Methodology report 2024

LUC impact Tool

Documentation of the LUC Impact Tool:
Methodology and basic principles

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1. Introduction

Through this document we share the methodology and data sources used to calculate land use change (LUC) emissions in the LUC Impact tool version 2024.

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Deforestation is one of the major issues caused by the global agriculture production system. About 5–14% of the global greenhouse gas (GHG) emissions are attributable to land use and land-use change due to the global food system (LULUC) (IPCC, 2019). Many publications have focused on this issue and have provided solid global or country specific estimations of CO_2 emissions due to land use change based on available statistics and/or satellite imagery.

A big challenge for practitioners of Life Cycle Assessments (LCA) is to translate this impact of land use change to specific crops from specific countries when little primary data is available. Calculation methodologies are often not straightforward, even in the case when detailed information is available. The calculation becomes even more challenging when no specific information is available for the crop of interest. Our LUC Impact tool and dataset aim to provide insights into the impact of land use change of a wide variety of crop-country combinations and is specifically designed to support LCA practitioners and other professionals or academics.

2. Calculation methodology

New in 2024: Results with managed grassland and crop system efficiency index (CSEI)

Starting from 2024, there are two new features of the dLUC tool: 1) the option to choose from calculations with or without managed grassland using equal and linear amortization, and 2) another resulting dataset with or without managed grassland, also using equal and linear amortization.

Four LUC calculation methods are implemented in the LUC Impact tool. Each of the methods is explained in more detail in the following paragraphs.

2.1 Previous Land use Known

In case the country and both the current and the previous land use is known, the carbon stock change of a selected crop is calculated using mainly IPCC defaults.

2.1.1 Calculation steps

1. Based on worldwide climate and soil types provided by EU, climate zone and soil types are selected which are representable for the country. With this, carbon stock can be calculated. For forest land, specific biomass is obtained per country from the Global forest resources assessment 2020. For grassland, biomass is derived from continent and climate condition (based on European commission data and IPCC values). Soil carbon content is based on IPCC 2019 soil carbon defaults for climate regions and soil types, stock change factors from IPCC 2019 are used to calculate the soil carbon stock for different land use and land management practices. Biomass of crops is obtained from either the IPCC or PAS 2050, one value represents all annual crops and another all perennial crops (with some exceptions, described in the data sources chapter).
2. Change in carbon stock between previous and current land use is multiplied with 44/12 to convert kg carbon to kg CO_2.
3. Direct N_2O emissions, which occur as a direct results of soil carbon stock losses are calculated following IPCC 2019. In case of carbon sequestration in the soil, direct N_2O emissions are zero, and never negative.
4. Emissions are amortized over the amortization period following the selected approach:
    a. Equal (calculated & amortized w/ single calculation): Emissions are divided equally over amortization period; in practice this means that the emissions accounted for in the assessment year are found by dividing the total emissions by the amortization period (which is 20 years by default). The conversion year does not influence the results, as long as it is within the amortization time from the assessment year. This method is in described in PAS:2050
    b. Equal (calculated & amortized equally each year): Emissions are divided equally over amortization period; in practice this means that the emissions accounted for in the assessment year are found by dividing the total emissions by the amortization period (which is 20 years by default). The conversion year does not influence the results, as long as it is within the amortization time from the assessment year. This method is referred in the draft GHG protocol.
    c. Linear (calculated & amortized linearly each year): Emissions are linearly discounted over the amortization period, meaning that recent conversion will result in higher emissions compared to more historic conversion. The amortization percentage for the assessment year is equal to: (1 / amortization time (by default 20 years)) + (((amortization time / 2) - (((assessment year - conversion year) + 1) - (1 / 2))) * (2 / amortization time^2)). The emissions accounted for in the assessment year are obtained by multiplying the total emissions by the amortization percentage. This method is referred in the draft GHG protocol and recommended by SBTi FLAG.

5. The crop yield is derived from FAOSTAT and determines impact per kg of product.

2.1.2 Input parameters

The calculation is based on the main inputs: country and crop under study, year of assessment, conversion year (year in which the land use change occurred) and previous land use (land use before conversion to current land use for agriculture). Apart from these inputs, certain input parameters can be selected. These are described further in this section.

One of the most important parameters is the amortization period and method. Both these settings are prescribed in different LCA and GHG standards.

PAS2050: 20 years amortization period and equal amortization over 20 years. Emissions calculated and amortized in a single calculation over 20-year period. This basic methodology is described in the PAS 2050-1 published by BSI (BSI, 2012) and now widely referenced in LCA guidelines, such as the Product Environmental Footprint (PEF) guidelines (Zampori & Pant, 2019) & Envifood protocol.

Draft GHG protocol for the land sector: 20 years amortization period and either equal or linear amortization. Emissions calculated and amortized for each year in the 20-year period.

SBTi/FLAG: 20 years amortization period and linear amortization. Emissions calculated and amortized for each year in the 20-year period (Christa Anderson et al., 2022).

An overview of all calculation input parameters is provided in the table below.

Table 1. Overview of input parameters for 'Previous land use known' calculation method.

