Annex A
(Normative)

Procedures for Calculating
Category Indicator Results by Impact Category

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To be inserted

1. Introduction.

The calculation of indicator results for each impact category is described in this Annex. This process includes:

- Establishing the stressor-effects network for each impact category;
- Establishing the environmental relevance of the selected category indicator;
- Determining the environmental data needed to assess the selected category indicator;
- Establishing characterization models to calculate stressor characterization factors (S-CFs) and environmental characterization factors (E-CFs); and
- Establishing equations to calculate the category indicator.

Guidance and requirements are provided for each of these steps, for each impact category. In some cases, tables of data are provided for S-CFs whenever such data involve fundamental chemical relationships not subject to further data collection.

The table below provides a list of impact groups, impact categories, and category indicators. Impact categories are named based upon midpoints/endpoints of the stressor-effects networks. Category indicators are named based upon the characterization models which are used to derive characterization factors.
Table 1. The impact groups, impact categories, and recommended category indicators.

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<th>Recommended Category Indicator</th>
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<td>Ocean Acidification</td>
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<td><strong>Group 4: Emissions with Regional Environmental Impacts</strong></td>
<td>Regional Acidification</td>
</tr>
<tr>
<td>Regional Acidification</td>
<td></td>
</tr>
<tr>
<td>Stratospheric Ozone Depletion</td>
<td>Stratospheric Ozone Depletion</td>
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<td>Hazardous Environmental Contaminant (HEC) Exposure Risks</td>
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<td>Ground Level Ozone (GLO) Exposure Risks</td>
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<td>PM 2.5 Exposure Risks</td>
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<td>HFWC Emissions</td>
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<td><strong>Group 6: Risks From Untreated Hazardous and Radioactive Waste</strong></td>
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</tr>
<tr>
<td>Risks from Radioactive Wastes</td>
<td></td>
</tr>
<tr>
<td>Risks from Untreated Hazardous Wastes (by type)</td>
<td>Hazardous Waste Generated (by type)</td>
</tr>
</tbody>
</table>

Section 1.1 describes in depth about the selection of category indicators in each impact category.

**1.1 Selection of Category Indicators.** As described in ISO 14044, the environmental relevance is a qualitative assessment of the degree of linkage between category indicator result and the category endpoint(s) (ISO 14044 §4.4.2.2.2). Higher levels of environmental relevance provide results which have a stronger linkage to endpoints, and are therefore more desirable.
There are two aspects which determine the environmental relevance of a category indicator (from ISO 14044 §4.4.2.2.4):

a) The ability of the category indicator to reflect consequences on category endpoint(s); and

b) The incorporation of environmental data into the characterization model, used to represent the category endpoint(s).

The environmental relevance which can be achieved in a given impact category is limited by the availability of characterization models and environmental characterization data. Proceeding along the stressor-effects network for an impact category, additional aspects of the environmental mechanism are incorporated into category indicator results (e.g., spatial and temporal variability), which generally requires more sophisticated characterization models and additional environmental characterization data.

For example. For some impact categories (i.e., Hazardous Ambient Air Exposure Risks, and Hazardous Indoor Air Exposure Risks), the current lack of characterization models and/or characterization data prevents establishing category indicators at higher nodes. This limits the environmental relevance which can be achieved.

For other impact categories (i.e. Global Climate Change), characterization models and data exist to establish results at higher nodes. However, as one proceeds along the stressor-effects network, the integration of more sophisticated characterization models and additional environmental data results in additional measurement uncertainty. The following discussion from Spatial differentiation in Life Cycle impact assessment, published by the Danish Ministry of the Environment, provides this description:

As characterization modelling is extended to include more of the causality chain, the uncertainty in interpretation is typically reduced as the environmental relevance of the predicted impact is increased. On the other hand, the introduction of additional environmental models into the calculation of characterization factors also introduces some additional sources of uncertainty.

The overall uncertainty of a category indicator reflects its overall linkage to category endpoint(s). The inverse of the overall uncertainty of a category indicator is its environmental relevance. A category indicator with high overall uncertainty has low environmental relevance; and a category indicator with low overall uncertainty has high environmental relevance.

The overall uncertainty is affected by two aspects of uncertainty:

1) Uncertainty arising from weakness in the linkage to category endpoint(s). This uncertainty is based upon the ability of the category indicator to reflect consequences of the LCI results on category endpoint(s).

2) Uncertainty inherent in the characterization of category indicator results. This arises from uncertainty in the LCI results, characterization model, and environmental characterization data which is used.
When considering the overall uncertainty of category indicators at different nodes in the stressor-effects network for a given impact category, there is a trade-off between these two sources of uncertainty. Figure 1 graphically shows this trade-off for the example of one impact category: Regional Acidification.

**Regional Acidification**

**Node 1:** Total levels of acidifying emissions.

**Node 2:** Contribution to increased atmospheric concentrations of acids, leading to increased deposition.

**Node 3:** Contribution to deposition of acids into environments in which buffering capacity has been exceeded.

**Node 4:** Contribution to accumulated deposition of acids, leading to changes in pH of water bodies and soils.

**Node 5:** Contribution to various endpoint effects (e.g., changes to vegetative composition, fish kills)

Figure 1. On the left, the category indicators and characterization models which could be selected for Regional Acidification are shown. On the right, the sources of uncertainty which determine the overall uncertainty (and environmental relevance). As characterization proceeds further along the stressor-effects network for Regional Acidification, the uncertainty arising from weakness in linkage to endpoint(s) decreases. At the same time, additional uncertainty is introduced through uncertainties in the characterization model, characterization data, assumptions applied, and etc. Category indicators must be selected so that the overall uncertainty is minimized (i.e., the environmental relevance is maximized).

Figure 1 shows that for Regional Acidification, the uncertainty arising from weakness in linkage to endpoint(s) decreases as characterization proceeds further along the cause-effects chain. However, the uncertainty in characterization, related in this case to uncertainty introduced from dispersion modeling, and uncertainty in the environmental data which is used (i.e., meteorological data, topographical data, and etc.), increases. The category indicator is selected so as to minimize the overall uncertainty, which maximizes the environmental relevance of results. For Regional Acidification, the lowest overall uncertainty is at Node 3.

The level of overall uncertainty for different category indicators differs significantly for different impact categories, particularly when considering impact categories in different groups. Accordingly, optimization of the trade-off between the two sources of uncertainty must be determined separately for each impact category. For some impact categories, the availability
of environmental data varies by region, and optimization must be performed separately for
different LCA studies, considering the goal and scope of the study.

For example. For Ground Level Ozone Exposure Risks, ambient concentrations of ozone are unavailable
in some regions (i.e., in countries such as China and India). Although the recommended category
indicator for this impact category is at Node 4, if a study considers emission sources in China or India,
environmental data is unavailable to characterize results at this node. For this impact category,
characterization is allowed at Node 3, for which the environmental data required is available globally (i.e.,
the data required for dispersion modeling and population density mapping).

For each impact category, this Annex provides guidance and requirements for selection of the
category indicator, as part of the section describing Stressor-Effects networks. The category
indicators which can be used are noted, and a category indicator is recommended for use which
has the highest environmental relevance (i.e., the category indicator where the overall
uncertainty is minimized). As more accurate and new levels of environmental data become
available, practitioners are encouraged to move to higher nodal indicators, increasing the
environmental relevance beyond that possible if the recommended category indicator is used.

For a given LCA study, the availability of environmental data may limit the environmental
relevance which can be achieved, and it may not be possible for results to be calculated using
the recommended indicator. For each impact category, the Annex provides further guidance
and requirements for the selection of category indicators in case of this lack of data availability.

For certain category indicators in certain impact categories, the overall uncertainty is so high
that there is effectively no environmental relevance. Use of these category indicators is not
permitted under this Standard.
2 Resource Depletion Group.

This section describes the procedures for calculating results for those category indicators related to the consumption and depletion of resources.

Aside from energy resource depletion, which can be aggregated on the basis of energy, the aggregation of material abiotic or biotic resources into a single category indicator result is not allowed.

Definition of Renewable and Non-renewable Resources

In this Standard, nonrenewable resources are defined as those which, after being consumed, are not completely regenerated within a timeframe relevant to the energy resource (i.e., the total consumption must equal or exceed the total accretion of the resource with the timeframe). Renewable resources are defined as those which, after being consumed, are completely regenerated a timeframe relevant to the energy resource (i.e., the total accretion must equal or exceed the total consumption of the resource with the timeframe). Similarly, nonrenewable and renewable consumption of resources is distinguished by considering if the resource is completely regenerated within a timeframe relevant to the energy resource.

NOTE. The defined timeframe which is used will vary based on the resource. However, this timeframe should never be longer than the century scale, based on the timeframe of LCA studies. The timeframe will be as short as 5-10 years for some types of biotic resources.

Definitions of Reserve Base Types

To understand the stressor-effects network in this group of impact categories, and for proper classification and characterization, consistent definitions of the types of “reserve base” relevant to energy resources are very helpful. In practice, there are a variety of definitions for different types of reserve bases used by different agencies, which vary by resource type.


For the purposes of this Standard, the following definitions are used:

- Technically Recoverable Reserve Base. Also referred to simply as “reserve base” in this Standard, a technically recoverable reserve base refers to that part of an identified resource reserve that could be commercially extracted at a given time. The technically recoverable reserve base meets specific minimum physical and chemical criteria related to extraction practices for the given energy resource. The technically recoverable reserve base may encompass those parts of a resource that have a reasonable potential for becoming economically recoverable within planning horizons that extend beyond those which assume
proven technology and current economics.¹ For a given resource type, the technically
recoverable reserve base includes:

- **Economic reserves**, including those resources that are currently economically
  recoverable, given current extraction technologies and market conditions.

- **Marginal reserves**, including those resources that are marginally economically
  recoverable, given current extraction technologies and market conditions.

- **Sub-economic reserves**, including those reserves which are not economically viable
  to recover given current extraction technologies and market conditions, but which
  could become economically viable to recover within reasonable planning time
  horizons.

- **Proven reserves**. These are reserves that are based on estimated quantities of an energy
  resource, that analysis of geologic and engineering data demonstrates with reasonable
  certainty are recoverable given current technology and current economics.²

- **Unproven reserves**. These are reserves that are yet undiscovered, but are reasonably assured
  to exist in favorable geological settings.³

- **Speculative reserves**. These are reserves which are thought to exist, mostly on the basis of
  indirect evidence and geological extrapolations, in resource bases which are discoverable
  with existing exploration techniques.⁴

### 2.1 Energy Resource Depletion

#### 2.1.1 Impact Category

The impact category characterizes the depletion of energy resources which can be linked to the
product system under study. Energy resource depletion considers not only energy
consumption, but also the total extent of reserve bases and consumption rates of the various
feedstocks used for energy production, over a specific time horizon. Based on the data which is
commonly available regarding reserve bases and resource consumption, this time horizon is
usually 25 years.

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¹ This is based upon the definition of the Demonstrated Reserve Base for coal, used by the US Energy Information Administration. See *U.S. Coal Reserves, 1996, Appendix A, Specialized Resource and Reserve Terminology*.

² This definition is based upon the definition of proved reserves of crude oil published by the US Energy Information Administration in the *International Energy Outlook*.

³ This is based upon the definition of unproven technically recoverable reserves of crude oil and natural gas, yet undiscovered, as defined by the US Energy Information Administration. It roughly parallels the definitions of inferred resources used by the OECD and International Atomic Energy Agency to describe available uranium reserves.

⁴ This is based upon the definition for Speculative Resources of uranium used by the OECD and International Atomic Energy Agency.
The category indicator for this impact category accounts for both biotic and abiotic feedstocks that are consumed for energy generation. Energy resource depletion only accounts for the nonrenewable consumption of energy resources.

### 2.1.2. Stressor-Effects Network

This stressor-effects network represents the depletion of energy resources extracted from the providing environment, and is described in Table 2. The providing environment includes reserve base(s) which can be at the local, regional, or global scale, depending on the characteristics of the market where the energy resource is consumed. Accordingly, the midpoint of contribution to nonrenewable energy resource consumption from a specific reserve base should be understood (Node 2 in Table 2.1); this is required to accurately characterize results at Node 3, energy resource depletion.

**Table 2.1. Stressor effects network for Energy Resource Depletion.**

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Stressors)</td>
<td>Energy resource consumption of energy resources by unit processes in the product system under study.</td>
<td>High uncertainty. Characterization does not account for: the renewability of energy resource consumption; the total consumption rate of energy resources by all users; projections of accumulated consumption over timeframes of interest; or the extent of technically recoverable reserves.</td>
<td>Low uncertainty. Data requirements: Amount of energy resources consumed in the product system, and energy content of each resource.</td>
</tr>
<tr>
<td>2 (Midpoint)</td>
<td>Contribution to total energy consumption of energy resources by all users from a specific reserve base.</td>
<td>High uncertainty. Characterization does not account for: the renewability of energy resource consumption; projections of accumulated consumption over timeframes of interest; or the extent of technically recoverable reserves.</td>
<td>Low uncertainty. Data requirements: Amount of energy resources consumed in the product system, and energy content of each resource. Total amount of energy resources consumed, and energy content of each resource.</td>
</tr>
<tr>
<td>3 (Midpoint)</td>
<td>Contribution to nonrenewable energy consumption of energy resources by all users, leading to drawdown in extent of technically recoverable reserves within projected timeframes of interest (i.e., energy resource depletion).</td>
<td>Moderate uncertainty. This indicator reflects endpoints, but its environmental relevance is limited by the omission of the total extent of technically recoverable reserves and likely timeframe of exhaustion.</td>
<td>Moderate uncertainty. Data requirements: Amount of energy resources consumed in the product system, and energy content of each resource. Amount of energy resources consumed globally, and energy content of each resource. Estimates of accretion of energy resources (where applicable). Extent of technically recoverable reserve base of each resource.</td>
</tr>
</tbody>
</table>
For a specific LCA study, the data sources and definitions used to assess each type of reserve base must be described in the LCA report.

2.1.2.1. Selection of Category Indicator(s). The indicator for this impact category shall be characterized at Node 3, characterizing the contribution to energy resource depletion within projected timeframes of interest.

2.1.2.2. Identifying Core Impact Categories and Category Indicator(s). All known product systems contribute to the non-renewable consumption of energy resources, and energy resource depletion is always a relevant impact category.

2.1.3. Classification

This Standard requires all energy resources which are consumed in a non-renewable fashion be included in final category indicator results. This includes all abiotic energy resources that are extracted from inherently limited reserve bases. In practice, consumption of hydrocarbon-based fossil fuels and uranium ore are always classified. These feedstocks are listed in Table 2.2.

Table 2.2. Non-renewable energy resources which are classified in Energy Resource Depletion. For a given LCA study, additional energy resources may also be classified.

<table>
<thead>
<tr>
<th>Nonrenewable Energy Resource Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
</tr>
<tr>
<td>Crude oil</td>
</tr>
<tr>
<td>Natural Gas</td>
</tr>
<tr>
<td>Uranium ore</td>
</tr>
</tbody>
</table>

2.1.3.1. Classification of “Renewable” Resources

In some instances, energy resources which are usually considered to be “renewable” will be classified, if the energy resource is being consumed in a nonrenewable fashion. This reflects the fact that a given “renewable” energy resource may not actually be consumed at a renewable rate.

An energy resource commonly thought of as renewable can be classified as non-renewable if the amount of accretion of the resource is less than the amount of consumption within a specific time horizon relevant to the energy resource.

For biotic resources, the time horizon used should reflect the typical planning time horizons used in industry practice.
FOR EXAMPLE. To be classified as renewable, the growth rate of timber at a forestry operation must exceed the harvest rate of the tree species being extracted. In forestry, the growth-to-harvest ratio is typically assessed as a rolling 10-year average, and renewability should be determined using a 10-year time horizon.

For a given energy resource, the timeframe used to determine the renewability shall be described in the LCA report.

NOTE. The time horizon used to determine renewability is not necessarily the same as the time horizon used in RDF calculations.

2.1.3.2. Classification of Non-renewable Energy Consumption Used in Standby Power Generation

Some renewable energy resources are unable to provide energy as a stand-alone source when deployed in the electricity grid, but rather must be combined with non-renewable energy resources in order to provide a continuous source of energy.

FOR EXAMPLE. Due to its intermittency, wind power plants must be backed up with “standby” power plants fueled by non-renewable energy resources. These standby plants must increase energy output to compensate for the variability of wind resources. The consumption of non-renewable energy resources in these standby plants will increase as the penetration of wind energy increases in regional electricity grids.

If renewable energy resources which are intermittent are included in the scope of the LCA study, the consumption of non-renewable energy resources at the standby power plants must be classified. This will affect results for other impact categories, for which there are stressor effects networks linked to consumption of non-renewable energy resources at standby power plants.

2.1.4. Characterization

2.1.4.1. Stressor Characterization Factor

The S-CF is the energy content of each energy resource classified in the study, in units of Gigajoules of energy per unit of feedstock.

When assessing results for a category indicator, the same definitions of the energy content must be used. If the higher heating value is used as the basis of the S-CF for one feedstock (e.g., coal), the higher heating value must also be used for all other relevant feedstocks (e.g., natural gas and crude oil).

NOTE. To assess the energy content of fuels which are combusted to generate energy, the higher heating value is more commonly used. This Standard recommends the use of the higher heating value to assess the energy content of combustible fuels.

The data sources used as the basis of S-CFs shall be described in the LCA report. The following characteristics should be taken into account in calculating the S-CF:

- The type of feedstock considered.
- The data source used to derive the energy content.
• The region in which the feedstock is produced.
• The grade of the feedstock (e.g., the coal assay).
• The volumetric density of the feedstock.
• For energy resources which are combusted to generate energy, whether the energy content is based upon the higher or lower heating value.
• Any other characteristics which could influence the value of the S-CF for a specific energy resource.

The use of generic data for the energy content of specific feedstocks can be used in the first iteration, to determine the elementary flows which are the main contributors to final results in this impact category; however, in the second iteration, the characteristics above should be integrated into S-CF calculations. If data is unavailable for any of these characteristics, the effect on final results should be considered, in the context of the goal and scope of the study. Sensitivity analysis is a useful tool to determine the significance to final results of differences in possible S-CFs which could be used.

If a characteristic used to determine S-CF values is found to have a strong effect on final results, but no specific data is available to accurately assess the S-CF, it may not be possible to achieve the goals of the study. In these cases, the goal and/or scope may need to be revised.

### 2.1.4.2. Environmental Characterization Factors

The E-CF for each energy resource is the resource depletion factor (RDF). The RDF is a unitless factor, which considers the net consumption (accounting for any accretion which may occur) by all users of the technically recoverable reserve base of that resource, over a specific time horizon. The RDF is calculated using Equation 2.1 for a given energy resource, factoring in total consumption, total accretion (if applicable), and the reserve base extent.

Equation 2.1. Equation for calculating the Resource Depletion Factor (RDF), for a given energy resource over a specific time horizon for Energy Resource Depletion.

\[
RDF_{TH} = \frac{\text{Consumption}_{TH} - \text{Accretion}_{TH}}{\text{Reserve Base}_{TH}}
\]

Where
- \( TH = \text{Time Horizon (usually 25 years)} \)
- \( RDF = \text{Resource depletion factor for a specific energy resource type.} \)
- \( \text{Reserve base is the technically recoverable reserves for the given energy resource in a given market.} \)
- \( \text{Consumption, accretion, and reserve base all measured in units of mass or energy, depending upon the energy resource.} \)

For most energy resources, a 25 year time horizon is used to calculate the RDF, because this timeframe reflects a reasonable planning period for energy producers, and because the uncertainty of the reserve bases, consumption and accretion levels is relatively low.
NOTE. Many governmental and international organizations (such as the US Energy Information Administration) provide estimates of projected consumption on multiple time horizons, up to 25 years.

2.1.4.2.1. Assessing Total Consumption and Extent of Reserve Base of an Energy Resource

In assessing the RDF for a given energy resource, the regional market conditions which are relevant must be understood. The source region and grade of an energy resource feedstock must be understood, in order to understand the relevant consumption estimates and reserve bases for use in RDF calculations. In many markets, regional consumption and reserve base estimates should be used. Reserve base and consumption estimates can also vary based on the grade of the non-renewable energy feedstock which is considered.

FOR EXAMPLE. In the United States, between 90-99% of coal and natural gas consumed will be produced domestically over the next 25 years. However, a significant fraction of the oil and uranium consumed in the United States comes from global suppliers, including suppliers from Africa and the Middle East. For a unit process located in the United States, when assessing the RDF for coal and natural gas, data based on consumption and reserve bases of these resources in the United States is appropriate, while RDFs for crude oil and uranium should be based on global data.

For the major non-renewable energy feedstocks (i.e., coal, crude oil, natural gas, and uranium), national and international agencies provide data on projections of consumption of fuels over specific time horizons, usually up to 25 years. Different data sources can provide different estimates on overall consumption; the data source used as the basis of consumption values used in RDF calculations shall be described in the LCA report. Sensitivity analysis can help to understand the significance to final results on the data sources used.

The RDF should be based upon the best estimate for the relevant technically recoverable reserve base. This reserve base can be regional, or global. Proven reserves of all relevant non-renewable energy resources shall be included in the reserve base estimate. Unproven reserves shall also be included in the reserve base estimate, provided that the expected uncertainty in the extent of unproven reserves is less than the expected bias introduced through the omission of the unproven reserves.

For the major non-renewable energy feedstocks (i.e., coal, crude oil, natural gas, and uranium), national and international agencies provide data on the reserve bases according to several different definitions. The reserve bases definitions used vary between resource types, and between agencies; these definitions, as well as the correlations between different terms and data, should be understood, to ensure that data is correctly interpreted and integrated into RDF calculations.

In the LCA report, all data sources used in the RDF calculation shall be described, as well as the reserve base definitions used.

To estimate the depletion of renewable energy resources that are consumed at a nonrenewable rate (i.e., consumption in excess of accretion), site-specific data must be obtained on the consumption and accretion of the specific reserve in question.
FOR EXAMPLE. Geothermal energy resources can be consumed at a non-renewable rate. The specific lengths of time that geothermal reservoirs maintain their useful commercial heat transfer are well established and can be obtained from operators of the geothermal units.

2.1.5. Indicator Equation and Unit of Measure
The indicator equation for calculating energy resource depletion for a single unit process is shown in Equation 2.2. For this category indicator, the unit of measure is expressed in units of energy equivalents (e.g., Gigajoule equivalents).

Equation 2.2. Indicator equation for Energy Resource Depletion for a single unit process.

<table>
<thead>
<tr>
<th>Energy Resource Depletion = ( \sum_n (\text{Amount of Non-renewable Energy Resource Consumption} \times S-CF \times RDF) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Where:</td>
</tr>
<tr>
<td>( n ) represents the total number of types of energy resources consumed by a unit process</td>
</tr>
<tr>
<td>• ( S-CF ) is the equivalent energy content between energy resources</td>
</tr>
<tr>
<td>• ( RDF ) is the resource depletion factor</td>
</tr>
</tbody>
</table>

2.1.6. Additional Reporting Requirements. There are no additional reporting requirements for this impact category.

2.1.7. Addressing Additional Limitations in the Types, Accuracy and Availability of Environmental Data
The critical environmental data are the estimation of the reserve bases for different resources, and the projected consumption of these resources over time. While most energy sources rely on global reserves and are traded on a global basis, others are regional in nature, depending on the energy resources in question, the location, and the market factors associated with the product or system. It is recommended that official government estimates of energy reserves serve as the default environmental data for the major energy resources.

2.2. Water Resource Depletion

2.2.1. Impact Category
The impact category represents the depletion of water supplies in the providing environment (i.e., in hydrological reserves) linked to the product system under study. Hydrological reserves include, but are not limited to, surface waters supplies, reservoirs of potable water, and groundwater aquifers.

2.2.2. Stressor-Effects Network
The stressor-effects network may contain stressors, midpoints, and endpoints for water resource depletion which are distinct for different unit processes in the product system under study. The stressor effects network shown in Table 2.3 generally describes the nodes in the cause-effects chain; however, the scale, severity, and reversibility of midpoints can vary significantly for different affected hydrological reserves, based upon considerations such as: the total net water withdrawals from the reserve, by all users; the replenishment rates of the hydrological reserve; the extent of the hydrological reserve; and other considerations.
In the first iteration, the net water consumption should be assessed; unit processes which are major contributors to net water consumption should be identified. The relevant hydrological reserve(s) from which these unit processes obtain water should be identified. The stressor effects networks should initially be modeled separately for each of these hydrological reserve(s). This will greatly aid in classification and characterization.

### Table 2.3. Stressor Effects Network for Water Resource Depletion.

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
</table>
| 1 (Stressors)  
**High Overall Uncertainty (Low Environmental Relevance)** | Net water consumption at unit processes in the product system under study. | *High uncertainty.* Characterization does not account for: the total net water withdrawals from the hydrological reserve by all users; replenishment rates of the given hydrological reserves. | Low uncertainty.  
Data requirements:  
Net water consumption at unit processes in the product system under study. |
| 2 (Midpoint)  
**Moderate Overall Uncertainty (Moderate Environmental Relevance)** | Contribution to total net water consumption by all users for hydrological reserves where net withdrawals are a significant fraction of replenishment rates (i.e., water resource depletion). | *Low uncertainty.* Hydrological reserves are typically replenished on an annual or semi-annual basis, and contribution to total net consumption in excess of replenishment is has strong linkage to endpoints. | Moderate uncertainty.  
Data requirements:  
Relevant hydrological reserve(s) for unit processes in the product system under study.  
Total net water consumption by all users in the relevant hydrological reserve(s).  
Replenishment rates of the relevant hydrological reserve(s). |
| 3 (Endpoints)  
**Characterization at this node not possible given data limitations.** | Contribution to significant drawdowns in the hydrological reserve base on an ongoing basis. Water prices increase, and water supplies are inadequate for humans and ecosystems. Other endpoints include saltwater intrusion into aquifers and surface water, and desiccation of certain ecosystems. | *Low uncertainty.* Directly reflective of endpoints. | Data is generally not reliable which can project the timeframe of exhaustion of hydrological reserve bases, due to uncertainty in extent of reserves and projections of consumption, and due to uncertainties in future condition of the regional climate. |

### 2.2.2.1. Selection of Category Indicator(s).
The category indicator should be at Node 2, characterizing the contribution to total net water consumption, in hydrological reserves where total net withdrawals are a significant fraction of replenishment rates (see Table 2.3).

