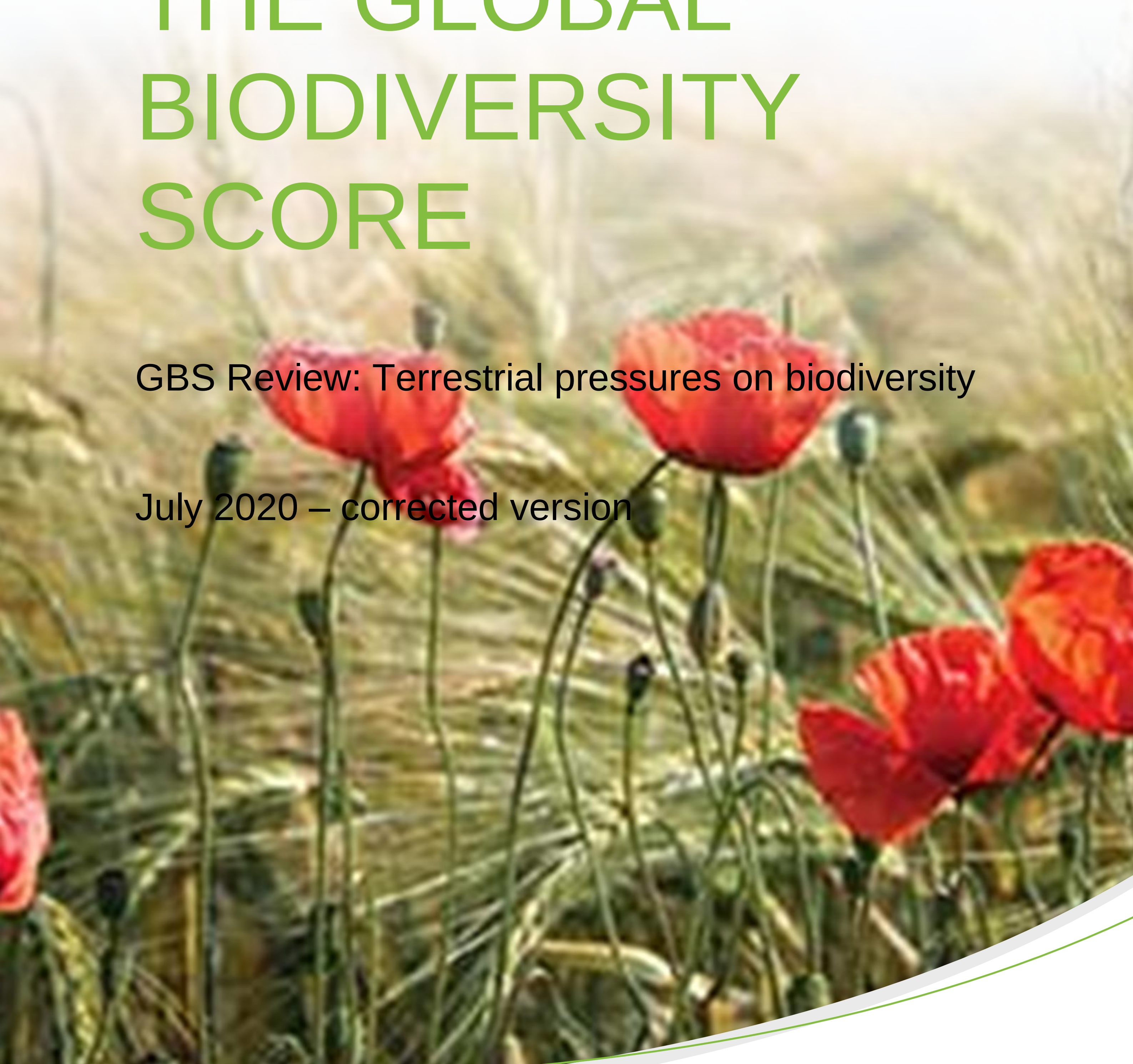
THE GLOBAL BIODIVERSITY SCORE

GBS Review: Terrestrial pressures on biodiversity

July 2020 – corrected version



CDC BIODIVERSITÉ | Caisse des Dépôts GROUPE

Content

CDC BIODIVERSITÉ

Note to the reader

GBS review reports are not completely independent from each other. Readers of this report are advised to first read the report dedicated to Core concepts of the GBS (CDC Biodiversité 2020a) to ensure a good overall comprehension of the tool and the present report.

The following colour code is used in the report to highlight:

- Assumptions

- Important sections

- Developments of the GBS planned in the future

The GBS review reports are aimed at technical experts looking for an in-depth understanding of the tool and contribute to the transparency that CDC Biodiversité considers key in the development of such a tool. They focus on technical assumptions and principles. Readers looking for a short and easy-to-understand explanation of the GBS or on an overview of existing metrics and tools should instead read the general audience reports published by CDC Biodiversité (CDC Biodiversité 2017; CDC Biodiversité, ASN Bank, and ACTIAM 2018; CDC Biodiversité 2019b).

1 Context

1.1 Objective and overview of this report

This report presents how the GBS uses GLOBIO 3.6 Terrestrial cause-effect relationships (Rob Alkemade et al. 2009; Schipper et al. 2016) to assess the impacts of terrestrial pressures on biodiversity and how it combines it to other data sources to build impact factors which can be used in combination with the GBS CommoTools and input-output approach. Figure 1 shows the linkages with the overall GBS approach: the “default” approach uses the area circled in orange while the “refined” approach allows to directly use pressure-related corporate data inputs to assess impacts.

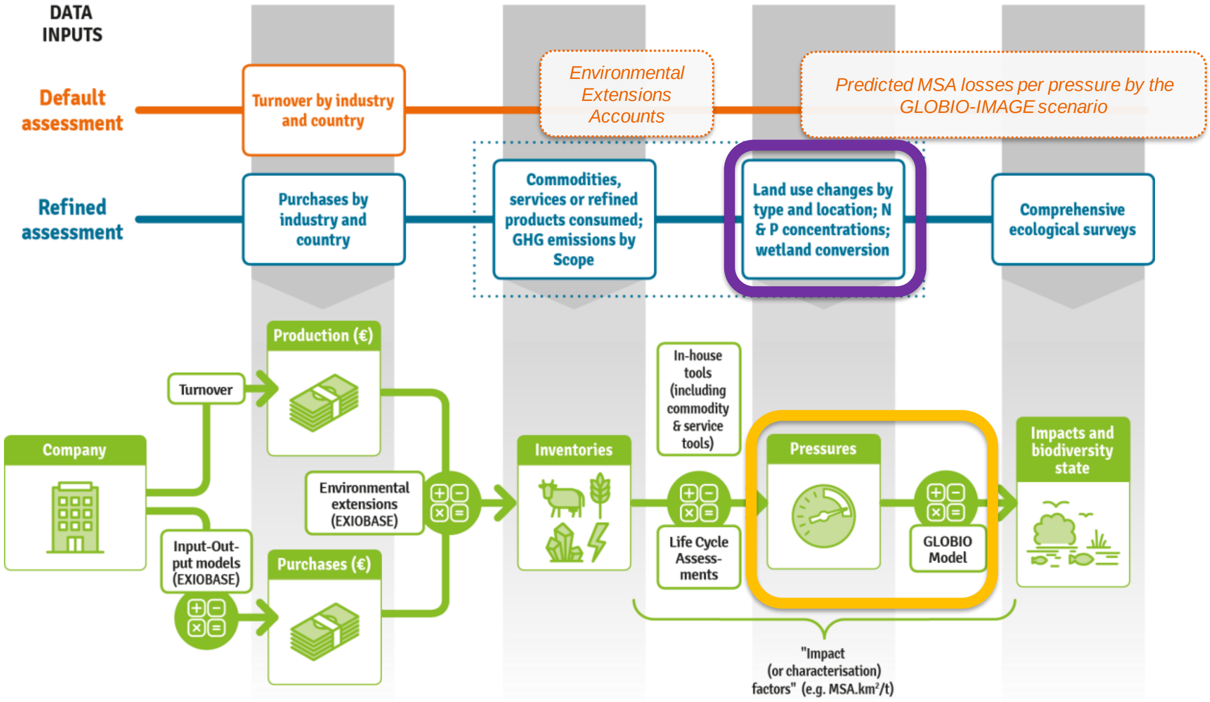


Figure 1: Link between the content of this report and the GBS framework

1.2 Pressures covered

GLOBIO Terrestrial cause-effect relationships cover the following IPBES main drivers of biodiversity loss:

- Land / sea use change: Land use, Fragmentation and Encroachment;
- Pollution: Atmospheric nitrogen deposition, and on-site pollution is partly accounted for in the pressure Land use. Pollution related to pesticides and ecotoxicity will be covered in another document as it will not rely on GLOBIO Terrestrial (CDC Biodiversité 2020b). Other pollution sources such as plastic pollution are not covered yet;
- Climate change.

The following driver is not yet covered: Invasive alien species. Due to the way it is defined, the Mean Species Abundance (MSA) can however reflect the impacts of invasive alien species: an ecosystem where original species populations drop sharply whereas invasive populations skyrocket will show a drop in MSA since only naturally occurring species count in the calculation of MSA.

Direct exploitation is not directly associated to specific pressures in GLOBIO Terrestrial. The GBS however includes the impacts of extraction of living biomass (crops, wood logs) and non-living materials (metal ores, fossil fuels). The pressures associated to unsustainable hunting (and fishing for aquatic and marine pressures) are not yet covered.

Based on the assessment of the relative importance of drivers of biodiversity loss by the IPBES (Díaz et al. 2019), the GBS covers about 75% of them. For most industries, material impacts will be covered. However, GBS 1.0 will not be adequate for industries where overexploitation through hunting or invasive alien species are material.

The GBS will be regularly updated and it aims to cover all the main drivers of biodiversity loss as listed by the IPBES. As soon as reliable data are available, the GBS will include impacts from the pressures currently not covered.

1.3 Cause-effect relationships versus global coverage forecast data

As noted in the Introduction document (CDC Biodiversité 2020a), two types of data constantly used in the GBS should be differentiated. They are both produced by the PBL and they are closely linked together although they have a fundamental difference. On one side, the cause-effect relationships link a pressure intensity to a biodiversity impact expressed in MSA% or MSA.km² for each biodiversity loss driver; all together they form what we refer to as the GLOBIO cause-effect relationships. On the other side, global biodiversity state predictions. This data is produced by the PBL through the combination of GLOBIO cause-effect relationships and the integrated assessment model IMAGE. The IMAGE model is a scenario-based model designed to predict the impact of various scenarios (like RCP 2.6 for instance) on various components of the Earth. The IMAGE model spatially predicts biodiversity loss drivers' intensities and GLOBIO cause-effect relationships translate them into biodiversity impacts expressed in MSA% or MSA.km². This combination of IMAGE and GLOBIO in scenario framework is referred as GLOBIO-IMAGE scenarios.

Ideally, when building location-specific average impact factors (e.g. national average impact factors), it would be best to use data based on direct measurements, for instance satellite monitoring of the fragmentation of natural habitats. However, we have not been able to find direct measurements at a global scale to build impact factors related to terrestrial pressures. Therefore, we fell back to the modelled data of the GLOBIO-IMAGE scenario on the extent of pressures globally. This leads to more uncertainties as this data is a composite of IMAGE sub-models, all encompassing a certain degree of uncertainty. Whenever direct measurements of pressures become available, the GBS will switch to more accurate data sources.

1.4 About GLOBIO 4

GLOBIO 4 model is out since early 2020 (Schipper et al. 2020). We have not yet been able to get access to the detailed projection data up to 2050 to update the GLOBIO3.6 data used in the GBS. This data update is considered for the next GBS version.

2 Land use

2.1 Context

A GLOBIO CAUSE EFFECT-RELATIONSHIPS

Land-use categories number varies depending on GLOBIO's version. In this section we focus on the GLOBIO version which was used for a technical supplement to the Global Biodiversity Outlook 4 (Kok et al. 2014), which we call "GLOBIO GBO4". This is the version used to produce scenario-based data used in GBS' default assessments. In other GLOBIO's versions, other categories and their associated MSA% are characterized and can be used in the refined approach. A summary of all land use types, with their description and associated MSA is presented in Figure 2.