Setting	Description	Consideration
Amortization method	This defines how LUC emissions from a LUC event (or within a certain year) are accounted for over the amortization time. More information on amortization method provided in section 2.2.2.1.	Assess the requirement set by the calculation standard you follow, as indicated above this table.
Amortization time	The amortization time defines over how many years emissions from a LUC event are divided. The lookback period (period over which land use change emissions are relevant for the assessment year) is equal to the amortization time.	Assess the requirement set by the calculation standard you follow, as indicated above this table.
Tillage	This defines the degree of soil disturbance due to tillage operations. The level defines the soil carbon stock calculation, as described in Section 3.2 of this document. Definition is obtained from IPCC 2019. Full: Substantial soil disturbance with intense tillage operations. Reduced: Primary and/or secondary tillage but with reduced soil disturbance. No till: Only minimal soil disturbance.	Select the option that best matches the cultivation system under study.
Organic matter input	This defines the degree of organic matter input, such as crop residues and manure. The level defines the soil carbon stock calculation, as described in Section 3.2 of	Select the option that best matches the cultivation system under study.

	this document. Definition is obtained from IPCC 2019. The choices are described as follows: Low: Low residue return due to removal of residues or production of crops yielding low residues. Medium: All crop residues are returned to the field. If residues are removed then supplemental organic matter (e.g., manure) is added. High without manure: Significantly greater crop residue inputs due to additional practices, such as production of high residue yielding crops, use of green manures, etc. High with manure: Significantly higher C input over medium C input cropping systems due to an additional practice of regular addition of animal manure.	
Carbon stock method	Carbon stocks for annual and perennial cropland are proposed by both the IPCC and in the PAS2050-1 method. This parameter defines the choice for either of the two sources.	By default, we recommend the use of IPCC carbon stocks. In case the PAS2050 is to be followed, these values can be selected.
GWP factor N2O	It is possible to select other Global Warming Potential (GWP) factors for characterization of N_2O. IPCC AR5 and AR6 GWP 100 factors (incl. climate carbon feedback) can be selected.	Assess the requirement set by the calculation standard you follow. Most standards require to include the most recent IPCC GWP100 factor, which would be AR6 at the time of writing.
Allow negative values	Due to a higher carbon stock after a land use change (for example when conversion from annual to perennial crop land occurred), there might be a negative result. This signifies a carbon sequestration. This checkbox will set the negative values to zero or will allow negative values to be shown.	For a conservative approach, negative values are not allowed in the LUC Impact dataset.
Crop system efficiency index (CSEI)	To represent multiple cropping practices more accurately in LUC and land occupation calculations, we propose the use of the ‘Crop System Efficiency Index’ (CSEI). What we are calculating with the Crop System Efficiency Index, is the (average) length of the harvest cycle of temporary crops (in yr/harvest).	The index considers both land efficiency gains from multiple cropping, and efficiency losses due to temporary fallow land. A possible solution for the calculation of land occupation and transformation related to crop production in countries with more precision will be proposed next, using a consistent and already-used data set (FAOSTAT).
Managed grassland	Also new in this update is the addition of managed grassland as a land use category and an additional crop type, included only for specific countries where data is available, such as Brazil.	Managed grassland are determined based on the sum of ‘Temporary grassland’ data in FAOstat ‘Land Use’ dataset & ‘Permanent grassland – cultivated’ data in FAOstat ‘Land Use’ dataset.

2.2 Previous Land use Unknown, Country Known

The calculation is based on country-level statistics of the expansion and contraction of forestland, grassland, annual cropland, and perennial cropland (FAO). The land use change of a selected crop is based on country-level statistics on the relative expansion of the selected crop (FAOSTAT).

2.2.1 Calculation steps

A summary of the procedure to calculate emissions from dLUC when country of cultivation is known and the previous land use is unknown, is provided below. The exact calculation method is described in the PAS 2050-1:2012 (horticulture), in section 5.2.3.3 “Assessment of average GHG emissions from land use change when the previous land use is not Known”.

When selecting the amortization method ‘Equal (calculated & amortized w/ single calculation)’, calculation steps 1 to 6 are performed once for the amortization period. When selecting the amortization method ‘Equal (calculated & amortized equally each year)’ or ‘Linear (calculated & amortized linearly each year)’, calculation steps 1 to 6 are performed for each year in the amortization period, obtaining multiple so-called ‘year-to-year’ LUC emissions by the beginning of step 7.

1. Expansion and contraction of forest and grassland per country (as defined in PAS 2050) are based on FAO land occupation change over the amortization period.
2. Expansion and contraction of specific crop is based on FAO harvested area change over the amortization period. Cropland is either classified as perennial or annual cropland.
3. For each crop: transformation in hectares from forest, grassland, perennial crop and annual crop is calculated.
    a. The weighted average takes into account relative differences in crop expansion at the expense of forest, grassland, annual/perennial based on the expansion/contraction of forest, grassland and cropland.
    b. The normal average is a simple average of these options (all 1/3).
    c. All results are scaled to the relative amount of expansion of the crop. This is described in the PAS2050.
4. Based on worldwide climate and soil types provided by EU, climate zone and soil types are selected which are representable for the country. With this, carbon stock can be calculated. For forest land, specific biomass is obtained per country from the Global forest resources assessment 2020. For grassland, biomass is derived from continent and climate condition (based on European commission data and IPCC values). Soil carbon content is based on IPCC 2019 soil carbon defaults for climate regions and soil types, stock change factors from IPCC 2019 are used to calculate the soil carbon stock for different land use and land management practices. Biomass of crops is obtained from either the IPCC or PAS 2050, one value represents all annual crops and another all perennial crops (with some exceptions, described in the data sources chapter).
5. Change in carbon stock between previous and current land use is multiplied with 44/12 to convert kg carbon to kg CO_2.
6. Direct N_2O emissions, which occur as a direct results of soil carbon stock losses are calculated following IPCC 2019. In case of carbon sequestration in the soil, direct N_2O emissions are zero, and never negative.
7. Emissions are amortized over the amortization period following the selected approach:
    a. Equal (calculated & amortized w/ single calculation): Emissions calculated once for the entire amortization period and are divided equally over amortization period; in practice this means that the emissions accounted for in the assessment year are found by dividing the total emissions by the amortization period (which is 20 years by default).
    b. Equal (calculated & amortized equally each year): Emissions are calculated for each year in the amortization period and divided equally over amortization period. In practice this means that the emissions accounted for in the assessment year

are equal to the sum of all year-to-year LUC emission, divided by the amortization period (which is 20 years by default).

c. Linear (calculated & amortized linearly each year): Emissions are calculated for each year in the amortization period, and linearly discounted over the amortization period; meaning that recent conversions will result in higher emissions compared to more historic conversions. Each year-to-year emission thus corresponds to a different amortization percentage. The amortization percentage for the assessment year is equal to: (1 / amortization time (by default 20 years)) + (((amortization time / 2) - ((years from assessment year + 1) - (1 / 2))) * (2 / amortization time^2)). The emissions accounted for in the assessment year are the sum of the year-to-year emissions multiplied by their corresponding amortization percentage.