If data is unavailable for characterization at Node 2, characterization is at Node 1. This characterizes the net water consumption of unit processes in the product system under study. Characterization at Node 1 has low environmental relevance.
2.2.2.2. Identifying Core Impact Categories and Category Indicator(s). Water resource depletion is a relevant impact category only in cases where net water consumption at a unit process is contributing to total net withdrawals which are a significant fraction of total replenishment rates for the affected hydrological reserve(s).

To minimize data collection requirements, in the first iteration, the main contributors to net water consumption (the Node 1 result) should be assessed. At those unit processes which are main contributors to this result, the hydrological reserves from which water is withdrawn should then be identified.

For a given unit process, water resource depletion can be excluded as a core impact category if the total net water withdrawals by all users from the relevant hydrological reserve is negligible compared to the replenishment rate. This comparison of net withdrawals to replenishment can be assessed using direct measurements of net withdrawals and replenishment, or by other considerations (e.g., assessing economic conditions in water supplies in this region).

FOR EXAMPLE. At a unit process in Humboldt County, net water consumption is occurring, with water being diverted from surface water supplies. However, due to a surplus of surface water supplies in Humboldt County, the regional water supply agency is attempting to sell exported water. Water resource depletion is excluded as relevant for this unit process, as net withdrawals are negligible compared to the replenishment rate of surface water supplies.

FOR EXAMPLE. Desalination, where saline water is withdrawn from oceans and treated to generate potable water, contributes to net water consumption. However, the annual replenishment rate of the world’s oceans is far in excess of total net withdrawals by all users. Net withdrawals of ocean water will not contribute to water resource depletion.

In some cases, data will be unavailable regarding conditions in relevant hydrological reserves linked to net water consumption in the product system. The effect on final results of this lack of data should be considered in the content of the goal and scope of the LCA study. A sensitivity analysis can help to understand the significance of including or excluding net water consumption at unit process(es) affecting this hydrological reserve. If the effect of inclusion or exclusion on final results is significant, results may need to be characterized at Node 1, reporting net water consumption. If the effect of inclusion or exclusion is within the expected confidence interval of results estimated from an analysis of uncertainty for the other unit processes, simplifying assumptions can be made regarding inclusion or exclusion.

If water resource depletion is excluded as a relevant impact category, the justification for the exclusion shall be provided in the LCA report.

2.2.3. Classification

In general, net water consumption is classified. This accounts for the amount of a water withdrawal which is not returned to their original source. Net water consumption can include:

- Water which is withdrawn from a hydrological reserve, but returned to another (e.g., water pumped from a groundwater aquifer, but returned to a surface water supply in a different hydrological reserve).
- Water which is withdrawn and subsequently evaporated.
- Water which is withdrawn and then incorporated into products or co-products.
- Water which is withdrawn and then incorporated into waste products (e.g., water used and stored in treated wastes).

When using secondary inventory data (i.e., from commercial databases such as Ecoinvent), care should be taken that flows of net water consumption are properly classified. In the first iteration, a validation of data regarding water use across the product system under study should be conducted, checking that unit processes which are known to be significant net consumers of water (i.e., thermal power plants and agriculture in certain regions) are in fact, accounted for in the LCI analysis as contributing to net water consumption.

Unit process(es) which are major contributors to results for net water consumption, but have high levels of variability in net water consumption (e.g., agriculture) should also be identified; the use of secondary data to model net water consumption at these unit processes can introduce uncertainty in results. This introduced uncertainty should be considered in the context of the goal and scope of the LCA study.

2.2.4. Characterization

2.2.4.1. Stressor Characterization Factor. There are no equivalencies in this impact category. The S-CF is equal to one.

2.2.4.2. Environmental Characterization Factor. The E-CF for all extracted water resources is the resource depletion factor (RDF), which is assessed separately for each affected hydrological reserve. The RDF characterizes the total net water withdrawals by all users from the hydrological reserve, compared to total replenishment of the hydrological reserve, assessed over a specific time horizon. The RDF for water resource depletion is calculated using Equation 2.3.

\[
\text{RDF}_{TH} = \frac{\text{Withdrawals}_{TH}}{\text{Replenishment}_{TH}}
\]

Where:
- \(\text{RDF}_{TH}\) is the Resource Depletion Factor, evaluated over a specified time horizon
- \(\text{Withdrawals}_{TH}\) is the total net water withdrawals from the hydrological reserve, by all users, over the specified time horizon.
- \(\text{Replenishment}_{TH}\) is the total water replenishment of the hydrological reserve, over the specified time horizon.

The time horizon used in most cases should be one year, representing an annual average of total net withdrawals compared to total replenishment.

\[\text{This RDF is equivalent to the criticality ratio.}\]
The data sources used in RDF calculations should be carefully chosen, considering the data source and year of the data. For all hydrological reserves, replenishment rates (which are driven by weather patterns), will fluctuate over time; the level of total net water withdrawals will also vary, as a result of economic and ecosystem conditions. The scale of this variability will depend upon the hydrological reserve.

In most cases, it is recommended that the RDF be calculated using data from multiple time periods, to capture the variability and uncertainty inherent in the balance between net withdrawals and replenishment of hydrological reserves. The data sources and calculation steps used to calculate RDFs shall be described in the LCA report.

There is always uncertainty inherent in the calculation of the RDF, which is linked to inherent variability in the ratio of net withdrawals to replenishment. The level of uncertainty can vary considerably for RDFs assessed for different hydrological reserves. This uncertainty should be considered in the context of the effect on final results, and the goal and scope of the LCA study. More complex analyses and data collection should be focused on RDFs applied to net water consumption for unit processes that are major contributors to final indicator results, taking the goal and scope of the LCA study into consideration.

NOTE. In rare cases, the total net withdrawals will exceed replenishment rates. This results in a drawdown over time in water available in the hydrological reserve. This can occur, for example, when groundwater aquifers are being pumped in excess of natural replenishment rates. In these cases, following Equation 2.3, the RDF will be greater than one.

2.2.5. Indicator Equation and Unit of Measure. The indicator equation for calculating energy resource depletion for a single unit process is shown in Equation 2.4. For this category indicator, the unit of measure is expressed in units of volume equivalents of water.

Equation 2.4. Indicator equation for Water Resource Depletion for a single unit process.

\[
\text{Water Resource Depletion} = \text{Net Water Consumption} \times \text{RDF}
\]

Where:

- \text{Water Resource Depletion} is the indicator result, for a single unit process.
- \text{Net Water Consumption} is the net water consumption for the unit process.
- \text{RDF} is the resource depletion factor.

2.2.6. Additional Reporting Requirements. If there is a significant amount of uncertainty in calculation of RDFs, particularly for key unit processes, a confidence interval can be reported for indicator results. The upper and lower confidence bounds can be assessed using results from multiple sensitivity analyses exploring the effect of different RDFs on final indicator results.

2.2.7. Addressing Additional Limitations in the Types, Accuracy and Availability of Environmental Data. For a single hydrological reserve, the two types of environmental data required to calculate the RDF for this category indicator are the total net water withdrawals and total replenishment, over a specific time horizon. Groundwater reserves usually have historic records on total hydrological levels as well as current drawdowns, which can help in the calculation of RDFs. Surface water supplies tend to exhibit more variability, due to complicated
variations in annual rainfall; multi-year averages should be used to establish RDFs. Lakes also are subject to variations in annual and decadal rainfall patterns and require multi-year averaging.

2.3. Minerals and Metals Resource Depletion

2.3.1. Impact Category. The impact category reflects the net consumption of mineral and metals linked to unit process(es) in the product system under study, for which total supplies are projected to be scarce within reasonable planning timeframes. Recycling of a given mineral or metal should be factored into calculations of net consumption at the end-of-life.

2.3.2. Stressor-Effects Network. This stressor-effects network represents the depletion of a mineral or metal resource extracted from the providing environment, and is described in Table 2.4.

The providing environment includes reserve base(s) which vary based on the mineral or metal resource, and can be at the local, regional, or global scale, depending on the characteristics of the market where the resource is consumed. The midpoint of contribution to overall mineral or metal resource consumption from a specific reserve base should be understood (Node 2 in Table 2.4), to understand the relevance of consumption of the mineral or metal resource.

For certain resources, due to large deposits of the mineral or metal and high recycling rates, the extent of technically recoverable reserves are essentially unlimited within reasonable planning timeframes. Consumption of these resources are not considered relevant in this impact category (see Section 2.3.2.2).
Table 2.4. Stressor effects network for Minerals and Metals Resource Depletion.

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Stressors)</td>
<td>Net consumption of a specific mineral or metal resource by unit processes in the product system under study.</td>
<td>High uncertainty. Characterization does not account for: the total consumption the resource by all users; projections of accumulated consumption over timeframes of interest; or the extent of technically recoverable reserves.</td>
<td>Low uncertainty. Data requirements: Amount of a specific mineral or metal consumed in the product system.</td>
</tr>
<tr>
<td>2 (Midpoint)</td>
<td>Contribution to total net consumption of a specific mineral or metal resource by all users from a specific reserve base, which will lead to limited supplies within projected timeframes of interest.</td>
<td>Moderate uncertainty. Characterization accounts for contribution to consumption of minerals or metals from limited reserves. However, characterization does not account for the likely timeframe of exhaustion.</td>
<td>Low uncertainty. Data requirements: Amount of a specific mineral or metal resource consumed in the product system. For the relevant reserve base, the total amount of a specific mineral or metal resource consumed. Rough projections of total consumption of a resource, compared to its technically recoverable reserve base.</td>
</tr>
<tr>
<td>3 (Midpoint)</td>
<td>Contribution to net consumption of a specific mineral or metal resource by all users, leading to significant drawdown in extent of technically recoverable reserves within projected timeframes of interest.</td>
<td>Moderate uncertainty. Characterization does not account for the likely timeframe of exhaustion.</td>
<td>Data is generally not reliable which can project the timeframe of drawdown of technically recoverable reserve bases, due to uncertainty in extent of reserves, recycling rates, and projections of consumption rates of each reserve.</td>
</tr>
<tr>
<td>4 (Endpoint)</td>
<td>Contribution to the exhaustion of technically recoverable reserve bases. Price of the resource increases, and resource scarcity may occur.</td>
<td>Low uncertainty. Directly reflective of endpoints.</td>
<td>Data is generally not available which can project the timeframe of exhaustion of technically recoverable reserve bases, due to uncertainty in extent of reserves, recycling rates, and projections of consumption rates of each reserve.</td>
</tr>
</tbody>
</table>

2.3.2.1. Selection of Category Indicator(s). In general, for each instance of net consumption of a mineral or metal resource, distinct category indicators will be defined, as the stressor-effects network of each resource is usually distinct.

NOTE. Although for some materials, substitution with other materials can alleviate the endpoints of exhaustion of the technically recoverable reserve base, at this time, there is no characterization model which supports assessment at this node of endpoints. Given this limitation, no aggregation is possible between materials, and separate category indicators are defined for each mineral and metal resource which is consumed in the product system.
Characterization is at Node 2, the contribution to net consumption of a mineral or metal resource. Due to the uncertainty in estimates of technically recoverable reserve bases, and projections of consumption of minerals and metals, data is not sufficient to establish results past Node 2.

2.3.2.2. Identifying Core Impact Categories and Category Indicator(s). Net consumption of a given mineral or metal resource in the product system is a relevant impact category only in cases where the product system measurably contributes to drawdowns of the technically recoverable reserves of the material. Additionally, the only minerals and metals which are considered could have limited technically recoverable reserve bases within reasonable planning timeframes, as a result of net consumption by all users. The technically recoverable reserve base should also include secondary reserves which exist in products in use, and the potential for recovery of those secondary material reserves.

FOR EXAMPLE. In a product system, net consumption of magnesium is occurring. Considering current consumption rates by all users and the extent of technically recoverable reserves of magnesium according to the United States Geological Survey, there are over 400 years of magnesium (in magnesite ore) remaining. The technically recoverable reserve base for magnesium will not be limited in any reasonable planning timeframe, and consumption of magnesium is excluded as relevant as an impact category.

For certain resources, due to high recycling rates and large deposits of the mineral or metal, the extent of technically recoverable reserves are essentially unlimited within any planning timeframe. Consumption of these resources are not relevant in this impact category.

FOR EXAMPLE. Materials such as iron have high recycling rates, ameliorating net consumption. Furthermore, iron is a substantial component of the Earth’s crust, and the extent of technically recoverable reserves are, in practice, unlimited. Net consumption of iron is not relevant to this impact category.

The providing environment includes reserve base(s) which vary based on the mineral or metal resource, and can be at the local, regional, or global scale, depending on the characteristics of the market where the resource is consumed. To understand the extent of the technically recoverable reserve base, and the effect on this extent of net consumption from all users, the midpoint of contribution to mineral or metal resource drawdown in a specific reserve base should be understood (Node 3 in Table 2.4).

To identify materials where this is a relevant impact category, a screening of the net consumption of all minerals and metals in the product system should first be conducted. In this screening, results should be assessed using a scale of functional unit which is conservatively large.

Once results for net consumption of all minerals and metals are assessed in this screening, previous experience and general knowledge should be used to exclude those minerals and metals for which technically recoverable reserves will not be limited within reasonable planning timeframes. This will lead to a set of indicator results for several minerals and metals resources experiencing net consumption, for which supplies could be limited within reasonable planning timeframes.
A category indicator for a given mineral or metal resource can be excluded as relevant if the scale of the indicator result is negligible, when compared to the measurements in estimates of projected consumption and/or extent of the relevant technically recoverable reserve base.

FOR EXAMPLE. In the screening phase of an LCA study of an office furniture product, net consumption of chromium, copper, fluorspar/fluorite, manganese, and nickel, were found to occur as a result of net consumption at unit processes in the product system. The functional unit used in this screening was 1,000 units of product, which was a conservatively large estimate of the annual production volume. Once recycling of each of these materials was accounted for at end-of-life, net consumption for all these materials is less than 400 kilograms (for fluorspar/fluorite and molybdenum, net consumption is less than 20 kilograms). The measurements of technically recoverable reserve bases for all of these resources (published by the United States Geological Survey) are at the scale of millions of tons. With consumption of only 20 to 400 kilograms, net consumption in this product system is negligible compared to the existing reserve base. Category indicators for these materials were not assessed.

In the LCA report, any net consumption of minerals or metals which are excluded as relevant should be described, and the basis of the exclusion shall be provided.

2.3.3. Classification. Metals and minerals that are not considered inexhaustible (e.g. sand) and have limited technically recoverable reserve bases within reasonable planning timeframes are classified under this impact category, according to the requirements of Section 2.3.2.1 and 2.3.2.2. At a given unit process, only net consumption of a mineral or metal is classified.

Aggregation of different metals and minerals into a single category indicator is not permitted. Each mineral or metal is reported under a separate category indicator.

A given material may be extracted from several different types of ore. Consumption of all ores containing a single material should be classified into the single relevant category indicator.

In some instances, multiple materials are extracted from the same ore; in these instances, consumption of multiple material co-products may be classified into multiple category indicators.

FOR EXAMPLE. Lead and zinc are often co-produced during mining and refining, as these two materials commonly occur in the same type of geologic deposits. The net consumption of lead and zinc from a single ore should be considered for classification into separate category indicators for lead consumption and zinc consumption.

At end-of-life, recycling of a mineral or metal should be classified as a negative contribution to net consumption, if the material can be re-processed into a quality which is identical to virgin feedstock in the next product life cycle. However, for products with long useful lifetimes, care should be taken when including recycling at end-of-life into indicator calculations. Use of current data regarding recycling rates and processing techniques to model end-of-life processes far in the future introduces significant uncertainty into indicator results; this uncertainty should be considered in the context of the goal and scope of the LCA study. If the uncertainty which is introduced is significant, it may not be possible to achieve the goal of the LCA study, and the goal and/or scope may need to be revised.
2.3.4. Characterization

2.3.4.1. Stressor Characterization Factor. For each category indicator, the S-CF represents the mass of the relevant mineral or metal per mass of classified flow. The mass of an inventory flow multiplied with the S-CF gives results in units of mass of the mineral or metal which is considered in the category indicator.

For example, in regions of the Eastern United States where zinc is produced, zinc is typically extracted from carbonate hosted ores. In these ores, zinc occurs with copper, silver, and barite, with host rocks of limestone and dolomite. In deposits like this, zinc content is typically roughly 5%. The S-CF relevant for zinc consumption, applied to the total mass of this carbonate hosted ore, is 0.05, representing the zinc content or the ore.

Because each mineral or metal covered under this impact category is accounted for separately, there is no need to establish a resource equivalencies between materials.

2.3.4.2. Environmental Characterization Factor. Due to the uncertainty in estimates of technically recoverable reserve bases, and projections of consumption of minerals and metals, data is not sufficient to establish results past Node 2, which characterizes net consumption of minerals and metals (see Section 2.3.2.1). There is no E-CF.

2.3.5. Indicator Equation and Units of Measure. The indicator equation for calculating mineral and metal resource depletion is shown in Equation 2.5. The reported unit of measure of the indicator result is expressed in mass of mineral or metal which is consumed.

Equation 2.5. Indicator equation for mineral or metal resource consumption, for a single material, for a single unit process.

\[
\text{Net Mineral or Metal Resource Consumption} = \sum_i (\text{Net Material Consumption} \times \text{S-CF})
\]

Where:
- **Net material consumption** is the mass of flow which is classified in the category indicator
- **S-CF** is the Stressor Characterization Factor, characterizing the mass of mineral or metal per mass of flow which is classified.
- **i** represents the total number of flows classified in the category indicator (for cases where multiple ore types are classified into this category indicator)
2.3.6. Additional Reporting Requirements. In LCA reports and EPDs or C-EPDs, for relevant category indicators, it can be informative to provide data on the current consumption rates from all users and the extent of technically recoverable reserve bases. Discussion could be provided regarding when drawdowns of a given material resource could become significant.

2.3.7. Addressing Additional Limitations in the Types, Accuracy and Availability of Environmental Data. The two most important pieces of environmental data are required to determine the relevance of category indicators, and include information on the projected consumption of a mineral or metal by all users, and the existing technically recoverable reserves. These data are generally available in published literature. Assessments can be based upon official government estimates, such as those provided by the United States Geological Survey. Limitations in the data which is used should be documented in the LCA report.

Additional environmental data which are useful include: 1) whether the relevant reserve base is regional or global in nature; 2) the size of the potential global reserve base; and 3) published projections of recycling and reclamation rates. Limitations in the data which is used should be documented in the LCA report, provided it has relevance to final results.

2.4. Biotic Resource Depletion (by type)

2.4.1. Impact Category. This impact category includes the net depletion of biotic natural resources (e.g., wood), that are normally considered renewable, but that in practice have been found to be depleted due to an imbalance between consumption and replenishment rates.

This category takes into account local conditions, the rate of consumption, and the rate of regrowth of biotic resources. This impact category considers only biotic resources not used for energy production.

2.4.2. Stressor-Effects Network. The stressor-effects network for biotic resource depletion can vary broadly. Stressors can be related to activities at unit process(es) considered in the product system under study, as well as to unit processes outside the scope of the LCA.

The stressor-effects network for biotic resource depletion shown in Table 2. 5 provides a general framework; however, separate stressor-effects networks should be modeled and described for each separate indicator for biotic resource depletion identified within the study scope according to the requirements of Sections 2.4.2.1 and 2.4.2.2. The specific stressor-effects network should describe the site-specific circumstances of stressors, midpoints, and endpoints, in the cause-effect relationship in the biotic reserve base under study. This should consider the past history of resource management affecting the biotic reserve base, current management practices, and other considerations relevant to the environmental mechanism. This detailed modeling of the stressor-effects network will greatly aid in the characterization of each category indicator.
Biotic resource depletion is nearly always linked to impact categories in the Land Use Ecological Impacts group, as disturbances to biomes very often occur as a result of drawdowns in available biotic reserves (the valuable component of biotic systems). If impacts are found to be relevant in the Land Use Ecological Impacts group, the stressor-effects network of various disturbances should be explored, to understand if biotic resource depletion is occurring, as well.

Table 2.5. Stressor effects network for biotic resource depletion.

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Stressors)</td>
<td>Consumption of biotic resources by a unit process included in the study scope.</td>
<td><em>High uncertainty.</em> Characterization does not account for: the regrowth rates of the biotic reserve; or the extent of the biotic reserve base.</td>
<td><em>Low uncertainty.</em> Data requirements: Amount of biotic resource consumed at a unit process.</td>
</tr>
<tr>
<td>2 (Midpoint)</td>
<td>Consumption of the biotic resource in excess of regrowth rates leads to net decline in extent of biotic reserve.</td>
<td><em>High uncertainty.</em> This indicator reflects the renewability of the biotic resource consumption. However, it does not factor in the extent of the biotic reserve base.</td>
<td><em>Moderate uncertainty.</em> Data requirements: Amount of biotic resource consumed at a unit process. Regrowth rates in the biotic reserve base.</td>
</tr>
<tr>
<td>3 (Midpoint)</td>
<td>Nonrenewable consumption of biotic resource leads to drawdown in extent of biotic reserve (i.e., biotic resource depletion).</td>
<td><em>Moderate uncertainty.</em> Characterization does not consider the timeframe of exhaustion of the total biotic reserve.</td>
<td><em>Moderate uncertainty.</em> Data requirements: Amount of biotic resource consumed at a unit process. Regrowth rates in the biotic reserve base. Extent of biotic reserve base.</td>
</tr>
</tbody>
</table>
2.4.2.1. Selection of Category Indicator(s). Separate category indicators shall be reported for each distinct biotic resource affected by unit process(es) within the product system under study. Biotic resource depletion is distinguished into separate category indicators by functional characteristics of the end products in use, not by biological or ecological characteristics of the resource (e.g., by species type).

Care should be taken in distinguishing the multiple category indicators for biotic resource depletion. To aggregate multiple biotic resources into a single category indicator, the following requirements must be met:

- The function(s) of the products, and well as the function(s) of any co-products, must be similar.

- The functional performance of the products and co-products in use must be similar. If the performance is significantly different for any products or co-products (e.g., leading to significantly longer product longevity or durability), aggregation may be inappropriate.

- There must be data available for aggregation. Aggregation into a single category indicator is only possible if S-CFs can be established (see Section 2.4.4.1).

- The characterization model for each indicator of biotic resource depletion must be distinct.

- The relative scarcity of the biotic resources must be similar. Although separate biotic resources may be used for similar functions, if the one is much scarcer than another, aggregation may be inappropriate.

The basis of aggregation between multiple biotic resources shall be described in the LCA report. The function(s) of the products and co-product(s) for biotic resources considered in a given category indicator shall be described in the LCA report and should be described in EPDs or C-EPDs.

Characterization shall be at Node 3, characterizing the extent of drawdown in biotic resource availability, if data is available.

For a given biotic resource, data may be unavailable for characterization at Node 3, and results instead must be reported at Node 1 or 2. If characterization is at these lower nodes, the basis of the characterization model and data sources which are used must be described in the LCA report.
2.4.2.2. Identifying Core Impact Categories and Category Indicator(s). While biotic resources are often assumed to be inherently renewable, this depends on the regrowth rate of the biotic resource, the rate of harvest, and the past history of resource management in the region under study. If activities associated with a unit process lead to rates of consumption exceeding the rate of regrowth for a given biotic resource, the unit process will be contributing to the drawdown in the biotic reserve base. However, even in regions where current harvests are less than regrowth rates, biotic resource depletion may be relevant if the past history of resource management has led to a drawdown in biotic resources, as these resources can take a significant amount of time to recover.

FOR EXAMPLE. At a forestry operation in North America, past forest management removed over 60% of the standing stock of timber, leading to biotic (timber) resource depletion. The current forest operator is harvesting timber at a rate in the forest that is much less than the regrowth rate. By doing so, the operator is recovering the standing timber stocks in the forest, and reducing the result for timber resource depletion. However, biotic resource depletion is still relevant, as a result of past forest management.

Due to the data collection and analysis requirements to characterize category indicators for biotic resource depletion, the product system under study should be screened to identify those unit process(es) which are contributing to biotic resource depletion. This screening should be intended to minimize the amount of data collection required.

For a given unit process, this impact category can be ruled out as a relevant if there is no measurable contribution to any environmental mechanism of biotic resource depletion. For a given unit process, the following guidance can be used to exclude biotic resource depletion as relevant:

- If the product system under study were to halt all activity, and all relevant intermediate flows throughout the entire product system were likewise stopped, no measurable change in the stressors, midpoints, or endpoints of biotic resource depletion would be observed.

- If it can be demonstrated through observation that the activities at the unit process do not contribute to a measurable drawdown in the availability of biotic resources at any location.

When conducting this screening, it is important to identify any types of unit process(es) in the product system which have been known in the past to contribute measurably to biotic resource depletion. This includes land-intensive production activities, such as forestry.

When screening to determine if biotic resource depletion is a core impact category, the scale of the functional unit used shall be large enough to include observed instances of biotic resource depletion. The functional unit must not be set arbitrarily low, which could rule out this impact category even in cases where biotic resource depletion is occurring and can be linked to a unit process. This screening may require sensitivity analysis.
2.4.3. **Classification.** In this category indicator, the historic extent of the biotic reserve base is classified for each relevant instance of biotic resource depletion identified according to Section 2.4.2.2. (Classification may entail delineation of distinct historic reserve bases into separate category indicators, based upon the requirements of Section 2.4.2.1.)

The “historic reserve base” is intended to represent the historic condition of the biotic reserve base. This historic reserve base should be established using historic data, if it is available.