GLOBIO GBO4 (used in default assessments)	***Marquardt et al. 2019 (used in refined assessments)***	***MSA value (%)***	***Description from GLOBIO 3 (Alkemade et al. 2009)***	***GLOBIO GBO4's man-made area***
Natural_forest	**Natural forest**	100%	Also called **Primary vegetation (forest)**. Minimal disturbance, where flora and fauna species abundance are near pristine	Non-man-made land
Forestry_plantation	**Plantation forest**	30%	Planted forest often with exotic species	Non-man-made land
Forestry_harvest	**Clear-cut forest**	50%	Also called **Secondary forests**. Areas originally covered with forest or woodlands, where vegetation has been removed, forest is re-growing or has a different cover and is no longer in use	Non-man-made land
Forestry_selective_logging	**Selectively logged forest**	70%	Also called **Lightly used natural forest**. Forests with extractive use and associated disturbance like hunting and selective logging, where timber extraction is followed by a long period of re-growth with naturally occurring tree species	Non-man-made land
Forestry_reduced_impact_logging	**Reduced impact logging (RIL) forest**	85%	***Didn't exist in GLOBIO3***	Non-man-made land
Natural_schrub_grassland	**Natural grassland**	100%	Also called **Primary vegetation (grass- or scrublands)**. Grassland or scrubland-dominated vegetation (for example, steppe, tundra, or savannah)	Non-man-made land
Cultivated_grazing_area	**Moderately and Intensively used pasture**	60%	Also called **Livestock grazing**. Grasslands where wildlife is replaced by grazing livestock	Man-made land
/	**Man-made pasture**	30%	Also called **Man-made pastures**. Forests and woodlands that have been converted to grasslands for livestock grazing.	Non applicable
Agriculture_extensive	**Rain-fed low input cropland - temporary and permanent**	30%	Also called **Low input agriculture**. Subsistence and traditional farming, extensive farming, and low external input agriculture	Man-made land
Agriculture_intensive	**Rain-fed high input cropland - temporary and permanent**	10%	Also called **Intensive agriculture**. High external input agriculture, conventional agriculture, mostly with a degree of regional specialization, irrigation-based agriculture, drainage-based agriculture.	Man-made land
Agriculture_irrigated	**Irrigated cropland - temporary and permanent**	5%	***Didn't exist in GLOBIO3***	Man-made land
Agriculture_woody_biofuels		30%	***Didn't exist in GLOBIO3***	Man-made land
Natural_bare_ice_other	**Bare area**	100%	Areas permanently without vegetation (for example, deserts, high alpine areas)	Non-man-made land
Urban	**Urban**	5%	Also called **Built-up areas**. Areas more than 80% built up	Man-made land

Figure 2: Summary of GLOBIO land use types and associated MSA[1]

Thirteen land-use categories are factored into GLOBIO GBO4. Three categories refer to natural areas insofar as they are not dedicated to any human activity in particular, i.e., natural forests, natural grasslands, and natural bare ice. Ten other categories correspond to: intensive agriculture, extensive agriculture, woody biofuel agriculture, irrigated agriculture, cultivated grazing areas, forestry plantation, harvest forestry, selective logging forestry, low-impact selective logging forestry, and urban areas. The classes reflect the (management) intensity of land use on cultivated land (including forests) and grazing areas. To assess the MSA% of each land use class, 89 peer-reviewed articles comparing species' abundance between at least one land-use type and primary vegetation were selected by the PBL. Though tropical forests are overrepresented in this sample, studies from other biomes confirm the general picture. For urban areas no proper data was found and the value of 5% was assigned by the PBL by expert opinion.

It is important to note that GLOBIO land use cause-effect relationships focus on long-term management intensity. For instance, "Forestry - clear cut harvesting" should be understood as a type of forestry management here, not a punctual action. Over a period of 50 years, when trees are cut, they are cut through clear-cutting and not selective logging. Even though biodiversity level varies over time, it is assumed that on average over time, MSA% is equal to 50%.

Also, plantations related to the production of other commodities than wood (palm oil, rubber...) are considered as croplands. Those actively managed therefore falls in the intensive agriculture land use type with an MSA value of 10%.

B LAND USE DATA

As noted above, lacking direct measurements of land use (i.e. land cover combined with management intensity) and land use changes globally, we fall back to GLOBIO-IMAGE scenario's land use projections.

Global land coverage data was compiled by the PBL from different sources. The Global Land Cover 2000 (GLC2000) map representing land cover in the year 2000 was used by the PBL in GLOBIO3 as a starting

[1] For the GLOBIO GBO4 land use "Forestry plantation", GLOBIO GBO4 actually uses a MSA% of 20% instead of 30%. In the GBS calculations, MSA% of 30% is used, in line with GLOBIO 3.6 (Schipper et al. 2016). Since only the projected areas (km^2) of land use, and not the projected static biodiversity impacts ($MSA.km^2$), are used in default calculations, the discrepancy does not cause errors in our results. However, results from the GBS cannot be directly compared to forecasts made with GLOBIO GBO4 for the Forestry plantation land use. The land-use classes and MSA% values of (Marquardt et al. 2019) are used in refined assessments (they are actually very similar to GLOBIO 3.6 land use classes). In the figure, "temporary" and "permanent" land-use classes are regrouped as they have the same MSA% (e.g. Irrigated cropland - temporary and Irrigated cropland – permanent). Similarly, Moderately used pasture and Intensively used pasture are merged in the table as they both have a MSA% of 60%. Two additional land use classes could be used in refined assessment in future versions of the GBS, based on (R. Alkemade et al. 2013): Intensively used pasture (50% MSA) could be distinguished from Moderately used pasture (60% MSA), and an additional class could be introduced Ungrazed abandoned rangelands (70% MSA).

point. The 23 land cover classes in the GLC2000 were aggregated into broader classes according to their MSA value to fit the 13 land-use classes displayed in GLOBIO GBO4 (as described above).

Intensity is measured by the PBL based on the research of J. Dixon (Dixon, Gibbon, and Gulliver 2001) for cultivated areas, data from the GLOBIO-IMAGE scenario for grazing areas, and data provided by the FAO (2001) for forests.

Global land coverage data and forecast is used as a default approach when we are not able to collect directly land use surface data (either static or dynamic) and conduct a refined assessment. More details will be provided in the following sections and for each commodity specific documentation.

2.2 Default assessment dimensioning

A DYNAMIC FOOTPRINT

2.2.A.1 Restricted perimeter concept

Let's consider a fixed perimeter P. This perimeter can be a GLOBIO cell, a country, a region, etc. From year n to year n+1 (the approach is similar if the assessed period is not one year), the land uses on this perimeter P changed, some of them extended and, as the total surface remains constant, some of them shrank. In other word, land conversion happened leading to a change in the state of biodiversity ("biodiversity variation") which can be a loss or a gain. The question here is how to allocate this biodiversity variation to the different types of land uses. First, we define the restricted perimeter RP which sums up land use differences between year n and year n+1. Areas where the land use did not change between year n and n+1 are excluded from RP (step 1 in Figure 3). The change in biodiversity is then allocated to the final land uses of RP (year n+1), as we consider that responsibility for the biodiversity variation falls on land uses that remain at the end of the period. Since the exact conversion process is unknown – land use repartition in years n and n+1 is known but no data on the evolution of each specific land use is available, e.g. which land use replaced which one – we assume that the conversion started from an average land use reflecting the average biodiversity value of RP in year n (step 2 in Figure 3). Biodiversity loss due to land conversion allocated to each land use LU is computed as follow:

$$MSA\ dynamic_{LU}^{n \to n+1} = S_{RP\ LU}^{n+1} \times (MSA_{RP}^{n} - MSA_{LU})$$

With $MSA\ dynamic_{LU}^{n \to n+1}$: biodiversity variation due land use conversion attributed to land use LU (MSA.m²)

$S_{RP\ LU}^{n+1}$: surface in RP at year n+1 for land use LU

MSA_{RP}^{n} : average MSA in year n of all land uses within RP (in %)

CDC BIODIVERSITÉ | Caisse des Dépôts GROUPE

MSA_{LU} : MSA for land use LU (in %)

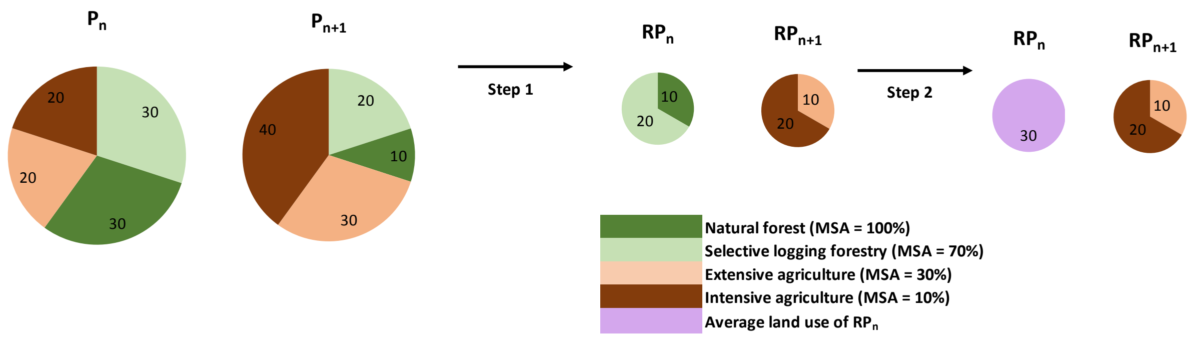
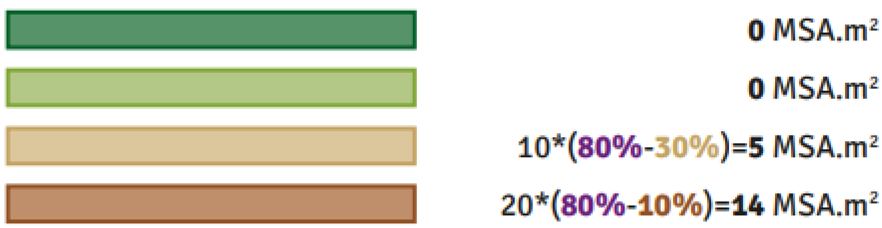


Figure 3: Illustration of the calculation of the dynamic footprint for land use conversion with a simplified example

Figure 3 gives a simplified example with only 4 land uses distributed on a perimeter P of surface 100 m² to illustrate the methodology. The biodiversity loss for each land use is finally computed as follows:



In default assessments, i.e. assessments based on scenario-based data only, biodiversity gains due to spatial pressures (land use, fragmentation and encroachment) are capped at 0. This reflects the conservative stance adopted by the GBS in default assessments: if no data is available to demonstrate that farmers are actually reducing cropland area (leading to less biodiversity being lost due to spatial pressures), we consider that the reduction in agricultural area is due to some farmers stopping their activity, while the remaining farmers maintain their existing areas. It does not mean that GBS methodology cannot account for potential gains for spatial pressures, it is still possible in the refined assessment with appropriate and robust data justifying it.

2.2.A.2 Implementation

Terrestrial: land use dynamic

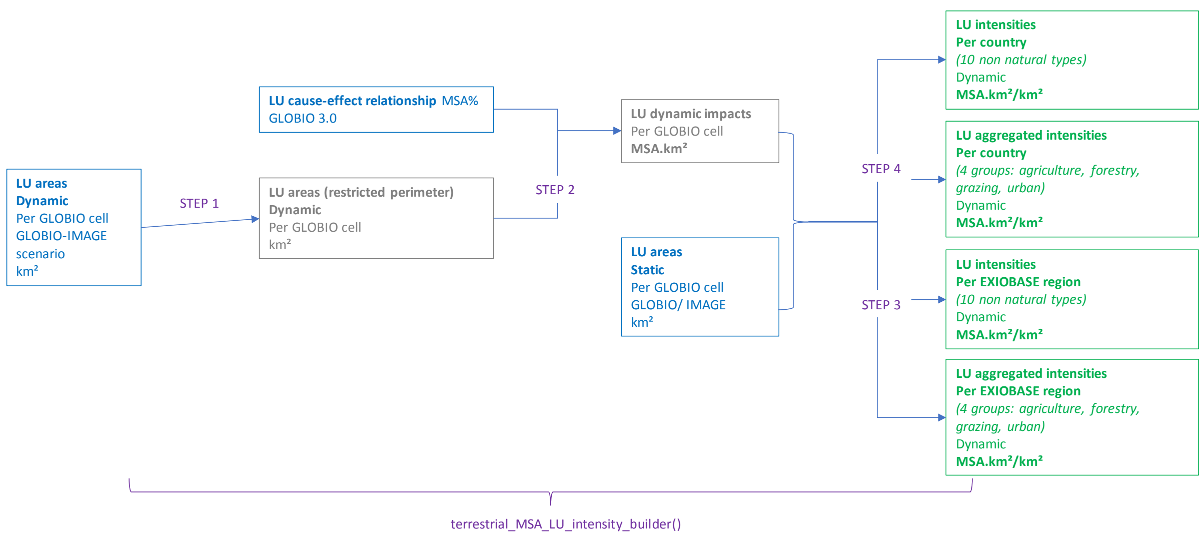


Figure 4: General layout default assessment for land use dynamic footprint

Based on computation rules described in the previous section, for an assessment from year n to year n+1, for each cell:

- (STEP 1) the restricted perimeter is evaluated by computing land use annual changes areas (dynamic, in km²). Within the restricted perimeter, land use types which extended are final land uses and they replaced initial land uses whose area decreased.

