

4. Acidification

4.1. Terrestrial acidification

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4.1.1. Impact pathways and indicators

Terrestrial acidification impacts on ecosystem quality are covered at endpoint level for the terrestrial realm. The impacts are derived from the approach followed by Lebrun et al. (2025) and are expressed in $PDF.yr/kg_{emitted}$ for each of the three main air-emitted substances contributing to terrestrial acidification: NO_x , SO_x , NH_3 .

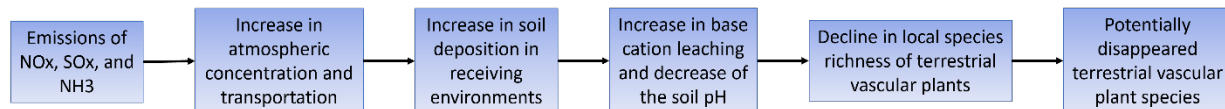


Figure 4. 1: Impact pathway for terrestrial acidification impacts included in LC-Impact

The impact pathway starts with anthropogenic emissions of acidifying substances, mainly from fossil fuels combustion and agricultural practices (Bouwman et al., 2002; Psenner, 1994; van Zelm et al., 2015). Once into the air, these compounds are transported following atmospheric circulation patterns, and undergo chemical reactions to form acidifying dissociation products, such as NO_3^- , NH_4^+ or SO_4^{2-} (van Zelm et al., 2015). The resulting pollutants eventually reach receiving terrestrial environments through dry and/or wet deposition (van Zelm et al., 2015). The increased deposition of acidifying substances onto terrestrial systems leads to the leaching of essential base cations and the decline of the soil pH; this is what is referred to as “terrestrial acidification” (Norton and Veselý, 2003). Because of diverse local soil characteristics (geological reactivity, soil alkalinity), some environments are more sensitive than others to this phenomenon (van Zelm et al., 2015). Terrestrial acidification causes the disruption of the nutrient balance in the soil and thus directly affects vascular plant species. Gade et al. (2021) quantified the resulting potential species richness decline by calculating the potential disappeared fraction of vascular plant species due to a marginal pH decrease.

4.1.2. Calculation of characterization factors

The marginal endpoint characterization factors (CFs) implemented in LC-IMPACT are taken from the study of Lebrun et al. (2025). The characterization factors, expressed in $PDF_{global,yr}/kg_{emitted}$, are derived based on Equation 1:

$$CF_{s,p} = \frac{1}{N_r} \times \sum_r (FF_{s,r,p} \times RF_{r,p} \times EF_r \times GEP_{vascPlants,r})$$

Eq. 1

$CF_{s,p}$ represents the impact that a small increase in the emission of a pollutant p from a country source s has in the whole world (composed of N_r receiving ecoregions) (Lebrun et al., 2025). This is different from many other ecosystem quality characterization factors. Most other impacts happen at the place of emission (i.e. the place of emission and impact are the same). This is the case, for instance, for stressors such as land use, water use and overexploitation. For terrestrial acidification, the CFs reflect the impact of an emission p in a certain country s on all ecoregions r where the emissions from that country deposit.

The characterization factor of country s should be interpreted as the impact of country- s 's emissions (of 1 kg of pollutant p) on vascular plants in the whole world.

The different elements composing the marginal characterization factors (marginal fate factors - FF, marginal soil response factors - RF, marginal effect factors - EF, and global extinction probabilities - GEP) are detailed in the subsections below.

4.1.2.1. Fate factors (FF)

$FF_{s,r,p}$ quantifies the mass fraction of a pollutant p deposited onto a receiving environment r due to a minimal rise of emission from a source location s (Lebrun et al., 2025). The fate factors are expressed in $kg_{deposited}/kg_{emitted}$ and are derived according to Equation 2 (Roy et al., 2012):

$$FF_{s,r,p} = \frac{dDeposition_{r,p}}{dEmission_{s,p}}$$

Eq. 2

$Deposition_{r,p}$ and $Emission_{s,p}$ correspond to the pollutant p deposition rate ($kg_{deposited}/yr$) in the receiving environment r and to the pollutant p emission rate ($kg_{emitted}/yr$) from the source location s , respectively.