In most cases, historic data will be unavailable, and reference reserve bases must be identified, which represent the historic reserve base. Monitoring data evaluating the extent of the reference reserve base through direct measurement is required. The reference reserve base should be a reserve base which has not been affected by anthropogenic activities, with similar ecological characteristics to the biotic reserve base affected by the unit process under study, considering characteristics such as:

- The regional biome (see definitions in Section 3.1, 3.2 and 3.3).
- The climate, topography, hydrology, and other physical characteristics.
- The species which compose the reserve bases. (Reserves with significantly different species composition are not suitable for use as a reference reserve base.)

In practice, there will rarely be a reference reserve base for which data is available which has not been affected by anthropogenic activities. Even reference reserve bases based on primary-growth reference areas in extremely remote regions never affected by any resource extraction are still affected by anthropogenic climate change. Therefore, the selection of the reference reserve base will always entail a careful consideration of possible alternatives that best represents the idealized historic extent of the biotic reserve base.

The final results for biotic resource depletion are sensitive to the selection of the historic reserve base which is used. Sensitivity analysis should be a key part of this selection process. A description and justification of the historic reserve base selected must be provided in the LCA report, along with a clear description of its extent and the data sources used in its classification.

2.4.4. **Characterization**

2.4.4.1. **Stressor Characterization Factor.** When aggregating the depletion of multiple biotic resources into a single category indicator, S-CFs must be established which are used as the basis of equivalencies. The derivation of the S-CF depends upon the biotic resources in question. If equivalencies using S-CFs cannot be established, multiple flows of biotic resource depletion cannot be aggregated into a single category indicator.

2.4.4.2. **Environmental Characterization Factor.** The E-CF for this category indicator is the Resource Depletion Factor (RDF), which is a factor which characterizes the drawdown of the biotic reserve base compared to historic conditions. The RDF is calculated using Equation 2.6. The RDF is unitless, but can be expressed as a percentage reduction in the extent of the historic reserve base.
2.4.4.2.1. Determining the Extent of the Biotic Reserve Base. The stressor-effects network linked to activities at a unit process in the product system can vary greatly based upon the region, past history of resource management, and other considerations (see Section 2.4.2). The midpoint of the drawdown of the biotic reserve base (Node 3 in Table 2. 5) will also vary significantly. Accordingly, site-specific assessment of the extent of the biotic reserve base is required.

The data sources and methods used to assess the extent of the biotic reserve base depends upon the biotic resource which is depleted, region, species of biotic resource, and other considerations. Monitoring data evaluating the extent of the biotic reserve base through direct measurement is required.

For instances of biotic resource depletion which are associated with land-based unit processes (i.e., forestry), the current biotic reserve base should be evaluated using data for a specific classified area, which has experienced a drawdown in biotic resources as a result of current or historic activities at the unit process under study.

For example. In 650,000 acres of forests in a county of the Pacific Northwest of the United States, the total aboveground biomass in standing live trees is approximately 60 metric tons per acre; this corresponds to a total biotic reserve base of 39 million metric tons of standing timber. These forests are in private ownership, and have been affected by over 100 years of commercial forestry, involving heavy clear cutting. The reference reserve base is a forest in an adjacent national park, with very similar species composition and ecological characteristics; in the reference reserve base, the total aboveground biomass in standing live trees is roughly 250 metric tons per acre. In the biotic reserve base under study, this corresponds to a loss of 190 metric tons of standing timber per acre, with a corresponding RDF of 0.76. The result for timber resource depletion is 39 million metric tons x 0.76, equal to 30 million metric tons of standing timber.

If data is unavailable to assess the current or historic extent of the biotic reserve base, it may not be possible to achieve the goals of the LCA study. The goal and scope may need to be revised.


\[
\text{RDF} = \frac{\text{Historic Reserve Base} - \text{Current Reserve Base}}{\text{Historic Base}}
\]

Where:
- \( \text{RDF} = \text{Resource depletion factor} \)
- \( \text{Historic reserve base} \) is the historic extent of the biotic reserve base, defined according to requirements in Section 2.4.3.
- \( \text{Current reserve base} \) is the current extent of the biotic reserve base.
2.4.5. Indicator Equation and Unit of Measure. The indicator equation for results calculated at Node 3 in the stressor-effects network, characterizing the drawdown in biotic resources, is shown in Equation 2.7. The category indicator results are reported in units dependent upon the biotic resource under study.

Equation 2.7. Equation for calculating results for Biotic Resource Depletion at Node 3, characterizing the total drawdown in biotic resources, for a single unit process.

\[
\text{Biotic Resource Depletion} = \sum_i (\text{Biotic Resource Use}_i \times \text{S-CF}_i \times \text{RDF})
\]

Where:
- Biotic Resource use is expressed in units dependent on the characteristics of the resource (e.g., board feet for wood)
- S-CF, is the Stressor Characterization Factor, which establishes equivalencies between different biotic resources included in a single category indicator.
- RDF is the resource depletion factor, determined by resource type.
- \(i\) represents the total number of biotic resources included in the category indicator.

2.4.6. Additional Reporting Requirements. For a given unit process, the results for biotic resource depletion vary inversely with production levels in a nonlinear fashion. Increased production, if that production is in excess of regrowth rates, leads to increasing indicator results over time. Furthermore, due to the typically long recovery time required for biotic reserve bases, even if all stressors associated with a given unit process were to stop, and all production cease, in most situations, it would take decades for the biotic resource to recover to its historic extent. As a result, indicator results normalized to production volumes (i.e., intermediate flows) can be misleading.

The functional unit should be scaled such that the total biotic reserve base which is affected by unit process(es) in the product system is included and reported in final results. Results should not be normalized to production volume on the site. The RDF, expressed as a percentage, and extent of the historic reserve base shall be reported in the LCIA profile.
3. Land Use Ecological Impacts Group

This group of impact categories accounts for impacts caused by unit processes in the product system under study, that can lead to physical disturbances to biomes and losses of key species, and resulting endpoints of effects to regional interconnected ecosystem[s]. This group accounts for changes in conditions of these ecological systems from “undisturbed” conditions, unaffected by anthropogenic interference. The assessment must consider the past history of changes, as well as the current degree of disturbance.

The group includes four impact categories:

- Terrestrial biome disturbance.
- Freshwater biome disturbance.
- Wetland biome disturbance.
- Loss of key species.

The first three impact categories account for physical changes in the conditions of biomes resulting from activities at unit processes in the product system. The types of biomes which are disturbed can vary greatly, and additional impact categories of biome disturbance to these three could be added if found to be relevant (e.g., coastal biome disturbance.) In these impact categories, structural changes to specific biomes within the affected area are measured, and compared to the “undisturbed” conditions, which are defined by biome.

Within each type of biome disturbed, separate reporting indicator results may be required. For example, an industrial operation (e.g. forestry, mining) may result in disturbance to several distinct watersheds, each of which have distinct endpoints and should be reported as a separate category indicator results.

The last impact category measures the loss of key species, usually measured through an assessment of habitat disturbance. This considers impacts leading to losses of key faunal or floral species that are the most vulnerable, threatened, or endangered, or are extirpated. These impacts are reported separately for each species affected. It is representative of effects to biodiversity in the affected area.

Disturbance to biomes and loss of key species can occur in two ways:

- Direct disturbance at the site of a physical disruption activity associated with a unit process. Examples include forest clear cuts, excavation of open-pit mines, and construction of roads.
- Indirect disturbance, away from the site of a physical disruption activity associated with a unit process. These disturbance results from cascading effects caused by physical disruptions (e.g., increased sedimentation in watercourses downstream from a forestry operation), and also from changes in the continuity of biomes and species communities such that the overall ecology of the area changes over time.

The disturbance of biomes and loss of key species can impact ecosystem functions and biodiversity. Ideally, these ecosystem impacts would be directly measured in terms of the disturbance to the affected ecosystems. However, such comprehensive assessment is not supported by ecological field assessment techniques. This group of indicators relies on
measuring the amount and degree of biome disturbance and key species losses rather than changes in ecosystem health for the following reasons:

- While effects to specific biome and key species can be measured, little or no data are typically available to measure the disturbance of overall ecosystem health.
- The disturbance of specific biomes and loss of key species reflects site-dependent situations related to the specific location of unit processes, providing a spatial context for analysis.
- Different biomes and key species are not equivalent and may not be aggregated; evaluation of different biomes may therefore highlight impacts that might be overlooked in an analysis of overall ecosystem health.

The measurement of biome disturbance involves assessing the size, severity, and duration of disturbance associated with activities at unit processes included in the study scope. The measurement of key species loss typically involve assessing the size, severity, and duration of habitat disturbance. In some instances, key species loss can include measurements of regional population reductions.

3.1. Terrestrial Biome Disturbance

3.1.1. Impact Category. This impact category addresses the disturbance to terrestrial biomes caused by stressors associated with the product system under study. In this Standard, a terrestrial biome is defined as a biotic community in a specific terrestrial area, which is defined by conditions such as prevailing vegetation structure, leaf types, plant spacing, vegetative species composition, vegetative compositional structure, vegetative age structure, presence of large living trees and snags (if relevant), presence of biomass (above and below ground), soil conditions, connectivity, landscape heterogeneity, fragmentation, climate, and topography.6

In this Standard, disturbance to a terrestrial biome is defined as the measurement of overall ecological conditions in the classified area under study (see Section 3.1.3), when compared to undisturbed conditions (i.e., unaffected by anthropogenic activities since the pre-industrial era) and fully disturbed conditions (i.e., representing maximally disturbed areas) in an area within the same biome type.

The degree, scale, and duration of terrestrial biome disturbance associated with different unit processes will vary broadly, depending on factors such as the land use management practices, regional biome, history of the landscape, duration of disturbance, and scale of disturbance. Likewise, the midpoints and endpoints associated with this impact category vary for all of these reasons. Accordingly, site-specific assessment of terrestrial biome disturbance associated with a unit process is required. Secondary data shall not be used in the assessment of terrestrial biome disturbance.

3.1.2. Stressor-Effects Networks. The stressor-effects network for terrestrial biome disturbance is distinct for disturbances caused by each unit process. The stressors can vary broadly, and the resulting midpoints and endpoints will vary for many reasons. Stressors can be

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related to activities at unit process(es) considered in the product system under study, as well as to unit processes outside the scope of the LCA.

The stressor-effects network for terrestrial biome disturbance shown in Table 3.1 provides a general framework; however, separate stressor-effects networks should be modeled and described for each separate terrestrial biome disturbance indicator in the study scope. The specific stressor-effects network should describe the site-specific circumstances of stressors, midpoints, and endpoints, in the cause-effect relationship in the classified area under study. This should consider the past history of disturbance and land management in the classified area, current management practices, and other considerations relevant to the environmental mechanism. Additionally, the terrestrial biome affected shall be reported and described, as well as a justification for its definition. This detailed modeling of the stressor-effects network will greatly aid in the characterization of each category indicator.

### Table 3.1. Stressor-Effects Network for Terrestrial Biome Disturbance.

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Stressors)</td>
<td>Area within a terrestrial biome is affected by land use management activities, with direct and indirect effects, causing incremental changes to ecological conditions.</td>
<td>High uncertainty. Characterization does not consider the degree of alteration in ecological conditions or past land use management affecting current conditions.</td>
<td>Low uncertainty. Data requirements: Spatial data related to the extent of land use management activities.</td>
</tr>
<tr>
<td>2 (Endpoints)</td>
<td>Terrestrial biome disturbance, defined as measurements of changes in ecological conditions in the terrestrial biome of the classified area under study.</td>
<td>Low uncertainty. Direct characterization of terrestrial biome disturbance.</td>
<td>Low uncertainty. Data requirements: Spatial data related to the extent of land use management activities. Measurements of ecological conditions in affected areas and reference areas.</td>
</tr>
<tr>
<td>3 (Endpoints)</td>
<td>Ecosystem disturbance: Alterations in the regional interconnected ecosystem, caused by effects to terrestrial, freshwater, and wetlands biomes, the presence of key species, and other impacts.</td>
<td>Low uncertainty. Directly characterization of ecosystem disturbance.</td>
<td>Little or no data are available to measure the disturbance of overall ecosystem health.</td>
</tr>
</tbody>
</table>

The disturbance of a terrestrial biome is considered an endpoint in its own right; however, this endpoint is linked to endpoints and midpoints of other stressor-effects networks, including those related to disturbance to other biome types (e.g., freshwater and wetlands) and habitats (defined in this Standard, Section 3.4, as an environment within which a specific key species normally occurs). The endpoint of ecosystem disturbance is affected by midpoints and endpoints of all of the affected biomes and habitats.
3.1.2.1. **Selection of Category Indicator(s).** Separate category indicators shall be reported for disturbance to each distinct terrestrial biome affected by unit process(es) within the product system under study. This reflects the distinct nature of each terrestrial biome experiencing disturbance. No aggregation of results is allowed between distinct category indicators.

**NOTE.** In practice, at least one separate category indicator is reported for each unit process causing terrestrial biome disturbance. Unit processes are usually located in different terrestrial biomes, and stressors associated from different unit processes are usually different, as well. This leads to distinct environmental mechanisms for disturbance.

**NOTE.** In some cases, a unit process will be of a large enough spatial scale to affect multiple terrestrial biomes.

The definition of a specific terrestrial biome should be based upon widely accepted frameworks, which could include terrestrial ecoregions defined by the WWF,\(^7\) or Bailey's Ecoregions. In some cases, the environmental mechanism associated with terrestrial biome disturbance for a given unit process requires a definition that is different than reported in these frameworks. It is acceptable to use a different definition for a terrestrial biome, provided a justification is reported for the use of such definition, and the relationship to a commonly used framework is described.

**FOR EXAMPLE.** Within a broader biome type, distinct biomes with recognized high conservation value could exist, and should be reported under separate category indicators.

Site-specific biome definitions will often be required in situations where the classified area under study has very different disturbance levels and past history from other parts of the terrestrial biome.

In some cases, only specific land cover types within a given terrestrial biome are affected by the stressor(s) associated with a given unit process. In these cases, these specific land cover type(s) should be described.

**FOR EXAMPLE.** For most forestry operations, harvests occur almost exclusively in forest stands dominated by merchantable timber species. An operation in Northern California that produces redwood and Douglas fir lumber, for example, will almost exclusively harvest from redwood, Douglas fir, and tanoak forest types. These forest types should be noted in addition to the affected terrestrial biome.

The indicator shall be at Node 2, if data is available, which characterizes terrestrial biome disturbance by measuring alterations in ecological conditions in the terrestrial biome, when compared to the undisturbed and fully disturbed reference areas.

In some instances, data will not be available to assess terrestrial biome disturbance. In these cases, measurements of the spatial extent of disturbed area at Node 1 should be used. This

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\(^7\) WWF. Ecoregions. http://worldwildlife.org/biomes
represents the inventory for terrestrial biome disturbance, and should be reported as such.

Characterization at Node 1 has low linkage to endpoints, as disturbance levels can vary broadly, even with the same biome type, based on the land use management activities associated with a given unit process. The limitations associated with the use of this category indicator should be described wherever results are reported.

3.1.2.2. Identifying Core Impact Categories and Category Indicators. Due to the extensive data collection and analysis required to characterize multiple category indicators for terrestrial biome disturbance, it is essential to carefully screen the product system under study to identify those unit process(es) which are contributing to terrestrial biome disturbance. This screening should be intended to minimize the amount of data collection required, by focusing the scope of the study on stressor(s) associated with unit process(es) which are linked to terrestrial biome disturbance.

Terrestrial biome disturbance can be ruled out as a relevant impact category if there are no unit process(es) that contribute measurably to any environmental mechanism of terrestrial biome disturbance. For a given unit process, the following guidance can be used to exclude terrestrial biome disturbance as relevant:

- If the product system under study were to halt all activity, and all relevant intermediate flows throughout the entire product system were likewise stopped, no measurable change in the stressors, midpoints, or endpoints of terrestrial biome disturbance would be observed.

**FOR EXAMPLE.** The scope of a study is the assessment of an office wall, which includes components made from primary (mined) aluminum. The total annual production volume of these wall systems requires the production of 181 tons of bauxite ore from a mine located in Jamaica, which produces 4.5 million tons of bauxite ore each year. Terrestrial biome disturbance can be excluded as relevant for this product system. Even if production of all office walls were to cease, the reduction in demand of 181 tons of bauxite (0.004% of total production of the Jamaica mine) is well within market fluctuations, and will not affect any stressors, midpoints, or endpoints for terrestrial biome disturbance at the mine.

**FOR EXAMPLE.** If the scope of a study is instead the assessment of the bauxite ore mine itself, terrestrial biome disturbance will be a relevant core impact category. If all production of bauxite ore were to halt, the stressors associated with this production (i.e., excavation, creation of tailings ponds) would be affected.

- If it can be demonstrated through observation that the activities at the unit process do not contribute to a measurable alteration in ecological conditions of the affected terrestrial biome.

- If the spatial extent of the unit process is small enough that it cannot result in a measurable change to conditions in the terrestrial biome.

When conducting this screening, it is important to identify any types of unit process(es) in the product system which have been known in the past to contribute measurably to terrestrial biome disturbance. This includes land-intensive production activities, such as forestry, agriculture, and mining. Unit process(es) located in regions where terrestrial biome
disturbance is an issue of concern to regional government agencies, non-governmental
organizations, or other stakeholders, should also be identified. There will almost always be
relevant impact categories for terrestrial biome disturbance associated with these types of unit
processes.

Whether this impact category is included as relevant to a product system depends on the goal
and scope of the LCA study. When screening to determine if terrestrial biome disturbance is a
core impact category, the scale of the functional unit used shall be large enough to include
observed instances of terrestrial biome disturbance. The functional unit must not be set
arbitrarily low, which could rule out this impact category even in cases where terrestrial biome
disturbance is occurring and can be linked to a unit process. This screening will require expert
judgment, and may require sensitivity analysis.

An initial screening for the relevance of terrestrial biome disturbance as an impact category
may determine that the scale of the functional unit may need to be revised, or that goal and/or
scope may need to be revised in other ways. The exclusion of terrestrial biome disturbance as a
core impact category should be a key subject of the critical review phase.

Due to the complex data collection and analysis requirements, resources may be unavailable for
an assessment of terrestrial biome disturbance for a given LCA study. This will limit the
comparability of results. If terrestrial biome disturbance cannot be characterized, the relevant
category indicators shall be listed in the LCIA profile. The affected biome types should be
described for each in the LCA report, and in EPDs and C-EPDs.

3.1.3. Classification

Once category indicator(s) are determined to be relevant for a given unit process in the product
system under study, the spatial extent of the affected terrestrial area should be measured. The
classified area consists of all areas in which alterations in ecological conditions (i.e., terrestrial
biome disturbance) can be linked to stressor(s) associated with the unit process.

It is important that the classified area include lands that are directly affected by physical
disruption activities at a unit process as well as adjacent areas that are indirectly affected.
Generally, the portion of the classified area that is indirectly affected by an activity will be larger
than the portion that is directly affected. In the classification step, disturbance to the overall
landscape should be considered at a landscape scale, to capture all affected areas.

In many instances, three levels of affected areas can be identified to aid in classification. These
affected areas can generally be identified using publicly available satellite imagery through
software such as Google Earth. The classification of these areas can serve as a starting point in
an assessment of terrestrial biome disturbance:

1. *Areas affected by an activity through direct physical disruption.* This can include areas
affected by long-term land occupation, such as roads, dams, agriculture, or buildings. It can
also include areas affected by short-term land use, such as areas harvested during forestry,
and other land uses characterized by temporary activities.

2. *The buffer zones surrounding areas affected directly by physical disruption.* These areas can
be indirectly affected by cascading effects, as well as changes in the continuity of the biome
and by edge effects. The area of buffer zone to be included depends on the activity leading
to terrestrial biome disturbance, characteristics of the regional biome, and other
considerations.

3. The landscape as a whole. Even areas that not directly adjacent to those directly affected can
experience terrestrial biome disturbance, as a result of cascading effects and changes in the
overall continuity of the biome.

The classified area should be clearly defined geographically, with specific boundaries described.

Secondary LCI databases should not be used to classify the area affected by a given activity, for
several reasons:

- There is wide variation in the area that will be affected by a given activity, based upon the
  specific region, land use management activity, and past history of disturbance. Even the use
  of secondary LCI data for a unit process in the same region as the one under study could
  result in inaccurate and misleading results.
- Secondary LCI databases do not account for the areas that are indirectly affected, although
  these areas may dominate the area that must be classified.
- Secondary LCI databases do not account for changes in classified areas over time. The area
  affected by terrestrial biome disturbance is not static, and can change significantly even
  over short time periods.

If there are no data available for classification, satellite imagery and other techniques can be
relied upon to create first-order estimates of the area that is classified. For forestry, calculations
of per-acre timber yields, if relevant to the region and tree species under study, can be used to
calculate the areas directly affected by timber harvests. However, approaches such as these
cannot generally be used to calculate the area that is indirectly affected.

**FOR EXAMPLE.** In Northern Brazil, roughly 200,000 hectares of forest must be cleared to produce
sufficient fuelwood for the charcoal required to produce 4 million metric tons of pig iron. This estimate is
based upon the aboveground carbon content of forests in this region. Thus, 200,000 hectares of clear-cut
forest are classified under the terrestrial biome disturbance indicator for every 4 million metric tons of
pig iron produced. However, this only accounts for areas of direct disturbance, not the indirectly
disturbed areas, which are generally a much larger area.

In some instances, a classification of all affected areas will not be possible, based on limitations
in available data. In these cases, the effect on final results of these omissions should be
considered and described in the underlying LCA report and any materials made publicly
available. If the effect on the results is significant, the goal and scope of the study may need to
be revised.
3.1.4. Characterization.

3.1.4.1. Stressor Characterization Factor. As noted in Section 3.1.2.1, no aggregation is allowed between separate category indicators representing different environmental mechanisms for terrestrial biome disturbance. For a single category indicator identified according to Section 3.1.3, the classified area has an S-CF of 1.

3.1.4.2. Environmental Characterization Factor. The environmental characterization factor is called the “Biome Disturbance Factor”, or BDF. The BDF characterizes the average disturbance level across the classified area. The disturbance level is calculated based on measurements of a relevant set of ecological conditions in the classified area, which are compared to measurements of these conditions in fully disturbed and undisturbed reference areas. The BDF thus assesses the ecological conditions in the classified area, on the full spectrum of possible conditions.

The BDF is a unitless number from 0 to 1, but is usually expressed as a percentage value.

Generally, there are several iterative steps in characterization of the BDF for the classified area:

- selection of the reference areas;
- selection of ecological conditions used to represent terrestrial biome disturbance; and
- characterization of disturbance.

Each of these steps requires careful consideration and expert judgment, and the specific methods used should be a key subject of any critical review. The methods used should be reviewed by a trained field ecologist.

3.1.4.2.1. Selection of Reference Areas. The first step in characterization is the selection of the two reference areas. These areas are located within the same terrestrial biome as the classified area, and are as similar as possible to the classified area in terms of location, climate, topography, and land cover. The difference in these reference areas is the ecological conditions:

- The fully disturbed reference area. This reference area provides little or no ecosystem services to any species of flora or fauna.
- The undisturbed reference area. This reference area has not been affected by anthropogenic activities. Although it may have been affected by natural disturbance events which commonly occur in the terrestrial biome (e.g., wildfires), it has also been unaffected by rare, but catastrophic, natural events such as a tsunami, volcanic eruption or meteor strike.

In practice, there will rarely be reference areas available which can truly be said to be fully disturbed or undisturbed according to these definitions. Even permanently occupied areas will experience regrowth of flora, albeit to a limited degree, and provide some ecosystem services to some species. Conversely, even primary-growth reference areas in extremely remote regions never affected by any resource extraction are still affected by anthropogenic climate change.

Therefore, the selection of the reference areas will always entail a careful consideration of possible alternatives that can best represent the idealized definitions of “fully disturbed” and “undisturbed”. Most commonly, reference areas are defined by choosing representative areas close to the classified area. The fully disturbed reference area can be represented by occupied...
areas experiencing significant permanent disturbance (e.g., the interior of open pit mines, or paved areas), or by areas which have just experienced a significant disturbance event, whether it be natural or anthropogenic (e.g., a forested area which just experienced a catastrophic wildfire or clear-cut). The undisturbed reference area can be represented by mature set-side areas, such as national parks.

The final results for terrestrial biome disturbance are very sensitive to the selection of the two reference areas. Sensitivity analysis should be a key part of this selection process. If the study is intended for use in an Environmental Product Declarations (EPD), the selection process of reference areas should be specified in the relevant Product Category Rule (PCR). For LCA studies not used for EPDs, a justification of the reference areas selected must be provided, along with a clear description of its boundaries and the data sources used in its characterization.

3.1.4.2.2. Selection of Measurements of Ecological Conditions to be Included. Disturbance is calculated through a quantitative comparison of measurements of ecological conditions in the classified area and the two reference areas. The ecological conditions selected represent the key conditions in the affected terrestrial biome. Selection of the ecological conditions to be included in the comparison, and the data sources to be used, is a key part of the assessment, and requires careful consideration and expert judgment. As much as possible, sensitivity analysis should be used to assess the effect on final results of using different ecological conditions, measurements, and data sources. The selection of these conditions should be based on a careful review of the stressor-effects network and characteristics of the terrestrial biome.

In cases where measurements of ecological conditions are already available for the two reference areas and the classified area, the following steps can be used to guide a selection of the ecological conditions to be included in the study:

- The available data sources, and measurements of various conditions that could be included, should be reviewed. A list of measurements available for each reference area and the study area should be created, noting the data source, uncertainty (expressed as a confidence interval, if possible), and date of each measurement.
- A set of measurements should be selected which assess ecological conditions relevant to the regional biome. These measurements should be available for conditions in the classified area, and both reference areas.
- This set of measurements should be validated to determine their suitability for use. Some of the factors considered in the validation include: the uncertainty in each measurement at each site; the magnitude of difference in measurements between each site; whether there is a statistically significant difference in conditions in the fully disturbed and undisturbed reference area (if not, the measurement may not be suitable for use); and the number of sample sites included in the measurement.
- Based on this validation step, the list of measurements to be included in the calculation of disturbance may need to be refined.
- The final list of measurements used in the calculation for biome disturbance should be reported. Conditions in the two reference areas and area under study shall be included in the LCA report.