- (STEP 2) average biodiversity variation (MSA.km^2) is computed for restricted perimeter at year n (area weighted MSA% of initial land uses),

- dynamic impacts (MSA.km^2) are computed for final land uses with gains capped to 0.

```
#STEP 1
  #Compute restricted perimeter area and MSA start
  land_use_annual_change_neg <- land_use_annual_change %>%
    select(contains("Area_LU_")) %>%
    mutate_all(funs(replace(., .>0, 0))) %>%
    mutate(restricted_perimeter_area = -rowSums(.))

  #Compute MSA.km² start on restricted perimeter
  inter_neg <- - select(land_use_annual_change_neg, LU_column_names[1])* LU_specs$msa[1]
  for (i in (2:length(LU_column_names))) {
```

```
    inter_neg <- inter_neg  - select(land_use_annual_change_neg, LU_column_names[i]) *
LU_specs$msa[i]
  }

  #STEP 2: Compute MSA.km² losses per land use type
  #Compute MSA% start on restricted perimeter
  land_use_annual_change_neg <- land_use_annual_change_neg %>%
    cbind(inter_neg %>% rename(restricted_perimeter_msa_start = 1)) %>%
    mutate(restricted_perimeter_msa_start =
      case_when(
        restricted_perimeter_area != 0 ~ restricted_perimeter_msa_start/
restricted_perimeter_area,
        restricted_perimeter_area == 0 ~ 0
    ))

  #Reminder: allocation of msa loss (GAINS ARE CAPPED) to expanding land uses
  #Selection of expanding land uses
  land_use_annual_change_pos <- land_use_annual_change %>%
    select(contains("Area_LU_")) %>%
    mutate_all(funs(replace(., .<0, 0)))

  #MSA loss computation
  terrestrial_MSA_land_use_dynamic_cell <- select(land_use_annual_change, CellCd)
  for (i in (1:length(LU_column_names))) {
    terrestrial_MSA_land_use_dynamic_cell <- terrestrial_MSA_land_use_dynamic_cell %>%
      cbind(select(land_use_annual_change_pos, LU_column_names[i]) *
        (land_use_annual_change_neg$restricted_perimeter_msa_start - LU_specs$msa[i]))
  }

  #Cap application: Selection of only positive figures (losses)
  terrestrial_MSA_land_use_dynamic_cell <- terrestrial_MSA_land_use_dynamic_cell %>%
    mutate_all(funs(replace(., .<0, 0))) %>%
    rename(globio_cell_id = CellCd)
  names(terrestrial_MSA_land_use_dynamic_cell) <-
map_chr(names(terrestrial_MSA_land_use_dynamic_cell), str_replace, "Area", "MSA")

  #Add land use surfaces (current)
  terrestrial_MSA_land_use_dynamic_cell <- terrestrial_MSA_land_use_dynamic_cell %>%
    left_join(GBStoolbox::terrestrial_get_land_use_data("current", "cell") %>%
rename(globio_cell_id = CellCd), by= "globio_cell_id")
```

- (STEP 3&4) For each spatial entity (country and EXIOBASE region), intensities for each non-natural land use type are then computed as follow:

$$Land\ use\ dynamic\ MSA\ Intensity\ _{SE}^{LU\ type} = \frac{MSA\ losses_{SE}^{LU\ type}}{Area_{SE}^{LU\ type}}$$

With $Land\ use\ dynamic\ MSA\ Intensity\ _{SE}^{LU\ type}$: land use dynamic intensity for spatial entity SE and land use type LU [MSA.km²/km²]

$MSA\ losses_{SE}^{LU\ type}$: total MSA losses for land use type LU in spatial entity SE [MSA.km²]

$Area_{SE}^{LU\ type}$: total area for land use type LU in spatial entity SE [km²]

$MSA\ losses_{SE}^{LU\ type}$ and $Area_{SE}^{LU\ type}$ are computed as sums of respectively losses and areas for all cells composing spatial entity SE.f

On the same principle, intensities (static and dynamic) are also computed for the following aggregated land use types:

- "all agriculture" regrouping intensive, extensive, irrigated and woody biofuels,

- "all forestry" regrouping forestry plantation, harvest forestry, selective logging forestry, low-impact selective logging forestry.

In this version of GBS, we compute only the "average" intensity. In future versions we would like to compute as well optimistic and conservative intensities based on uncertainties around cause-effect relationships and land use areas forecast.

Land use dynamic intensities do not directly apply GLOBIO cause-effect relationships as they rely on regional average land use changes, they thus fall into data quality tier 3.

B STATIC FOOTPRINT

In any case, for default and refined assessments, static footprint computation is directly derived from cause-effect relationships. Therefore, for a given area A, it is computed using the following function:

$$Land\ use\ static\ impact\ (A)\ = f(S_A, MSA\%_A) = S_A \times (100\% - MSA\%_A)$$

With $Land\ use\ static\ impact$ (A): static footprint for area A (in MSA.m²)

S_A: surface of area A (in m²)

$MSA\%_A$: MSA% of area A (in MSA%)

Using the previous simplified example of Figure 3, we obtain:

$$MSA\ static_P^n = 30 \times (1-1) + 30 \times (1-0.7) + 20 \times (1-0.3) + 20 \times (1-0.1) = 41\ MSA.m^2$$

$$MSA\ static_P^{n+1} = 20 \times (1-1) + 10 \times (1-0.7) + 30 \times (1-0.3) + 40 \times (1-0.1) = 60\ MSA.m^2$$

Note that, on a fixed perimeter and when only land use pressures apply, the following equation is verified:

$$MSA\ static_P^{n+1} = MSA\ static_P^n + \sum_{LU} MSA\ dynamic_{LU}^{n \to n+1}$$

2.3 Refined assessment dimensioning

A PRINCIPLE

The functions described here aim to **assess the biodiversity impacts caused by terrestrial land use changes** when land use data on a **delimited geographical perimeter** are available. One or several polygons which can be drawn on a map is what we understand as a "delimited" perimeter. The type of data required is the **classes of land uses and their respective areas at two different dates**. Figure 5 represents the relationships between the different functions constructed and used when these refined data are available. The following sections mainly focus on the Steps I and II, using the functions `pressure_LU_pre_treatment()`for the automatic pre-treatment step and `pressure_LU_evaluator()` for the evaluation step, Step 0 where the data from companies is manually pre-treated first and then imported is not detailed.

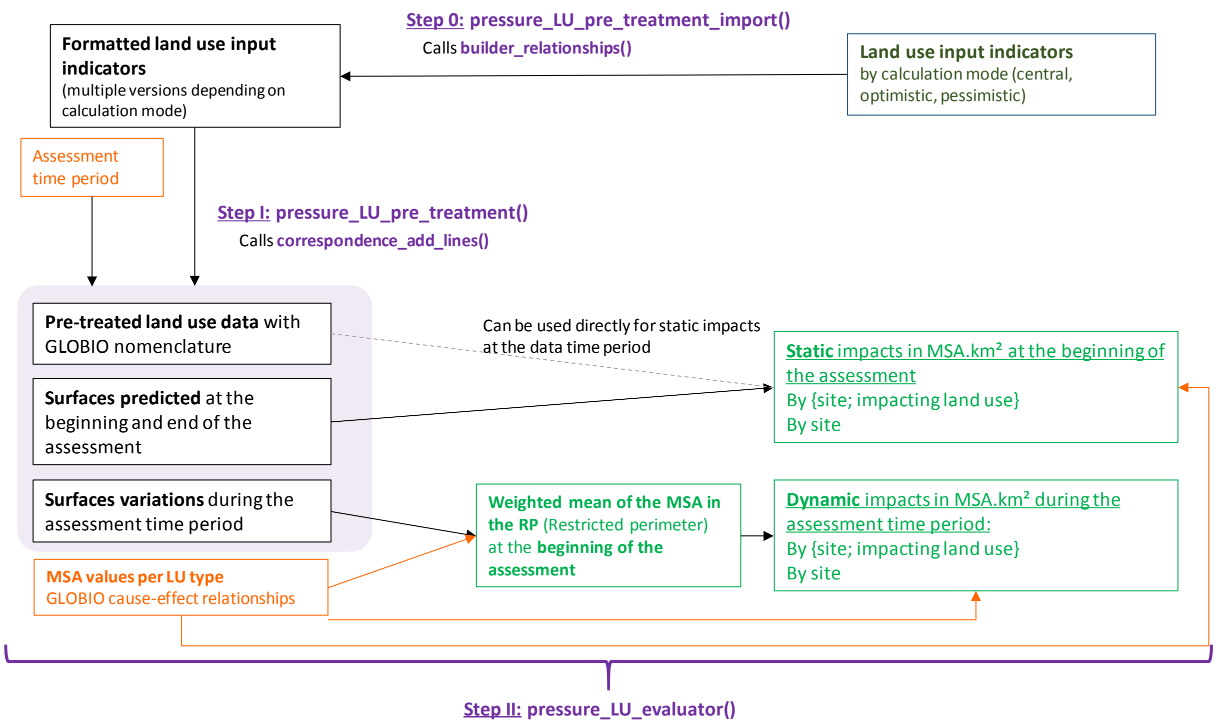
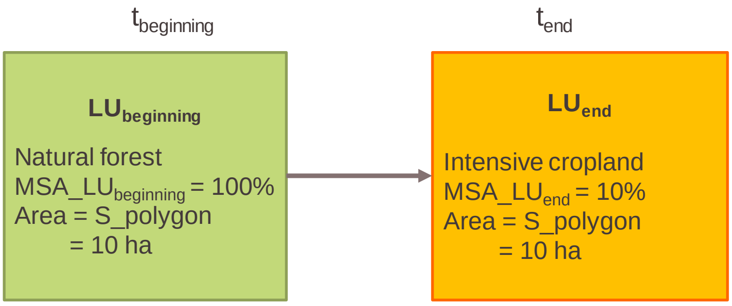


Figure 5: Overview of the refined terrestrial land use pressure assessment functions

Figure 6 explains the basic principles to assess the terrestrial impact on biodiversity caused by land use with the refined method on one polygon with only one land use. The dynamic impact is attributed to the appeared land use, that has caused an MSA loss on the polygon. The method is further explained in the first publication of the GBS (CDC Biodiversité 2017).



Dynamic impact due to LU change on biodiversity between $t_{beginning}$ and t_{end}:
S_polygon * (MSA_LU_{end} - $MSA\_LU_{beginning}$)
*Ex: 10 * (100% - 10%) = 9 MSA.ha, due to the cropland*

Static impact due to LU on biodiversity at $t_{beginning}$:
S_polygon * (100% - $MSA\_LU_{beginning}$)
*Ex: 10 * (100% - 100%) = 0 MSA.ha*

Static impact due to LU on biodiversity at t_{end}:
S_polygon * (100% - MSA_LU_{end})
*Ex: 10 * (100% - 10%) = 9 MSA.ha, due to the cropland*

Figure 6: Basic principle to assess the biodiversity impacts of land use

In real cases with corporate data on multiple entities or sites, there are usually multiple land use classes. This issue is tackled with the principles explained in section 2.2A and in the last GBS publication (CDC Biodiversité 2019b).

In cases where we do not know precisely which land use replaces which, we use the "restricted perimeter" methodology as described in section 2.2.A.1.

The static impact computation method is quite the same as in *Figure 6*. Static biodiversity loss impacts at a given year are attributed to the present land uses according to the area they occupy and the associated %MSA, with the formula:

$$MSA\ static_{LU}^{n} = S_{LU}^{n} \times (100\% - MSA_{LU})$$

Equation 1: Static impact on biodiversity caused by land use

Where S_{LU}^{n} is the area occupied by the land use LU that is present in year n.

For cases where the exact land conversion process is known. allocation is straightforward and MSA impacts are computed using land use respective MSA% values as described in Figure 6.

B INPUT DATA FORMAT FOR THE PRE-TREATMENT

The requirements of **format for input data** at the beginning of Step 0 are listed in the data collection guidelines (CDC Biodiversité 2019a). In addition to format requirement the total area for each site must remain constant over time (though the mix of land uses can obviously change). This verification is for now done manually before using the functions.

This section focuses on the **pre-treatment** -(Step 1). Data at the beginning of Step 1 is formatted as shown by Table 1.

Pressure[2]	Group[3]	Scope	Land Use	Stage	Year	Area (km^2)[4]
Land-use	… site A	1	Forest - Natural	Year_stage_1	2016	30
Land-use	… site A	1	Forest - Selective logging	Year_stage_1	2016	30
Land-use	… site A	1	Extensive cropland	Year_stage_1	2016	20
Land-use	… site A	1	Intensive cropland	Year_stage_1	2016	20
Land-use	… site A	1	Forest - Natural	Year_stage_2	2017	20
Land-use	… site A	1	Forest - Selective logging	Year_stage_2	2017	10

[2] The "**Pressure**" and "**Scope**" columns contain data needed to identify to which pressure and Scope the result of the assessment is related.
[3] "**Group**" can take a number of values (for example a field, a production site, a business unit..) depending on the entity type relevant for the assessment. Here, to simplify, we take the example of production sites (noted "Site" in the rest of the text) for the geographically most precise level of group).
[4] Data for site A is the same as the example from and the previous GBS report (CDC Biodiversité 2019b), except that the unit is now km^2 instead of m^2.