The marginal fate factors are calculated at a grid-cell resolution of $2^\circ \times 2.5^\circ$ (source and receiving locations) for acidifying pollutants comprising nitrogen oxides (NO_x , HNO_3), sulfur oxides (SO_2 , SO_4) and ammonia (NH_3) (Roy et al., 2012). In order to combine them to the other components of the characterization factors (RF, EF, GEP) and derive country characterization

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factors, the fate factors from Roy et al. (2012) are adjusted to the desired spatial resolution with two spatial transformations (Lebrun et al., 2025):

- One on the emission side, aggregating grid-cell emissions to country scale. This spatial transformation is performed using emission weighting from EDGAR's database.
- One on the receiving side, aggregating grid-cell deposition to ecoregion scale. This spatial transformation is performed using area weighting.

4.1.2.2. Response factors (RF)

$RF_{r,p}$ quantifies the rise of the soil's molarity of H^+ ions (i.e. the decline of the soil pH) in the receiving ecoregion r due to a marginal (10%) increase of a pollutant p deposition rate (Lebrun et al., 2025). The soil response factors are expressed in $(mol_{H^+}/L).(yr/kg_{deposited})$ and are derived according to Equation 3 (Lebrun et al., 2025):

$$RF_{r,p} = \frac{d[H^+]_r}{dDeposition_{p,r}} \approx \frac{\Delta[H^+]_r}{\Delta Deposition_{p,r}} \approx \frac{10^{-pH_{new}} - 10^{-pH_{ref}}}{0.1 \times Deposition_{ref,p,r}}$$

Eq. 3

pH_{ref} and pH_{new} correspond to the soil pHs of ecoregion r before ("ref") and after a 10% increase in the deposition rate of pollutant p ("new"), respectively. $Deposition_{ref,p,r}$ estimates the deposition rate of pollutant p ($kg_{deposited}/yr$) in ecoregion r in the reference state (before the simulated 10% increase).

The marginal soil response factors are calculated at ecoregion resolution (767 ecoregions) for the following substances: NO_3^- , NH_4^+ , SO_4^{2-} (Lebrun et al., 2025).

4.1.2.3. Effect factors (EF)

EF_r quantifies the regional potential disappeared fraction of vascular plant species (decline in species richness) due to a marginal rise of the soil's molarity of H^+ ions in the receiving ecoregion r (Lebrun et al., 2025). The effect factors are expressed in $PDF_{regional}.(L/mol_{H^+})$ and are derived according to Equation 4 (Gade et al., 2021):

$$EF_r = \frac{1}{A_{tot,r}} \times \sum_k \left(A_{k,r} \times \frac{dPNOF_{k,r}}{d[H^+]_r} \right)$$

Eq. 4

$A_{k,r}$ represents the area that pH-value k covers within the ecoregion r , while $A_{tot,r}$ is the sum of $A_{k,r}$ for all pH-value k considered. $PNOF_{k,r}$ corresponds to the potential non-occurring fraction of vascular plant species in ecoregion r at pH-value k (subsequently converted into regional potential disappeared fraction of vascular plant species - $PDF_{regional}$ - by a factor of 1, as recommended by the Global Guidance on Environmental Life Cycle Impact Assessment Indicators - Volume 2 (Frischknecht and Jolliet, 2019)). $[H^+]_r$ estimates the soil's molarity of H^+ ions in ecoregion r .

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The marginal effects factors are calculated at ecoregion resolution (688 ecoregions) including 189,185 distinct species of vascular plants (i.e. 49% of the world's accepted vascular plant species) (Gade et al., 2021).

4.1.2.4. Global Extinction Probability (GEP)

$GEP_{vascPlants,r}$ converts the regional PDF value (representing a reversible impact) of ecoregion r into a global PDF value (irreversible impact) (Verones et al., 2022). The computation and clarification of the GEP calculation can be found in the Global Extinction Probability chapter of the documentation.

Here and in agreement with the scale of the effect factors, we have used the GEP for the vascular plant species group at ecoregion level (Lebrun et al., 2025).

4.1.2.5. Calculation of the Global Characterization Factor

The global CF value for terrestrial acidification is calculated as the average country value across all countries covered (205 in total). For a certain pollutant p , Equation 5 expresses the global value $CF_{global,p}$ mathematically:

$$CF_{global,p} = \frac{1}{N_{countries}} \sum_{s=1}^{N_{countries}} CF_{s,p}$$

Eq. 5

4.1.2.6. CFs calculation for an emission to an “unspecified” air compartment

The characterization factors provided by LC-IMPACT and based on the approach from Lebrun et al. (2025) have been developed for emissions of acidifying substances to an “unspecified” air compartment. They are therefore applicable to all air compartments, except of the “indoor air” compartment.