8. The crop yield is derived from FAOSTAT and determines impact per kg of product.

2.2.2 Input parameters

The calculation is based on the main inputs: country and crop under study and year of assessment. Apart from these inputs, certain input parameters can be selected. These are described further in this section.

One of the most important parameters is the amortization period and method. Both these settings are prescribed in different LCA and GHG standards.

PAS2050: 20 years amortization period and equal amortization over 20 years. Emissions calculated and amortized in a single calculation over 20-year period. This basic methodology is described in the PAS 2050-1 published by BSI (BSI, 2012) and now widely referenced in LCA guidelines, such as the Product Environmental Footprint (PEF) guidelines (Zampori & Pant, 2019) & Envifood protocol.

Draft GHG protocol for the land sector: 20 years amortization period and either equal or linear amortization. Emissions calculated and amortized for each year in the 20-year period.

SBTi/FLAG: 20 years amortization period and linear amortization. Emissions calculated and amortized for each year in the 20-year period (Christa Anderson et al., 2022).

An overview of all calculation input parameters is provided in the table below.

Table 2. Overview of input parameters for 'Previous land use known' calculation method.

Setting	Description	Consideration
Amortization method	This defines how LUC emissions from a LUC event (or within a certain year) are accounted for over the amortization time. More information on amortization method provided in section 2.2.2.1.	Assess the requirement set by the calculation standard you follow, as indicated above this table. More information on the amortization method is provided in the next section.
Amortization time	The amortization time defines over how many years emissions from a LUC event are divided. The lookback period (period over which land use change emissions are relevant for the assessment year) is equal to the amortization time.	Assess the requirement set by the calculation standard you follow, as indicated above this table.

Tillage	This defines the degree of soil disturbance due to tillage operations. The level defines the soil carbon stock calculation, as described in Section 3.2 of this document. Definition is obtained from IPCC 2019. Full: Substantial soil disturbance with intense tillage operations. Reduced: Primary and/or secondary tillage but with reduced soil disturbance. No till: Only minimal soil disturbance.	Select the option that best matches the cultivation system under study.
Organic matter input	This defines the degree of organic matter input, such as crop residues and manure. The level defines the soil carbon stock calculation, as described in Section 3.2 of this document. Definition is obtained from IPCC 2019. The choices are described as follows: Low: Low residue return due to removal of residues or production of crops yielding low residues. Medium: All crop residues are returned to the field. If residues are removed then supplemental organic matter (e.g., manure) is added. High without manure: Significantly greater crop residue inputs due to additional practices, such as production of high residue yielding crops, use of green manures, etc. High with manure: Significantly higher C input over medium C input cropping systems due to an additional practice of regular addition of animal manure.	Select the option that best matches the cultivation system under study.
Carbon stock method	Carbon stocks for annual and perennial cropland are proposed by both the IPCC and in the PAS2050-1 method. This parameter defines the choice for either of the two sources.	By default, we recommend the use of IPCC carbon stocks. In case the PAS2050 is to be followed, these values can be selected.
GWP factor N2O	It is possible to select other Global Warming Potential (GWP) factors for characterization of N_2O. IPCC AR5 and AR6 GWP 100 factors (incl. climate carbon feedback) can be selected.	Assess the requirement set by the calculation standard you follow. Most standards require to include the most recent IPCC GWP100 factor, which would be AR6 at the time of writing.
Allow negative values	Due to a higher carbon stock after a land use change (for example when conversion from annual to perennial crop land occurred), there might be a negative result. This signifies a carbon sequestration. This checkbox will set the negative values to zero or will allow negative values to be shown.	For a conservative approach, negative values are not allowed in the LUC Impact dataset.

2.2.2.1 Amortization method

Results with equal and linear amortization

There are two versions of the dLUC dataset: a result dataset calculated with linear amortization and a result dataset calculated using equal amortization. The choice for equal or linear amortization in the dLUC emission calculation is related to the guideline that the user wishes to comply to: the PAS2050-1 (and thus the European Commission's PEF guidance) prescribes the use of equal amortization; the recently published SBTi FLAG calculation guidance prescribes the use of linear amortization. The amortization method in direct Land Use Change defines how the impact of a land use change event (e.g., deforestation) is accounted for in the years following the event. In equal amortization, dLUC emissions are equal for each year after the land use change event, for the duration of the amortization period (in this case: 20 years). In linear amortization, dLUC emissions linearly decrease towards zero after the land use change event, for the duration of the amortization period (in this case: 20 years). Linear amortization thus implies that the years directly after a land use change event carry a larger burden compared to years further away from the land use change event. This implies that for the emission calculation not only the question *if* land use change in the last 20 years is related to a specific crop-country combination is relevant, but also *when* the land use changes took place.

Equal amortization

The Excel dataset gives the results of the three calculation methods from the 'country known, land use unknown' functionality of the tool. The weighted average takes into account relative differences in crop expansion at the expense of forest, grassland, annual/perennial. The normal average is a simple average of these options. All results are scaled to the relative amount of expansion of the crop. The worst case of the average and weighted average is used in the PAS2050-1 protocol. The Food SCP method requires the weighted average for the estimation of land use change emissions when previous land use is unknown. The GHG Protocol Product Standard requires that the method used to calculate land use change impacts, including the average approach, be included in the inventory report.