Land-use	… site A	1	Extensive cropland	Year_stage_2	2017	30
Land-use	… site A	1	Intensive cropland	Year_stage_2	2017	40
…						

Table 1: Data after Step 0

Companies have to provide land use data at two different dates, so that the land use conversion can be calculated. Each {site; land use class} is thus associated to two lines in Table 1, the first for the earlier date, called "Year_stage_1" (or t_1) and the second for the later date, called "Year_stage_2" (or t_2). The **"Stage"** column contains this information. All the t_1 and the t_2 are not necessarily the same for each {site; land use} depending on the data available to companies.

The '**Land Use**" column contains the name of the land use class of the concerned combination of {site; land use}. If the land use class information is **directly provided in the same nomenclature as in GLOBIO**, it can be directly fed to the pressure-impact relationships and the provided data is classified in the data quality tier 4. If translation is needed, it is classified in the data quality tier 3. The automatic pre-treatment function is parly in charge of this the translation process in the code by calling other specialized functions as detailed in the following section.

Ranges of values (central, optimist, pessimist) for the surface area of each {land use class; site} can and should be provided to assess input data uncertainty. When such ranges are input, they are passed on through the subsequent calculation steps through a "calculation mode" column.

C PRE-TREATMENT

The function `pressure_LU_pre_treatment()` takes data at the format of Table 1 as input and converts all land use inputs into the GLOBIO nomenclature, computes a **yearly surface variation rate for each couple of land use class and site,** and the **area variation over the whole assessment period**. These surface variations correspond to the surface area of the "**Restricted Perimeter" (RP)** introduced in Figure 3 for a particular land use; if its area variation is positive over time, it means that it extended over the period and therefore it appears in the restricted perimeter for year n+1. The other way around, if its variation is negative, it means that its area reduced and therefore it appears in the restricted perimeter for year n. At the end, by construction the restricted perimeter gives a summary of the land use conversions between n and n+1. The function also calculates the **surfaces occupied by the land use of interest** in the associated site at the beginning and end of the assessment period.

In our experience from case studies, companies never have yearly data on land occupation or land conversion. It is thus very often necessary to estimate the land occupation for the time boundaries of the assessment. For instance, if the period assessed is the 2018 financial year, but data on land occupation are only available at the end of 2012 and 2018, then land occupation at the end of 2017 needs to be calculated.This example is illustrated by Figure 7 with 2 land use classes. The horizontal axis represents the time and vertical axis represents the surface area, and each coloured point corresponds to a land use type. We have data for LU_1 in 2017 and 2018, which fits the assessment period, but for LU_2, data are available only in 2012 and 2018. Its area in 2017 needs to be calculated.

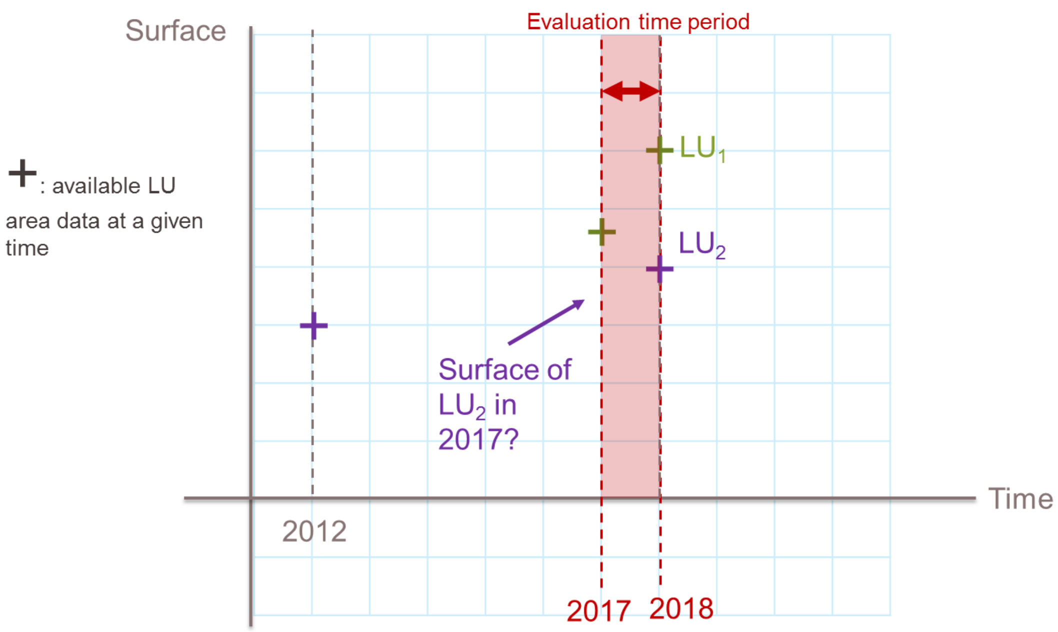


Figure 7: Illustration of the collected land-use data (type and corresponding area) in 2012, 2017 or 2018. The evaluation period is from 2017 to 2018.

<u>Assumption and terms definitions</u>

We assume that when we have land use data at two different dates, and when at both of these two different dates total area remain constant, we can linearly extrapolate the land occupation <u>between</u> these time dates, as described in Figure 8.

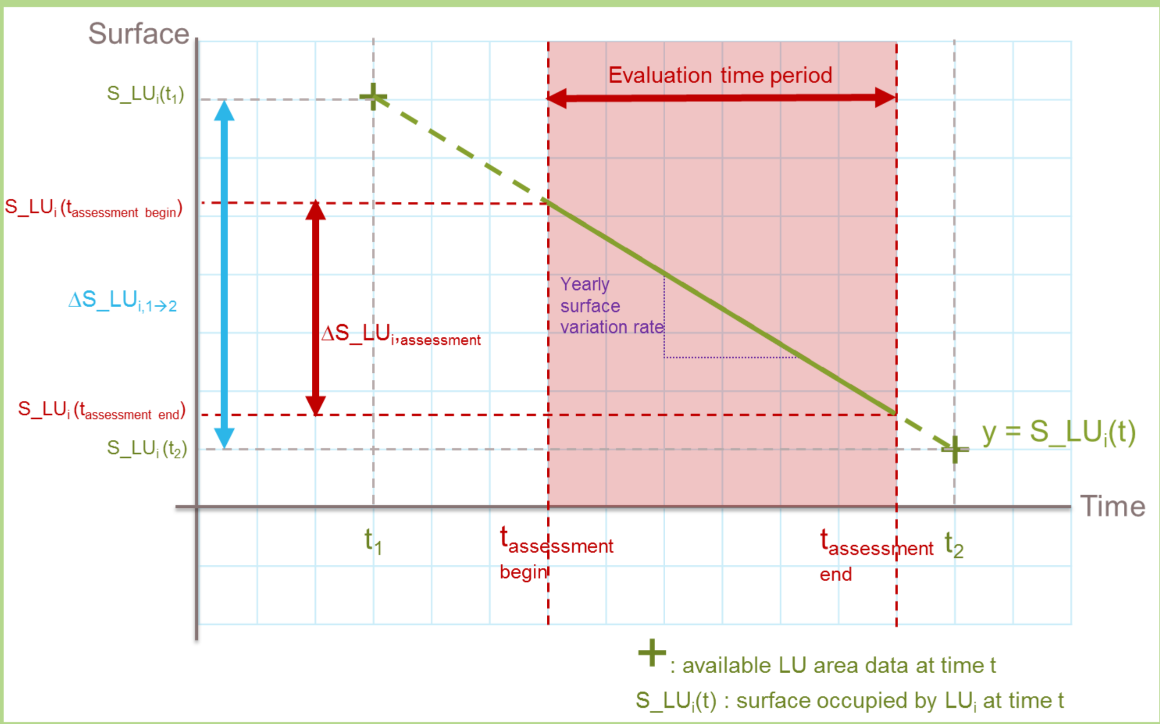


Figure 8: Linear assumption of land uses evolution within a constant perimeter

t_1 and t_2 are dates with available data, in the code they correspond to the dates at the **Stage 1** and at the **Stage 2**. **We can only assess impacts within the time period [t_1; t_2] (with $t_1 \neq t_2$), the case where the assessment time period is outsite this time interval is excluded for now.**

Here are the different definitions of the terms on the Figure 8, and the core calculations of the functions:

Evaluation time period = $t_{assessment\ end} - t_{assessment\ begin}$

Surface variation between t_1 and t_2 of the land use class LU_i on a given site:

$\Delta S\_LU_{i,1\rightarrow 2} = S\_LU_i(t_2) - S\_LU_i(t_1)$

We can deduce a linear **yearly surface variation rate** of the land use LU_i :

$$\frac{\Delta S\_LU_{i,\,1\rightarrow 2}}{t_2 - t_1}$$

Graphically, it is the slope of the curve of $S\_LU_i(t)$ function plotted in Figure 8.

Surface variation over the time period of the land use LU_i on a given site (needed for **dynamic** impact):

$$\Delta S\_LU_{i,assessment} = S\_LU_i(t_{assessment\ end}) - S\_LU_i(t_{assessment\ begin})$$

The latter is also equal to:

$$\Delta S\_LU_{i,assessment} = \frac{\Delta S\_LU_{i,\,1\rightarrow 2}}{t_2 - t_1} \times Assessment\ time\ period$$

If $\Delta S\_LU_{i,assessment} > 0$, it means that LU_i has expanded or appeared, this surface variation corresponds to $S_{RP\ LU}^{n+1}$ in **Erreur ! Source du renvoi introuvable.**, with n+1 = $t_{assessment\ end}$ and LU = LU_i. The dynamic impacts are attributed to this LU that have expanded/appeared.

If $\Delta S\_LU_{i,assessment} < 0$, it means that LU_i has shrinked or disappeared, this surface variation corresponds to $S_{RP\ LU}^{n}$ in the **Erreur ! Source du renvoi introuvable.**, with n = $t_{assessment\ begin}$ and LU = LU_i. No impact is attributed to this LU.

Surface prediction at any time between t_1 and t_2, needed for **static** impact:

(t_x is a time where LU data are available, here x can be 1 or 2)

$$S\_LU_i(t) = S\_LU_i(t_x) + \frac{\Delta S\_LU_{i,1à2}}{t_2 - t_1} \times (t - t_x)$$

This formula is applied to predict surfaces at $t_{assessment\ begin}$ and $t_{assessment\ end}$.

During Step I of Figure 5, `pressure_LU_pre_treatment()` pre-treats the data to the correct formats (notably converting the "custom" land use classes to the GLOBIO nomenclature) and computes the surface area variations over the assessment period and the surface areas at the beginning and end of the assessment. These figures are then used by `pressure_LU_evaluator()` in Step II of Figure 5.

2.3.C.1 Dynamic impacts

In Step I of Figure 5, `pressure_LU_pre_treatment()` computes the `yearly_surface_variation_rate` and deduces from it the `surface_variation_during_assessment` following the formulas presented in Figure 8 and the Assumptions in 2.3C:

```
mutate(yearly_surface_variation_rate = surface_variation_stage_1_to_2 /period_stage_1_to_2,
       surface_variation_during_assessment = yearly_surface_variation_rate *
(assessment_end_year - assessment_begin_year))
```

2.3.C.2 Static impacts

The **land uses areas** at the beginning and end of the assessed period are necessary to assess the **static biodiversity impact**. They are thus computed by `pressure_LU_pre_treatment()` also in the Step I of the Figure 5 through the formulas presented in Figure 8 and the Assumptions in 2.3C.

```
mutate(assessment_predicted_area = case_when(
        Stage == "Year_stage_1" ~ Area + yearly_surface_variation_rate *
(assessment_begin_year - Year),
        Stage == "Year_stage_2" ~ Area + yearly_surface_variation_rate *
(assessment_end_year - Year)),
```

Two different cases are distinguished here in the code because the data format principle is that on one line, there are areas information only about one assessment stage / date for one {land use type; site}:

- When the available data is t_1 (data at the "stage 1"): we can predict data on the date of assessment beginning with the formula $S\_LU_i(t_1) + \ yearly\ surface\ variation\ rate\ \times (t_{assessment\ beginning} \ - t_1)$

- When the available data is t_2 (data at the "stage 2"): we can predict data on the date of assessment end with the formula$S_LU_i(t_2) + \ yearly\ surface\ variation\ rate \times (t_{assessment\ end} \ - t_2)$

If the beginning and end of the assessment was located outside the period for which data are available, the linear assumption could end up **estimating negative surface areas**. We thus impose that the **time period of input data at least exceeds the period assessed**, i.e. $t_1 \leq t_{assessment\ end}$ and $t_2 \geq t_{assessment\ beginning}$ for all {land use type; site}, as precised in the Assumptions in 2.3C.