In cases where measurements of ecological conditions are not available for either one of the two reference areas, or the classified area, measurements will have to be conducted to complete an assessment of terrestrial biome disturbance. The process of selecting the measurements to
include should follow the same general steps of selection, validation, and iterative refinement. On-site sampling may be required. This sampling should consider the goal and scope of the LCA study.

In all cases, the geographical distribution of sampling points used to measure ecological conditions should be understood to the extent possible. Measurements shall only be used if they have sufficient geographical coverage across the classified area, for both directly and indirectly affected areas. If stressor(s) are leading to extensive fragmentation of a terrestrial biome, the disturbance levels in indirectly affected areas can be very high. In some cases, the disturbance levels in such areas could be comparable to those in areas that are directly affected.

In some instances, measurements of all desired ecological conditions may not be available. In these cases, omitted measurements of ecological conditions must not result in significant changes to the resulting terrestrial biome disturbance. Any expected biases and/or increases in uncertainty should be described in the LCA report. If omitted measurements have a significant effect on final indicator results, the goal and scope of the LCA may need to be revised.

In extreme cases, where no measurements are available, the category indicator for terrestrial biome disturbance must be assessed at Node 1, including only the measurement of the spatial extent of the classified area. Results calculated at Node 1 are not comparable.

In the underlying LCA report, the list of measurements of ecological conditions that were included shall be described, as well as those that were excluded. For EPDs, the PCR should describe the ecological conditions to be included.

### 3.1.4.2.3. Characterization of Biome Disturbance Factor

To assess the BDF, the average disturbance level across the classified area is assessed. There are three steps:

- The measurements of each ecological condition are independently averaged across the classified area, the undisturbed reference area, and the fully disturbed reference area.
- These average measurements in are compiled into three independent sets of data, representing conditions in each of the reference areas and the classified area. The uncertainty (expressed as a confidence interval, if possible) associated with each average measurement shall also be compiled.
- The averaged measurements are normalized to units which are comparable between the fully disturbed reference area, the undisturbed reference area, and the study area. Depending on the type of measurement, this normalization is usually on a per-acre basis.

**FOR EXAMPLE.** The measurements of total aboveground biomass, measured in tons, is normalized to tons of biomass per acre, each for the fully disturbed reference area, undisturbed reference area, and area under study.

These steps will result in three average values for each measurement of an ecological condition, including values for the fully disturbed reference area, the undisturbed reference area, and the classified area. The uncertainty associated with these measurements should be considered. If the uncertainty is very high, a revision to the list of included measurements may be required.

Once all of the measurements of ecological conditions have been compiled, the average conditions in the classified area are compared to the undisturbed and fully disturbed reference
areas. The numerical deviation of each measurement is assessed, which is a unitless number from 0 to 1 often expressed as a percentage, representing the condition of the classified area when compared to the fully disturbed and undisturbed reference areas. A deviation value of “1” for a measurement corresponds to the classified study area being fully disturbed in the ecological condition; a deviation value of “0” corresponds to the undisturbed state.

For a given ecological condition, several approaches can be used to assess the deviation in conditions in the classified area.

- **Linear comparison.** The deviation is calculated by taking the difference between the average measurement value in the undisturbed reference area and the classified area. This difference is then divided by the difference between the measured value in the undisturbed and fully disturbed reference areas. The absolute value of this ratio is taken, to assess a positive deviation value, from 0 to 1.

**FOR EXAMPLE.** At a forestry operation in Northern California, the measurement of the number of trees greater than 29” in diameter was one of the ecological conditions included. In the fully disturbed reference area, measurements showed that there were 1.3 trees per acre; in the study area, 7.8 trees per acre; in the undisturbed reference area, 23 trees per acre. The difference between the undisturbed and reference area is 15.2 trees per acre, and between the undisturbed and fully disturbed reference areas, 21.7 trees per acre. Dividing these two values, the deviation value for this condition is 0.7, or 70%.

- **Threshold approach.** A specific threshold is chosen for a given condition, based on the condition in the undisturbed and/or fully disturbed reference area. If the condition in the study area meets this threshold, the deviation is 0; if it does not meet this threshold, the deviation is 1.

- **Other approaches.** Other approaches could be used to assess the deviation for each measurement. These approaches could use a nonlinear equation to calculate the deviation, or other functions.

Whichever approach is used, it must be described in the LCA report. For EPDs, the approach used should be based upon the PCR.

To assess the average disturbance level and the BDF, the average of all deviation measurements is taken. The confidence interval can then be assessed, based upon the standard deviation of all the deviation values. An example of the calculation of disturbance for a forest site in the United States Southeast is shown below in Table 3.2. This example is calculated using the linear approach to calculating deviation.
Table 3.2. Calculating the Biome Disturbance Factor for a Forest Site in the United States Southeast

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Units</th>
<th>Fully Disturbed Reference Area</th>
<th>Study Area</th>
<th>Undisturbed Reference Area</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon in litter</td>
<td>tons per acre</td>
<td>2.9</td>
<td>3.5</td>
<td>5.1</td>
<td>76%</td>
</tr>
<tr>
<td>Carbon in live trees (belowground)</td>
<td>tons per acre</td>
<td>2.1</td>
<td>2.6</td>
<td>4.3</td>
<td>77%</td>
</tr>
<tr>
<td>Carbon in live trees (aboveground)</td>
<td>tons per acre</td>
<td>9.2</td>
<td>11.5</td>
<td>18.8</td>
<td>76%</td>
</tr>
<tr>
<td>Number of trees</td>
<td># of trees per acre</td>
<td>577.7</td>
<td>410.6</td>
<td>289.2</td>
<td>42%</td>
</tr>
<tr>
<td>Percent of trees longleaf-slash pine</td>
<td>Percent</td>
<td>46%</td>
<td>48%</td>
<td>74%</td>
<td>93%</td>
</tr>
<tr>
<td>Percent of trees loblolly-shortleaf pine</td>
<td>percentage</td>
<td>30%</td>
<td>29%</td>
<td>0%</td>
<td>98%</td>
</tr>
<tr>
<td>% stands &lt; 40 years old</td>
<td>Percent</td>
<td>100%</td>
<td>91%</td>
<td>39%</td>
<td>86%</td>
</tr>
<tr>
<td>% stands &lt; 60 years old</td>
<td>Percent</td>
<td>100%</td>
<td>100%</td>
<td>47%</td>
<td>100%</td>
</tr>
<tr>
<td>% stands &lt; 80 years old</td>
<td>Percent</td>
<td>100%</td>
<td>100%</td>
<td>96%</td>
<td>100%</td>
</tr>
<tr>
<td>Connectance</td>
<td>Percent</td>
<td>0.3</td>
<td>0.3</td>
<td>0.5</td>
<td>100%</td>
</tr>
<tr>
<td>Patch Cohesion Index</td>
<td>Percent</td>
<td>87.9</td>
<td>91.9</td>
<td>99</td>
<td>64%</td>
</tr>
<tr>
<td>Division</td>
<td>Percent</td>
<td>1</td>
<td>1</td>
<td>0.7</td>
<td>100%</td>
</tr>
<tr>
<td>Mesh</td>
<td>hectares</td>
<td>15.8</td>
<td>88.4</td>
<td>1145</td>
<td>94%</td>
</tr>
<tr>
<td>Split</td>
<td>Number</td>
<td>268.6</td>
<td>109</td>
<td>3.7</td>
<td>40%</td>
</tr>
<tr>
<td>Patch richness</td>
<td>Unitless</td>
<td>28</td>
<td>21</td>
<td>9</td>
<td>63%</td>
</tr>
<tr>
<td>Shannon's diversity index</td>
<td>Unitless</td>
<td>2.5</td>
<td>2.3</td>
<td>1.1</td>
<td>86%</td>
</tr>
<tr>
<td>Shannon's evenness index</td>
<td>Unitless</td>
<td>0.8</td>
<td>0.7</td>
<td>0.4</td>
<td>75%</td>
</tr>
<tr>
<td>Aggregation Index</td>
<td>Unitless</td>
<td>62.5</td>
<td>63.3</td>
<td>82.7</td>
<td>96%</td>
</tr>
</tbody>
</table>

Average Disturbance Level (Biome Disturbance Factor) 81% ± 19%

3.1.5. Indicator Equation and Unit of Measure. For disturbance caused by a given unit process in a single biome, the indicator result is calculated using Equation 3.1. The result is expressed in units of equivalent acres of fully disturbed biome.

Equation 3.1. Indicator result for terrestrial biome disturbance.

Terrestrial Biome Disturbance = Classified Acres × Biome Disturbance Factor
3.1.6. Additional Reporting Requirements. The results in this impact category and the other impact categories in the Land Use Ecological Impacts group are unique, in that the indicator results do not vary with production levels on the site. Even if all stressors associated with a given unit process were to stop, and all production cease, in most situations, it would take decades for the disturbance levels to decline across the classified area. As a result, indicator results normalized to production volumes (i.e., intermediate flows) can be misleading.

*FOR EXAMPLE.* At a 160,000-acre forestry site in Northern California composed of redwood, Douglas fir, and tanoak, historical practices based mainly in intensive clear cutting were changed to use only minimal selective harvests, during a change of ownership. During the clear cutting era, production was at an average level of roughly 160 million board feet each year; this decreased to 25 million board feet per year under the selective harvest regime. The practice of intensive clear cutting left the forest in an elevated state of disturbance, with a BDF of approximately 70%. Although the policy of selective harvests will result in eventual recovery to the forest biome, no recovery was observable 5 years after operations began, due to the long time period required for recovery of this type of forest biome. Therefore the indicator result assessed a gross scale is 112,000 equivalent acres of fully disturbed forest biome, during both the current period of selective harvests, and during the period of intensive clear cutting. If this result were normalized to production of million board feet each year, the forestry practice which caused the elevated disturbance levels would have a result six times lower than the current operator. This result is extremely misleading, as it would lead a user to believe that the current practices of selective harvests (which are promoting biome recovery) have a higher result for terrestrial biome disturbance than the intensive clear cutting which caused the elevated disturbance levels. Therefore, results cannot be presented normalized to production volume.

The functional unit should be scaled such that the total extent of area of terrestrial biome affected by unit process(es) in the product system is included and reported in final results. Results should not be normalized to production volume on the site.

Meaningful comparisons for terrestrial biome disturbance can only be drawn if the scale of functional unit is reflective of the spatial scale of biome disturbance linked to activities associated with unit process(es) in the study scope, considering the entire classified area. When making comparisons, the current disturbance level, past history of disturbance at the sites under study, current practices, and anticipated trends in disturbance levels, must be considered. Expert judgment will be required to appropriately define the scope of the study such that comparisons are justified.

The BDF, expressed as a percentage, and extent of classified area shall be reported along with the indicator result, in the LCIA profile.

In addition, the trend in average disturbance levels over time at the site must be described, including both the past disturbance and expected future trends, in the LCA report, and in EPDs and C-EPDs. If data are unavailable for a quantitative characterization of BDFs over time at a site, then a qualitative description of the expected trends in disturbance can be included.

3.1.7. Addressing Limitations in the Types, Accuracy, and Availability of Environmental Data. Due to the complex data collection and analysis requirements, resources may be unavailable for an assessment of terrestrial biome disturbance for a given LCA study. This will limit the comparability of results.
In cases where data are unavailable for an accurate characterization, the list of category indicators representing distinct environmental mechanisms for terrestrial biome disturbance (identified according to the requirements of Sections 3.1.2.1 and 3.1.2.2) shall be provided. This list will provide a large amount of information in the LCIA profile regarding impacts to terrestrial biomes.

If data are unavailable to identify affected terrestrial biomes, the comparability of results will be limited significantly. The goal and scope of the study may need to be revised.

3.2. Freshwater Biome Disturbance

3.2.1. Impact Category. This impact category addresses the disturbance to freshwater biomes associated with a product system.

In this Standard, a freshwater biome is defined as an interconnected biotic community, including watercourses, lakes, wetlands, and adjacent riparian areas, within specific watershed boundaries, defined by: salinity; turbidity; water temperature; sedimentation rates; sediment size distribution; flow rates; depths; channel contours; hydrology and hydraulics; water quality; watershed area; tributary areas; stream lengths; presence of large woody debris; riparian canopy cover; riparian zone vegetative species composition; climate; and geology.

In this Standard, disturbance to a freshwater biome is considered separately by watershed, and is defined as the measurement of the overall ecological conditions in watercourses, lakes, wetlands, and adjacent riparian areas, when compared to undisturbed conditions in that watershed, and fully disturbed conditions in that watershed.

The level of freshwater biome disturbance associated with different unit processes will vary widely, depending on factors such as land use management practices, regional biome, history of the landscape, duration of disturbance, and scale of disturbance. Likewise, the midpoints and endpoints associated with this impact category vary for all of these reasons. Accordingly, site-specific assessment of freshwater biome disturbance associated with a unit process is required. Secondary data shall not be used in the assessment of freshwater biome disturbance.

3.2.2. Stressor-Effects Networks. The stressor-effects network for freshwater biome disturbance is distinct for disturbance caused by each unit process. The stressors affecting freshwater biome disturbance vary widely, and the resulting midpoints and endpoints for disturbance within each freshwater biome are distinct. Stressors can be related to activities at unit process(es) considered in the product system under study, but also can also be associated with unit processes outside of the scope of the LCA.

The stressor-effects network for freshwater biome disturbance, shown in Table 3.3, provides a general framework. A separate stressor-effects network shall be modeled and described for each separate indicator included for freshwater biome disturbance within the study scope. The specific stressor-effects network should describe the site-specific circumstances of stressors, midpoints, and endpoints in the environmental mechanism in the classified watershed. This should consider the past history of disturbance and land management in the region, current management practices, and other considerations relevant to the cause-effects chain. Additionally, the characteristics of the affected freshwater biome should be reported and
described, including but not limited to data such as the total watershed area, and length of watercourses, when data are available. This detailed modeling of the stressor-effects network will greatly aid in the characterization of each category indicator considered in this impact category.

Table 3.3. Stressor-Effects Network for Freshwater Biome Disturbance.

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Stressors)</td>
<td>A freshwater biome is affected by land use management activities, including direct stressors, such as construction of stream crossings and changes to hydrology, and indirect stressors, such as increased sedimentation resulting from land clearing. This leads to incremental changes in ecological conditions.</td>
<td>High uncertainty. Characterization does not consider variability inherent in the conditions in freshwater biomes, or alterations in conditions in freshwater biome.</td>
<td>Low uncertainty. Data requirements: Varies by stressor. Examples include: increase in sedimentation rates, or number of stream crossings per mile.</td>
</tr>
<tr>
<td>2 (Endpoints)</td>
<td>Freshwater biome disturbance, defined as measurements of changes in ecological conditions in the freshwater biome of the classified watershed under study.</td>
<td>Low uncertainty. Direct characterization of freshwater biome disturbance.</td>
<td>Low uncertainty. Data requirements: Measurements of ecological conditions in affected watershed. Measurements or projections of conditions in undisturbed and fully disturbed condition for that freshwater biome.</td>
</tr>
<tr>
<td>3 (Endpoints)</td>
<td>Ecosystem disturbance: Alterations in the regional interconnected ecosystem, caused by effects to terrestrial, freshwater, and wetlands biomes, the presence of key species, and other impacts.</td>
<td>Low uncertainty. Direct characterization of ecosystem disturbance.</td>
<td>Little or no data are available to measure the disturbance of overall ecosystem health.</td>
</tr>
</tbody>
</table>

The disturbance of a freshwater biome is considered an endpoint in its own right; however, this endpoint is also linked to the endpoints and midpoints of other stressor-effects networks, including those related to disturbance to other biome types (e.g., terrestrial and wetlands) and habitats. The endpoint of ecosystem disturbance is affected by midpoints and endpoints of all of the affected biomes and habitats.

3.2.2.1. Selection of Category Indicator(s). Separate category indicators shall be reported for disturbance to each distinct freshwater biome within specific watershed boundaries affected by unit process(es) within the product system under study. This reflects the distinct nature of each freshwater biome experiencing disturbance. No aggregation of results is allowed between distinct category indicators.
Category indicators for freshwater biome disturbance are defined for each unit process in the product system that contributes measurably to any environmental mechanism of freshwater biome disturbance. It is important that the selected category indicators include all freshwater biomes that are directly affected by physical disruption activities at a unit process, and adjacent areas that are indirectly affected. Generally, if this impact category is relevant for a given unit process, there will be multiple environmental mechanisms relevant for freshwater biome disturbance, and therefore, multiple category indicators.

The specific watershed boundaries used to delineate each freshwater biome can be defined on multiple levels, depending on the hydrological characteristics of the region, and the level of data available. These levels range from the regional scale, where watersheds are defined on the scale of hundreds of millions of acres, to the sub-watershed level, where watersheds are defined on the scale of thousands of acres.

**NOTE.** These multiple levels of watersheds are “nested”, such that multiple smaller watersheds exist within the boundaries of a single larger watershed. The hierarchical definitions of each level of watershed depend upon the watershed classification techniques used.

When classifying the category indicators for freshwater biome disturbance, the level of watershed selected must be based upon the stressor-effects network of disturbance. This, in turn, depends on the spatial scale of the stressors affecting the freshwater biome. Generally, the area of the watershed used should roughly match the spatial extent of the stressor(s) leading to freshwater biome disturbance.

**FOR EXAMPLE.** In even-aged forestry, harvests are performed by clear-cuts, which are generally never more than one thousand acres in size, with harvests spread out in multiple parts of the landscape. Disturbance to freshwater biomes occurs on a corresponding spatial scale. Category indicators should therefore be based upon sub-watersheds, which generally match the scale of thousands of acres.

**FOR EXAMPLE.** In iron ore mining, the creation of open pit mines and tailings ponds will directly and indirectly affect tens of thousands to hundreds of thousands of acres. The scale of the watershed should match this spatial scale.

When identifying the specific watershed boundaries that delineate each freshwater biome disturbed by a given unit process, spatial mapping will be required. In this mapping, the watersheds in which stressors are present must be identified. The mapping of watershed boundaries should use existing datasets, such as provided by government agencies or other parties (e.g., the US Geological Survey’s Watershed Boundary Dataset). Generally, such datasets are freely available, though the data quality and level of watershed specificity will vary. The data quality of the dataset used should be considered in the context of the goal and scope of the study.

**NOTE.** Advanced software tools such as ArcGIS can help this analysis, but are not required. Coarse imagery provided by Google Earth or the US Geological Survey’s National Atlas can be used.
In some cases, the available data will not be sufficiently granular to define a comprehensive set of watershed boundaries at the spatial scale matching the stressor(s) associated with a given unit process. In these cases, the best available data should be used to define watershed boundaries. In addition, it shall be noted in the LCA report and EPDs and C-EPDs that the number of watersheds affected is underreported. The effect on final results should be considered in the context of the goal and scope of the LCA. Comparisons cannot be based on results where the number of affected category indicators is significantly understated.

**FOR EXAMPLE.** In Northern Brazil, there is extensive deforestation associated with the production of timber products and fuelwood for charcoal. This deforestation is occurring as a result of clear-cuts which are at most one thousand acres in size, and the watershed assessment should be consistent with this scale. However, the dataset available for this region only provides comprehensive watershed boundaries defined at the regional scale, with watersheds between 2.5 million and 25 million acres in size. Results must report the affected watersheds to the best extent available, and note that the number of affected watersheds is understated.

Disturbance shall be characterized at Node 2, if data is available — i.e., characterizing freshwater biome disturbance by measuring alterations in ecological conditions in the freshwater biome when compared to the undisturbed and fully disturbed condition. This will require on-site monitoring across a representative area of the biome, according to recognized techniques in field ecology.

In many cases, site data will be unavailable to assess freshwater biome disturbance. In these cases, measurements related to stressors could be made at Node 1.

In cases where data are unavailable for characterization at Node 1 or Node 2, the list of category indicators representing distinct environmental mechanisms for freshwater biome disturbance shall be reported in the LCIA profile.

### 3.2.2.2. Identifying Core Impact Categories and Category Indicators

Due to the extensive data collection and analysis required to characterize multiple category indicators for freshwater biome disturbance, it is essential to carefully screen the product system under study to identify the unit process(es) contributing to freshwater biome disturbance. This screening is intended to minimize the amount of data collection required by focusing the scope of the study on stressor(s) associated with a product system that are linked to freshwater biome disturbance.

Freshwater biome disturbance can be ruled out as a relevant impact category if no unit process(es) in the product system contribute measurably to any environmental mechanism of freshwater biome disturbance. For a given unit process, the following guidance can be used to exclude freshwater biome disturbance as relevant:

- If the product system under study were to halt all activity, and all relevant intermediate flows throughout the entire product system were likewise stopped, no measurable change in the stressors, midpoints, or endpoints of freshwater biome disturbance would be observed.
- If it can be demonstrated through observation that the activities at the unit process do not contribute to a measurable alteration in ecological conditions of any freshwater biome.
• If the spatial extent of the unit process is small enough in relation to the affected watershed that it cannot result in a measurable change to ecological conditions in any freshwater biome.

If freshwater biome disturbance is excluded for these or other reasons, the reasons should be stated and justification provided for the exclusion in the LCA report.

When conducting this screening, it is important to identify any types of unit process(es) in the product system which have been known in the past to contribute measurably to freshwater biome disturbance. This includes land-intensive production activities, such as forestry and mining. Unit process(es) located in regions where freshwater biome disturbance is an issue of concern to regional government agencies, non-governmental organizations, or other stakeholders should also be identified. In some situations, regulatory agencies will set specific requirements intended to protect the integrity of freshwater biomes within specific watersheds, by controlling land use management activities associated with a unit process. These types of unit processes should be considered for inclusion in the scope.

The scale of the functional unit used in the screening should be large enough to include observed instances of freshwater biome disturbance. The functional unit shall not be set arbitrarily low, which could rule out this impact category even in cases where freshwater biome disturbance is occurring and can be linked to a unit process(es).

The geographical scope of the study should also be sufficient to identify where freshwater biome disturbance is occurring and can be linked to a unit process(es) in the product system. This screening will take expert judgment, and may require sensitivity analysis.

An initial screening for the relevance of freshwater biome disturbance as an impact category may determine that the scale of the functional unit may need to be revised, or that goal and/or scope may need to be revised in other ways. Any exclusion of freshwater biome disturbance as a core impact category should be a key subject of the critical review phase.

Due to the complex data collection and analysis requirements, resources may be unavailable for an assessment of freshwater biome disturbance for a given LCA study. This will limit the comparability of results. If freshwater biome disturbance cannot be characterized, the relevant category indicators shall be included in the LCIA profile. The areas of the affected watersheds for each should be provided in the LCA report, and in EPDs and C-EPDs, if data are available. A disclaimer shall be included explaining the limitations of comparability in EPDs and C-EPDs.

3.2.3. Classification. Once category indicator(s) are determined to be relevant for a given unit process in the product system under study, the affected watershed should be mapped out, and its spatial extent measured. For each given category indicator, there is a distinct classified watershed.

The data required for mapping and classification are readily available in hydrological datasets. It can also be useful to understand additional characteristics of the freshwater biome, such as length of watercourses, area of riparian zones, and number of lakes.

In some cases, a classification of all affected watersheds experiencing freshwater biome disturbance will not be possible, based on limitations in available data. In these cases, the effect
on final results of these omissions should be considered and described in the underlying LCA report and any materials made publicly available. If the effect on the results is significant, the goal and scope of the study may need to be revised.

3.2.4. Characterization

3.2.4.1. Stressor Characterization Factor. As noted in Section 3.2.2.1, no aggregation is allowed between separate category indicators representing different environmental mechanisms for freshwater biome disturbance. The S-CF is 1 for all indicators.

3.2.4.2. Environmental Characterization Factor. The environmental characterization factor is called the biome disturbance factor (BDF). The BDF characterizes the average disturbance level across a freshwater biome, including all interconnected watercourses, lakes, wetlands, and adjacent riparian areas, within specific watershed boundaries. The disturbance level is calculated based on measurements for a relevant set of ecological conditions compared to fully disturbed and undisturbed reference conditions. The BDF is a unitless number from 0 to 1, but is usually expressed as a percentage value.

Generally, there are several iterative steps in characterization of freshwater biome disturbance:

- selection of measurements of ecological conditions used to represent freshwater biome disturbance;
- definition of the undisturbed and fully disturbed reference conditions; and
- characterization of the BDF.

All of these steps require careful consideration and expert judgment, and the specific methods used should be a key subject of any critical review. The methods should be reviewed by a trained field ecologist.

In some cases, monitoring of conditions in freshwater biomes at a site may be required by local regulatory agencies. Characterization should take advantage of monitoring that has already been completed, to streamline data collection and improve the accuracy and consistency of results.

3.2.4.2.1. Selection of Measurements of Ecological Conditions. A set of measurements of ecological conditions must be selected to use as the basis of characterization. Disturbance is calculated through a quantitative comparison of measurements of ecological conditions in the freshwater biome to reference conditions.

The ecological conditions selected represent the key conditions in the affected freshwater biome. During the selection process, the stressor-effects network and freshwater biome definition should be reviewed. In some cases, the required conditions of habitats for indicator species could be used as a proxy. In cases where monitoring of ecological conditions in a freshwater biome is already required by local regulatory agencies, the set of conditions used in that application can be adapted to streamline data collection.

In the LCA report, the list of measurements of ecological conditions that were included shall be described, as well as a list of measurements that were excluded. For EPDs and C-EPDs, the PCR...
shall specify the ecological conditions to be included. If there are limitations in the available data, this should be noted in the LCA report.

