|
| **CU Allocation** | | | | |
| Rapeseed oil | 1,404 | 3.8 | 3.8 | 52.6 |
| Rapeseed meal | 2,096 | 1.6 | 1.6 | 22 |
| Palm oil | 4,211 | 10.5 | 1.8 | 24 |
| PKC | 477 | 0.6 | 0.1 | 1.4 |
| **Economic Allocation** | | **Monetary Value[c) [USD $ha^{-1}$]** | **Monetary Value ($A_{LUC}$) [USD]** | |
| Rapeseed oil | 1,404 | 1,734 | 1,734 | 55 |
| Rapeseed meal | 2,096 | 748 | 748 | 23.7 |
| Palm oil | 4,211 | 3,958 | 660 | 20.9 |
| PKC | 477 | 63 | 10 | 0.3 |
| **Energy Allocation** | | **LHV[d) [MJ $ha^{-1}$]** | **LHV ($A_{LUC}$) [MJ]** | |
| Rapeseed oil | 1,404 | 52,236 | 52,236 | 43.9 |
| Rapeseed meal | 2,096 | 39,820 | 39,820 | 33.5 |
| Palm oil | 4,211 | 153,707 | 25,626 | 21.5 |
| PKC | 477 | 8,116 | 1,353 | 1.1 |

[a) Calculated using an average rapeseed yield of 3.5t $ha^{-1}$ [35]; average rapeseed oil yield of 0.4t $t^{-1}$ of rapeseed; average rapeseed meal yield of 0.6t $t^{-1}$ of rapeseed [36]; average palm oil yield of 4.2t $ha^{-1}$; average PKC yield of 0.48t $ha^{-1}$ [37].

[b) Calculated using an average CU of 2.74t $t^{-1}$ of rapeseed oil and 0.77t $t^{-1}$ of rapeseed meal [23]; average CU of palm oil of 2,5t $t^{-1}$ of palm oil (based on energy value 36.5kJ $kg^{-1}$ of palm oil and 14.6kJ $kg^{-1}$ of barley) [38].

[c) Calculated using the average prices in 2012: 1,235USD $t^{-1}$ of rapeseed oil, 357USD $t^{-1}$ of rapeseed meal (UFOP 2012); exchange ratio 1 EUR = 1.28 USD, 940USD $t^{-1}$ of palm oil [39] and 131USD $t^{-1}$ of PKC [37].

[d) Calculated using the following LHV: 37.2MJ $kg^{-1}$ of rapeseed oil, 19.0MJ $kg^{-1}$ of rapeseed meal, 36.5MJ $kg^{-1}$ of palm oil [32] and 17.0MJ $kg^{-1}$ of PKC [40].

$CO_2$ emissions resulting from the conversion of peat bogs to oil palm plantations are calculated to be 50.8t $CO_2$ $ha^{-1}$ $yr^{-1}$ for a period of 20yr based on IPCC [25]. Overall some 8.5t $CO_2$ $yr^{-1}$ will be released as only 0.17ha of new oil palm plantations have to be generated in order to substitute the loss of rapeseed oil to the biodiesel market. These emissions must be allocated to all products gained on 0.17ha of oil palm plantation and on one hectare of rapeseed. The main products are rapeseed oil (1.4t), rapeseed meal (2.1t), palm oil (0.7t) and palm kernel cake (PKC: 0.1t); other products such as empty fruit bunches and shells have not been considered here. As the amount of rapeseed meal in the market will not change if rapeseed oil is used in the biodiesel sector instead of in the food sector, we do not have to consider any substitution effects caused by a change in the supply of rapeseed meal. Substitution effects caused by the additional supply of PKC are assumed to be negligible. The allocation factors and data used to derive these factors are shown in Table 2.

**Table 3:** Results of different options of how to consider ILUC and DLUC.

| Case | Description | $CO_2$ Emissions from LUC | | | | |
|---|---|---|---|---|---|---|
| | | [g $CO_2$ $kg^{-1}$ Rapeseed Oil] | [g $CO_2$ $kg^{-1}$ Rapeseed Meal] | [g $CO_2$ $kg^{-1}$ Palm Oil] | [g $CO_2$ $kg^{-1}$ PKC] | [g $CO_2$ $MJ^{-1}$ Rapeseed Biodiesel] |
| A | only ILUC | 3.4 | 1.7 | 0 | 0 | 104 |
| B | only DLUC | 0 | 0 | 11.5 | 5.3 | 0 |
| C | ILUC and DLUC | 3.4 | 1.7 | 11.5 | 5.3 | 104 |
| D | Economic all. | 3.3 | 1 | 2.5 | 0.4 | 101 |
| E | Energy all. | 2.6 | 1.4 | 2.6 | 1.2 | 80 |
| F | Cereal unit all. | 3.2 | 0.9 | 2.9 | 1.5 | 96 |