D IMPACT EVALUATION

In Step II of Figure 5, the function `pressure_LU_evaluator()` computes the **dynamic MSA.area** loss due to new or expanded land uses at the end of the assessed period, and the **static MSA.area loss due to the initial land uses** at the beginning of the assessment period.

2.3.D.1 GLOBIO pressure-impact relationships for refined assessment of the land use pressure

First, **MSA values** corresponding to each land uses (**GLOBIO pressure-impact relationships for the land use pressure** are presented in Figure 2) are retrieved to match to the input land use classes.

2.3.D.2 Dynamic impacts

As a reminder, **Erreur ! Source du renvoi introuvable.** says:

$$MSA\ dynamic_{LU}^{n \to n+1} = S_{RP\ LU}^{n+1} \times (MSA_{RP}^{n} - MSA_{LU})$$

$\mathrm{MSA}_{\mathrm{RP}}^{\mathrm{n}}$, or **the average MSA in the restricted perimeter of the disappeared or shrinked land uses** (i.e. RP_n in **Erreur ! Source du renvoi introuvable.**) can be calculated in each site as the average MSA of those land uses present at the site weighted by their surface variation, i.e.:

```
weighted.mean(x = MSA_LU, w = surface_variation_during_assessment, na.rm = TRUE)
```

The following code bloc shows the formula used for the dynamic impact assessment, based on **Erreur ! Source du renvoi introuvable.**, where dynamic impacts are only attributed to land uses that have appeared or expanded (thus their `surface_variation_during_assessment > 0`):

```
mutate(dynamic_MSA_loss_due_to_LU_assessment_end = case_when(
      surface_variation_during_assessment > 0 ~ - (MSA_LU -
MSA_average_restricted_perimeter_assessment_beginning) *
surface_variation_during_assessment,
      surface_variation_during_assessment <= 0 ~ 0))
```

Finally the dynamic MSA.area loss are **aggregated for each site**.

2.3.D.3 Static impacts

The biodiversity static loss is computed for each site, due to previous land uses following Equation 1.:

The part `get(area_static_area_column_name, envir = as.environment(static_pressure_LU_evaluation)))` is used to select the column containing the information about areas occupied by the land uses at the beginning of the evaluation.

```
mutate(static_MSA_loss_assessment = (1 - MSA_LU) * get(area_static_area_column_name, envir
= as.environment(static_pressure_LU_evaluation)))
```

Then the static land uses impacts are aggregated per site.

2.4 Attributing the impact

For the land use pressure, 100% of the impact is attributed to the final land use. For instance in Figure 3, the impacts are attributed to the intensive and extensive agriculture land uses.

2.5 Example

The `GBStoolbox` package contains `example_pressure_LU_impport.rda`. The file is an example of an input file provided by a fictitious GBS user. The associated Excel file `example_pressure_LU_import.xlsx` is provided in appendix. The example contains land use change data for nine sites.

The successive application of `pressure_LU_pre_treatment_import()`, `pressure_LU_pre_treatment()`, and `pressure_LU_evaluator()` leads to the results displayed in Figure 9 and Figure 10. Site A is the same site as in Figure 3, except that figures are now expressed in ha instead of m^2.

For site A, we find the same results as in section 2.2.A.1: the footprint is 14 MSA.ha for intensive cropland and 5 MSA.ha for extensive cropland.

Site D registers gains of biodiversity totaling 24.75 MSA.ha due to a conversion of 55 ha of Intensive cropland to Forest – Used. Forest – Used is a land use group, and the input file specifies that it should be split into 20% Forest – Plantation, 50% Forest - Clear-cut harvesting, 10% Forest - Selective logging, and 20% Forest - Reduced impact logging.

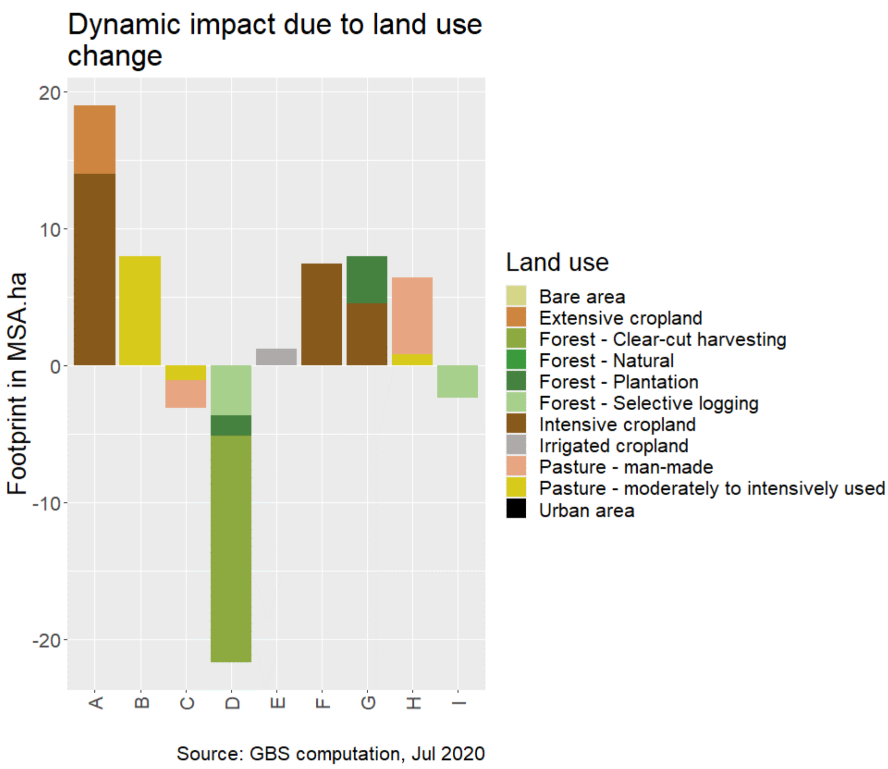


Figure 9: Dynamic impact of the 9 sites of the refined land use assessment example. Source: GBS computation July 2020

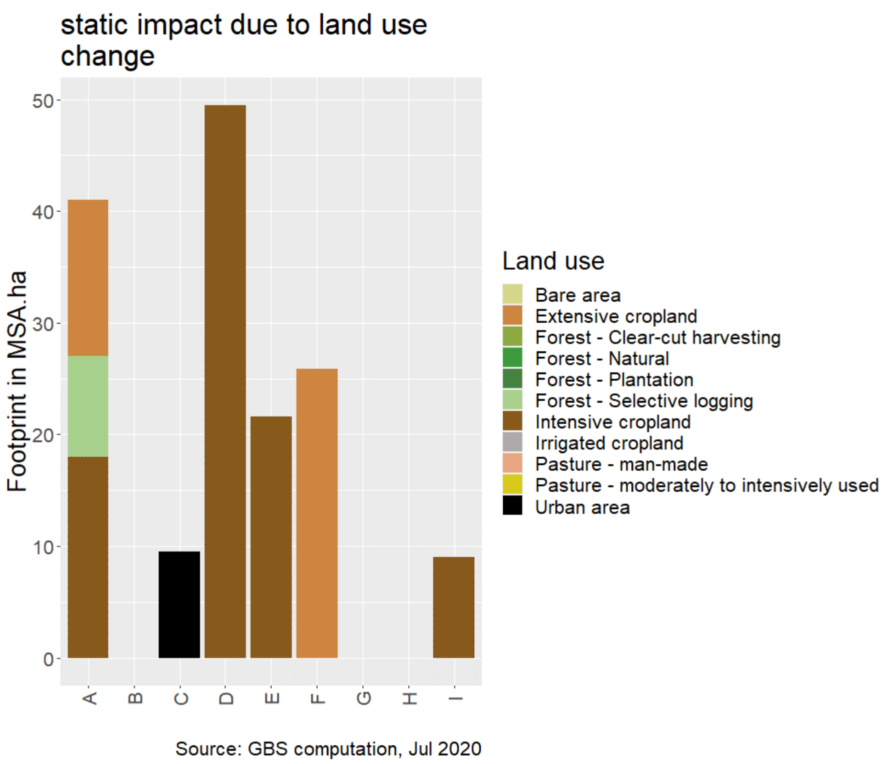


Figure 10: Static impact of the 9 sites of the refined land use assessment example. Source: GBS computation July 2020

2.6 Limits and future developments

To test the relevance of global land coverage forecast, we compared it to other sources. We focused on deforestation (i.e. land conversion of natural forest). As one of the most critical topics regarding biodiversity for land use, historical and projected deforestation are well documented. For historical deforestation we referred to FAO's 2015 Forest Resource Assessment (MacDicken et al. 2016) and for forecast to WWF's deforestation fronts study (WWF 2019). For both historical and predicted deforestation, we notice that GLOBIO global estimate is pretty much in-line, but we observe that deforestation for Africa is over-estimated whereas it is under-estimated for south-east Asia.

We are aware that this is one key area where the GBS default approach needs to be perfected and we plan for future versions to either correct forecast by integrating historical trends and consensual forecast data such as WWF's, or, ideally, switch to satellite-based data as we see strong developments happening in that area.

Another limit comes from the fact that the GLOBIO-IMAGE scenario has a regional parametrization. The model is set to predict the land use coverage patterns for those regions. Regions used by GLOBIO-IMAGE (42 total) can be countries or macro-regions composed of several countries. In the latter case, the model considers the group of countries as one single entity, therefore the projection makes senses at this level of analysis but not necessarily at the country level. This limitation is true for every pressure related to land-use and is particularly important to have in mind for dynamic impacts. For static impact this effect is tempered by the fact that the starting point for global land coverage is observed data (GLC2000).

In this version we only have an average estimation of the impact. In a later version we will introduce conservative and optimistic assessments.

In refined assessments, data must currently be available at dates before and after the assessment period. This prevents having aberrant area predictions (such as negative areas).

The methodology will be expanded to deal with evaluation outside of the data time period.

The treatment of uncertainties in the refined land use impact assessment will be improved by adding the untertainty ranges of GLOBIO pressure-impact relationships to our calculations.

3 Fragmentation of natural habitats and human encroachment

3.1 Context

A GLOBIO CAUSE-EFFECT RELATIONSHIPS

Species' populations are positively correlated with habitat size. As natural habitats shrink and are more and more fragmented due to human activity the functioning of ecosystems is hampered, causing biodiversity loss. In GLOBIO cause-effect relationships, six datasets on a large sample of species were used by the PBL to derive the relationship between MSA and patch size, i.e. the effect of **fragmentation of natural habitats**. The proportion of species that have a viable population was used as a proxy for MSA (Verboom et al. 2007). Cause-effect relationship for fragmentation is summarized in Figure 11.

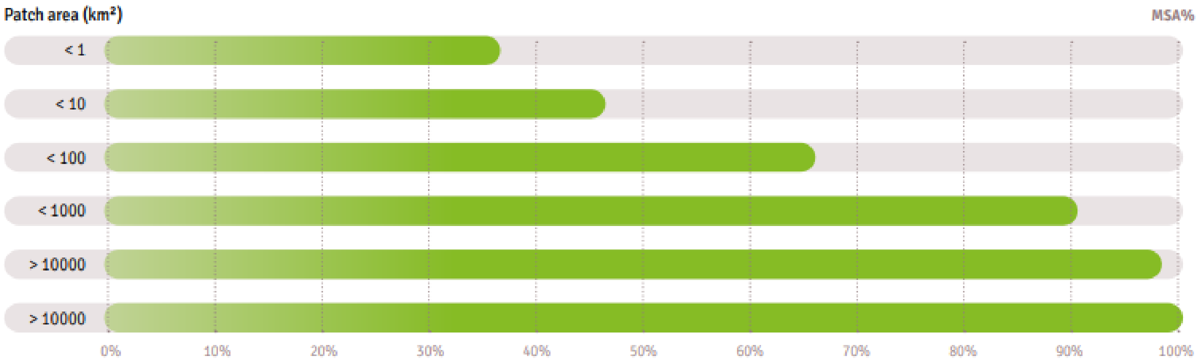


Figure 11: MSA values relative to natural patch size (Alkemade R., 2009)

Human encroachment comprises anthropogenic activities in otherwise natural areas. Direct (noise, pollutions, etc.) and indirect impacts (right of way for hunting, tourism, etc.) are accounted for and an MSA of 85% is applied within a 10-km zone around man-made areas for all types of biomes based on Benítez-López, Alkemade, and Verweij (2010). The database of peer-reviewed articles on which this rule is based is not available for this driver.

GLOBIO GBO4 land use types are classified into 2 categories: man-made and non-man-made (Figure 2). Man-made land use types are urban areas, croplands (intensive, extensive, woody biofuel and irrigated) and cultivated grazing areas and non-man-made land uses are all the other ones. Man-made land use types are responsible for fragmentation and encroachment over non-man-made land use types.