Once ecological conditions have been selected, measurements of each condition are to be conducted across a representative set of monitoring locations in the classified watershed. Measurements shall be used only if they have sufficient geographical coverage to accurately represent conditions in the freshwater biome.

Wherever possible, measurements which have already been collected should be used to streamline data collection. These measurements may have been conducted as a result of mandatory regulatory requirements or for other purposes.

If primary data collection is required, a monitoring plan and sampling schedule must be implemented, and measurements conducted according to clearly described procedures, all of which must be described in the LCA report. This process should be in accordance with common practices in field ecology.

3.2.4.2.2. Definition of Undisturbed and Fully Disturbed Reference Conditions. The fully disturbed and undisturbed reference conditions are defined according to two possible states within the freshwater biome, as follows:

- **The fully disturbed reference conditions.** These reference conditions are a state in which the freshwater biome provides little or no ecosystem services to any species of flora or fauna.

- **The undisturbed reference conditions.** These reference conditions are equivalent to the condition in the freshwater biome if it were unaffected by anthropogenic activities. Although it may have been affected by natural disturbance events which commonly occur in the freshwater biome, it is unaffected by rare but catastrophic natural events, such as a tsunami, volcanic eruption or meteor strike.

For each monitoring site in the freshwater biome, values for the fully disturbed and undisturbed reference conditions must be specified for each ecological condition, taking into account differences in sites (e.g., channel width, gradient, depth).

Measurements of conditions in the freshwater biome at each site are compared against these fully disturbed and undisturbed reference conditions. These reference conditions can be defined based upon conditions in an adjacent watershed, or can be based upon minimum requirements for suitable habitat for indicator species.

**FOR EXAMPLE.** At a site in Northern California, measurement of ecological conditions in a freshwater biome includes the monitoring of the total piece frequency of large woody debris in streams. The undisturbed condition for large woody debris is defined at each sampling site, and depends upon the channel width at that site. At one site, the undisturbed condition is defined as at least 6.22 pieces per 100 feet, while at another site, the undisturbed condition is defined as at least 7.15 pieces per 100 feet.
3.2.4.2.3. Characterization of Biome Disturbance Factor. To assess the BDF, the deviation in conditions for ecological variables at each monitoring site is assessed, compared to the undisturbed and fully disturbed conditions. One deviation measurement is considered for each monitoring site and each ecological condition: a deviation value of “1” for a measurement corresponds to the site being fully disturbed, while a deviation value of “0” corresponds to the undisturbed state. The deviation can be expressed on a continuum from 0 to 1, for intermediate conditions.

This deviation can also be assessed using a threshold approach, where a condition at a site is compared to a threshold defined based upon the undisturbed state. If the condition meets this threshold, the deviation is 0; if it does not meet this threshold, the deviation is 1.

Other approaches can be used to assess the deviation for each measurement. Whichever approach is used, it must be described in the LCA report. For EPDs, the approach used should be based upon the PCR.

To assess the BDF, the deviation in all conditions at all sites is considered. It can be evaluated as an average of these deviation measurements, or by another approach. Whichever approach is used, it must be described in the LCA report. For EPDs, the approach used should be based upon the PCR.

3.2.5. Indicator Equation and Unit of Measure. The indicator results for a single category indicator characterizing disturbance caused by a given unit process are determined based on Equation 3.2. The result is the BDF from 0 to 1, which can be expressed as a percentage.

Equation 3.2. Indicator equation for freshwater biome disturbance.

Freshwater Biome Disturbance = Biome Disturbance Factor

3.2.6. Additional Reporting Requirements. The results in this impact category and the other impact categories in the Land Use Ecological Impacts group are unique, in that the indicator results do not vary with production levels on the site. Even if all stressors associated with a given unit process were to stop, and all production cease, in most situations, it would take decades for the disturbance levels to decline.

As a result, for Freshwater Biome Disturbance, indicator results normalized to production volumes (i.e., intermediate flows) are misleading. The BDF for Freshwater Biome Disturbance for a given category indicator (i.e., watershed biome) must be expressed as a gross value, regardless of the scale of the functional unit. As required by ISO 14044, results are expressed relative to the functional unit; however, results are invariant to its scale. The BDF, expressed as a percentage, shall be reported, if data are available for its characterization.

Regardless of whether the BDF is reported, the complete list of category indicators noting watersheds affected by freshwater biome disturbance shall be included in the LCIA profile. If the BDF cannot be characterized, the stressor(s) causing disturbance, and observed conditions of midpoints, should be described in the LCA report and in EPDs and C-EPDs, so as to provide information on the stressor-effects network. The stressor-effects network itself shall be included in any LCA report.
In addition, the trend in average disturbance levels over time in the freshwater biome should be described, including both the past disturbance and expected future trends, in any public disclosure of the results. Due to the high relevance of past activities at a site, this must be included. If data are unavailable for a quantitative characterization of BDFs over time in freshwater biome, then a qualitative description of the expected trends in disturbance can be included.

3.2.7. Addressing Limitations in the Types, Accuracy, and Availability of Environmental Data. Due to the complex data collection and analysis requirements, resources may be unavailable for an assessment of freshwater biome disturbance for a given LCA study. This will limit the comparability of results.

In cases where data are unavailable for an accurate characterization, the list of category indicators representing distinct environmental mechanisms for freshwater biome disturbance (identified according to the requirements of Sections 3.2.2.1 and 3.2.2.2) shall be provided. This list will provide a large amount of information in the LCIA profile regarding impacts to freshwater biomes.

If data are unavailable to identify affected freshwater biomes, the comparability of results will be limited significantly, and it may not be possible to achieve the goals of the study. The goal and scope of the study may need to be revised.

3.3. Wetland Biome Disturbance

3.3.1. Impact Category. This impact category addresses the disturbance to wetland biomes that can be associated with a product system.

In this Standard, a wetland biome is defined as a biotic community in a specific wetland, defined by: salinity; turbidity; water quality; sedimentation rates; sediment size distribution; flow rates; depths; hydrology; vegetative cover; plant structure (if plants are present); bottom particle composition and structure; channel connectivity; channel complexity; tidal action (for saltwater wetlands); wave action (for saltwater wetlands); and climate.

In this Standard, disturbance to a wetland biome is defined as the measurement of the overall ecological conditions in the wetland under study when compared to undisturbed conditions (i.e., unaffected by anthropogenic activities) and fully disturbed conditions (i.e., maximally disturbed).

The degree, scale, and duration of wetland biome disturbance associated with different unit processes will vary broadly, depending on factors such as the land use management practices, regional biome, history of the landscape, duration of disturbance, and scale of disturbance. Likewise, the midpoints and endpoints associated with this impact category vary widely. Accordingly, site-specific assessment of wetland biome disturbance associated with a unit process is required. Secondary data shall not be used in the assessment of wetland biome disturbance.

3.3.2. Stressor-Effects Networks. The stressor-effects network for wetland biome disturbance is distinct for disturbance caused by each unit process. The stressors affecting wetland biome disturbance vary widely, and the resulting midpoints and endpoints for
disturbance within each wetland biome are distinct. Stressors can be related to activities at unit process(es) considered in the product system under study, but also can also be associated with unit processes outside of the scope of the LCA.

The stressor-effects network for wetland biome disturbance, shown in Table 3.4, provides a general framework. A separate stressor-effects network shall be modeled and described for each separate indicator included for wetland biome disturbance within the study scope. The specific stressor-effects network should describe the site-specific circumstances of stressors, midpoints, and endpoints in the cause-effect relationship in the wetland under study. This should consider the past history of disturbance and land management in the classified area, current management practices, and other considerations relevant to the cause-effects chain. Additionally, the characteristics of the affected wetland biome should be reported and described, including, but not limited to, the watershed in which it is located, area of the affected wetland, the wetland type (e.g., forested wetland, emergent wetland, saltwater estuary). This detailed modeling of the stressor-effects network will greatly aid in the characterization of each category indicator considered in this impact category.

Table 3.4. Stressor-Effects Network for Wetland Biome Disturbance.

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Stressors)</td>
<td>A wetland biome is affected by land use management activities, including direct stressors, such as construction of dikes and dams, and indirect stressors, such as increased sedimentation resulting from land clearing upstream. This leads to incremental changes in ecological conditions in the wetland biome.</td>
<td>High uncertainty. Characterization does not consider variability in the conditions in wetland biomes, or alterations in conditions in wetland biomes.</td>
<td>Low uncertainty. Data requirements: Varies by stressor. Examples include: increase in sedimentation rates; reduction in presence of large woody debris; presence of dams and dikes.</td>
</tr>
<tr>
<td>2 (Endpoints)</td>
<td>Wetland biome disturbance, defined as measurements of changes in ecological conditions in the wetland biome.</td>
<td>Low uncertainty. Direct characterization of wetland biome disturbance.</td>
<td>Low uncertainty. Data requirements: Measurements of ecological conditions in affected wetland. Measurements or projections of conditions in undisturbed and fully disturbed condition for that wetland biome.</td>
</tr>
<tr>
<td>3 (Endpoints)</td>
<td>Ecosystem disturbance: Alterations in the regional interconnected ecosystem, caused by effects to terrestrial, freshwater, and wetlands biomes, the presence of key species, and other impacts.</td>
<td>Low uncertainty. Measurements directly characterize the endpoint of ecosystem disturbance.</td>
<td>Little or no data are available to measure the disturbance of overall ecosystem health.</td>
</tr>
</tbody>
</table>

The disturbance of a wetland biome is considered an endpoint in its own right; however, this endpoint is linked to endpoints and midpoints of other stressor-effects networks, including those related to disturbance to other biome types (e.g., terrestrial and freshwater) and habitats.
The endpoint of ecosystem disturbance is affected by midpoints and endpoints of all of the affected biomes and habitats.

In most instances, wetland biome disturbance will be linked to freshwater biome disturbance. These linkages should be understood. This will aid in the characterization of wetland biome disturbance.

3.3.2.1. Selection of Category Indicator(s). Separate category indicators shall be reported for disturbance to each distinct wetland biome affected by unit process(es) within the product system under study. This reflects the distinct nature of each wetland biome experiencing disturbance. No aggregation of results is allowed between distinct category indicators.

Category indicators for wetland biome disturbance are defined for each unit process in the product system that contributes measurably to any distinct environmental mechanism of wetland biome disturbance. It is important that the selected category indicators include all wetland biomes directly affected by physical disruption activities at a unit process, as well as wetlands that are indirectly affected.

To identify affected wetlands, all freshwater biomes that could be affected by stressor(s) in the product system must first be identified and described, according to the requirements of Section 3.2.2.1 and 3.2.2.2. Once specific watershed boundaries are defined for each freshwater biome, the wetlands within each can be identified. If wetland biome disturbance is occurring for a specific wetland within these watershed boundaries, a category indicator should be described if the environmental mechanism is distinct in nature from disturbance to the freshwater biome in which the wetland is present.

There are a large number of wetlands of many different types, such as forested wetlands, emergent wetlands, saltwater estuaries, and others. The wetland type should be considered when a category indicator for wetland biome disturbance is being defined.

In some cases, multiple wetlands within a freshwater biome may be experiencing disturbance. Separate category indicators shall be used for each wetland if the environmental mechanism is distinct.

Disturbance should be characterized at Node 2, if data are available — i.e., characterizing wetland biome disturbance by measuring alterations in ecological conditions in the biome, when compared to the undisturbed and fully disturbed condition.

In many cases, site data will be unavailable to assess wetland biome disturbance. In these cases, measurements related to stressors could be made at Node 1, if data are available.

In cases where data are unavailable for characterization at Node 1 or Node 2, the list of category indicators representing distinct environmental mechanisms for wetland biome disturbance shall be reported in the LCIA profile. If data is unavailable to define a comprehensive set of indicators for wetland biome disturbance, see Section 3.3.7.
3.3.2.2. Identifying Core Impact Categories and Category Indicators. It is essential to carefully screen the product system under study to identify the unit process(es) contributing to wetland biome disturbance. This screening is intended to minimize the amount of data collection required, by focusing the scope of the study on stressor(s) associated with a product system linked to wetland biome disturbance. Wetland biome disturbance can be ruled out as a relevant impact category if no unit process(es) in the product system contribute measurably to any environmental mechanism of wetland biome disturbance.

For a given unit process, the following guidance can be used to exclude wetland biome disturbance as relevant:

- If the product system under study were to halt all activity, and all relevant intermediate flows throughout the entire product system were likewise stopped, no measurable change in the stressors, midpoints, or endpoints of wetland biome disturbance would be observed.
- If it can be demonstrated through observation that the activities at the unit process do not contribute to a measurable alteration in ecological conditions in the wetland biome which is affected.

If wetland biome disturbance is excluded for these or other reasons, the reasons should be stated and justification provided for the exclusion in the LCA report.

The scale of the functional unit used in the screening should be large enough to include observed instances of wetland biome disturbance; it must not be set arbitrarily low, which could rule out this impact category even in cases where wetland biome disturbance is occurring and can be linked to a unit process(es). An initial screening for the relevance of wetland biome disturbance as an impact category may determine that the scale of the functional unit may need to be revised, or that goal and/or scope may need to be revised in other ways. The exclusion of wetland biome disturbance as a core impact category should be a key subject of the critical review phase.

In some instances, identification of all affected wetland biomes experiencing disturbance will not be possible, based on limitations in available data. In these cases, the effect on final results of these omissions should be described in the LCA report. If the effect on the results is significant, the goal and scope of the study may need to be revised.

Due to the complex data collection and analysis requirements, resources may be unavailable for an assessment of wetland biome disturbance for a given LCA study. This will limit the comparability of results, and may affect the ability to achieve the goals of the study. If wetland biome disturbance cannot be characterized, the relevant category indicators shall be listed in the LCIA profile. If data are unavailable to identify affected wetland biomes, see Section 3.3.7.

3.3.3. Classification. For a given category indicator, the affected wetland is classified. Once category indicator(s) are determined to be relevant for a given unit process, it can be useful to understand additional characteristics of each classified wetland, such as area. Mapping of the affected wetland for each category indicator will aid in the characterization.

3.3.4. Characterization
3.3.4.1. Stressor Characterization Factor. As noted in Section 3.3.2.1, no aggregation is allowed between separate category indicators representing different environmental mechanisms for wetland biome disturbance. The S-CF is 1 for all indicators.

3.3.4.2. Environmental Characterization Factor. The environmental characterization factor is called the biome disturbance factor (BDF). The BDF characterizes the average disturbance level across a classified wetland, where the disturbance level is calculated based on measurements for a relevant set of ecological conditions compared to fully disturbed and undisturbed reference conditions. The BDF is a unitless number from 0 to 1, but is usually expressed as a percentage value.

Generally, the iterative steps in characterization at Node 2 for wetland biome disturbance will include:

- selection of measurements of ecological conditions used to represent wetland biome disturbance;
- definition of the undisturbed and fully disturbed reference conditions; and
- characterization of the BDF.

Wherever possible, the same methods and data sources should be used in the characterization of wetland biome disturbance as are used in the characterization of freshwater biome disturbance (see Section 3.2.4). Since the stressor-effects network for wetland biome disturbance and freshwater biome disturbance are almost always linked, there are very often stressors and/or midpoints in common. Data sources from assessment of freshwater biome disturbance should be used in the assessment of wetland biome disturbance at either Node 1 or Node 2, dependent on the nature of the environmental mechanism.

The stressor-effects networks for different instances of wetland biome disturbance are extremely diverse, and the characterization model and nodal indicator used to calculate the BDF will vary considerably. In some cases, the main stressors could result in the complete elimination of wetlands (i.e., de-watering of wetlands); alternatively, stressors could be entirely indirect, involving increased sediment from land use practices in upstream watershed reaches far away from the wetland boundaries. Characterization of wetland biome disturbance is site-dependent, and will require the assistance of a trained field ecologist in most cases.

The specific methods used shall be described in detail in the LCA report. The characterization of the BDF for wetland biome disturbance should be a key subject of any critical review.

3.3.5. Indicator Equation and Unit of Measure. Due to the diverse nature of the environmental mechanisms for wetland biome disturbance, different units of measure and indicator equations will be applicable in different contexts. The indicator equation and unit of measure used should be reported and described in the LCA report.

3.3.6. Additional Reporting Requirements. The results in this impact category and the other impact categories in the Land Use Ecological Impacts group are unique, in that the indicator results do not vary with production levels on the site. Even if all stressors associated with a given unit process were to stop, and all production cease, in most situations, it would take decades for the disturbance levels to decline.
The functional unit should be scaled such that the total extent of area of wetland biome affected by unit process(es) in the product system is included and reported in final results. Results for Wetland Biome Disturbance should not be normalized to production volume on the site.

Meaningful comparisons for wetland biome disturbance can only be drawn if the scale of functional unit is reflective of the spatial scale of biome disturbance linked to activities associated with unit process(es) in the study scope. When making comparisons, the current disturbance level, past history of disturbance at the sites under study, current practices, and anticipated trends in disturbance levels, must be considered. Expert judgment will be required to appropriately define the scope of the study such that comparisons are justified.

Regardless of the indicator results reported, the affected wetland included in each category indicator for wetland biome disturbance shall be reported in the LCA report. The category indicator name shall be descriptive of the affected wetland. If data are available, the type of wetland, size of wetland, and other relevant characteristics of the wetland biome should be disclosed in the LCA report, EPDs, and C-EPDs.

If the BDF cannot be characterized, the stressor(s) causing disturbance and observed conditions of midpoint, should be described in the LCA report. The stressor-effects network itself shall be included in any LCA report.

In addition, the trend in average disturbance levels over time in the wetland biome should be described, including both the past disturbance and expected future trends, in the LCA report, as well as EPDs and C-EPDs. Due to the high relevance of past activities at a site, this must be included. If data are unavailable for a quantitative characterization of BDFs over time in wetland biome, then a qualitative description of the expected trends in disturbance can be included.

3.3.7. Addressing Limitations in the Types, Accuracy, and Availability of Environmental Data. Due to the complex data collection and analysis requirements, resources may be unavailable for an assessment of wetland biome disturbance for a given LCA study. This will limit the comparability of results.

In cases where data are unavailable for an accurate characterization at any node, the list of category indicators representing distinct environmental mechanisms for wetland biome disturbance (identified according to the requirements of Sections 3.3.2.1 and 3.3.2.2) shall be provided.

If data are unavailable to identify affected wetland biomes, the comparability of results will be limited significantly, and it may not be possible to achieve the goals of the study. The goal and scope of the study may need to be revised.
3.4. Key Species Loss

3.4.1. Impact Category. This impact category addresses the loss of key species that can be associated with a unit process. Separate category indicators are evaluated for each affected key species. In most cases, key species loss will be associated with the loss or disturbance of suitable habitat. However, key species losses can occur even if there is no measurable disturbance to biomes or habitats.

FOR EXAMPLE. A run-of-river hydropower system may not significantly alter surrounding habitats but may impede migration of fish or injure individuals passing through turbines.

In this Standard, a key species is defined as a species of flora or fauna that meets one of the following criteria in a given region:

- For the given region, the species has been listed as threatened, endangered, or extirpated on an official government list. These lists can be: national in scale (i.e., the threatened and endangered species lists maintained by the US Fish and Wildlife Service and National Oceanic and Atmospheric Administration); or at a region, state, or local level (e.g., the Species of Special Concern list maintained by the California Department of Fish and Wildlife).

- For the given region, the species is listed as vulnerable, threatened, endangered, or extirpated on lists maintained by non-governmental stakeholders, such as ENGOs (i.e., the International Union for the Conservation of Nature, or WWF).

- A species that has experienced a large reduction in populations in a given region, or has been completely extirpated from a region, but is not included on any formal lists.

- Other species of concern based on their special significance or uniqueness within a given region.

Species that meet one of the above criteria may sometimes be excluded if they are not on national governmental lists, have healthy populations throughout their historical range, and are outside or at the edge of their historical range in the area for which they are listed. Critical review by a trained field ecologist may be necessary to resolve the classification of a given species as “key” if it is not officially recognized but is important to stakeholders.

In rare cases, data will be sufficient to evaluate category indicator results through the loss of key species populations in the classified study area. However, in most cases, category indicator results will be based on the loss or disturbance of suitable habitat for the key species. This will depend on the stressor-effects network of key species loss and the available data.

In this Standard, a habitat is defined as an environment where a species normally occurs. Habitats may be defined independently for different life cycle stages of a single species. Stages of a life cycle can include, but are not limited to: stages of maturity; breeding stages (e.g., nesting, spawning); estivation or hibernation stages; roosting stages; or foraging stages. Many species will require different habitat types for different life cycle stages.
Habitat types can include terrestrial, freshwater, or wetland habitats, which will overlap with the respective biomes on the site. Habitats can also include more specialized environments such as old growth trees, ponds, or riparian zones. For a given unit process, there can be multiple habitat types affected for a given species. Distinct category indicators are assessed if distinct types of habitat are disturbed for key species. While generally there will be one category indicator assessed for each key species experiencing habitat disturbance, there may be multiple category indicators assessed for a key species, if multiple habitat types for different life cycle stages for a single species are impacted.

The habitat for a given life cycle stage of a given key species must be defined carefully based upon the stressor-effects network of habitat disturbance. The definition of a habitat should draw upon existing databases or published literature. Where relevant, it is useful to define habitats using the same conditions as used to define biome types, using conditions defined in Section 3.1.1, 3.2.1, and 3.3.1. However, while habitats may overlap with biomes, species very often require only specific aspects within a given biome, or may require additional aspects. Different species will require different habitats, which may overlap geographically.

The degree, scale, and duration, of key species loss associated with different unit processes will vary broadly, depending on factors such as the land use management practices, regional biomes, history of the landscape, duration of disturbance, and scale of disturbance. Likewise, the midpoints and endpoints associated with this impact category vary for all of these reasons. Accordingly, site-specific assessment of category indicators considered under key species loss is required. Secondary data shall not be used in the assessment.

**3.4.2. Stressor Effects Networks.** The stressor-effects network for key species loss is distinct for disturbance caused by each unit process. The stressors can vary broadly, and the resulting midpoints and endpoints will vary for many reasons. Stressors can be related to activities at unit process(es) considered in the product system under study, but also can also be associated with unit processes outside of the scope of the LCA.

The stressor-effects network for key species loss, shown in Table 3.5, provides a general framework. A separate stressor-effects network should be modeled and described for each separate indicator included in key species loss in the study scope. The specific stressor-effects network should describe the site-specific circumstances of stressors, midpoints, and endpoints in the cause-effect relationship. This should consider the past history of disturbance and land management in the classified area, current management practices, and other considerations relevant to the cause-effects chain.

Separate category indicators will be defined for each affected key species. The affected species shall be described in the LCA report and EPDs or C-EPDs, including its current population conditions and its key life cycle stages, drawing on available databases and published research. When the category indicator used is habitat disturbance or loss (as will usually be the case), the affected habitat shall be reported and described in the LCA report and EPDs or C-EPDs. A justification for its definition should be provided in the LCA report, along with a description of habitat requirements. Detailed modeling of the stressor-effects network will greatly aid in the characterization of each category indicator.
Table 3.5. Stressor-Effects Network for Key Species Loss.

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Stressors)</td>
<td>A habitat is incrementally affected by land use management activities, including direct and indirect stressors.</td>
<td>High uncertainty. Characterization does not consider the degree of alteration in ecological conditions affecting habitat conditions, and past land use management affecting current conditions.</td>
<td>Low uncertainty. Data requirements vary by stressor.</td>
</tr>
<tr>
<td>2 (Midpoints)</td>
<td>Habitat disturbance or loss.</td>
<td>Low to moderate uncertainty. Some species will migrate to other regions where habitat is preserved, with a low resulting linkage to endpoints of key species loss. Other species will experience direct reductions in species populations due to a reduction in habitat.</td>
<td>Low uncertainty. Data requirements: Spatial data related to the extent of land use management activities affecting habitat. Measurements of conditions in affected habitat and reference areas.</td>
</tr>
<tr>
<td>3 (Endpoints)</td>
<td>Reductions in key species populations in a given region.</td>
<td>Low uncertainty. Directly reflects endpoints of reductions in key species populations in a given region.</td>
<td>Moderate to high uncertainty. Data requirements: Census counts of past and current key species populations in a given region.</td>
</tr>
<tr>
<td>4 (Endpoints)</td>
<td>Reductions in global population of key species.</td>
<td>Low uncertainty. Directly reflects endpoints of reductions in key species populations globally.</td>
<td>High uncertainty. Data requirements: Census counts of past and current key species populations globally.</td>
</tr>
<tr>
<td>5 (Endpoints)</td>
<td>Ecosystem disturbance: Alterations in the regional interconnected ecosystem, caused by effects to terrestrial, freshwater, and wetlands biomes, the presence of key species, and other impacts.</td>
<td>Low uncertainty. Measurements directly characterize the endpoint of ecosystem disturbance.</td>
<td>Little or no data are available to measure the disturbance of overall ecosystem health.</td>
</tr>
</tbody>
</table>

The stressor-effects network in Table 3.5 includes the loss or disturbance of key species habitat. However, in rare cases, key species loss may occur without a reduction in habitat. In these cases, this stressor-effects network will not apply, as stressors occur directly at Node 3. This illustrates the need to develop a unique stressor-effects network for each key species affected by a given unit process.

The loss of key species is considered an endpoint in its own right; however, this endpoint is linked to endpoints and midpoints of other stressor-effects networks, including those related to...
disturbance to biomes and habitats for other species. The endpoint of ecosystem disturbance is
affected by midpoints and endpoints of all of the affected biomes and key species.

3.4.2.1. Selection of Category Indicator(s). Separate category indicators shall be reported for
each key species for which a reduction in species populations can be linked to unit process(es)
within the product system under study. This reflects the distinct nature of the loss of population
for each key species. Generally, if this impact category is relevant for a given unit process, there
will be multiple environmental mechanisms relevant for key species loss, related to different
key species, and multiple corresponding category indicators. No aggregation of results is
allowed between distinct category indicators.