If all $CO_2$ emissions resulting from peat bog transformation are allocated to rapeseed oil and rapeseed meal, $CO_2$ emissions from ILUC will amount to 3.4g $CO_2$ $t^{-1}$ of rapeseed oil and 1.7g $CO_2$ $t^{-1}$ of rapeseed meal (case A) (see Table 3). This is concordant with 104g $CO_2$ $MJ^{-1}$ of biodiesel. If all $CO_2$ emissions are allocated to palm oil and PKC, emissions from DLUC will amount to 11.5g $CO_2$ $t^{-1}$ of palm oil and 5.3g $CO_2$ $t^{-1}$ of PKC (case B). ICA of LUC-induced $CO_2$ emissions again leads to a range of results depending on which allocation approach is used. The percentage of the overall LUC $CO_2$ emissions allocated to rapeseed oil varies between 44 and 55%. The results prove that the choice of the allocation procedure significantly influences the CF of all products. ILUC $CO_2$ emissions revealed values between 80 and 101g $CO_2$ $MJ^{-1}$ of biodiesel; DLUC $CO_2$ emissions were between 2.1 and 3.5g $CO_2$ $t^{-1}$ of palm oil and 0.4 and 1.6g $CO_2$ $t^{-1}$ of PKC respectively [46]. Without ICA ILUC emissions amount to 104g $CO_2$ $MJ^{-1}$ of biodiesel and DLUC emissions amount to 11.5g $CO_2$ $t^{-1}$ of palm oil and 5.3g $CO_2$ $t^{-1}$ of PKC. If energy allocation is applied in ICA, the approach leads to 23% lower ILUC emissions than without ICA. Thus, in this case study the application of ICA significantly reduces the amount of ILUC induced $CO_2$ emissions related to biodiesel production.

## Conclusion

During the last years many efforts have been made to quantify $CO_2$ emissions from ILUC attributed to biofuel production. The proposal to consider such indirect $CO_2$ emission effects in the CF



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of biofuels however still has methodological challenges, especially if the scope is extended to all agricultural products. The problem is that ILUC of the one agricultural activity is always DLUC of another agricultural activity. This fact has neither been sufficiently discussed nor properly reflected in the models proposed for ILUC quantification. Including both ILUC induced $CO_2$ emission in the CF of one product and DLUC induced $CO_2$ emissions in the CF of the other product would cause double counting. Only considering ILUC induced $CO_2$ emissions would however cause a free-rider effect for the crops that directly lead to natural ecosystem conversion. To tackle this problem, it is necessary to allocate the $CO_2$ emissions from the final LUC to all agricultural activities involved as drivers in the process of natural ecosystem conversion. The resulting approach proposed in this paper is called inter-crops-allocation (ICA). The feasibility and applicability of the ICA approach was demonstrated by a simplified model of two crops and the exemplary calculation of two case studies. Allocation has been conducted based on the CU, the LHV and on the market value.

The first case study refers to sugarcane ethanol production in Brazil that displaces cattle farming to the Amazonian rain forest. The results prove that the choice of the allocation procedure influences the CF of beef and ethanol albeit not to the same degree as the general decision on whether and how to consider DLUC and ILUC. Compared to the influence of various uncertainties in ILUC quantification the influence of ICA is rather small in this case study: 46g $CO_2$ $MJ^{-1}$ of sugarcane ethanol without ICA; 41 - 45g $CO_2$ $MJ^{-1}$ of sugarcane ethanol with ICA. The second case study refers to rapeseed biodiesel production in Germany. Rapeseed oil produced in Germany was assumed to be substituted by rapeseed oil produced in Ukraine and by palm oil produced in Malaysia by 50% each. We also considered rapeseed cake and PKC accruing as by-products. The results prove that the approach can have a significant influence on the ILUC emissions debited to biofuels: 104g $CO_2$ $MJ^{-1}$ of rapeseed biodiesel without ICA; 80 -101g $CO_2$ $MJ^{1}$ of rapeseed biodiesel with ICA. The difference between ILUC quantification with and without ICA is the highest in the case of energy allocation when ILUC emissions debited to biodiesel are 23% lower than without ICA. Thus, it is worth and necessary to have a closer look at this topic in prospective research activities.

The great advantage of allocating LUC $CO_2$ emissions to all directly and indirectly expanding agricultural activities and end products is that free-rider-effects can be prevented while avoiding double counting at the same time. In the scope of this study the ICA approach has only been applied to simplified case studies. Thus, more research and case studies are needed before results can be generalized. Finally, a model that covers the whole agricultural sector will be necessary to properly allocate LUC $CO_2$ emissions between all drivers for natural ecosystem conversion. However, in the absence of such an ultimate solution, any implicit or explicit attribution or allocation of $CO_2$ emissions to DLUC or ILUC remains a value choice and is not scientifically proven.

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