Following the PAS2050-1 protocol, implies that emissions are calculated over the net expansion of a specific crop-country combination over the last 20 years. In case the crop area expanded first, and then contracted to equal to, or less than the area 20 years ago, the net expansion is zero.

Linear amortization

For the calculation of dLUC emissions through linear amortization, the exact same steps are takes as described in section 2.1, with the important difference that the calculation is made 20 times over a 1-year period (although still with a three-year average). The results found for the most recent year (difference 2019-2021 compared to 2018-2020) will be multiplied by the highest percentage, and the results found for the most historic years (difference 1998-2000 compared to 1999-2001) is multiplied with the lowest percentage. The percentage of each year is calculated as: amortization percentage = (1 / amortization time (= 20 years)) + (((amortization time / 2) - ((conversion year + 1) - (1 / 2))) * (2 / amortization time^2)).

Following this calculation method implies that emissions are calculated for all (yearly) expansions which occurred of a specific crop-country combination in the last 20 years. In case the crop area expanded first, and then contracted to equal to, or less than the area 20 years ago, the total expansion is considered larger than zero. Due to fluctuations in cultivated area for crops in FAO statistics, most of the crop-country combinations are associated with some total expansion. For this reason, many crop-country combinations which lead to zero expansion (and thus zero emissions) when using equal amortization will be associated with some expansion (and thus emissions) when using linear amortization.

2.2.3 LUC calculation in standards

Different standards are transparently summarized in the table below.

	FLAG	Draft GHG protocol	PAS 2050
Amortization period	20 years	20 years	20 years
Amortization method	Linear amortization	Linear or equal amortization	Equal amortization

Approach	Shared responsibility or Product specific	Shared responsibility and/or Product specific	Product specific
Separately report GHG	Not mentioned	Should be separately reported	Not mentioned
Emissions from biomass burning	Not mentioned	Should be included	Not mentioned
Emissions from peatland drainage	Not mentioned	Should be included	Not mentioned

2.3 Previous Land use Unknown, Country Unknown

2.3.1 Calculation steps

The 'average' LUC GHG emissions for a selected crop are determined by taking the weighted average of all producing countries, based on cultivated area obtained from FAO statistics for the year under study. The GHG emissions for each relevant country are determined through the methodology as described in 'Previous Land use Unknown, Country Known'.

2.3.2 Input parameters

The same input parameters as defined in the paragraph on the 'Previous Land use Unknown, Country Known' methodology are used in this calculation.

The calculation is based on the main inputs: crop under study and year of assessment. Apart from these inputs, certain input parameters can be selected. These are described further in this section.

One of the most important parameters is the amortization period and method. Both these settings are prescribed in different LCA and GHG standards.

PAS2050: 20 years amortization period and equal amortization over 20 years. Emissions calculated and amortized in a single calculation over 20-year period. This basic methodology is described in the PAS 2050-1 published by BSI (BSI, 2012) and now widely referenced in LCA guidelines, such as the Product Environmental Footprint (PEF) guidelines (Zampori & Pant, 2019) & Envifood protocol.

Draft GHG protocol for the land sector: 20 years amortization period and either equal or linear amortization. Emissions calculated and amortized for each year in the 20-year period.

SBTi/FLAG: 20 years amortization period and linear amortization. Emissions calculated and amortized for each year in the 20-year period (Christa Anderson et al., 2022).

An overview of all calculation input parameters is provided in the table below.

Table 3. Overview of input parameters for 'Previous land use known' calculation method.

Setting	Description	Consideration
Amortization method	This defines how LUC emissions from a LUC event (or within a certain year) are accounted for over the amortization time. More information on amortization method provided in section 2.2.2.1.	Assess the requirement set by the calculation standard you follow, as indicated above this table. More information on the amortization method is provided in the next section.
Amortization time	The amortization time defines over how many years emissions from a LUC event are divided. The lookback period (period over which land use change emissions are	Assess the requirement set by the calculation standard you follow, as indicated above this table.

	relevant for the assessment year) is equal to the amortization time.	
Tillage	This defines the degree of soil disturbance due to tillage operations. The level defines the soil carbon stock calculation, as described in Section 3.2 of this document. Definition is obtained from IPCC 2019. Full: Substantial soil disturbance with intense tillage operations. Reduced: Primary and/or secondary tillage but with reduced soil disturbance. No till: Only minimal soil disturbance.	Select the option that best matches the cultivation system under study.
Organic matter input	This defines the degree of organic matter input, such as crop residues and manure. The level defines the soil carbon stock calculation, as described in Section 3.2 of this document. Definition is obtained from IPCC 2019. The choices are described as follows: Low: Low residue return due to removal of residues or production of crops yielding low residues. Medium: All crop residues are returned to the field. If residues are removed then supplemental organic matter (e.g., manure) is added. High without manure: Significantly greater crop residue inputs due to additional practices, such as production of high residue yielding crops, use of green manures, etc. High with manure: Significantly higher C input over medium C input cropping systems due to an additional practice of regular addition of animal manure.	Select the option that best matches the cultivation system under study.
Carbon stock method	Carbon stocks for annual and perennial cropland are proposed by both the IPCC and in the PAS2050-1 method. This parameter defines the choice for either of the two sources.	By default, we recommend the use of IPCC carbon stocks. In case the PAS2050 is to be followed, these values can be selected.
GWP factor N2O	It is possible to select other Global Warming Potential (GWP) factors for characterization of N_2O. IPCC AR5 and AR6 GWP 100 factors (incl. climate carbon feedback) can be selected.	Assess the requirement set by the calculation standard you follow. Most standards require to include the most recent IPCC GWP100 factor, which would be AR6 at the time of writing.
Allow negative values	Due to a higher carbon stock after a land use change (for example when conversion from annual to perennial crop land occurred), there might be a negative result. This signifies a carbon sequestration. This checkbox will set the negative values to zero or will allow negative values to be shown.	For a conservative approach, negative values are not allowed in the LUC Impact dataset.