Additionally, if characterization is at the node of habitat disturbance or loss, multiple category
indicators should be assessed for a single key species if multiple habitat types for that species
are affected.

**FOR EXAMPLE.** In the state of Minnesota, iron ore mining has caused disturbance to both terrestrial
and freshwater biomes. One of the affected key species is Blanding’s turtle. This species spends most of
its life in freshwater habitats, but ventures into terrestrial habitats to nest. For Blanding’s turtle, two
category indicators should be assessed: disturbance to nesting habitat (in terrestrial settings) and
freshwater habitat.

It is important that the selected category indicators account for all key species experiencing
population reductions from physical disruption activities at a unit process, but also in adjacent
areas, which are indirectly affected.

The identification of affected key species requires mapping. Key species that have a range
overlapping any classified terrestrial, freshwater, or wetland biomes should be considered for
inclusion. Additional key species may be classified if reductions in local species populations can
be linked to the activities at a unit process(es) in the product system under study.

**NOTE.** The range map of key species can be found in official government databases (e.g., the US Fish
and Wildlife Service), or in databases provided by other organizations (e.g., WWF or International Union
for the Conservation of Nature).

As a first step, a list of key species to be included should be generated using publicly available
databases and published literature. In some cases, regulatory agencies may require monitoring
of species at a given site, and any data generated from this monitoring can be used to add to the
list of key species.

In some cases, published data sources will not be sufficient to create a comprehensive list of key
species affected by a given unit process, and on-site sampling or more detailed research may be
required to establish a complete list. This type of detailed research should be considered in the
context of the goal and scope of the study. If the list of key species generated from available data
are inadequate, this limitation must be disclosed in the LCA report and described as a limitation in results in EPDs and C-EPDs; the goal and scope may need to be revised.

Once a list of key species has been compiled, the species to be included will be screened according to the requirements of Section 3.4.2.2. Species loss should preferentially be characterized at Node 3 — i.e., characterizing the reduction in populations of key species in the habitats affected by a unit process. This reduction shall be expressed as an absolute number (i.e., number of individuals lost), but should also be reported as a percentage value, considering the previous population in the classified habitat, if such data are available.

However, in most cases, data are unavailable to characterize the reduction in key species populations in a classified habitat; in such instances, characterization shall be at Node 2, the loss or disturbance of key species habitat. Characterization at either of these nodes requires site measurements across a representative area of affected species habitat, according to recognized techniques in field ecology.

In cases where data are unavailable for characterization of suitable habitat loss/disturbance or the reduction in species populations, the list of category indicators representing distinct environmental mechanisms for key species loss shall be included in the LCIA profile. If data are unavailable to create a comprehensive list of key species to be included, see Section 3.4.7.

### 3.4.2.2. Identifying Core Impact Categories and Category Indicators

Due to the extensive data collection and analysis required to characterize multiple category indicators for key species loss, it is essential to carefully screen the product system under study to identify unit process(es) contributing to this impact category. This screening is intended to minimize the amount of data collection required, by focusing the scope of the study on stressor(s) associated with unit process(es) linked to key species loss.

Key species loss can be ruled out as a relevant impact category if no unit process(es) in the product system contribute measurably to any environmental mechanism of key species loss. For a given unit process, a preliminary list of potential key species which could be included should be generated based on the requirements of Section 3.4.2.1. Once this preliminary list has been generated, the following guidance can be used to exclude a given unit process as contributing to loss of population for a given key species:

- If detailed mapping finds that the historic range of the key species does not overlap with any area that is affected by activities of the unit process, either directly or indirectly.

- If the product system under study were to halt all activity, and all relevant intermediate flows throughout the entire product system were likewise stopped, no measurable change in the stressors, midpoints, or endpoints of key species loss would be observed.

- If it can be demonstrated through observation that the activities at the unit process do not contribute to a measurable alteration in the habitat conditions for the key species.

When conducting this screening, it is important to identify types of unit process(es) in the product system which have been known in the past to contribute measurably to key species loss. This includes land-intensive production activities such as forestry, agriculture, and mining.
Additionally, unit process(es) should be identified for consideration if they are located in regions where key species loss is an issue of concern to regional government agencies, non-governmental organizations, or other stakeholders. If a unit process is located in a region in which key species loss is of high concern to regional governments, non-governmental organizations, or other stakeholders, it shall be assessed for the presence of key species affected.

**FOR EXAMPLE.** WWF has identified several “priority places” for conservation based on “the wealth and variety of life they support, the destructive challenges they face, and our ability to positively impact them.” Among these places are Borneo/Sumatra and the Amazon. If a plantation is located in these regions, it must be screened to determine if key species loss is occurring as a result of on-site activities.

If a unit process is located in such a region, it is possible for a large number of category indicators to be identified that are relevant for key species loss. Whether this impact category is included as relevant to a product system depends on the goal and scope of the LCA study. The scale of the classified habitats considered in the screening should be large enough to include observed instances of key species loss. This scale must not be set arbitrarily low, which could rule out the impact category even in cases where key species loss is occurring and can be linked to a unit process(es). This screening may require sensitivity analysis.

An initial screening for the relevance of key species loss as an impact category may determine that the scale of the habitat considered must be revised, or that goal and/or scope must be revised in other ways. The exclusion of key species loss as a core impact category should be a subject of the critical review phase.

**3.4.3. Classification.** Regardless of the nodal indicator used, classification first entails the identification of the historic range of the key species in which populations have been affected by activities associated with a given unit process. This is the classified range of a given species.

If characterization is of loss or disturbance to suitable habitat (Node 2 in Table ), the affected habitat(s) within the classified range are defined, which depend upon the stressor-effects network. This includes all historic habitat(s) that existed prior to the onset of significant anthropogenic activities at the site. These are the classified habitat(s). The extent of classified habitat should be measured.

**NOTE.** Classified habitat(s) can be composed of many different components of different biomes at a site. The extent of classified habitat will be measured in different ways depending on the habitat type.

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FOR EXAMPLE. Classified terrestrial habitat is measured using units of acres. However, classified
habitat for a species that depends on trees of specific species or size could be measured in terms of the
number of trees.

If characterization is of loss of population (Node 3 in Table 3.5), the historic population prior to
the onset of significant anthropogenic activities began at this location is defined. This is the
classified population.

NOTE. If historical observations are unavailable, the classified population could be evaluated by assessing
the number of individuals present in optimal habitat in undisturbed reference areas.

3.4.4. Characterization

3.4.4.1. Stressor Characterization Factor. No aggregation is allowed between key species.
The S-CF is 1.

3.4.4.2. Environmental Characterization Factor. Characterization of key species loss can be
based upon one of three different characterization models, at one of two different nodes in the
stressor-effects network:

1. For key species loss evaluated at the node of reduction in key species populations (Node 3
in Table 3.5), the E-CF is the Species Depletion Factor (SDF). The SDF is a unitless fraction
from 0 to 1 (usually expressed as a percentage), which characterizes the reduction in the
number of individuals in the classified population resulting from activities at a given unit
process.

2. For key species loss evaluated as the disturbance of habitat (Node 2 in Table 3.5), the E-CF
is the Habitat Disturbance Factor (HDF). The HDF is a unitless fraction from 0 to 1 (usually
expressed as a percentage), which is a measurement of the overall ecological conditions in
the classified habitat(s) when compared to undisturbed or optimal habitat conditions, and
fully disturbed conditions.

3. For key species loss evaluated as the loss of habitat (Node 2 in Table 3.5), the E-CF is the
Habitat Loss Factor (HLF). The HLF is a unitless fraction from 0 to 1 (usually expressed as a
percentage), which expresses the reduction in the amount of habitat in the classified
habitat(s) under study.

The choice of model and indicator used is based upon the environmental mechanism for key
species loss and the available data. While characterization of the SDF is preferred, data will be
available for this characterization only in rare cases, and typically the HDF or HLF will be used.
3.4.4.2.1. Characterization of the Loss of Species Populations. The SDF characterizes the reduction in species population compared to the classified population. This is expressed as a fraction from 0 to 1, but can also be expressed as a percentage.

3.4.4.2.2. Characterization of the Loss or Disturbance of Species Habitat. For characterization at Node 2, whether the HDF or HLF is used depends on the stressor-effects network:

- The HDF shall be used if a key species will still occur in a habitat that has been altered as the result of activities at a given unit process.
- The HLF shall be used if a key species will not occur in a habitat that has been altered.

**FOR EXAMPLE.** At a site in Northern California, past forestry practices created many stressors that resulted in freshwater biome disturbance, arising from increased sedimentation, changes in canopy cover in the riparian zone, changes in water temperature, and other effects. Although alterations have affected habitat for salmonid species, salmonids still occur in these freshwater habitats. Disturbance to suitable habitat should be characterized using the HDF.

**FOR EXAMPLE.** At the same site in Northern California, past harvests have removed over 90% of trees greater than 60” in diameter. The Marbled murrelet is a key species that nests only on large limbs of trees of this size class. Since 90% of this nesting habitat has been removed, and will no longer be used by this species, the HLF should be used for characterization.

There are several steps in characterizing the loss or disturbance of habitat:

- defining the undisturbed and fully disturbed habitat conditions;
- collecting measurements of conditions in the classified habitat(s); and
- characterizing the HLF or HDF.

3.4.4.2.2.1. Defining the Undisturbed and Fully Disturbed Habitat Conditions. If the HLF or HDF are used for a given key species, the undisturbed habitat condition must first be defined.

The undisturbed habitat condition for a key species is optimal habitat (sometimes known as “high-value” habitat) for the given life cycle stage for that species. The key species should show a very strong preference for optimal habitat above all other habitat conditions. Optimal habitat must be clearly defined in terms of measurements of a set of ecological conditions. An HDF or HLF of 0 corresponds to optimal habitat conditions.

**FOR EXAMPLE.** In redwood forests of Northern California, high value nesting habitat for the Northern spotted owl includes redwood and Douglas fir forests made up of trees over 24” inches in diameter, with dense canopy cover (over 60%) in contiguous patches of at least 80 acres. These conditions define the undisturbed, or optimal, habitat condition, for nesting habitat for the Northern spotted owl.

Optimal habitat conditions can be based upon observations of species in actual habitat, or based upon measurements in reference areas close to the classified habitat(s) under study. Category indicator results are sensitive to the definition of optimal habitat; the definition used should be based upon peer-reviewed research. The definition of optimal habitat used should be a key subject of the critical review phase, and should be reviewed by an ecology expert.
If characterization uses the HDF, the characterization must also consider the fully disturbed habitat condition, defined using the same set of measurements of habitat conditions as define the optimal habitat condition. An HDF of 1 corresponds to measurements of those conditions in which the habitat is fully disturbed.

**FOR EXAMPLE.** The Northern spotted owl will not nest in redwood forests if they are made up of trees less than 11” in diameter and less than 60% canopy cover. Such conditions define the fully disturbed condition.9

**3.4.4.2.2.2. Conducting Measurements of Habitat Conditions.** When using either the HLF or HDF, measurements of ecological conditions must be collected in the classified habitat(s). The ecological conditions measured must be the same set used to define the fully disturbed and undisturbed habitat conditions.

Measurements must be collected from a sufficient number of sites to result in statistically significant measurements that are representative of conditions in the classified habitat(s). These measurements should be conducted using well-accepted practices in field ecology.

Databases and published literature containing data on conditions in the classified habitat(s) should be collected first. If these data sources are inadequate for the purposes of characterization, then on-site monitoring must be completed. This site monitoring should consider the goal and scope of the LCA study. If adequate data are unavailable for the complete set of ecological conditions, the effect on final results for a category indicator should be considered in the context of the goal and scope of the LCA study. The goal and scope may need to be revised.

**3.4.4.2.2.3. Characterization of the Habitat Loss Factor.** If characterization is based upon the loss of habitat using the HLF, then characterization considers the amount of useable habitat that has been lost as a result of activities at a given unit process. The HLF is the fraction of the classified habitat(s) which the species cannot use. It can be characterized by assessing the fraction of optimal habitat which has been lost.

**3.4.4.2.2.4. Characterization of the Habitat Disturbance Factor.** To assess the HDF, measurements of ecological conditions in the classified habitat(s) are compiled. The ecological conditions measured are the same as those used to define the undisturbed and fully disturbed habitat conditions.

Once these measurements of conditions in the classified habitat(s) have been compiled, the numerical deviation is assessed for each condition. The deviation is a unitless number from 0 to 1 (often expressed as a percentage), which represents the condition of the classified habitat(s) when compared to the fully disturbed and undisturbed habitat conditions. A deviation value of “1” for a measurement corresponds to the classified habitat(s) being fully disturbed in this

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ecological condition. A deviation value of “0” corresponds to undisturbed (or optimal) habitat. The HDF is the average of all deviation measurements.

Each deviation can be calculated using various approaches, such as a linear approach or threshold approach, similar to the approaches described in Sections 3.1.4, 3.2.4, or 3.3.4. Whichever approach is used, it must be described clearly in the LCA report.

3.4.5. Indicator Equation and Unit of Measure. For assessments of the loss of species populations, the indicator result for a given unit process is the classified population, multiplied by the SDF, in resulting units of number of individuals.

**Equation 3.3. Results for Key Species Loss.**

\[
\text{Key Species Loss} = \text{Classified population} \times \text{SDF}
\]

Where

- Classified population is the historic population of the key species in the area affected by a unit process
- SDF is the Species Depletion Factor

For assessments of the loss or disturbance of key species habitat, the indicator result depends on the type of habitat affected. For many types of habitat, results can be expressed as area of classified habitat multiplied by the HLF or HDF, resulting in units of habitat lost or equivalent habitat disturbed, respectively. However, for some habitat types, results must be expressed simply as the HLF or HDF across the classified habitat(s).

**FOR EXAMPLE.** If freshwater habitat supporting a specific species is disturbed, the indicator result is the HLF or HDF.

3.4.6. Additional Reporting Requirements. The results in this and the other impact categories in the Land Use Ecological Impacts group are unique, in that the indicator results do not vary with production levels on the site. Even if all stressors associated with a given unit process were to stop, and all production cease, in most situations, it would take decades for habitats or populations to recover across the classified range, if recovery is indeed possible.

Meaningful comparisons for key species loss can only be drawn if the scale of functional unit is reflective of the spatial scale of habitat disturbance or population loss linked to activities associated with unit process(es) in the study scope, considering the entire classified range. When making comparisons, the current disturbance or population level must be considered in the context of historical disturbances at the sites under study, and anticipated future trends. Expert judgment will be required to appropriately define the scope of the study such that comparisons are justified.
All category indicators reflecting key species loss shall be reported in LCIA profile. The SDF, HLF, or HDF (expressed as a percentage), and extent of classified habitat(s) shall be included in the LCIA profile.

In addition, the trend in population and habitat conditions over time at the site should be described in the LCA report, EPDs, and C-EPDs, including both the past and expected future trends. Due to the high relevance of past activities at a site, this must be included. If data are unavailable for a quantitative characterization over time, then a qualitative description of the expected trends can be included.

3.4.7. Addressing Limitations in the Types, Accuracy, and Availability of Environmental Data. Due to the complex data collection and analysis requirements, resources may be unavailable for an assessment of key species loss for a given LCA study. This will limit the comparability of results.

In cases where data are unavailable for an accurate characterization at any node, the list of category indicators representing distinct environmental mechanisms for key species loss (identified according to the requirements of Sections 3.4.2.1 and 3.4.2.2) shall be provided.

If data are unavailable to identify affected key species, the comparability of results will be limited significantly, and it may not be possible to achieve the goals of the study. The goal and scope of the study may need to be revised.
4. Climate Change and Ocean Acidification Impacts

This impact group addresses three major impacts with distinct environmental mechanisms, which are linked to emissions of CO\(_2\) and other climate forcing substances (including precursors). This includes emissions of greenhouse gases (GHGs), aerosols, particulates, and emission precursors.

**NOTE.** Some emissions addressed in these impact categories also have impacts on human health. This includes emissions of black carbon, which is a component of particulate matter, and emissions of ozone precursors, which can contribute to ground level ozone formation. Human health impacts linked to these emissions are addressed in the impact categories of Ground Level Ozone Exposure Risks and PM2.5 Exposure Risks (see Sections 6.1 and 6.2 of the Annex).

The three impact categories considered in this group are: Global Climate Change, Arctic Climate Change and Ocean Acidification.

- **Global Climate Change (Section 4.1).** This impact category addresses the wide range of endpoints which are linked to global climate change. The S-CF for this impact category is calculated based upon the integrated climate (i.e., radiative) forcing of a given emission, relative to the integrated climate forcing of an emission of CO\(_2\), with units reported in mass of CO\(_2\) equivalent (CO\(_2\)e). This is calculated using the Global Warming Potential (GWP) equation for a pulse emission source, defined by the Intergovernmental Panel on Climate Change (IPCC).\(^9\) The S-CF, called the Integrated Global Climate Forcing Potential (I-GCFP), or the Global Forcing Potential (GFP), is calculated using the GWP equation.

**Note.** This Standard uses the term, Integrated Global Climate Forcing Potential, rather than the more common term, Global Warming Potential, to more accurately reflect the fact that the factors characterize the global integrated radiative forcing of climate forcers relative to CO\(_2\), not any induced temperature change (which could be implied by the word “warming”).

**Note.** Additionally, the radiative forcing which is characterized in the I-GCFP may be positive or negative (i.e., leading to warming or cooling). The term “Global Warming Potential” implies that only positive forcing is considered.

To establish I-GCFPs, a time horizon must be selected to use in the GWP equation.\(^11\) In this Standard, the time horizon used is based on the projected date of the exceedance of key global mean temperature (GMT) anomaly thresholds. When these thresholds are exceeded, increasing levels of anthropogenic interference with the climate system will occur.

Three key GMT anomaly thresholds are recognized in this Standard, based on the preponderance of evidence:

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\(^9\) Intergovernmental Panel on Climate Change WGI: 2.10.1 Definition of an Emission Metric and the Global Warming Potential.

\(^11\) In this Standard, the GMT anomaly is the increase in global mean temperature compared to the pre-industrial era.
• +1.5°C GMT anomaly threshold, projected to be exceeded by approximately 2030. The 52-member Alliance of Small Island States (AOSIS) and the group of 49 Least Developed Countries (LDC) are seeking a strict target to limit the GMT anomaly increase to +1.5°C. This precautionary threshold was proposed in 2009 to serve as the agreed-upon temperature target under the United Nations Framework Convention on Climate Change process.

• +2.0°C GMT anomaly threshold, projected to be exceeded by approximately 2050. This threshold was defined and agreed upon in the 2009 Copenhagen Accord under the UN Framework Convention on Climate Change process as the threshold beyond which “dangerous” impacts to the climate are likely to occur. The preponderance of evidence suggests that beyond +4°C, the effects to the climate could be “potentially devastating.”

Any one of these thresholds can be used as the basis of calculating results for Global Climate Change using I-GCFPs; multiple results, linked to multiple time horizons, can also be used and reported. The choice of threshold used in a given study depends on the goal and scope.

**NOTE.** These are “fixed-date” time horizons. This means that the time horizon used will decrease over time as each impending threshold approaches. Although tied specifically to GMT anomaly thresholds, these time horizons can respectively be considered to represent integrated climate forcing over the short-term, medium-term, and long-term.

**NOTE.** The GWP-100 was initially presented in 1990 along with GWP values calculated on alternative time horizons (20 years and 500 years). When first published, it was noted that these three time horizons (20 years, 100 years, and 500 years) were presented as “candidates for discussion [that] should not be considered as having any special significance.” The IPCC, in its Fifth Assessment Report, noted that “there is no scientific argument for selecting 100 years compared with other choices.” This Standard enables the use of different (or multiple) time horizons, recognizing that there is no clear single choice of timeframe for considering the effects of emissions on climate forcing.

• **Arctic Climate Change (Section 4.2).** The Standard recognizes regional “hot spots” for climate change — i.e., areas affected by distinct regional environmental mechanisms for climate change, that should be reported separately from the Global Climate Change impact category. The Arctic is one such regional hot spot. The preponderance of the evidence from studies conducted of this region show that the Arctic has experienced accelerated warming compared to the planet as a whole. The Arctic Monitoring Assessment Programme (AMAP) report, among others, provides data linking short-lived climate forcers, such as black carbon, to as much as half of the Arctic radiative forcing anomaly. The method for calculating the

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12 The 1992 UN Framework Convention on Climate Change has as its objective “to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.”


15 Intergovernmental Panel on Climate Change 2013. AR5. WGI, Section 8.7.1.2.
Arctic Climate Change profiles are based upon the Absolute Regional Temperature Potentials developed by Dr. Drew Shindell and Dr. Gregory S. Faluvegi of the National Aeronautics and Space Administration (NASA).\textsuperscript{16}

As more is understood about distinct climatic environmental mechanisms in the Earth system, additional regional impact categories may be considered (e.g., Antarctic Climate Change, Mid-Latitude Band Climate Change, etc.).

- **Ocean Acidification (Section 4.3).** This impact category represents the distinct environmental mechanism linked to the increase in carbonic acid concentrations and subsequent drop in ocean pH in the world’s oceans caused by oceanic absorption of CO$_2$. These midpoints and endpoints are unique from climate change and have nothing to do with radiative forcing. The environmental mechanism includes effects on Aragonite saturation levels, and subsequent effects on marine organisms of many types around the world.

4.1. **Global Climate Change**

4.1.1. **Impact Category.** This impact category addresses the contributions of greenhouse gas (GHG) and aerosol emissions (and their precursors) to global climate change. Specifically, it characterizes the total radiative heat trapped through radiative forcing before key thresholds in the Global Mean Temperature\textsuperscript{17} (GMT) anomaly are projected to be exceeded (as described in Section 4.1.1.1). In this Standard, the GMT anomaly is the increase in global mean temperature compared to the pre-industrial era.

A large number of endpoints are associated with this impact category, occurring on global, continental, and regional scales, including: biome disturbance, especially to tundra, boreal forest, mountain, Mediterranean-type ecosystems, coastal mangroves, and salt marshes; species extinctions, especially in these biomes; severe impacts to tropical forests; contraction of productive areas in polar sea-ice biomes; reduction in summer and autumn water flows due to loss of water stored in glaciers and snow cover; melting of Himalayan-Tibetan glaciers that provide water for more than one-sixth of the world population\textsuperscript{18,19}; melting of terrestrial ice sheets in Greenland, Antarctica, and other regions; melting of Himalayan glaciers and Arctic sea ice (where black carbon has been shown to play a significant role)\textsuperscript{20}; increases in drought-affected areas; increases in occurrence of extreme precipitation events; enhanced sea-level rise due to the melting of terrestrial ice sheets; increases in air pollution where pollution is already

\textsuperscript{17} GMT is typically measured on an annual average basis. Specifically, it is measured based on the area-weighted global average of the local departures of the daily-average of the observed maximum and minimum near-surface air temperatures at long-term stations.
significant\textsuperscript{21,22}; warming of surface and deep ocean layers, leading to vertical stratification and decreased nutrient cycling, coral bleaching, and other impacts; and a large number of other endpoints affecting the environment and human health.\textsuperscript{23}

4.1.1.1. Definition of Exceedance of Threshold for Global Climate Change. Three key GMT anomaly thresholds exist, based on the preponderance of evidence. The date of each projected exceedance of threshold is based on the preponderance of evidence from major climate models:\textsuperscript{24,25,26}

- +1.5°C GMT anomaly threshold, projected to be exceeded by approximately 2030. This threshold is considered precautionary, and was initially proposed under the United Nations Framework Convention on Climate Change (UNFCCC) as the target to achieve to avoid dangerous interference with the climate. The 52-member Alliance of Small Island States (AOSIS) and the group of 49 Least Developed Countries (LDC) are seeking a strict target to limit the GMT anomaly increase to +1.5°C. This threshold can also be referred to as the “precautionary principle threshold” for the climate.

- +2.0°C GMT anomaly threshold, projected to be exceeded by approximately 2050. This threshold was defined in the 2009 Copenhagen Accord under the UNFCCC process as the threshold beyond which “dangerous” impacts to the climate are likely to occur. This threshold can also be referred to the as the “UNFCCC threshold.”

- +4.0°C GMT anomaly threshold, projected to be exceeded by approximately 2100. The preponderance of evidence suggests that beyond +4°C, the effects to the climate could be “potentially devastating.”\textsuperscript{27} If this threshold is used, results can be referred to as “legacy” forcing caused by emissions of climate forcers, or as based on the “Kyoto Protocol Framework” (KPF), since the time horizon is identical to that used in this framework.

The exceedance of each of these temperature thresholds will lead to increasing levels of anthropogenic interference with the climate system, and each are relevant. Any one of these thresholds can be used as the basis of characterization; multiple results, linked to multiple time horizons, can also be used and reported (see Section 4.1.6). The choice of threshold used in a given study depends on the goal and scope. The effect on final results for Global Climate Change of the different time horizons should be analyzed using sensitivity analysis.

\begin{itemize}
\item \textsuperscript{22} Jacobson, M.Z., The enhancement of local air pollution by urban CO\textsubscript{2} domes, \textit{Environ. Sci. Technol.}, 44, 2497-2502, doi:10.1021/es903018m, 2010
\item \textsuperscript{24} Climate Change 2007, IPCC 4th Assessment Report (AR4).
\item \textsuperscript{26} Intergovernmental Panel on Climate Change. Fifth Assessment Report.
\item \textsuperscript{27} World Bank. \textit{Turn Down the Heat: Why a 4°C Warmer World Must be Avoided}. 2013.
\end{itemize}
4.1.2. Stressor Effects Network. The stressor-effects network is global in scope, encompassing the full spectrum of climate forcers contributing to global climate change, including but not limited to: GHGs, absorbing and reflecting aerosols, and precursor emissions.

The stressor-effects network is shown in Table 4.1.