B LAND USE

Fragmentation is assumed to be caused by man-made land use types and infrastructures. Therefore, in the GLOBIO-IMAGE scenario, natural patch size is measured by making an overlay of the Global Roads Inventory Project (GRIP) infrastructure map and the GLC2000 land-cover map. This overlay is the starting point for land coverage forecast. For future years, the GLOBIO-IMAGE scenario estimates the land coverage dynamic but assumes that the infrastructure network is stable. **Human encroachment** estimation is based on the same land coverage forecast considering the interfaces between man-made and non-man-made land use types areas.

3.2 Default assessment

A DIMENSIONING THE IMPACTS

In the GBS, the default assessment of the extent of the impact of the Fragmentation and Encroachment pressures is not based on a direct cause-effect relationship applied to pressure data. Instead, due to a lack of pressure data in appropriate format, we rely on the assessments made in the GLOBIO-IMAGE scenario to dimension the impacts.

B FRAGMENTATION : PRELIMINARY ALLOCATION

The two causes of fragmentation in the model are man-made land use type areas and infrastructures. Theoretically, disentangling the individual impact of each is complex. For example, if a natural forest is surrounded by fields and crossed by a road, what proportion of fragmentation is due to the fields? What proportion is due to the road? Should we count all fields in the same manner? Because no solution is completely accurate, in the GBS, the attribution of impacts between the two sources, infrastructure and man-made land use areas, is deliberately simple. Impacts due to fragmentation are allocated based on the presence/absence of man-made land use areas and infrastructures close to the fragmented area. The allocation rule is the following:

- presence of man-made land use type areas without infrastructure: 100% of the fragmentation impact is split between man-made land use type areas in proportion of their surface,

- presence of infrastructure without man-made land use type areas: 100% of the fragmentation impact is allocated to infrastructure,

- presence of man-made land use type areas and infrastructure: 50% of the fragmentation is split between man-made land use type areas in proportion of their surface and 50% is allocated to infrastructure.

Let's take examples to illustrate this allocation rule.

Country A has the following land use composition: 100 km² of intensive agriculture, 50 km² of cultivated grazing area, 50 km² of "forestry – selective logging" and 200 km² of natural forest. Total fragmentation impact (static) for the natural forest is 20 MSA.km². Country A does not have any infrastructure. The allocation process is as follows: as there is no infrastructure, impacts are fully allocated to "man-made" land use types, here intensive agriculture and cultivated grazing areas. The impacts are allocated in proportion of their respective area; therefore, intensive agriculture gets 100 / 150 * 20 = 12 MSA.km² and cultivated grazing areas 50 / 150 * 20 = 6.7 MSA.km².

Country B has the same land use composition as country A and a road crosses the country. Fragmentation impact is allocated 50% to the road, and 50% to the man-made land use types in proportion of their area. Therefore, the road gets 50% * 20 = 10 MSA.km², intensive agriculture gets 50% * 100 / 150 * 20 = 6.7 MSA.km² and cultivated grazing areas get 50% * 50 / 150 * 20 = 3.3 MSA.km².

C IMPLEMENTATION – ATTRIBUTING THE FRAGMENTATION AND ENCROACHMENT IMPACTS

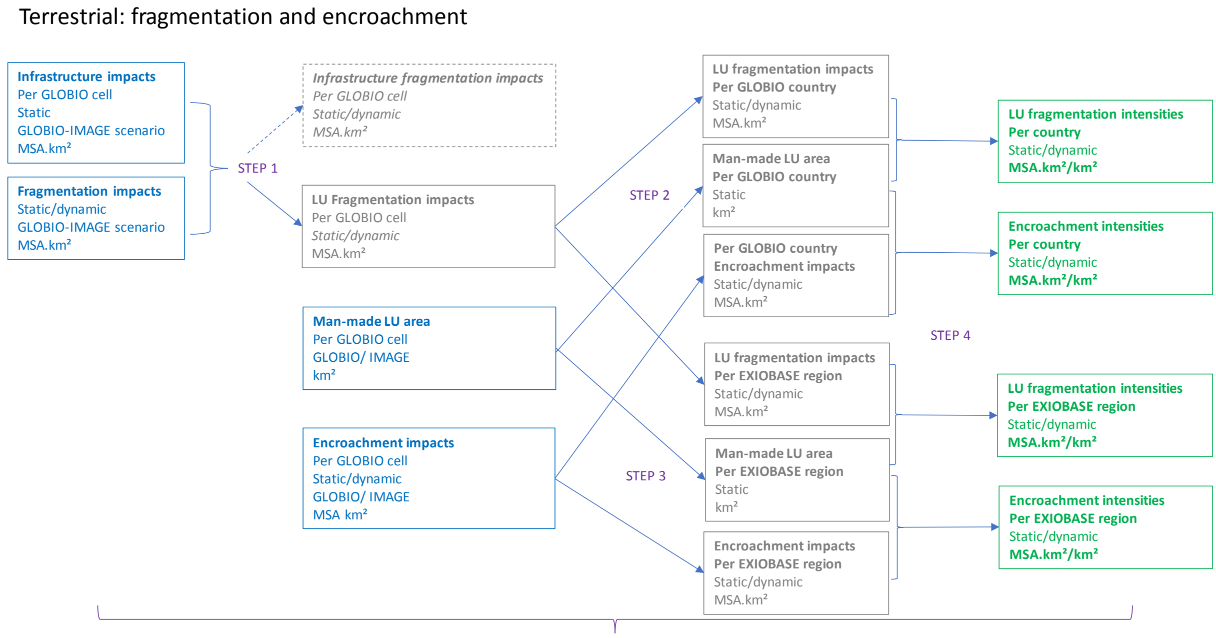


Figure 12: Computation of the fragmentation and encroachment biodiversity intensities (static and dynamic)

(STEP 1) First the allocation process between land use and infrastructure for the fragmentation pressure is done. At the cell level, the rule described in the previous section is applied. The presence/absence of infrastructure in the cell is estimated by the presence/absence of MSA impacts due to infrastructure.

(STEP 2&3) From there, intensities computation for fragmentation due to land use and encroachment is the same. At the country (or EXIOBASE region level), the following items are computed:

- man-made land-use type area (in km²),

- impacts (static and dynamic) due to fragmentation from land use (in MSA.km²),

- impacts (static and dynamic) encroachment (in MSA.km²).

(STEP 4&5) Intensities (static and dynamic) are computed as the ratio of impact over man-made land use type area, therefore expressed in $MSA.km^2/km^2$.

We do not differentiate land use type or aggregate land use type for fragmentation and encroachment. The main reason is that the link between land occupation and the associated impact is not direct for fragmentation or encroachment as it is for land use pressure. Therefore, as illustrated in Figure 13, trying to allocate fragmentation impact at the cell level between the different man-made land use does not work in many cases. In that example, in year n+1, natural forest is more fragmented leading to a fragmentation loss in both cell 1 and cell 2 altough only urban area extended in cell 2. Therefore, in this example, intensive agriculture area would get a share of the fragmentation loss despite being stable over time.

Figure 13: Illustration of non-local dynamic for fragmentation

For those allocation issues we find it more relevant not to differentiate intensities for the different land use types as we do not want to introduce an extra layer of modelling uncertainty.

Fragmentation and encroachement intensities are regional scenario-based data. Therefore, they fall into data quality tier 2.

3.3 Refined assessment

The **refined Encroachment and Fragmentation biodiversity pressures evaluations** are not implemented in the GBS for now, both pressures would require detailed spatialized data and eventually heavy geographic information system (GIS) treatments.

To evaluate the **Encroachment impacts**, we would ideally need data on all the land use types on a 10 km radius around the evaluated sites (considered as anthropic disturbing sites), broken down by GLOBIO land categories (Tier 4). If the data are expressed in another land use class nomenclature and translation to GLOBIO is needed, the data quality would be tier 3. The **“non man-made” land uses** (cf. Figure 2) would get a MSA for encroachment of 85% (meaning loss of 15%) (see the section 3.1A for more details on the GLOBIO pressure-impact relationship).

To evaluate the impacts of **Fragmentation**, we would ideally need data on the areas of non-man-made land uses by patch size classes in km², to which we would apply the corresponding GLOBIO pressure-impacts relationships detailed on Figure 11 (Tier 4).

3.4 Limits and future development

In this GBS version, impacts due to infrastructure are not allocated to any economic activities. A specific infrastructure work will be conducted to take into account both terrestrial and aquatic infrastructure impacts by assessing them and splitting them between the various economic and non-economic activities.

Also, for the allocation between infrastructures and man-made land uses, it would be more precise to work directly with land cover and infrastructure maps and determine for each fragmented area if it is crossed by at least one infrastructure. One major limitation for this approach is that the infrastructure map is stable in the future in the GLOBIO-IMAGE scenario. Another limitation is that we would have to deal with the allocation problems mentioned in the "preliminary allocation" section. This would lead in any case to arbitrary choices.

In this version we only have an average estimation of the impact. In later version we will introduce conservative and optimistic assessments.

4 Atmospheric nitrogen deposition on natural ecosystems

4.1 Context

A GLOBIO CAUSE-EFFECT RELATIONSHIPS

Adverse effects of nitrogen deposition are observed when nitrogen deposition in ecosystems exceeds their assimilative capacity, referred to as critical load. Nitrogen deposition originates from emissions of nitrogen to air (e.g. from croplands fertilization, or fossil fuel combustion). When deposited in excess on natural habitats, it can lead to eutrophication and acidification[5] of ecosystems. In such cases, species that are better adapted to these conditions become more competitive and may proliferate to the detriment of others.

To build cause-effect relationship, the PBL selected 22 papers on the experimental addition of nitrogen to natural systems and its effects on species richness and species diversity. Pressure-impact relationships were established by the papers' authors between the yearly amount of added nitrogen in exceedance of the critical-load and the relative local species richness (considered as a proxy for MSA). The experimental addition of nitrogen is assumed by the PBL to have effects similar to atmospheric deposition.

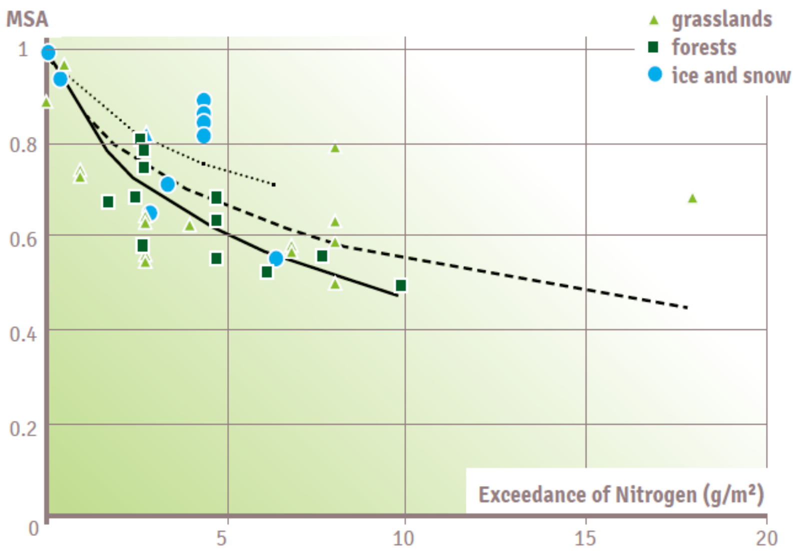


Figure 14: Regression values for MSA for nitrogen exceedance (Alkemade R., 2009)

B GLOBIO-IMAGE SCENARIO DATA

To assess impacts due to eutrophication, the GLOBIO-IMAGE scenario simulates nitrogen deposits **based on agriculture and livestock production data** (Alexander Felix Bouwman, Kram, and Klein Goldewijk 2006). Moreover, the PBL drew a map of critical nitrogen loads for the main ecosystems based on a map of the Earth's different soils and the sensitivity of ecosystems to added nitrogen (A. F. Bouwman et al. 2002). The output of this work are global maps for different years representing MSA impacts expressed in

[5] Impacts due to acidification are not included in GBS as GLOBIO cause-effect relationship focuses only on eutrophication

MSA.km^2. This data is used in the GBS for default assessment when we are not able to assess directly the exceedance of nitrogen and use the cause-effect relationship.

4.2 Default assessment

A DIMENSIONING THE IMPACTS

As for Fragmentation and Encroachment, in the GBS, the default assessment of the extent of the impact of the Atmospheric nitrogen deposition pressure is not based on a direct cause-effect relationship applied to pressure data. Instead, due to a lack of pressure data in appropriate format, we rely on the assessments made in the GLOBIO-IMAGE scenario to dimension the impacts.