2.4 Carbon Opportunity Cost

A simplified version of the method proposed by (Searchinger et al., 2018), to account for the difference between the carbon stock (in soil and vegetation) potential natural situation (PNV)[1], compared to the current use as agricultural land. By default, the carbon stock difference is amortized over 30 years, approximating the amortization method suggested in (Searchinger et al., 2018).

2.4.1 Calculation steps

1. The carbon stock of the selected crop, in the selected country is calculated following the following approach: Based on worldwide climate and soil types provided by EU, climate zone and soil types are selected which are representable for the country. Soil carbon content is based on IPCC 2019 soil carbon defaults for climate regions and soil types, stock change factors from IPCC 2019 are used to calculate the soil carbon stock for different land use and land management practices. Biomass of crops is obtained from either the IPCC or PAS 2050, one value represents all annual crops and another all perennial crops (with some exceptions, described in the data sources chapter).
2. The carbon stock of the potential natural vegetation (PNV) environment is obtained from country averaged carbon stocks in soil and vegetation, derived from data provided in the supplementary materials of (Searchinger et al., 2018).
3. Change in carbon stock between PNV and current land use is multiplied with 44/12 to convert kg carbon to kg CO_2.
4. Direct N_2O emissions are not calculated in this method.
5. Emissions are amortized over the amortization period following equal amortization; in practice this means that the emissions accounted for in the assessment year are found by dividing the total emissions by the amortization period (which is 30 years by default).

2.4.2 Input parameters

The calculation is based on the main inputs: country and crop under study. Apart from these inputs, certain input parameters can be selected. An overview of all calculation input parameters is provided in the table below.

Setting	Description	Consideration
Amortization time	The amortization time defines over how many years emissions from a LUC event are divided.	By default, 30 years is recommended.
Tillage	This defines the degree of soil disturbance due to tillage operations. The level defines the soil carbon stock calculation, as described in Section 3.2 of this document. Definition is obtained from IPCC 2019. Full: Substantial soil disturbance with intense tillage operations. Reduced: Primary and/or secondary tillage but with reduced soil disturbance. No till: Only minimal soil disturbance.	Select the option that best matches the cultivation system under study.

[1] Potential natural vegetation is a theoretic representation of the vegetation following human abandonment, simulated under current climate conditions.

Organic matter input	This defines the degree of organic matter input, such as crop residues and manure. The level defines the soil carbon stock calculation, as described in Section 3.2 of this document. Definition is obtained from IPCC 2019. The choices are described as follows: Low: Low residue return due to removal of residues or production of crops yielding low residues. Medium: All crop residues are returned to the field. If residues are removed then supplemental organic matter (e.g., manure) is added. High without manure: Significantly greater crop residue inputs due to additional practices, such as production of high residue yielding crops, use of green manures, etc. High with manure: Significantly higher C input over medium C input cropping systems due to an additional practice of regular addition of animal manure.	Select the option that best matches the cultivation system under study.
Carbon stock method	Carbon stocks for annual and perennial cropland are proposed by both the IPCC and in the PAS2050-1 method. This parameter defines the choice for either of the two sources.	By default, we recommend the use of IPCC carbon stocks. In case the PAS2050 is to be followed, these values can be selected.
Allow negative values	Due to a higher carbon stock after a land use change (for example when conversion from annual to perennial crop land occurred), there might be a negative result. This signifies a carbon sequestration. This checkbox will set the negative values to zero or will allow negative values to be shown.	For a conservative approach, negative values are not allowed in the LUC Impact dataset.

2.5 Methodological remarks

Our LUC calculation methodology is under constant development. Several important aspects to know about the current methodology, used to calculate the LUC emissions for the 2024 dataset are summarized in the table below.

Methodological aspect	Methodology in 2022 dataset	Consideration for future version
Emissions from peat oxidation and mineralization	Not included. The tool is applicable for mineral soils only.	No direct plans to include in 2025 version of tool or dataset.
Emissions from biomass burning	Not included	No direct plans to include in 2025 version of tool or dataset.
LUC emissions for grazing grassland (for other countries) and mangroves	LUC for grazing grassland (for most countries) and mangroves cannot be calculated due to data availability limitations.	Land uses which fall outside of the currently defined land use categories should be included. Efforts will continue to enable accounting of LUC emissions related to such land uses, for

example grazing grassland (for more countries) and mangrove.

3. Data sources

The current results are based on the average FAO statistics (harvested area) of 2019-2021 and 1999-2001.

3.1 Areas

Forest and grassland area

Forest and grassland area for all countries are obtained from FAOstat. The item definitions are:

- For grassland (Item: Land under perm. meadows and pastures, FAO item: 6655, FAO element: 5110)
- For managed grassland (Item: Land under perm. meadows & pastures – Cultivated, FAO item: 6656, FAO element: 5110)
- For forest (Item: Forest land, FAO item: 6646, FAO element: 5110)

Data is downloaded in end February 2024 and contains data up to and including 2021.

Harvested area

For each crop and country, we use FAO data from “Crops and livestock products”, obtained from FAOstat in end February 2024. The area harvested over the last 20 years is downloaded and contains data up to and including 2021.

3.2 Carbon stocks

Soil carbon stock

The carbon stock will depend on the country under study. Soil carbon content is based on IPCC 2019 soil carbon defaults for climate regions and soil types: From IPCC 2006 (no refinements in IPCC 2019 refinements) Volume 4, Table 2.3. stock change factors from IPCC 2019 are used to calculate the soil carbon stock for different land use and land management practices: From IPCC 2019 refinements, Volume 4, Table 5.5 (IPCC, 2019a). The climate in a country is often described by a combination of multiple climate types, just as the soil is described by a combination of different soil types. We take into account the 2 most prevalent climate types and soil types to calculate the climate- and soil-specific soil carbon stock.