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Stressors)</td>
<td>Emissions at a unit process of GHGs, warming aerosols such as black and brown carbon, cooling aerosol emissions, and precursor emissions. (Some cases) Activities associated with a unit process which are not related to emissions, which cause climate forcing (i.e. stressors affecting albedo or biogenic carbon storage.)</td>
<td>High uncertainty. Measurements of emissions do not directly reflect consequences on endpoints, as they do not consider: fate and transport; varying radiative efficiencies and atmospheric lifetime of these climate forcers; current and projected concentrations of pollutants; exceedance of relevant temperature thresholds.</td>
<td>Low uncertainty. Data required: • Data on emissions levels.</td>
</tr>
<tr>
<td>2 (Midpoint)</td>
<td>Contribution to increases in atmospheric concentrations of well mixed GHGs, due to accumulation in the atmosphere Contribution to increases in concentrations of short-lived climate forcers (SLCFs) due to continuous emissions of these forcing agents.</td>
<td>High uncertainty. Measurements of concentrations of these climate forcers very poorly reflect consequences on endpoints, due to varying radiative efficiencies and atmospheric lifetime of these climate forcers.</td>
<td>Low uncertainty. Data required: • Data on emissions levels. • Data on atmospheric lifetime and dispersion characteristics of climate forcing substances.</td>
</tr>
<tr>
<td>3 (Midpoint)</td>
<td>Contribution to increase in global instantaneous radiative forcing from increased concentrations of well mixed GHGs and SLCFs.</td>
<td>Moderate uncertainty. Measurements of instantaneous radiative forcing moderately reflect consequences on endpoints. However, the connection between instantaneous forcing and global mean temperature increase is limited due to time lag in the climate response.</td>
<td>Low uncertainty. Data requirements: • Data on dispersion characteristics of climate forcers. • Data on radiative efficiency of climate forcers.</td>
</tr>
</tbody>
</table>

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28 Intergovernmental Panel on Climate Change: Synthesis Report. 2.3: Climate sensitivity and feedbacks.
### 4.1.2.1. Selection of Category Indicator

The indicator for this impact category shall be at Node 4, the characterization of the integrated radiative forcing, compared to CO₂.

The characterization of integrated radiative forcing at Node 4 requires the use of a time horizon in calculations. In this Standard, the time horizon used in calculations are linked to the year in which

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization</th>
<th>Uncertainty</th>
<th>Data Requirements</th>
</tr>
</thead>
</table>
| 4 (Midpoint) | Contribution to additional heat energy trapped in the Earth-atmosphere system as a result of global radiative forcing anomaly continuing over time (integrated radiative forcing). | Low uncertainty. Projections of integrated radiative forcing reflects endpoints, due to established climate sensitivity and knowledge of threshold levels of dangerous interference with the climate system. | Low uncertainty. Data requirements:  
- Data on atmospheric lifetime and dispersion characteristics of climate forcers.  
- Data on radiative efficiency of climate forcers. |
| 5 (midpoint) | Contribution to increase in the Global Mean Temperature (GMT) | Low uncertainty. Measurement of the GMT anomaly directly relates to certain endpoints, including ranges of species habitats, and the melting of terrestrial ice sheets. | Moderate uncertainty. Data requirements:  
- Data on atmospheric lifetime and dispersion characteristics of climate forcers.  
- Data on radiative efficiency of climate forcers.  
- Data on heat transfer rates into the Earth-atmosphere system (including oceans and atmosphere).  
- Data on climate response to radiative forcing.  
- Magnitude of climate feedbacks (particularly for clouds). |
| 6 (midpoint - projected EOT) | Contribution to changes (some possibly irreversible) in the climate are anticipated when the GMT anomaly rises above key thresholds | Low uncertainty. Exceedance of GMT anomaly thresholds are directly related to increased risks for certain endpoints. | Data is not available which can link specific emissions to changes in the climate system |
| 7 (projected endpoints) | Contribution to endpoints of global climate change. | Low uncertainty. Endpoints. | Data is not available which can link specific emissions to endpoints of climate change |
key GMT anomaly thresholds are projected to be exceeded, as discussed in Section 4.1.1.1. Thus although characterization is at Node 4, the time horizon used is linked to thresholds at Node 6.

In some cases, limitations in the type, accuracy, and availability of environmental data may preclude assessment of integrated radiative forcing for flows that are classified. In these cases, characterization not possible, and results must be reported as inventory. See Section 4.1.7.

Only one environmental mechanism is relevant for this impact category: Global Climate Change. Accordingly, only one category indicator is reported.

**NOTE.** Characterization models are available to characterize incremental changes in the GMT resulting from well mixed GHGs at Node 5, such as the Global Temperature Potential (GTP). However, the GTP has larger measurement uncertainty than models of integrated radiative forcing, and effects from very short-lived climate forcers (VSCLPs) are not well characterized. As a result, a comprehensive and defensible set of characterization factors based on the GTP cannot currently be established.

### 4.1.2. Identifying Core Impact Categories and Category Indicators

All known product systems have stressors associated with this impact category. Global Climate Change is a core impact category for all LCA studies.

In cases where the net result for Global Climate Change is negligible, results shall still be reported, noting in the LCIA profile that stressors are contributing to both positive and negative radiative forcing, but that net results are negligible.

### 4.1.3. Classification

This impact category includes all emissions and activities which can be linked to positive or negative climate forcing (i.e., both warming and cooling are considered).

For certain unit processes, there may be activities linked to climate forcing effects, which are not associated with emissions. This can include effects from land use change, surface albedo changes, carbon uptake/storage, or the long-term loss of carbon storage in biogenic systems. These additional climate forcing effects should be included, if they are relevant to final indicator results, depending on the goal and scope of the study.

### 4.1.3.1. Classifying Emissions Contributing to Radiative Forcing

Emissions that lead to measurable radiative forcing are classified in this impact category. This shall include all emissions or other activities that cause direct radiative forcing, as well as those that lead to radiative forcing indirectly, through effects such as chemical reactions in the atmosphere and effects on cloud cover.

This includes substances with broadly varying atmospheric lifetimes. The atmospheric lifetime affects both the timeframe of response to emissions mitigation, and whether the forcing which

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is caused occurs regionally or globally. Three categories of substances with climate forcing properties are defined:

- Well mixed greenhouse gases (WMGHGs) have an atmospheric lifetime longer than the interhemispheric mixing time of the Earth's atmosphere (12 to 18 months). Over their atmospheric lifetime, these climate forcers cause radiative forcing globally.
- Short-Lived Climate Forcers (SLCFs) have an atmospheric lifetime shorter than approximately 35 years, the projected time until the +2°C GMT anomaly threshold exceedance.
- Very Short-Lived Climate Forcers (VSLCFs) have an atmospheric lifetime shorter than the mixing time of the Earth's atmosphere. Over their atmospheric lifetime, these climate forcers cause radiative forcing only in regions close to where they are emitted.

The emissions to be classified include, but are not limited to: all of the GHGs included in the Kyoto Protocol and commonly included in GHG accounting frameworks; all relevant short-lived climate forcers (SLCFs); all Ozone Depleting Substances (ODSs) included in the 1987 Montreal Protocol, which cause direct warming, and indirect cooling through depletion of stratospheric ozone; and aerosols and their precursors leading to negative radiative forcing (sulfates and nitrates). A list of substances to be classified is included in Table 4.2. Note that this list is not comprehensive, and there may be other emissions occurring at unit processes in the product system under study should be classified.

Table 4.2. Emissions of climate forcers to be classified.

<table>
<thead>
<tr>
<th>Well Mixed GHGs</th>
<th>Very Short-Lived Climate Forcers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>Black carbon aerosol</td>
</tr>
<tr>
<td>Carbon tetrachloride*</td>
<td>Brown carbon aerosol</td>
</tr>
<tr>
<td>Chlorofluorocarbons (CFCs)*</td>
<td>Carbon monoxide</td>
</tr>
<tr>
<td>Halons*</td>
<td>Mineral dust aerosol [32]</td>
</tr>
<tr>
<td>Hydrochlorofluorocarbons (HCFCs)**</td>
<td>Nitrogen oxides</td>
</tr>
<tr>
<td>Methyl Bromide*</td>
<td>Organic carbon aerosols (other than Brown Carbon)</td>
</tr>
<tr>
<td>Nitrous oxide (N₂O)</td>
<td>Other ozone precursors</td>
</tr>
<tr>
<td>Perfluorocarbons</td>
<td>Sea salt aerosols</td>
</tr>
<tr>
<td>Sulfur hexafluoride (SF₆)</td>
<td>Sulfur dioxide**</td>
</tr>
<tr>
<td><strong>Short-Lived Climate Forcers</strong></td>
<td><strong>VOCs</strong></td>
</tr>
<tr>
<td>Methane</td>
<td></td>
</tr>
<tr>
<td>Hydrofluorocarbons (HFCs)</td>
<td></td>
</tr>
</tbody>
</table>


* These ozone-depleting substances lead to an indirect cooling effect through the destruction of stratospheric ozone. This indirect cooling effect shall be included, even though for these pollutants, the net effect on a global-mean basis may be positive radiative forcing due to their stronger direct positive radiative effects.

** A fraction of sulfur dioxide (SO$_2$) emissions convert into tropospheric sulfate aerosols (TSA), which cause significant direct negative radiative forcing by increasing the clear-sky albedo when the air is over a dark surface. The indirect effects of this aerosol can cause additional negative radiative forcing through effects on clouds, including changes in cloud lifetime, brightness, and amount. While a fraction of SO$_2$ emissions can be converted into particulate matter that can cause significant human health effects, these health effects are addressed in the PM2.5 impact category (see Annex A, Section 6.2).

4.1.3.2. Classification of Effects on Biogenic Systems. In some product systems, certain unit operations cause significant effects to biogenic systems which are linked to effects on radiative forcing. These are typically unit operations that have associated biogenic absorption of atmospheric CO$_2$ (i.e., CO$_2$ absorption from photosynthesis), or which disrupt existing carbon storage pools through harvests or other changes, causing releases. This leads to inputs and outputs (i.e., absorption and emissions) of CO$_2$ and other substances, such as methane.

For such unit operations, the absorption and emissions of CO$_2$ and other substances shall be attributed solely to the unit operation in which they occur. If an intermediate flow of “biogenic” carbon is emitted during combustion or decay associated with a different unit process elsewhere in the product system, resulting emissions of CO$_2$ and other substances must be attributed to the unit process in which emissions occur, accounting for the time of emission. In this way, actual flows of biogenic carbon, which typically enter the product system via absorption of atmospheric CO$_2$ and leave the system through decay or combustion processes, must be traced across the product system. This more accurate accounting of carbon flows avoids simplistic assumptions such as counting CO$_2$ emitted at a tailpipe which was initially stored via a biogenic process as “carbon neutral.”

For some unit operations, past practices have led to a change in biogenic carbon storage levels in the regional biome, when compared to an undisturbed condition unaffected by anthropogenic activities. In these cases, biome disturbance which can be linked to unit process(es) in the product system under study has led to a net change in the atmospheric burden of climate forcers. This net change in atmospheric burden shall be classified. In practice, effects on biogenic systems are considered only if impact categories in the group of Land Use Ecological Impacts are relevant, according to the requirements of Section 3 of the Annex.

The net change should account for both changes in biogenic carbon storage levels in the biogenic system when compared to the undisturbed reference condition (see Section 3), and also the long-term storage of carbon in product carbon pools (e.g., durable wood products).

The radiative forcing resulting from this additional atmospheric burden of climate forcers is then integrated over the time horizon used in characterization, based on the requirements of Section 4.1.4.1.

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FOR EXAMPLE. For lumber products, timber harvests usually lead to significant reductions in the amount of carbon stored in regional forests, when compared to undisturbed conditions. While some of the carbon which was removed in timber may be stored in durable products, in most cases, the majority will have decayed or combusted, resulting in emissions of CO$_2$ and CH$_4$ to the atmosphere. The net increased atmospheric burdens of CO$_2$ and CH$_4$ must be classified.

When assessing inputs and outputs for a unit operation affecting a biogenic system, site-specific measurements will be required to track both fluxes and long-term storage loss. If this type of data is unavailable, the relevance to final study results from omitting these flows should be considered. A confidence interval can be reported. Results may have to be reported using an earlier node (see Section 4.1.2.1). If an omission has strong significance to final results, the goal and scope of the study may need to be revised.

4.1.4. Characterization

4.1.4.1. Stressor Characterization Factor. The Stressor Characterization Factor (S-CF) for each climate forcer is the integrated global mean radiative forcing compared to the integrated global mean radiative forcing of CO$_2$, assessed using the Integrated Global Climate Forcing Potential (I-GCFP). The I-GCFP may also be referred to as the Global Forcing Potential (GFP).

The I-GCFP is characterized using the Global Warming Potential (GWP) equation established by the IPCC, using CO$_2$ as the reference gas.$^{35}$ Alternative measurements of integrated radiative forcing (such as the Specific Forcing Pulse$^{36}$) may be used to calculate I-GCFP values, provided these calculations are consistent with the GWP equation.

In the GWP equation, a time horizon must be specified for calculations. The time horizon used in I-GCFP calculations is the estimated time from the year of emission to the year of the selected GMT anomaly threshold. Given the uncertainties in projections of the GMT over time, the following time horizons are used, which are based upon estimates of the expected time until the key GMT anomaly thresholds are exceeded (see Section 4.1.1.1):

- For the +1.5°C GMT anomaly threshold, a time horizon of 20 years is used in I-GCFP calculations, representing the minimum timeframe over which the I-GCFP can be calculated.$^{37}$
- For the +2.0°C GMT anomaly threshold, a time horizon of 35 years is used in I-GCFP calculations. This is the approximate amount of time before this GMT anomaly is reached in 2050.
- For the +4.0°C GMT anomaly threshold, a time horizon of 100 years is used in I-GCFP calculations. This is used as the approximate amount of time before this GMT anomaly is reached in 2100.

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$^{35}$ Intergovernmental Panel on Climate Change WGI: 2.10.1 Definition of an Emission Metric and the Global Warming Potential.


$^{37}$ The Global Warming Potential equation has not been validated for use with time horizons under 20 years, and is not used in I-GCFP calculations under this Standard.
In the future, when the Standard is revised, the time horizons which are used will be adjusted to reflect: the approach of the date in which these thresholds are exceeded; any changes in emissions which could delay or accelerate the exceedance of thresholds; and/or improvements in the accuracy of model projections. The GMT anomaly threshold which is selected for use in calculations depends on the goal and scope of the LCA study. See Section 4.1.1.1 and 4.1.6.

**NOTE.** The uncertainty in characterization of integrated radiative forcing past 100 years is uncertain, due to changing atmospheric conditions which can affect both the radiative efficiency and atmospheric lifetime of long-lived pollutants. Additionally, there is considerable uncertainty in projections of the GMT anomaly increase this far in the future, further adding to the uncertainty in characterization at long time horizons. Therefore characterization beyond the +4°C GMT anomaly threshold is not allowed.

**NOTE.** Characterization of integrated radiative forcing over time periods less than 20 years is also uncertain, due to inherent variability in the annual variations in forcing. Furthermore, characterization over time periods less than 20 years have limited environmental relevance, since forcing of many substances (i.e., CO\textsubscript{2}), occurs over time periods longer than 20 years, and so is not considered. For these reasons, characterization using time horizons less than 20 years is not allowed.

The I-GCFP equation for a pulse emission source (based upon the GWP equation) is given in Equation 4.1. The time horizon used in the calculation is 20 years, 35 years, or 100 years, depending on whether the +1.5°C, +2.0°C, or +4.0°C GMT anomaly threshold is selected.

**Equation 4.1. The Integrated Global Climate Forcing Potential (I-GCFP), also known as the Global Forcing Potential (GFP), of a substance i for a pulse emission source.**

\[
I\text{-GCFP}_i = \frac{\int RF_i(t)dt}{\int RF_{CO_2}(t)dt} = \frac{\int a_i[c_i(t)]dt}{\int a_{CO_2}[c_{CO_2}(t)]dt} = \frac{AGWP_i}{AGWP_{CO_2}}
\]

Where:
- \(i\) is the substance
- \(CO_2\) is carbon dioxide
- \(RF_i\) is the time-varying global mean radiative forcing of substance \(i\), for 1 Teragram of emission, considering a pulse emission, in units of mW m\textsuperscript{-2}
- \(a_i\) is the radiative efficiency of substance \(i\) (radiative forcing increase per mass increase in atmospheric abundance), in units of mW m\textsuperscript{-2} Tg\textsuperscript{-1}
- \([c_i(t)]\) is the unitless atmospheric concentration equation for a pulse emission, which is the time-dependent abundance of 1 Teragram of substance \(i\) emitted at time \(t\) (for a pulse emission), and the corresponding quantities for the reference gas \(r\) in the denominator. For most substances (but excluding \(CO_2\)), \(c_i(t) = e^{v/AL}\), where AL is the atmospheric lifetime of substance \(i\).
- \(AGWP_i\) is the Absolute Global Warming Potential (AGWP) of substance \(i\)
- \(AGWP_{CO_2}\) is the Absolute Global Warming Potential (AGWP) of carbon dioxide
- All GWPs use \(CO_2\) as the reference gas.

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38 Due to this uncertainty, the Intergovernmental Panel on Climate Change Fifth Assessment Report does not publish Global Warming Potentials calculated over any time periods longer than 100 years.

Characterization of continuous emission sources follows the requirements of Section 4.1.4.1.2.

**4.1.4.1.1. Characterizing Radiative Forcing.** The characterization of I-GCFPs will take into account the direct radiative effect of the climate forcer, as well as any effects leading to indirect radiative forcing. Indirect effects could include chemical responses of emitted substances in the atmosphere, or effects on clouds.

In characterization of I-GCFPs, the following data sources should be considered:

- Except for methane, the radiative efficiency, atmospheric concentration equation, and atmospheric lifetime equations published by the IPCC.
- The data published by IPCC does not consider the indirect effects of methane, which must be considered under this Standard.\(^{40}\)
- For the indirect radiative effects of ODSs caused by the depletion of ozone, the IPCC/TEAP Special Report should be used.\(^{41}\)
- Exact values of the integrated radiative forcing can be used, based on results from global climate models such as GISS.

For a given study, published data used to calculate I-GCFPs may be modified based upon credible research. Modifications must be described in the LCA report. Critical review can help to evaluate the credibility of the data used to establish I-GCFP values.

For very short-lived climate forcers (VSLCFs), characterization shall consider the location of emission, timing of emission, altitude of emission, and other factors that can affect the integrated radiative forcing. Published research which has been peer reviewed can provide estimates of integrated radiative forcing for VSLCFs on a regional basis.

**FOR EXAMPLE.** The integrated radiative forcing per ton of black carbon can differ significantly based on the region of emission, due to latitudinal differences in solar radiation, regional differences in baseline clouds, and vertical transport of black carbon.\(^{42}\)

To accurately assess I-GCFPs for VSLCFs, the following considerations must be taken into account:

- For all aerosols, indirect effects should be characterized, to the extent possible.
- For black carbon, the indirect effect of enhanced radiative forcing from deposition on ice and snow shall be included.
- For black and brown carbon aerosol, indirect effects on clouds should be included, if relevant.\(^{43}\)

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\(^{41}\) IPCC/TEAC Special Report: Safeguarding the Ozone Layer and Global Climate System.


For all carbonaceous aerosol emissions (black carbon, brown carbon, and organic carbon emissions), the type of combustion shall be included in the characterization. For example, black carbon emissions from fossil fuels are known to have different radiative properties than black carbon emissions from biomass sources, and will have different associated $I$-GCFP values.

When characterizing black carbon, data based in model results must be used with care, because many global models underestimate black carbon concentrations by factors ranging from 3 to 10.\textsuperscript{44,45} Characterization of $I$-GCFP for brown carbon should be included. When including brown carbon, simplifying assumptions may be required to assess results. Such assumptions shall be made taking the goal and scope of the study into consideration, and shall be recorded in the LCA report. Critical review can help to evaluate the effect on data quality of this assumption, taking the goal and scope into account.

\textbf{FOR EXAMPLE.} The preponderance of evidence indicates that the positive radiative forcing from brown carbon is of a very similar scale to the negative radiative forcing from organic carbon.\textsuperscript{46} It is possible to therefore make a simplifying assumption by excluding both brown and organic carbon aerosols, based on this finding.

Calculating $I$-GCFP values of VSLCFs without integrating regional effects may substantially increase their uncertainty, as the integrated forcing for these substances can vary significantly based on the region and timing of emission. For VSLCFs, the uncertainty associated with the use of any global-average $I$-GCFP values should be considered in the context of the goal and scope of the LCA study. If a large amount of uncertainty is introduced as a result of the use of global-average $I$-GCFP values, then it may not be possible to achieve the goal of the study.

\textbf{4.1.4.1.1. Including effects with different spatial and temporal scales.} Certain climateforcers cause multiple direct and indirect effects in the atmosphere, which can occur on different spatial and temporal scales. These differing spatial and temporal scales should be included in characterization to the extent they affect the global-mean integrated radiative forcing, taking the goal and scope of the study into account.

\begin{itemize}
\item\textsuperscript{2012; Ten Hoeve, J.E., M.Z. Jacobson, and L. Remer, Comparing results from a physical model with satellite and in situ observations to determine whether biomass burning aerosols over the Amazon brighten or burn off clouds, \textit{J. Geophys. Res.}, 117, D08203, doi:10.1029/2011JD016856, 2012.}
\end{itemize}
FOR EXAMPLE. For nitrogen oxides, the formation of tropospheric ozone and nitrate aerosols both represent short-lived effects that are inherently regional, while the indirect effect of the destruction of methane is a longer-term effect that is spread roughly evenly throughout the atmosphere (due to the longer lifetime of methane).  

4.1.4.1.2. Including additional radiative effects. While current research has been able to include many of the effects of climate forcers in the atmosphere, future research may determine additional effects that are important to take into account. These effects may include the additional indirect effects on clouds of black and brown carbon, formation of secondary aerosols, interactions between pollutants and ecosystems (e.g., suppression of CO₂ uptake by increased surface ozone concentrations), and other effects. These additional processes should be included as they become better understood.

In cases where a radiative effect is observed, but its characterization cannot be included in the calculation of the I-GCFP, the effect of the limitation on final indicator results should be considered in the context of the goal and scope of the study. The effect of the limitation on the goal of the study should be described in the LCA report.

If the limitation has a significant effect on results, it may not be possible to achieve the goals of the study. In these cases, the goal and scope may need to be revised.

4.1.4.1.3. Characterization of Changes in Biogenic Carbon Storage Levels. In some cases, changes in biogenic storage levels linked to activities at a unit process are linked to net changes in the atmospheric burden of CO₂ (and other climate forcers). Such net changes will lead to integrated radiative forcing, and should be classified in the scope of the study according to the requirements of Section 4.1.3.2.

NOTE. According to the Intergovernmental Panel on Climate Change, CO₂ emissions from land use change are responsible for roughly 33% of the additional CO₂ burden in the atmosphere resulting from anthropogenic activities, or roughly 0.5 W/m² of radiative forcing in 2011. This loss of carbon storage is a significant contributor to the midpoint of radiative forcing (Node 3 in Table 1), and must be accounted for.

In these cases, integrated radiative forcing resulting from the additional burden of climate forcers shall be characterized using Equation 4.1. To do so, the radiative forcing resulting from the net change in atmospheric burden of the climate forcer is integrated over the time horizon based upon the selected GMT anomaly threshold (i.e., 20, 35, or 100 years).

Net changes in radiative forcing caused by changes in biogenic storage are linked to biome disturbances. If effects on biogenic storage levels are relevant, the same minimum reporting levels required in Section 3 must be applied to ensure the scale of the functional unit is defined appropriately.

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4.1.4.1.4. Characterization of other climate forcing effects. For other climate forcing effects not associated with an emission (e.g., changes in surface albedo), I-GCFPs should be calculated by assessing the total integrated radiative forcing as an Absolute Global Warming Potential (AGWP), then normalized to the AGWP for CO₂, according to Equation 4.1. In this way, radiative forcing effects not related to emissions can be evaluated in relation to the equivalent integrated forcing resulting from CO₂ and aggregated with the integrated radiative forcing arising from emissions. This type of characterization is necessary only in rare instances, for certain types of unit processes, and should be evaluated on a site-specific basis, with the method for characterization clearly described in the LCA report.

4.1.4.1.2. Characterization of Continuous Emission Sources. Because LCA is sometimes carried out over extended time horizons (e.g., for 2015 to 2030), some studies will need to consider continuous emission sources occurring over multiple years. In these situations, Equation 4.2 shall be used in the calculation of the I-GCFP, which varies based upon the year of emission.

**Equation 4.2. The Integrated Global Climate Forcing Potential (I-GCFP), also known as the Global Forcing Potential (GFP), of a substance i for a continuous emission source.**

\[
I\text{-GCFP}_i = \frac{\int_{t_E}^{20,35,100} RF_i(t) dt}{\int_{t_E}^{20,35,100} RF_{CO_2}(t) dt} \frac{\int_{t_E}^{20,35,100} a_i[c_i(t)] dt}{\int_{t_E}^{20,35,100} a_{CO_2}[c_{CO_2}(t)] dt}
\]

Where:
- \(t_E\) is the years from the present when the substance is emitted
- 20, 35, 100 are the approximate number of years before the key GMT anomaly thresholds
- \(i\) is the substance
- \(CO_2\) is carbon dioxide
- \(RF_i\) is the time-varying global mean radiative forcing of substance \(i\), for 1 Teragram of emission, considering a pulse emission, in units of mW m⁻²
- \(a_i\) is the radiative efficiency of substance \(i\) (radiative forcing increase per mass increase in atmospheric abundance), in units of mW m⁻² Tg⁻¹
- \([c_i(t)]\) is the unitless atmospheric concentration equation for a pulse emission, which is the time-dependent abundance of 1 Teragram of substance \(i\) emitted at time \(t\) (for a pulse emission), and the corresponding quantities for the reference gas (\(r\)) in the denominator. For most substances (but excluding \(CO_2\)), \(c_i(t) = e^{t/AL}\), where \(AL\) is the atmospheric lifetime of substance \(i\).
- \(AGWP_i\) is the Absolute Global Warming Potential (AGWP) of substance \(i\)
- \(AGWP_{CO_2}\) is the Absolute Global Warming Potential (AGWP) of carbon dioxide
- All GWPs use \(CO_2\) as the reference gas.