4.1.3. Uncertainties

Although the approach does not provide quantified uncertainties, the practitioner should keep in mind that the method developed comes with various sources of inaccuracies.

First, in the fate factor modeling, the deposition was considered evenly distributed within a $2^\circ \times 2.5^\circ$ grid cell. This simplification neglects local factors favoring deposition (e.g. mountains) in certain regions within the grid. However, without higher resolved global atmospheric models, this situation cannot be averted. Moreover, the grid-cell-to-country spatial aggregation performed on the emission side loses the contribution of offshore emissions to terrestrial deposition. Thus, the adjusted fate factors presented by Lebrun et al (2025) only account for

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land-based emissions. It is therefore recommended that non-terrestrial activities be assigned the global average.

Second, on the soil response side, only direct consequences from pH decline were addressed. Indirect consequences such as nutrient depletion or aluminum toxicity were not evaluated, leading to a potential overlook of some of the terrestrial acidification effects.

Third, the effect factors only account for the “potential disappearance” of species and do not consider opportunistic species thriving because of the local pH decline. In addition, as the effect factors use vascular plants as proxy for the whole terrestrial biodiversity (as it is the most directly impacted species-group), the CFs provided may overestimate the relative contribution of terrestrial acidification to biodiversity loss compared to the other drivers.

4.1.4. Value choices

4.1.4.1. Time horizons

Time horizons do not apply for this impact category. First, the chemical processes accounted for occur within a very short time frame (yearly acidifying substance deposition, minute-to-week-long soil chemical responses to acidifying substance deposition). Second, the method developed covers marginal increases of pollutant emissions and does not include continuous emissions of acidifying substances. The time-horizon perspective is thus irrelevant for this approach.

4.1.4.2. Current match with the elementary flow list

The characterization factors for terrestrial acidification are provided for 7 matched elementary flows: NO_x , NO, NO_2 , NH_3 , SO_x , SO, and SO_2 .

4.1.4.3. Others if relevant

4.1.5. Availability of characterization factors

All characterization factors are available for download as Excel and TIFF files on www.lc-impact.eu.

4.1.6. References

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4.2 Ocean acidification

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4.2.1 Impact pathways and indicators

Marine acidification impacts are quantified at both the mid- and endpoint level for damage to ecosystem quality, following the approach by (Anderson et al., 2025). The impacts are calculated in pH*yr/kg at the midpoint level and PDF*yr/kg at the endpoint level, for each of the three main acidifying substances for marine acidification: CO₂, CO, and CH₄.

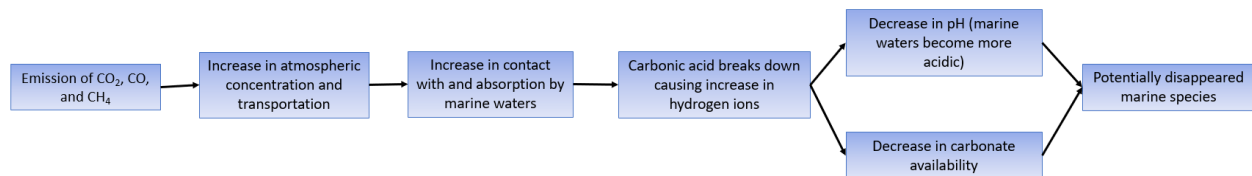


Figure 3. 2: Impact pathway for marine acidification impacts included in LC-Impact

The main contributors to marine acidification are greenhouse gases that convert to CO₂ in the atmosphere, namely CO₂, CO, and CH₄. The impact pathway begins with the emission of these three greenhouse gases to the atmosphere. CO and CH₄ convert to CO₂ in the upper atmosphere, and as the atmospheric concentration of CO₂ increases, the amount coming into contact with marine waters also increases. When CO₂ comes into contact with water, it devolves into carbonic acid which further devolves into hydrogen ions and carbonate ions. However, the chemical process results in more hydrogen ions than carbonate ions, lowering the carbonate availability in the water as well as the pH. Both of these effects, lowered carbonate availability and lowered pH, negatively affect marine species and result in potential extinction. The severity of acidification varies between marine ecosystems due to complex biogeochemical cycles including factors like salinity, temperature, currents, upwelling, and nutrient cycles, among others. Given the same rise in atmospheric CO₂, some ecosystems will become more acidic than others, and marine organisms will tolerate that acidification with different levels of sensitivity. Both literature and the model presented here have shown that polar regions are more vulnerable to acidification than equatorial regions, which have a larger buffering capacity. Thus, it is important to have spatially delineated CFs to capture these differences.