B ATTRIBUTING THE IMPACTS - CONCEPT

Unlike GHG emissions for climate change, nitrogen emissions' impact depend on where they occurred. Depending on their fate, they can be more or less impactful. Ideally, we would like to consider these specific fates and be able to link emissions to their impacts and therefore have spatially differenciated impact intensities. This analysis is highly complex has many parameters (hydrology, local climate, topography…) are at play. For the next GBS version, we are hoping to cooperate with the PBL in order to get access to the core of the model and in particular to the fate models for N emissions. This way, we should be able to properly evaluate spatially dependent impact factors for N deposition pressure. In this version of the GBS we simply compute a global intensity by evaluating the global N compounds emissions from EDGAR (Janssens-Maenhout et al. 2019) and the associated global impacts from GLOBIO-IMAGE scenario.

C ATTRIBUTING THE IMPACTS - IMPLEMENTATION

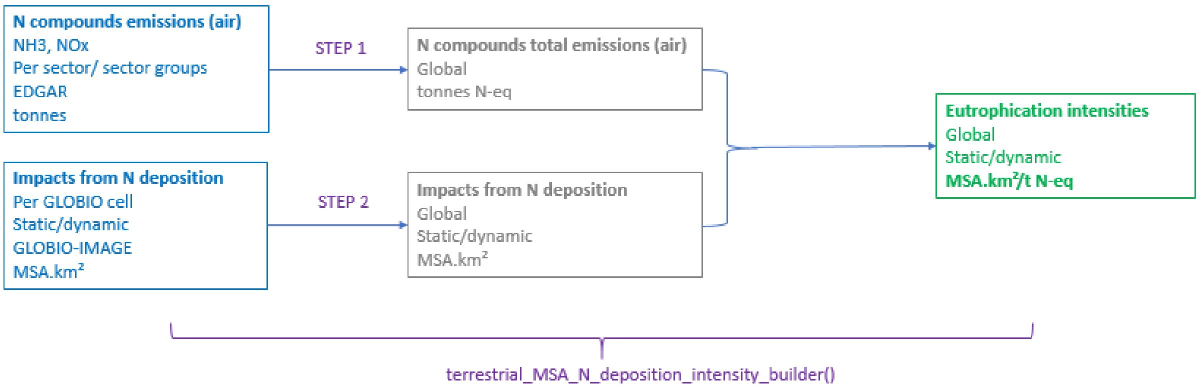


Figure 15: General layout default assessment for eutrophication impact

To be able to compare emissions from various compounds relative to their contribution to eutrophication molar masses are used to evaluate the relative weight of nitrogen in a given molecule. For instance, N relative weight in NH_3 is 82.3% ($\frac{14}{14+3\times1}$) therefore 1 kg of NH3 is worth 0.823 kg N-equivalent. For NOx we use NO_2 as a reference molecule ((Heijungs et al. 1992))

(STEP1) EDGAR emissions quantities for NOx and NH_3 are multiplied by their corresponding N-equivalent ratio as described above and summed up to get the global emission of N-equivalent.

(STEP 2) GLOBIO-IMAGE N-deposition impacts at the cell level are summed up to get a global impact.

Global intensity is simply computed by dividing the global impacts by the global emissions. It is expressed in MSA.km² per tonne N-equivalent.

Atmospheric nitrogen deposition intensities are modelled outputs at a regional level. Therefore, they fall into data quality tier 2.

4.3 Refined assessment

The GBS 1.0 does not allow the **refined assessment of the impacts related to the pressure atmospheric nitrogen deposition** . Doing so would indeed require spacialized data on exceedance of nitrogen (Tier 4). and to applying the pressure-impact relationships detailed on 4.1A. Such data is not available for now.

4.4 Limits and future developments

Ideally, we should use the fate model used in IMAGE (to build the GLOBIO-IMAGE scenario) to track emissions path and link them in more relevant way to their impact. We would then be able to take into account various bio-physical parameters (weather condition for instance) embedded in the model. Furthermore, it would be more consistent to use the same fate model that was used to assess the global impact maps. This is a potential update for next versions of GBS. For the first version we use the simpler approach based on a global intensity.

This version of the GBS only provides an average estimation of the impact. In later versions, we will introduce conservative and optimistic assessments.

5 Climate change

5.1 GLOBIO cause-effect relationships

Climate change causes shifts in the geographic distribution of biomes and threatens species unable to adapt. The cause-effect relationships are based on a meta-analysis of studies quantifying the influence of climate change on the distributions of plant and/or vertebrate species. These studies rely on climate models to estimate range shifts of many species in relation to projected future climate change, from which information was derived on the fraction of remaining species (FRS) relative to the original species richness at a given location (Arets et al., 2014). The FRS were then related to global mean temperature changes corresponding with the climate scenarios of concern. The FRS equals MSA under the assumption that

- outside the climate envelope relative to a species, the abundance of that species is zero;
- within the climate envelope, the abundance of a species is not related to climate.

Biome	$MSA_{loss} \cdot °C^{-1}$	SE	*p*-level	N
Boreal forest	0.0367	0.0125	0.005	48
Cool coniferous forest	0.1127	0.007	<0.001	15
Grassland and steppe	0.1201	0.023	<0.001	22
Hot desert	0.0521 [a]	-	-	-
Ice	0.0356	0.004	<0.001	8
Mediterranean shrub	0.0521 [a]	-	-	-
Savanna	0.0775	0.0104	<0.001	12
Scrubland	0.0661	0.0072	<0.0001	28
Temperate deciduous forest	0.071	0.008	<0.001	18
Temperate mixed forest	0.0487	0.0066	<0.001	18
Tropical forest	0.0521 [a]	-	-	-
Tropical woodland	0.1075	0.0128	<0.0001	39
Tundra	0.0426	0.0045	<0.001	8
Warm mixed forest	0.1457	0.0122	<0.0001	17
Wooded tundra	0.0521 [a]	-	-	-
Overall	0.0521	0.0047	<0.0001	239

[a] set equal to the overall MSA loss factor.

Table 2: Cause-effect relationships expressing MSA loss in relation to global mean temperature increase in °C (Arets, Verwer, and Alkemade 2014; Schipper et al. 2016)

5.2 Default assessment

A DIMENSIONING OF THE IMPACTS - CONCEPT

To assess the dynamic impact of a given GHG emission, we use a two-step approach consisting in 1) identifying the global mean temperature increase (GMTI) generated by this emission and 2) linking the temperature increase to impacts on biodiversity using GLOBIO cause-effect relationships.

The GBS can assess emissions' impacts of the six gases covered by the Kyoto Protocol, i.e. carbon dioxide (CO_2), fossil and biogenic methane (CH_4), nitrous oxide (N_2 O), sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). Depending on the context and use, GHG emissions can be taken from various sources: from company data (refined assessment), from the environmental extensions of the input-output model EXIOBASE version 3.4, from FAO emission data (e.g. for crop commodities), from LCA databases (e.g. for transformed products), etc. All GHG emissions are expressed in CO_2-equivalents using Global Warming Potentials (GWPs), considering a time horizon of 100 years in the calculations, consistent with the IPCC ((Stocker 2014), Table 3). The biodiversity loss factor per kg of CO_2-equivalent is calculated according to the two steps of the methodology described above, namely using the time-integrated absolute global temperature potential of 1 kg CO_2 (in $°C.year.kg\ CO_2^{-1}$) combined with the area-integrated global loss in MSA due to the corresponding Global Mean Temperature Increase or GMTI (in $MSA.km^2.°C^{-1}$). The temperature change caused by GHG emissions depends on how long they are supposed to remain in the atmosphere. The integrated absolute global mean temperature potential (IAGTP) of CO_2 for the 100-year time horizon considered is 4.76.10-14 $°C.yr.kg\ CO_2^{-1}$ (Joos et al. 2013). (Arets, Verwer, and Alkemade 2014) report losses in MSA per degree of GMTI for 14 terrestrial biomes (Table 2). We thus define the loss in MSA due to climate change across the globe as the weighted aggregation across the biomes using biome areas[6] reported by IMAGE for the year 2010, following (Wilting and van Oorschot 2017). Simply using the "Overall" MSA.$°C^{-1}$ factor reported in Table 2 instead of a mean of the biome factors weighted by biome areas would lead to an impact factor of about $3.29.10^{-9}$ MSA.km^2/kg CO_2-eq.

Combining the IAGTP and the cause-effect relationship provided by GLOBIO, a "time-integrated footprint" expressed in MSA.km^2.yr could be calculated[7]. It would amount to evaluate the current and future impacts caused by the GHG emissions (up to time horizon of 100 years considered here).

Though arguably useful, such a time-integrated footprint would not be consistent with the GBS approach, which seeks to relate the footprints assessed with biodiversity richness on the field and with the global average terrestrial biodiversity. These are usually not integrated over time (the GLOBIO model for instance does not integrate its results over time) and are best understood by non-specialists when expressed as their value at a given time (for instance global average terrestrial biodiversity stood at about 65% MSA in 2010). Accounting for long-lasting impacts is however undoubtedly necessary and the dynamic and static footprints framework allows to do so. Whenever additional impacts occur, they are accounted for as dynamic impacts. By definition, if these impacts persist beyond the period assessed, they are accounted for as static impacts (see Figure 16). In order to assess the non-time integrated impacts, the IAGTP (integrated over time) needs to be translated into an actual rise in temperature. A rectangular shape is assumed for the impulse response function for CO_2, i.e. an almost immediate increase of global mean temperatures in response to the CO_2 emission pulse, which then remains stable for 100 years (and beyond, see Figure 17) [8]. Under this hypothesis, the average increase in temperature caused by the GHG emission during the emission year (and the subsequent 99 years for a time horizon of 100 years) is equal to the IAGTP divided by the number of years considered. An IAGTP of 4.76.10-14 °C.yr.kg CO_2^{-1} over 100 years is equivalent to a global temperature increase of 4.76.10-16 °C.kg CO_2^{-1}. The impact factor thus calculated is $4.37.10^{-9}$ MSA.km^2/kg CO_2-eq.

[6] Biome area refers to the total terrestrial area of that biome excluding cropland and urban areas. The following areas have been calculated by summing up the areas of cells from the GLOBIO-IMAGE scenario for each biome. Ice: 2 269 549 km², Tundra: 6 416 065 km², Wooded tundra: 2 394 095 km², Boreal forest: 17 147 840 km², Cool coniferous forest: 2 676 959 km², Temperate mixed forest: 4 147 544 km², Temperate deciduous forest: 3 408 164 km², Warm mixed forest: 4 764 378 km², Grassland and steppe: 16 043 172 km², Hot desert: 21 623 633 km², Scrubland: 6 452 856 km², Savanna: 13 427 554 km², Tropical woodland: 7 323 116 km², Tropical forest: 8 185 654 km², Mediterranean shrub: 1 269 787 km².

[7] Such a time-integrated footprint is the classical approach taken by LCA methodologies.

[8] This is consistent with the impact observed in the MAGICC model on which IMAGE and GLOBIO rely. Indeed, in this model, the emission of 1 kg CO_2 leads to a rapid temperature increase in the first 5 years and a stabilization over the next 95 years (Joos et al. 2013).

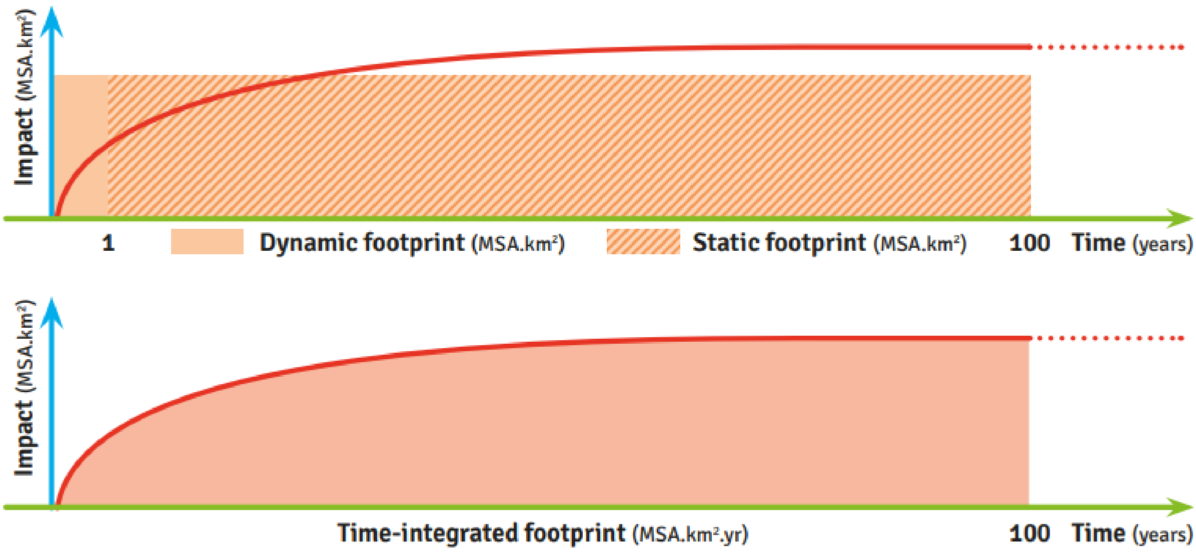


Figure 16: Illustration of the difference between the dynamic + static footprints approach and the time-integrated footprint approach