Tables are deleted in this version of the methodology description. A full version of this document is available for clients of the LUC impact tool or LUC impact dataset.

Forest vegetation carbon stock

Forest carbon stocks include above and below-ground biomass carbon stock and carbon stock in dead matter and litter. All of these carbon stocks are considered in the total vegetation carbon stock obtained from the Forest Resource Assessment (FRA) 2020 (FAO, 2020), published by the FAO. This assessment is updated every 5 years.

Grassland and vegetation carbon stock

For the calculation of the LUC dataset results, grassland carbon stocks of IPCC are used. For crops, values are obtained from the European Commission. The vegetation carbon stock for annual crops is taken to be 0 tonne C/ha, for perennials this value depends on the climate type. In specific, values are

obtained from C(2010) 3751: COMMISSION DECISION of 10 June 2010 on guidelines for the calculation of land carbon stocks for the purpose of Annex V to Directive 2009/28/EC, Official Journal of the European Union, L 151/19.

Tables are deleted in this version of the methodology description. A full version of this document is available for clients of the LUC impact tool or LUC impact dataset.

Natural carbon stock for carbon opportunity cost calculation

Reference state calculated by Blonk using the country average of overlaying country borders on top of data from (Searchinger et al., 2018) supplementary material: Extended Data Fig. 3 and 4.

4. Results

4.1 Definitions

Weighted average, normal average and worst case

Definitions of the three results are provided below:

- **Weighted average**: conversions of forestland to cropland and grassland to cropland and conversions between annual and perennial cropland are based on statistics of expansion/contraction of forestland, grassland and annual/perennial cropland. This is the methodology as described in chapter 2 of this document. The exact calculation method is described in the PAS 2050-1:2012 (horticulture), in section 5.2.3.3 “Assessment of average GHG emissions from land use change when the previous land use is not Known”.
- **Normal average**: conversion of forestland to cropland and grassland to cropland and conversions between annual and perennial cropland are all set to 1/3rd of the converted area. This means that a normal average of the emissions related to each of the three types of conversions is taken. This is also described in the PAS 2050.
- **Worst case** is the highest of the two above. It is prescribed by the PAS 2050 to take the highest of these two calculation methods.

Additional (intermediate) parameters

In the datasets where equal amortization is applied, additional parameters are provided. These parameters provide the user with insights into the main intermediate calculation parameters for the emissions from land use change, the additional parameters can also be used as an input for other calculations or other applications. The parameters which are included, in addition to the normal average and weighted average emissions from land use change, are the following:

- Crop expansion (%): Percentage of current harvested area of the crop under study which was not in use for cultivation of this crop 20 years ago.
- Expansion at expense of forest to analyzed crop (%): Percentage of current harvested area of the crop under study, which was forest 20 years ago.
- Expansion at expense of grassland to analyzed crop (%): Percentage of current harvested area of the crop under study, which was grassland 20 years ago.
- Expansion at expense of managed grassland (%): Percentage of current harvested area of the crop under study, which was managed grassland 20 years ago.
- Expansion at expense of perennials to analyzed crop (%): Percentage of current harvested area of the crop under study, which was perennial cropland 20 years ago.
- Expansion at expense of annuals to analyzed crop (%): Percentage of current harvested area of the crop under study, which was annual cropland 20 years ago.
- Emissions from conversion of forest (tonne CO2 eq per hectare): Emissions related to the conversion of a hectare forest to the type of cropland under study (annual or perennial), for the selected country.
- Emissions from conversion of grassland (tonne CO2 eq per hectare): Emissions related to the conversion of a hectare grassland to the type of cropland under study (annual or perennial), for the selected country.
- Emissions from conversion of perennials (tonne CO2 eq per hectare): Emissions related to the conversion of a hectare perennial cropland to the type of cropland under study (annual or perennial), for the selected country.
- Emissions from conversion of annuals (tonne CO2 eq per hectare): Emissions related to the conversion of a hectare annual cropland to the type of cropland under study (annual or perennial), for the selected country.
- Crop system efficiency index (yr/harvest): (average) length of the harvest cycle of temporary crops (in yr/harvest).

- Managed grassland data available: TRUE means managed grassland was included in the LUC results or FALSE means no managed grassland was included in the assessment.

4.2 Crop system efficiency index

Implementation of the Crop System Efficiency Index

With increasing global food demand, land use efficiency gains are part of the solution to halt deforestation and other natural land conversions for agricultural land. Multiple cropping is a practice, where a plot of land is subsequently planted with varying crops and harvested multiple times in a year. This practice is increasingly applied worldwide, contributing to increasing harvested areas without demanding additional agricultural land. However, in the Land Use Change (LUC) methodology the multiple cropping scenarios have not been considered yet, leading to inaccurate LUC emission calculations, especially for areas in the world where multiple cropping practices are often applied. Therefore, we've investigated the opportunities to include multiple cropping and make more fair calculations, by applying the 'Crop System Efficiency Index'. In this article we'd like to take a moment to explain the proposed methodology and the implementation for the latest LUC Impact Dataset.

Multiple cropping and LUC emissions
Currently there is no uniform guideline on how to account for multiple cropping in LUC methodologies. Within Life Cycle Assessment (LCA) studies it is often required to report the emissions emerging from LUC, such as the clearance of forests to cultivate crops, separately. Blonk's LUC Impact tool is a web-based solution, supporting the calculation of direct and statistical LUC emissions. It also provides the LUC emission inputs for Lifecycle Inventory databases, such Agri-footprint and GFLI. However, multiple cropping activities have previously not been considered in the implemented methodology. The assumption that the occupation duration for a harvest of temporary crops is always 1 year, led to an overestimation of both the LUC emissions and the land occupation impact, especially in countries where multiple cropping practices are ubiquitous. Multiple cropping primarily occurs in tropical and subtropical regions where there is a sufficient long rainy season or suitable irrigation to cultivate two or three crops sequentially within a single agricultural year. An example is a crop rotation system of planting soybeans during the summer months, harvesting the crops in late summer or early fall, and planting maize in the same field after and harvesting this in early spring.