4.2.2 Calculation of characterization factors

The mid- and endpoint ocean acidification CFs used in LC-IMPACT are quantified by Anderson, et al. (2025). The characterization model follows a three-step cause-effect chain: fate factors (FFs), describing the transfer of emitted substances to changes in surface ocean partial pressure of CO₂ (spCO₂); fate sensitivity factors (FSFs), quantifying the response of seawater pH to changes in spCO₂; and effect factors (EFs), converting pH changes into impacts on marine biodiversity. Midpoint CFs quantify the marginal change in marine pH per unit emission, while

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endpoint CFs quantify ecosystem damage in terms of the potentially disappeared fraction (PDF) of marine species. The midpoint CF, quantified in pH*yr/kg, for substance i in spatial unit j is calculated using Eq 1:

$$CF_{\text{midpoint},j,i} = FF_{j,i} \times (-FSF_j)$$

Eq. 6

The midpoint CF is calculated by multiplying the fate factor (FF) for area j and substance i with the negative fate sensitivity factor for area j . Due to the fact that CO and CH₄ convert to CO₂ in the atmosphere (Bach et al., 2016), there is only one set of FSFs, for CO₂. The fate sensitivity factor for marine acidification is inherently negative (representing pH decrease per spCO₂ increase), so a double negative is used to show that there is net impact. The substances (i) include CO₂, CO, and CH₄. The areas (j) are delineated at the marine ecoregion level for coastal areas and the Food and Agriculture Organization (FAO) fishing area level for open ocean.

The endpoint CFs are quantified in PDF*yr/kg and are calculated using Eq 2:

$$CF_{\text{endpoint},j,c,i} = FF_{j,i} \times (-FSF_j) \times EF_{j,c}$$

Eq. 2

The endpoint CF represents the impact at the damage level for area (j), calcification level (c), and substance (i). It is calculated by multiplying the midpoint CFs with the effect factor (EF) for area j and calcification level c .

4.2.2.1 Fate factors (FF)

Fate factors quantify the change in surface ocean spCO₂ resulting from the emission of a CO₂, CO, or CH₄. The marine carbonate system response is represented using the Revelle factor, which relates relative changes in dissolved inorganic carbon (DIC) to changes in spCO₂.

The marginal change in spCO₂ is calculated, using a known Revelle Factor, as:

$$\Delta \text{spCO}_2 = \text{spCO}_{2,\text{orig}} * RF * \left(\frac{\Delta \text{DIC}}{\text{DIC}_{\text{orig}}} \right)$$

Eq. 3

where RF is the Revelle factor, $\text{spCO}_{2,\text{orig}}$ is the reference surface partial pressure of CO₂, and DIC_{orig} is the reference dissolved inorganic carbon concentration.

The change in DIC resulting from an emission of substance i is calculated using Eq 4:

$$\Delta \text{DIC} = \frac{\left(\frac{\Delta E_i * DF_i}{M_{\text{CO}_2}} \right)}{A}$$

Eq. 4

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where ΔE_i is the emitted mass of substance i , and DF_i is the substance-specific dissolution factor accounting for atmospheric conversion and ocean uptake, from Bach et al. (2016). M_{CO_2} is the molar mass of CO_2 , and A is the surface volume of the ice-free global ocean (Cogley, 2012).

Fate factors are expressed in units of $Pa \cdot yr$ per kg emitted and are calculated for CO_2 , CO , and CH_4 . Emissions are assumed to be well mixed in the atmosphere, allowing ocean uptake to occur globally.

4.2.2.2 Fate sensitivity factors (FSFs)

Fate sensitivity factors quantify the response of ocean pH to changes in $spCO_2$ within each spatial unit. FSFs are derived using linear regression modeling of the relationship of pH with respect to $spCO_2$ based on global ocean biogeochemical data (Aumont et al., 2015). FSFs are expressed in units of pH/Pa and are negative, reflecting the decline in pH with increasing $spCO_2$. For consistency with LCIA conventions, a double negative is used in CF calculations to ensure that characterization factors represent positive (aka net) impacts.