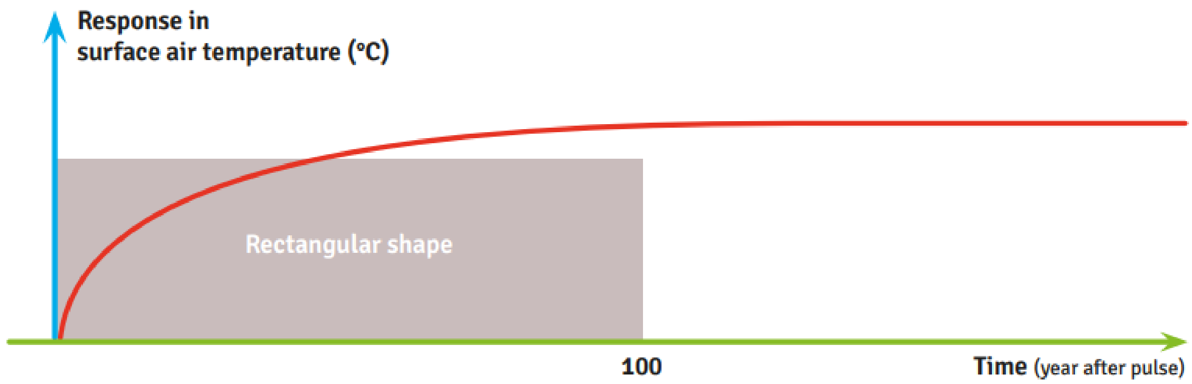


Figure 17: Illustration of the approximation of the impulse response of surface air temperature to a pulse of GHG emissions by a rectangular shape (schematic)

Greenhouse gas	GWP (kg CO_2-eq/kg) for 100 years
CO_2	1
CH_4	28
N_2O	265
SF_6	23 500

Table 3: Global Warming Potential of the main GHGs for a time horizon of 100 years, source: (Stocker, 2014)*

B DIMENSIONING OF THE IMPACTS - IMPLEMENTATION

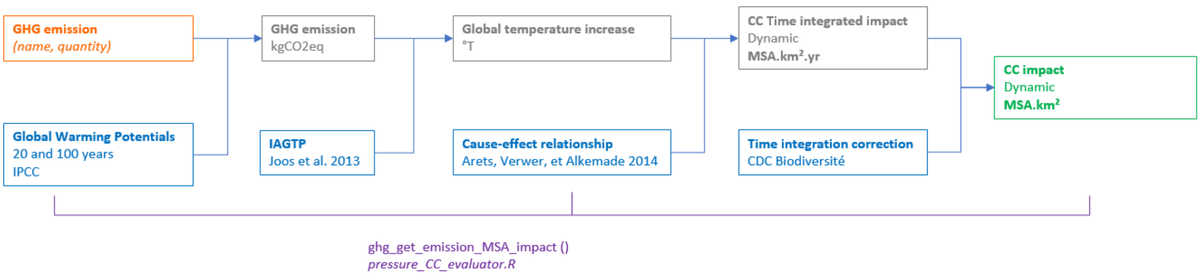


Figure 18: General layout for climate change terrestrial impact

The computation of climate change impact can is done is done by a function which design is summarized in Figure 18. It takes GHG name, and quantity as an input and use the various factors (GWP, IAGTP, cause-effect relationships and time integration correction) described in the previous section to compute an impact due to climate change on terrestrial biodiversity expressed in MSA.km².

In this version we only have an average estimation of the impact. In later version we will introduce conservative and optimistic assessments.

The result is a scenario-based model output at global level, therefore falling into data quality tier 1.

C ATTRIBUTING THE IMPACTS

Past emissions generated the static impacts, which are not attributed to any economic activity.

100% of the impacts dimensioned for GHG emitted during the period assessed with the GBS are attributed to the emission source, as dynamic impacts.

5.3 Refined assessment

The refined **climate change impacts on biodiversity** can be computed in the GBS based on GHG emission data. The possible data format (Scopes, perimeter…) are detailed in the GBS data collection guide (CDC Biodiversité 2019a). For now, in the GBS, climate change impacts are counted only as **dynamic impacts**. Figure 18 explains the computation process.

The GBS enables the computation of the biodiversity impacts of the following gases families: carbon dioxide (CO_2), fossil and biogenic methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF6), hydrofluorocarbons (HFCs) and perfulorocabons (PFCs). The time horizon is either 20 or 100 years.

The function `ghg_get_emission_MSA_impact()` converts a quantity of emitted GHG (in kg of GHG, no in kg CO_2-eq) to an MSA.area impact, by associating each GHG to its **GWP** (for CO_2-eq conversion, they are presented in Table 3) at a given time horizon and the corresponding MSA impact factor in **MSA.km²/kg CO_2-eq**. These factors are also used for default assessments. This function can be applied to different ranges of GHG emissions values depending on the data uncertainties, and therefore lead to different results with the **central, optimistic or pessimistic calculation modesl**.The used impact factors are in the data quality tier 1 as they are based on international default values.

Two other functions are used in other GBS features but not directly for the refined assessment of climate change:

- The function `ghg_get_emission_kg_co2_eq()` converts anemitted quantity of Greenhouse effect gas (GHG) to a quantity of **kg CO_2-eq**, thanks to the **Global Warming Potentials (GWP)** presented in Table 3 consistent with the IPCC (Stocker 2014).

- The function `ghg_get_emission_temperature_increase()` converts an emitted quantity of GHG (in CO_2-eq) into a temperature increase in °C, by applying to the emission in CO_2-eq the **IAGTP** (Integrated absolute global mean temperature potential in °C/kg CO_2-eq) for a time horizon of 20 or 100 years derived from (Joos et al. 2013) and dividing per number of years considered. The principle is illustrated by Figure 16.

5.4 Limits and future development

For the refined climate change assessment, a function `pressure_CC_evaluator()` will be built to link and integrate the features presented in this section to directly use corporate input data and assess dynamic and static impacts.

References

Alkemade, R., R. S. Reid, M. van den Berg, J. de Leeuw, and M. Jeuken. 2013. 'Assessing the Impacts of Livestock Production on Biodiversity in Rangeland Ecosystems'. *Proceedings of the National Academy of Sciences* 110 (52): 20900–905. https://doi.org/10.1073/pnas.1011013108.

Alkemade, Rob, Mark van Oorschot, Lera Miles, Christian Nellemann, Michel Bakkenes, and Ben ten Brink. 2009. 'GLOBIO3: A Framework to Investigate Options for Reducing Global Terrestrial Biodiversity Loss'. *Ecosystems* 12 (3): 374–90. https://doi.org/10.1007/s10021-009-9229-5.

Arets, Eric J.M.M., Caspar Verwer, and Rob Alkemade. 2014. 'Meta-Analysis of the Effect of Global Warming on Local Species Richness'.

Benítez-López, Ana, Rob Alkemade, and Pita A. Verweij. 2010. 'The Impacts of Roads and Other Infrastructure on Mammal and Bird Populations: A Meta-Analysis'. *Biological Conservation* 143 (6): 1307–1316.

Bouwman, A. F., D. P. Van Vuuren, R. G. Derwent, and Michael Posch. 2002. 'A Global Analysis of Acidification and Eutrophication of Terrestrial Ecosystems'. *Water, Air, and Soil Pollution* 141 (1–4): 349–382.

Bouwman, Alexander Felix, Tom Kram, and Ke Klein Goldewijk. 2006. 'Intergrated Modelling of Global Environmenthal Change: An Overview of IMAGE 2.4'.

CDC Biodiversité. 2017. 'Global Biodiversity Score: Measuring a Company's Biodiversity Footprint'. 11. Biodiv'2050 Outlook.

———. 2019a. 'GBS Biodiversity Footprint Assessments Documentation: Data Collection Guidelines'.

———. 2019b. 'Global Biodiversity Score: A Tool to Establish and Measure Corporate and Financial Commitments for Biodiversity'. 14. Biodiv'2050 Outlook. CDC Biodiversité.

———. 2020a. 'GBS Review: Core Concepts'.

———. 2020b. 'GBS Review: Ecotoxicity Pressures on Biodiversity'.

CDC Biodiversité, ASN Bank, and ACTIAM. 2018. 'Common Ground in Biodiversity Footprint Methodologies for the Financial Sector'. Paris: ACTIAM, ASN Bank, CDC Biodiversité. Supported by Finance in Motion. https://www.asnbank.nl/web/file?uuid=b71cf717-b0a6-47b0-8b96-47b6aefd2a07&owner=6916ad14-918d-4ea8-80ac-f71f0ff1928e&contentid=2412.

Díaz, S., J. Settele, E. Brondízio, H. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. Brauman, and S. Butchart. 2019. 'Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)'. IPBES.

Dixon, John A., David P. Gibbon, and Aidan Gulliver. 2001. *Farming Systems and Poverty: Improving Farmers' Livelihoods in a Changing World*. Food & Agriculture Org.

Heijungs, Reinout, Jeroen B. Guinée, Gjalt Huppes, Raymond M. Lankreijer, H. A. Udo de Haes, A. Wegener Sleeswijk, A. M. M. Ansems, P. G. Eggels, R. van Duin, and H. P. De Goede. 1992. 'Environmental Life Cycle Assessment of Products: Guide and Backgrounds (Part 1)'.

Joos, F., R. Roth, J. S. Fuglestvedt, G. P. Peters, I. G. Enting, W. von Bloh, V. Brovkin, et al. 2013. 'Carbon Dioxide and Climate Impulse Response Functions for the Computation of Greenhouse Gas Metrics: A Multi-Model Analysis'. *Atmospheric Chemistry and Physics* 13 (5): 2793–2825. https://doi.org/10.5194/acp-13-2793-2013.

Kok, Marcel, Rob Alkemade, Michel Bakkenes, Eline Boelee, Villy Christensen, M. Van Eerdt, Stefan van der Esch, Jan Janse, SISE Karlsson-Vinkhuyzen, and Tom Kram. 2014. *How Sectors Can Contribute to Sustainable Use and Conservation of Biodiversity*. 79. PBL.

MacDicken, K., Ö Jonsson, L. Piña, S. Maulo, V. Contessa, Y. Adikari, M. Garzuglia, E. Lindquist, G. Reams, and R. D'Annunzio. 2016. 'Global Forest Resources Assessment 2015: How Are the World's Forests Changing?'

Marquardt, Sandra G., Michael Guindon, Harry C. Wilting, Zoran J.N. Steinmann, Sarah Sim, Michal Kulak, and Mark A.J. Huijbregts. 2019. 'Consumption-Based Biodiversity Footprints – Do Different Indicators Yield Different Results?' *Ecological Indicators* 103 (August): 461–70. https://doi.org/10.1016/j.ecolind.2019.04.022.

Schipper, Aafke M., Jelle P. Hilbers, Johan R. Meijer, Laura H. Antão, Ana Benítez-López, Melinda MJ de Jonge, Luuk H. Leemans, Eddy Scheper, Rob Alkemade, and Jonathan C. Doelman. 2020. 'Projecting Terrestrial Biodiversity Intactness with GLOBIO 4'. *Global Change Biology* 26 (2): 760–771.

Schipper, Aafke M., Johan R. Meijer, Rob Alkemade, and Mark A. J. Huijbregts. 2016. 'The GLOBIO Model: A Technical Description of Version 3.5'. The Hague: Netherlands Environmental Agency (PBL). http://www.pbl.nl/sites/default/files/cms/publicaties/pbl_publication_2369.pdf.

Stocker, Thomas. 2014. *Climate Change 2013: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Verboom, Jana, Rob Alkemade, Jan Klijn, Marc J. Metzger, and Rien Reijnen. 2007. 'Combining Biodiversity Modeling with Political and Economic Development Scenarios for 25 EU Countries'. *Ecological Economics* 62 (2): 267–276.

Wilting, Harry C., and Mark M. P. van Oorschot. 2017. 'Quantifying Biodiversity Footprints of Dutch Economic Sectors: A Global Supply-Chain Analysis'. *Journal of Cleaner Production* 156 (July): 194–202. https://doi.org/10.1016/j.jclepro.2017.04.066.

WWF. 2019. 'Deforestation Fronts'. 2019. https://wwf.panda.org/our_work/forests/deforestation_fronts2/.

CDC BIODIVERSITÉ | Caisse des Dépôts GROUPE

102, rue Réaumur
75002 PARIS
T. +33 (0)1 80 40 15 00

contact@cdc-biodiversite.fr

www.cdc-biodiversite.fr

SAS au capital de 17 475 000 euros
RCS Paris 501 639 587
Siret 501 639 587 00028 - APE 6420Z
N° TVA Intracom. FR51501639587