Implementation of Crop System Efficiency Index
To represent multiple cropping practices more accurately in LUC and land occupation calculations, we propose the use of the 'Crop System Efficiency Index' (CSEI). What we are calculating with the Crop System Efficiency Index, is the (average) length of the harvest cycle of temporary crops (in yr/harvest). The index considers both land efficiency gains from multiple cropping, and efficiency losses due to temporary fallow land. A possible solution for the calculation of land occupation and transformation related to crop production in countries with more precision will be proposed next, using a consistent and already-used data set (FAOSTAT).

As only temporary (and no permanent) crops are associated with multiple cropping (and fallow land), we need to use information of the *hectares of crops harvested* in a country, and determine which crops belong to a productive period < 5 years: these are considered "*Temporary Crops*". In this category we can find annual and perennial crops (according to the FAO definition).

The other components required are the *Temporary Crops* and *Temporary fallow* areas from FAOSTAT. With this information we can start to calculate the Crop System Efficiency Index (CSEI).

Calculating the Crop System Efficiency Index

1. The calculation starts with the *Harvested area of temporary crops* and *Temporary Cropland* to decide if multiple cropping is the case.

$$Multiple\ Crop\ Index\ (MCI)[\frac{yr}{harvest}] = \frac{Temporary\ Cropland\ [ha * yr]}{Harvested\ area\ of\ temporary\ crops\ [ha * harvest]}$$

In case the result is smaller than 1, this is related to multiple cropping: the sum of harvested area for temporary crops is larger than the total temporary cropland.

The reason for an MCI of greater than 1, is not always clear or straightforward. Comparing national statistics with FAO data for the Netherlands showed that the harvested area of some fodder crops was not included in the harvested cropland in FAO data but was included in the total temporary cropland area. This example shows that a MCI > 1 can be associated with incomplete FAO data and does not always point to land use inefficiencies. Therefore, the following rule is implemented:

If MCI > 1, the value should be adjusted to 1, leading to a MCI corrected value (MCIc)

2. As fallow land is associated with crop rotation and multiple cropping, it is allocated to all Temporary Cropland. This is expressed in the Fallow Land Index (FI).

$$Fallow\ land\ Index\ (FI)[-] = \frac{Temporary\ Fallow\ Land\ [ha * yr]}{Temporary\ Cropland\ [ha * yr]}$$

3. In the last step the adjusted Crop System Efficiency Index can be obtained:

$$Crop\ System\ Efficiency\ Index\ (CSEI)\ \left[\frac{yr}{harvest}\right] = MCIc\ [\frac{yr}{harvest}] * (1 + FI\ [-])$$

Possible results:

- CSEI < 1: Multiple cropping is the case, more than one crop is produced and harvested per year, per hectare. The land occupation value calculated is multiplied by this value.
- CSEI = 1: There is no multiple cropping, or the efficiency gains from multiple cropping are counteracted by efficiency losses from fallow land. The land occupation value should not be modified.
- CSEI > 1: Per hectare harvested, more than 1 hectare should be destinated to this process. The land occupation value should be multiplied by this value.

It is important to note that the values for CSEI numbers are inverted to simplify the calculation. This means that a lower CSEI value represents higher crop system efficiency.

Separate box: Definitions & Concepts
Temporary Cropland: Land used for crops with a less-than-one-year growing cycle, which must be newly sown or planted for further production after the harvest. Some crops that remain in the field for more than one year may also be considered as temporary crops e.g., asparagus, strawberries, pineapples, bananas, and sugar cane. Multiple-cropped areas are counted only once.

Temporary Fallow Land: Land that is not seeded for one or more growing seasons. The maximum idle period is usually less than 5 years. Land is also considered as 'temporary fallow' if it is sown for the exclusive production of green manure. Land remaining fallow for too long may acquire characteristics requiring it to be reclassified, as for instance "Permanent meadows and pastures" if used for grazing or haying.

Harvested area of temporary crops: Surface of crops harvested with a productive period < 5 years between seedling and the final harvesting of the crop. This category includes both annual and perennial crops, like Maize and Banana.

Application of the Crop System Efficiency Index

One key step is to determine in which cases the Crop System Efficiency Index improves the results, and in which cases the use of the index is unsuitable. The CSEI should affect only the environmental impact linked to a proportion of time that the land is occupied by a harvested crop. An example is emissions linked to Land Use Change: if there are 2 crops produced in a year per hectare, the amount of LUC emissions will be split by 2 (50 % for each crop). Within Blonk we apply the CSEI in various models, such as Land Use Change, Peat, Land Occupation, Carbon Sequestration and Land Transformation.

Calculation approach and interpretation

a. Calculation of crop expansion of crop under study
    i. Multiply previous land area of crop with CSEI related to previous year.
    ii. Multiply current land area of crop with CSEI related to current year.
    iii. Calculate expansion of crop in selected country based on CSEI corrected areas.

b. Calculation of overall cropland expansion and contraction
    i. For each crop in the list of crops, the CSEI corrected previous and current area is determined (following steps above). The total sum of expansions and contractions of annual cropland and perennial cropland is computed based on the CSEI corrected areas.

c. Interpretation of results
    i. LUC Emissions: kg CO2eq./ha*yr
    ii. Transformations (per previous and current land use type): m2/ha*yr
    iii. CSEI of current year (average of nr of years as defined in input, default 3 years): yr/harvest

d. As part of crop inventory
    i. LUC emissions from LUC Impact dataset are reported as [kg CO2eq./ha*yr] and should be multiplied with the CSEI [yr/harvest] to obtain the emissions and transformation impact related to the harvest.
    ii. Land occupation related to the harvest is equal to the CSEI [yr/harvest].