4.2.2.3 Effect factors (EFs)

Effect factors convert midpoint pH changes into endpoint biodiversity impacts, expressed as the PDF of marine species. Effects are derived using species sensitivity distributions (SSDs) based on experimental ocean acidification studies. Hazardous pH thresholds (HC_x) are obtained from SSDs constructed using pH values (pH_x) associated with an x percent reduction in species' vital traits. A reference pH representing preindustrial ocean conditions is used as the baseline state (Jiang et al., 2019).

Following the approach suggested by Owsianiak et al. (2023), the effect factor based on HC_{20} derived from pH_{10} values is calculated as:

$$EF_{20} = \frac{0.20}{pH_{orig} - HC_{20_{pH10}}}$$

Eq. 7

For comparison with historical practice, an alternative effect factor based on HC_{50} is defined as:

$$EF_{50} = \frac{0.50}{pH_{orig} - HC_{50_{pH50}}}$$

Eq. 6

Effect factors are differentiated by calcification level and climate zone and expressed in units of PAF/pH unit. PAF values are converted to PDF assuming a 1:1 relationship, in line with existing LCIA guidance (Oginah, 2023).

4.2.2.4 Calculation of the Global Characterization Factor

Spatially explicit midpoint and endpoint CFs are aggregated to global values using area-weighted averaging across all marine spatial units:

$$CF_{\text{global},i} = \frac{1}{A_{\text{tot}}} \sum_j A_j \times CF_{j,i}$$

Eq. 7

where A_j is the area of spatial unit j and A_{tot} is the total marine area considered.

For midpoint indicators, global CFs are normalized relative to carbon dioxide to obtain CO₂-equivalent characterization factors:

$$CF_{\text{norm},i} = \frac{CF_{\text{agg},i}}{CF_{\text{agg},\text{CO}_2}}$$

Eq. 8

4.2.3 Uncertainties

The model does not provide quantified uncertainty ranges; however, several sources of uncertainty should be considered when interpreting the characterization factors.

Fate and fate sensitivity modeling relies on surface ocean data, as global spCO₂ observations are only available for the upper ocean layer. As a result, depth-dependent pH changes are not explicitly represented, which may affect impacts for benthic species included in the effect model. Incorporating depth-resolved carbonate chemistry would improve future assessments.

Uncertainty also arises from spatial delineation, particularly in the open-ocean FAO regions. While FAOs are relatively homogeneous for surface-level inputs, this assumption may not hold for benthic conditions, which are likely more heterogeneous at depth.

Fate factors assume that greenhouse gases are well mixed in the atmosphere prior to ocean uptake. Although this assumption is standard in atmospheric LCIA modeling, it neglects potential spatial and temporal variability in air-sea gas exchange that could influence regional acidification responses.

It is important when interpreting results to remember that midpoint CFs represent marginal, short-term pH changes under specific temporal conditions and do not capture long-term biogeochemical feedbacks such as seasonal variability, biological uptake, or changes in ocean buffering capacity. While parameters can be updated as new datasets become available, cumulative impacts should be interpreted within the broader context of ocean carbon cycle dynamics.

Lastly, effect factors are subject to uncertainty due to limited species coverage and experimental data, particularly for slightly calcifying organisms. In addition, some species exhibit neutral or temporarily favorable responses to acidification, which are not captured in the precautionary effect modeling. Endpoint CFs therefore represent conservative, marginal biodiversity impacts based on current scientific understanding.

4.2.4 Value choices

4.2.4.1 Time horizons

Time horizons are not explicitly defined for this impact category. The CFs represent marginal, short-term responses of the marine carbonate system to incremental greenhouse gas emissions. The chemical processes captured, such as air-sea CO₂ exchange and carbonate equilibrium reactions, occur on timescales ranging from seconds to months, while longer-term biogeochemical feedbacks like biological uptake or ocean circulation are not explicitly modeled. In addition, the method addresses marginal emission increases rather than sustained or cumulative emission trajectories. As such, the characterization factors describe immediate to intermediate impacts, and a time-horizon perspective is not applicable within the scope of this approach.

4.2.4.2 Current match with the elementary flow list

The characterization factors for ocean acidification are provided for 3 matched elementary flows: CO₂, CO, and CH₄.

4.2.4.3 Others if relevant

4.2.5 Availability of characterization factors

All characterization factors are available for download as Excel and TIFF files on www.lc-impact.eu.

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