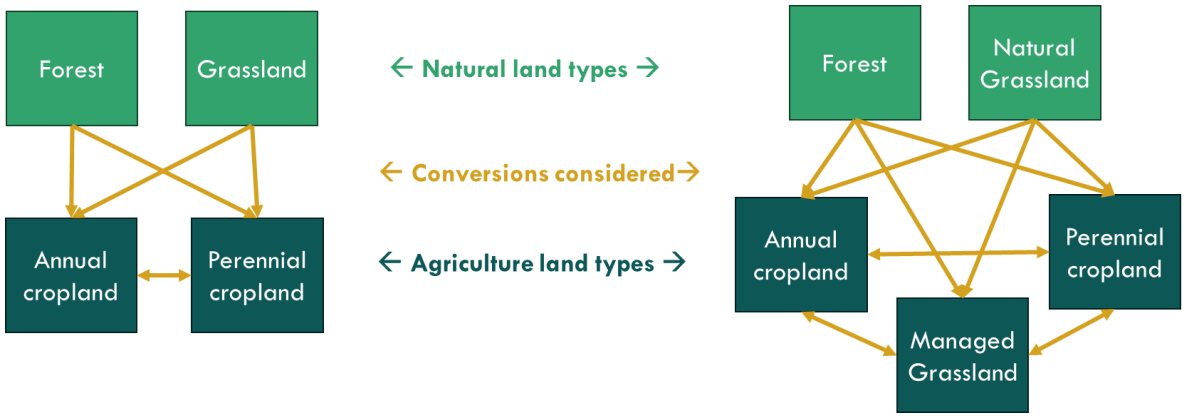
More information: https://blonksustainability.nl/news/crop-system-efficiency-index

4.3 Implementation of Managed grassland LUC emissions calculation

Prerequisites for calculation:

- Availability of ‘Temporary grassland’ data in FAOstat ‘Land Use’ dataset.
- Availability of ‘Permanent grassland – cultivated’ (or similar: slightly different naming in different FAO versions) data in FAOstat ‘Land Use’ dataset.
- Availability of ‘Permanent grassland – naturally growing’ (or similar: slightly different naming in different FAO versions) data in FAOstat ‘Land Use’ dataset.

If this data is not available, the tool will not be able to provide results for managed grassland, and will not consider managed grassland as a separate category (left situation in the figure below). If the data is available, results for managed grassland can be provided, and managed grassland is considered as a separate land use category for the LUC calculation of any crop (right situation in the figure below).



Calculation steps

If data is available, the calculation for 'country known, previous land use unknown' is adjusted as follows:

- The previous and current area of 'Managed grassland' are determined based on the sum of 'Temporary grassland' data in FAOstat 'Land Use' dataset & 'Permanent grassland – cultivated' (or similar: slightly different naming in different FAO versions) data in FAOstat 'Land Use' dataset.
    - This data is directly used to determine the expansion rate of 'Managed grassland', if this is the crop under study.
    - The 'Managed grassland' area is considered part of the 'Total agricultural land area', which is used in the first step of the conversion calculation to determine whether expansion of a crop happens at the expense of natural land, or other agricultural land.
    - The 'Managed grassland' area is considered a separate category of agricultural land area, which means that conversions from 'Managed grassland' to the selected crop are calculated and reported.
- The previous and current area of 'Natural grassland' is derived from 'Permanent grassland – naturally growing' (or similar: slightly different naming in different FAO versions) data in FAOstat 'Land Use' dataset.
    - The 'Natural grassland' area is considered part of the 'Total natural land area', and replaces the 'Grassland' area as used in the calculation when data is not available (default methodology before 2024).
- In the quantification of emissions from conversions to- and from managed grassland and natural grassland, the carbon stock of both soil and vegetation are considered equal for managed and natural grassland. This is a limitation which may be refined in upcoming updates of the LUC tool and dataset. *If both items which are considered in the 'Managed grassland' category (temporary grassland and cultivated permanent grassland) would be kept separate, it would be possible to assign a different carbon stock to the temporary grassland area compared to the cultivated permanent area.*

4.4 Drivers for change compared to previous version

General drivers for change

When interpreting the data (differences), it is important to realize where (changes in) dLUC emissions originate from. The changes in direct land use change emissions compared to previous years for a crop-country combination are mainly driven by three questions:

- *Did the total forest area in a country contract over the last 20 years?*
  Conversion from forest area to cropland results in the largest loss of carbon stock, compared to conversion from grassland or changes between annual and perennial croplands. Therefore, if the total forest area in a country did not reduce compared to 20 years ago, the emissions factors due to direct land use change will generally be low.
- *Did the total area for crop cultivation increase in a country?*
  If there is no increase in the total area used for crop cultivation, according to the PAS-2050-1, it can be assumed that no contractions of forest or grass land are caused by an increase of cropland. Therefore, the emissions factors for that country will generally be low.
- *Did the total area harvested for the crop under investigation expand?*
  If the area harvested for a crop under investigation did not increase over the last 20 years, there is no land use change. If there is an increase, the emissions due to land use change will be mainly driven by the factors mentioned above. For crops that are rapidly expanding, this can result in large changes in emissions factors between the chosen 20 year interval.

Other drivers for change

- Difference in soil carbon stock from IPCC 2006 (used in previous version) and IPCC 2019 (used in current versions).
- Changes due to historic data for harvested area on some crops and countries combinations in in the new FAO download (February 2024).

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