The denominator in Equation 4.2 is calculated using 20, 35, or 100 year time horizon (depending on the selected GMT anomaly threshold). The numerator in Equation 4.2 is calculated based on the years from when the substance is emitted to the approximate end of the selected time horizon. This will ensure the consistency of results.

**FOR EXAMPLE.** A study assessed a continuous emission source, with result based upon the +2.0°C GMT anomaly threshold. The denominator in Equation 4.2 is calculated using a 35-year time horizon. The numerator is calculated depending on the years after the present. In the present year, a 35-year time
horizon is used; one year after the present, a 34-year time horizon is used; two years after the present, a 33-year time horizon is used; and so on.

The time horizon used in I-GCFP calculations should never be shorter than 20 years, even if the time horizon from the year of emission to the year of the selected GMT anomaly threshold exceedance is less than 20 years.

The study time horizon, which is defined for the LCA study as the time period over which a continuous emission source is studied (distinct from the years until the projected exceedance of selected GMT anomaly threshold), should be carefully chosen in accordance with the goal and scope of the study, taking into account the data quality of projections of emissions over time.

In most situations, the emissions from a continuous source will vary over the entire study time horizon, and Equation 4.2 must be evaluated numerically, considering both the varying numerator of Equation 4.2, and the varying magnitude of emission in each year.

4.1.4.1.3. Effect of Time Horizon on I-GCFP values. For substances having long atmospheric lifetimes, the I-GCFP values do not vary significantly with different time horizons, generally decreasing slightly as the time horizon increases, because of how the removal rate for a particular gas compares with that for CO₂. For the SLCFs, however, the I-GCFP values tend to increase over shorter time horizons. What this makes clear, as is also shown in the UNEP/WMO report on black carbon and methane⁵¹, is that reductions in the emissions of short-lived species can play a significant role in reducing the rate of near-term warming.

4.1.5. Indicator Equation and Unit of Measure. The indicator result at Node 4 is calculated using Equation 4.3. The result is expressed in mass of carbon dioxide equivalent (CO₂e). The units used should also note that the GFP was used in the calculation, and describe the time horizon used. For example, results could be reported as tons CO₂e (GFP-20). The indicator is called the Integrated Global Climate Forcing,

Equation 4.3. Indicator result for a single unit process for Global Climate Change, calculated at node 4 (global integrated radiative forcing).

\[
\text{Integrated Global Climate Forcing} = \sum_{n} \left[ \sum_{j} (\text{Emissions}_j \times \text{I-GCFP}_j) \right]
\]

Where:
- Emissions, represents the emission of a climate forcer from a unit process in year j
- I-GCFP, represents the I-GCFP in year j
- j represents the total years in the study time horizon
- n represents all of the WMGHG and SLCF emissions emitted by unit process i

4.1.6. Additional Reporting Requirements. The selection of the key GMT anomaly threshold for use (see Section 4.1.1.1) has a strong influence on results, and which threshold used must be made clear in the LCIA profile, using descriptive language to refer to the time horizon used.

While not required under this Standard, if there is uncertainty in the I-GCFP value used, uncertainty analysis is a good technique to understand the relevance to final results. The results of this uncertainty analysis can be reported along with results as a confidence interval. This confidence interval should incorporate the uncertainty inherent in the GWP equation, which the IPCC estimates to be roughly ±35% (90% confidence interval) for the WMGHGs.\textsuperscript{52}

Results shall be reported as combined net results. The contribution to positive and negative radiative forcing (warming and cooling) could also be reported in addition to these net results.

### 4.1.7. Addressing Limitations in Types, Accuracy, and Availability of Environmental Data.

In some cases, there is insufficient data to characterize the I-GCFP for a classified flow. In these cases, conservative assumptions should be made regarding the integrated radiative forcing, in order to estimate the I-GCFP value. The effect on final results of these assumptions should be assessed using sensitivity analysis. If the effect on final results is not significant, the conservative assumption can be used in characterization of the I-GCFP. In this case, the description of the assumptions and methods used shall be included in the LCA report.

If the I-GCFP cannot be accurately characterized, and sensitivity analysis determines that is value has a significant effect on final results, care should be taken in how results are reported. A confidence interval could be reported to represent this uncertainty. If data are available to estimate only a lower or upper confidence bound for results, the upper or lower confidence bound of final results can be reported. In considering how to present results, the goal and scope of the LCA should be taken into account. In these cases, the confidence interval should be reported in the LCIA profile.

**FOR EXAMPLE.** At a forestry site in the Pacific Northwest, forest carbon storage levels have been reduced by 89 million tons of carbon, as compared to a similar undisturbed forest. This loss of carbon is a result of 200 years of harvests in the region. Of these 89 million tons, a fraction is still stored in durable wood products, while a fraction has been emitted to the atmosphere as CO\textsubscript{2}, CH\textsubscript{4}, or other pollutants, as a result of combustion or decay. As the character and timing of these emissions are unknown, conservative estimates are used to estimate the lower confidence bound of the integrated radiative forcing resulting from this forest carbon storage loss. Normalized to a pulse emission of CO\textsubscript{2}, the loss of 89 million tons of forest carbon results in the addition of at least 110 million tons of CO\textsubscript{2}e to the atmosphere, based on a selected time horizon of the +2°C GMT anomaly threshold. To arrive at this lower confidence bound, it was assumed that: 1) the lost forest carbon was entirely emitted as CO\textsubscript{2} 200 years in the past; 2) 30% of this CO\textsubscript{2} currently remains in the atmosphere, the remainder being absorbed by the oceans and terrestrial biogenic systems; and 3) 200 years after a pulse emission, 30% of CO\textsubscript{2} will remain in the atmosphere. In reality, more CO\textsubscript{2} than this will remain in the atmosphere, and some may have been converted to methane, with increased forcing. Results based on this assumption are a lower confidence bound, and must be reported as such.

\textsuperscript{52} IPCC AR4, WGI. 2.10.2: Direct Global Warming Potentials. 2007.
FOR EXAMPLE. The effect on carbon uptake by plants resulting from ground level ozone formation is a significant effect that roughly doubles the overall radiative forcing of ozone precursors. For a study of a wall system produced in the United States, data that characterize this indirect radiative effect of NOx emissions are aggregated by continent, which does not provide sufficient regional differentiation to accurately characterize the effects of ground level ozone on plant growth. Therefore, results were assessed as a confidence interval, with the upper confidence bound for the I-GCFP of NOx calculated assuming the maximum possible effect of ozone on carbon uptake, and the lower confidence bound calculated assuming no effect of ozone on carbon uptake.

In some cases, even a defensible upper or lower confidence bound of indicator results cannot be assessed with the available data. In these cases, results must be reported as inventory flows. This will limit the environmental relevance of results; this must be disclosed in the LCA report. For EPDs, the resulting limitations in comparability must also be described.

4.2. Arctic Climate Change

4.2.1. Impact Category. This impact category addresses the roles of emissions and of other climate changing activities (e.g., from breaking up of sea ice by ice-breaking ships) in Arctic climate change. These climate forcing emissions and activities can occur within the Arctic region, causing direct regional radiative forcing, or outside the region, where they might contribute warming in the Arctic by affecting the transport of energy in the form of heat or water vapor into the region. The characterization factor used is the Arctic Temperature Potential, which is the Regional Temperature Potential for the Arctic, established by Dr. Shindell and Dr. Faluvegi at the National Aeronautics and Space Administration (NASA).

When compared to a pre-Industrial baseline, the Arctic surface regional mean temperature\(^5^4\) (RMT) anomaly is already \(+2^\circ\text{C}\) or greater across land and ocean.\(^5^5\) Many environmental impact endpoints in this region are already occurring and increasing in severity, such as summertime reductions in Arctic sea ice extent and volume, loss of multi-year Arctic sea ice, loss of ice mass from Greenland, thawing of the permafrost, and disruptions to regional biomes and habitats. These regional impacts are immediate in nature; as such, the shortest practicable time interval is used in characterization (see Section 4.2.4.3).

In addition to the regional endpoints associated with impacts within the Arctic, there are endpoints of global relevance, such as addition of glacial meltwater to the oceans, and emissions of carbon dioxide and methane from the thawing of the permafrost and melting of methane hydrates.\(^5^6\) These endpoints – the potential emissions of CO\(_2\) and methane from Arctic carbon pools — have relevance not only for what is happening in the Arctic, but also would increase the forcing that is contributing to global climate change, and speed up the time horizon assumptions used in I-GCFP calculations under the global climate change indicator (see Section 4.1).

4.2.2. Stressor Effects Network. The stressor-effects network encompasses the full spectrum of emissions of GHGs, aerosols, and aerosol precursor gases as well as other climate forcers that contribute to warming and cooling of the Arctic region (Table 4.3). Emissions of these forcers can occur within the Arctic region, causing direct regional radiative forcing, and outside the region, where they might contribute to processes that cause warming or in the Arctic by affecting the transport of energy in the form of heat or water vapor into the region.

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\(^5^4\) For the purpose of this Standard, the Arctic surface regional mean temperature represents the Arctic regional mean near-surface air temperature.

\(^5^5\) National Aeronautics and Space Administration: Goddard Institute for Space Studies. GISS Surface Temperature Analysis (GISTEMP). http://data.giss.nasa.gov/gistemp/

# Table 4.3. Arctic Climate Change Stressor-Effects Network

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Stressors)</td>
<td>Emissions at a unit process of GHGs, warming aerosols such as black and brown carbon, cooling aerosol emissions, and precursor emissions.</td>
<td><strong>Very high uncertainty.</strong> Measurements of these emissions do not directly reflect the consequences on endpoints, as they do not consider: fate and transport of these emissions; varying radiative efficiency of each forcer; differences in the climate response in the Arctic based on the emission location and substance causing the radiative forcing; time variations in Arctic characteristics; or the current Arctic RMT anomaly.</td>
<td>Low uncertainty. Data required: • Data on emissions levels.</td>
</tr>
<tr>
<td></td>
<td><strong>(Very high overall uncertainty. (Very low environmental relevance.))</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 (Midpoint)</td>
<td>A. Contribution to increased concentrations of GHGs and SLCFs throughout the world</td>
<td><strong>High uncertainty.</strong> These measurements poorly reflective of consequences on endpoints due to: differing radiative effectiveness of each forcer; differences in climate sensitivity in the Arctic based on the timing of the emissions and the region and substance causing radiative forcing; the heat capacity of the Arctic-atmosphere system; or the current Arctic RMT anomaly.</td>
<td>Low uncertainty. Data required: • Data on emissions levels. • Data on dispersion characteristics of climate forcing substances. • Dispersion data regarding transport of emissions into the Arctic and other regions.</td>
</tr>
<tr>
<td></td>
<td>B. Contribution to increased concentrations of GHGs and SLCFs in the Arctic region</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C. (Rare instances) Contribution to land-use changes and changes in snow and sea ice cover that change net reflectivity in the Arctic region, and other climate forcing effects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 (Midpoint)</td>
<td>A. Contribution to increase in instantaneous radiative forcing outside of the Arctic</td>
<td><strong>High uncertainty.</strong> Global and regional measurements of radiative forcing for individual species poorly reflect consequences on endpoints, as these do not consider: the differences in climate responsiveness in the Arctic based on the region and substance causing radiative forcing; the time-varying nature of the Arctic-atmosphere system; or the current Arctic RMT anomaly)</td>
<td>Low uncertainty. Data required: • Data on emissions levels. • Data on dispersion characteristics of climate forcers. • Dispersion data regarding transport of emissions into the Arctic and other regions. • Measurements of radiative efficiency, inside and outside of the Arctic.</td>
</tr>
<tr>
<td></td>
<td>B. Contribution to increase in instantaneous radiative forcing inside the Arctic</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Annex A of Draft LEO-SCS-002 Standard, With Karsell Slate Added (June 17, 2014)

<table>
<thead>
<tr>
<th>Node (Type)</th>
<th>Contribution to Activity</th>
<th>Confidence Level</th>
<th>Data Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 (Midpoint)</td>
<td>A. Contribution to increases in energy content of the global Earth-atmosphere system from radiative forcing: fraction of heat transported northward into the Arctic by atmospheric and oceanic advection, mixing, and other heat transfer processes</td>
<td>High uncertainty. Projections of increased energy content do not consider the time varying conditions and heat capacity of this system, or the current Arctic RMT anomaly</td>
<td>Low uncertainty. Data required: Data on emissions levels. Data on atmospheric lifetime and dispersion characteristics of climate forcers. Dispersion data regarding transport of emissions into the Arctic and other regions. Measurements of radiative efficiency, inside and outside of the Arctic. Climate model projections of heat and water vapor transfers into and out of the Arctic region</td>
</tr>
<tr>
<td>5 (Midpoint)</td>
<td>Contribution to intensification of the Arctic surface Regional Mean Temperature (RMT) anomaly</td>
<td>Low uncertainty. Direct precursor to endpoints; Arctic surface temperatures directly reflect endpoints</td>
<td>Moderate uncertainty. Data on emissions levels. Data on atmospheric lifetime and dispersion characteristics of climate forcers. Dispersion data regarding transport of emissions into the Arctic and other regions. Data regarding Arctic climate sensitivity to radiative forcing, by region</td>
</tr>
<tr>
<td>6 (Regional Endpoints)</td>
<td>Contribution to regional endpoints, including: loss of permafrost up to 1,000 miles south of the Arctic Circle; complete loss of summertime sea ice; continuing decline in summertime terrestrial snow cover; disturbance and loss of Arctic biomes and habitats; and disruption of mid-latitude weather</td>
<td>Low uncertainty. Endpoints.</td>
<td>Data not available linking specific emissions sources to regional endpoints</td>
</tr>
<tr>
<td>7 (Global Endpoints)</td>
<td>Contribution to global endpoints, including: possible Arctic biogenic methane pulse from melting of methane hydrates and thawing of the permafrost; contribution to sea level rise from the melting of Arctic glaciers and ice sheets; additional contribution to intensification of the Global Mean Temperature (GMT anomaly)</td>
<td>Low uncertainty. Endpoints</td>
<td>Data not available linking specific emissions sources to global endpoints</td>
</tr>
</tbody>
</table>
4.2.2.1. Selection of the Category Indicator. Proceeding along the stressor-effects network for this impact category, the environmental relevance remains low through the node of instantaneous radiative forcing (Node 3), as measurements of radiative forcing for individual species will not be related to consequences on category endpoints. This will be the case, for example, because of differences in the climate response in the Arctic based on the location and substance causing the radiative forcing, the dependence of the response to radiative forcing on the season of the emission, and extent of sea ice. Instantaneous radiative forcing does not take into account the effects of aerosols on cloudiness. Subsequent midpoints rapidly increase in environmental relevance, with measurements of Arctic surface temperatures considered to be highly reflective of consequences on endpoints. For instance, changes in Arctic temperature are directly related to effects such as the northward shift in the annual average 0°C temperature isotherm, which directly influences the thawing of permafrost and changes to the range of suitable habitat for floral species, as well as other endpoints.

The indicator for this impact category shall be at Node 5 if data is available, characterizing the incremental change in the Arctic near-surface temperature, compared to the incremental change caused by an emission of CO₂. While direct measurements of certain endpoints are available (e.g., the reduction in Arctic summertime sea ice extent), there are currently no established characterization models with which to generate characterization factors at higher nodes.

In some cases, limitations in the type, accuracy, and availability of environmental data may preclude assessment of the incremental change in near-surface Arctic temperature for flows that are classified. In these cases, characterization not possible, and results must be reported as inventory. See Section 4.2.7.

Only one environmental mechanism is relevant for this impact category: Arctic Climate Change. Accordingly, only one category indicator is reported.

4.2.2.2. Identifying Core Impact Categories and Category Indicators. All known product systems have stressors associated with this impact category; for all LCA studies, Arctic Climate Change shall be a core impact category.

4.2.3. Classification. This impact category includes all effects causing changes in the Arctic surface RMT, both contributing to increases and decreases in RMT.

4.2.3.1. Classifying Climate Forcers Contributing to Changes in Arctic RMT. All stressors that amplify or contribute to changes in the Arctic RMT that can be linked to a product system are to be classified. This includes:

- all climate forcers causing regional radiative forcing in the Arctic region that change temperature through direct increases in the heat content of the Arctic-atmosphere system; and

---

• all climate forcers affecting the temperature of the Arctic indirectly, through non-local radiative forcing that causes heat to be trapped elsewhere in the Earth-atmosphere system and to be transported to the Arctic by the atmosphere or ocean.

Because the Arctic surface RMT is linked to global radiative forcing at Nodes 3 and 4 (nodes which are also included, in parallel, in the environmental mechanism for Global Climate Change impact category), all climate forcing effects described in Section 4.1.3 should be classified. All emissions that lead to positive or negative radiative forcing, on a global or regional basis, shall be classified. This includes all emissions that cause direct radiative forcing on a local or non-local basis, as well as emissions that lead to radiative forcing indirectly, through effects such as chemical reactions in the atmosphere, and effects on cloud cover, duration, and brightness.

Other stressors that lead to changes in the albedo or otherwise affect surface-air energy transport in the Arctic, such as land cover change, or the breaking up of Arctic sea ice, shall also be classified.

4.2.3.2. Classification of Effects on Biogenic Systems. The classification of effects from biogenic emissions for this impact category shall include all of the same flow(s) classified for Global Climate Change. The same guidance and provisions apply (see Section 4.1.3.2).

For the Arctic, additional flows which should be considered for classification include:
• Active mitigation of biogenic methane emissions that would have been released due to regional thawing of the permafrost or melting of methane hydrates.
• Active mitigation efforts leading to reductions in emissions of carbonaceous aerosols, including from boreal forest fires and other biogenic systems. Brown carbon is a very significant contributor to the radiative effects for such fires.

4.2.4. Characterization

The characterization factor used to establish results is the Arctic Temperature Potential (ATP), which is the ratio of the incremental change in the Arctic near-surface temperature resulting from a climate forcer to the incremental change in Arctic near-surface temperature caused by the emission of one Teragram of CO$_2$, the reference gas. The ATP is the Regional Temperature Potential for the Arctic, established by Shindell and Faluvegi at the National Aeronautics and Space Administration (NASA).

The ATPs are established by first calculating Absolute Arctic Temperature Potentials (AATPs). The AATP characterizes the change in the Arctic surface temperature resulting from a climate forcer over a 20-year time horizon, in units of mK Tg$^{-1}$ (millikelvins per Teragram of substance emission). All ATPs for a climate forcer are established by normalizing the AATPs to the ATP for CO$_2$, calculated using a 20-year time horizon. Since a 20-year time horizon is used, the characterization factors can be abbreviated as the AATP-20 and ATP-20. (See further discussion of the 20-year time horizon in Section 4.2.4.3.)

The AATP calculation formula in Equation 4.5 integrates both the S-CF and four E-CFs:
• The S-CF for this indicator represents the mass-normalized global-mean inherent radiative efficiency of a substance present in the atmosphere, expressed in units of mW
m² Tg⁻¹ (milli-Watts per square meter per Teragram of the substance). See further discussion in Section 4.2.4.1.

- There are four Environmental Characterization Factors (E-CFs), which respectively characterize: 1) the fraction of a substance remaining in the atmosphere in each year of the study time horizon after a pulse emission; 2) the radiative forcing caused in a particular region resulting from the emission; 3) the temperature response in the Arctic to radiative forcing in this region; and 4) the temporal nature of the climate response. Respectively, these aspects are characterized using Atmospheric Decay Factors (ADFs), Regional Forcing Potentials (RFPs), Arctic Response Coefficients (ARCs), and the Climate Sensitivity Factor (CSF). See further discussion in Section 4.2.4.2.

**NOTE.** Equation 4.5 allows an estimate of the Arctic temperature response to a climate forcer to be calculated without the expense of running a full climate model. However, both the S-CF and E-CFs can be modeled directly using appropriate full climate models. This modeling should directly assess changes to the Arctic surface RMT caused by a stressor. As climate models become more available, and the overall modeling process becomes more efficient, it is recommended that more accurate exact methods using these climate models be used whenever practical. 58

The AATP-20 calculated for a specific climate forser is shown in the equation below. The ATP-20 for an emission is calculated by normalizing the AATP-20 for a climate forser to the AATP-20 for CO₂, the reference gas.

**Equation 4.5. The calculation of the AATP-20.**

\[
\text{AATP-20} = \text{S-CF} \times \sum_{t=1}^{20} \{ \text{ADF}_t \times \text{CSF}_{20-t} \sum_a (\text{RFP}_{at} \times \text{ARC}_a) \}
\]

Where:
- \( t \) represents the number of years after emission
- \( a \) represents each region considered (i.e. the four latitude bands: Arctic, Northern hemisphere mid-latitudes, Tropics, and Southern hemisphere extratropics)
- 20 is the years in the study time horizon
- S-CF is the Stressor Characterization Factor
- ADF<sub>t</sub> is the Atmospheric Decay Factor, evaluated at \( t \)
- CSF<sub>20-t</sub> is the Climate Sensitivity Factor, evaluated as the years in the time horizon minus the given year
- RFP<sub>at</sub> is the Regional Forcing Potential for the given region \( a \) in the given year \( t \)
- ARC<sub>a</sub> is the Arctic Response Coefficient for the given region \( a \)

4.2.4.1 Stressor Characterization Factor. The S-CF for this indicator is the mass-normalized global-mean inherent radiative efficiency of a substance present in the atmosphere, expressed in units of mW m$^{-2}$ Tg$^{-1}$. As this characterization of radiative forcing is at the same node as for the characterization of radiative forcing for the Global Climate Change impact category (see Node 3 of the stressor-effects network), all of the considerations regarding characterization of radiative forcing described in Section 4.1.4 shall be taken into account.

For VSLCFs, the S-CF must be evaluated on a site-specific basis, accounting for the location, timing, source, and elevation of emission. Peer-reviewed studies can provide estimates of the S-CFs for VSLCFs, which can be used as the basis of calculations. Detailed modeling using atmospheric dispersion models, chemistry-transport, or chemistry-climate models, can be used to provide more precise estimates. Regardless of the method used, the characterization of the S-CFs should take into account all relevant aspects of the radiative forcing in the region described in Section 4.1.1, taking the goal and scope of the study into account.

4.2.4.2. Environmental Characterization Factors.

4.2.4.2.1. Atmospheric Decay Factor. The Atmospheric Decay Factor (ADF) is a unitless factor that characterizes the time-dependent mass of an emitted substance remaining in the atmosphere in each year after the initial pulse emission, expressed as an annual average value.

By definition, the ADF varies with time, and is calculated using the atmospheric concentration equation for a substance. These equations should be carefully calculated, taking into account the location, time, elevation, and type of an emission.

For the WMGHGs, the ADF is a single time-series for emissions from any location, which is calculated using the atmospheric concentration equation for a pulse emission source. The ADF can be calculated using the atmospheric concentration equations and atmospheric lifetimes defined by the IPCC, or other credible research. For VSLCFs, the ADF is 1 in the first year of emission, and 0 in each year after.

Peer-reviewed studies can provide estimates of the ADFs. Detailed modeling using atmospheric dispersion models, chemistry-transport, or chemistry-climate models can be used to provide more precise estimates.

4.2.4.2.2. Regional Forcing Potential. The Regional Forcing Potential (RFP) is a unitless factor that characterizes the radiative forcing from a substance emission in a zonal band, compared to the globally averaged radiative forcing caused by this climate forcer. The RFPs are multipliers to the S-CF. The result of the product of the S-CF and RFP is the average regional radiative forcing in a specific zonal band caused by the pulse emission of one Teragram of a substance, in units of mW m$^{-2}$ Tg$^{-1}$.


There are multiple RFPs for each climate forcer emission, defined for each of the four zonal bands considered. Each RFP is the mean radiative forcing caused in each zonal band by that emission, in relation to the global mean radiative forcing caused by that emission.

**NOTE.** Four RFPs are defined, each of which characterize the zonal-mean radiative forcing in four latitude bands: the Southern hemisphere extratropics (28°S - 90°S); the tropics (28°S - 28°N); the Northern hemisphere mid-latitudes (28°N - 60°N); and the Arctic (60°N - 90°N).

The RFP must characterize regional radiative forcing occurring in regions other than where the emission occurred. In general, any emission will cause regional radiative forcing in multiple regions, due to atmospheric transport and indirect climate effects, and the RFP must account for differences in the regional radiative forcing in each zonal band.

**NOTE.** For WMGHGs, the regional radiative forcing in all zonal bands will be approximately equivalent, and the RFPs will be equal to (or close to) one. For VSLCFs, regional radiative forcing will vary greatly by zonal band, and the RFPs will vary broadly.

The RFP values must account for the region, altitude, season, and source of emission, as well as any other parameters that can alter the regional radiative forcing in a latitude band resulting from a substance emission. RFP values for WMGHGs can be established using simplifying assumptions. For VSCLFs, modeling of atmospheric transport is required, which can be based upon data from peer-reviewed studies.

**4.2.4.2.2.1. Regional Forcing Potentials for the Arctic region (RFP_{Arctic}).** The characterization of regional radiative forcing in the Arctic, using RFP_{Arctic}, shall take into account the unique nature of the environmental mechanism of radiative forcing in this region. This includes, but is not limited to:

- The deposition of black carbon on ice and snow in this region;
- The altitudinal profile of each substance, especially black carbon;
- The emissions of black carbon into the stratosphere above the Arctic $^{61}$;
- The lack of direct solar radiation in the winter months, limiting the solar radiative forcing of aerosols that are radiatively active in visible, ultraviolet, and near-infrared radiation bands;$^{62}$
- For black and brown carbon in the Arctic, absorption of downwelling solar and reflected upward solar (at other latitudes, reflected upward solar is much lower);
- Cloud interactions;
- The increased atmospheric lifetime of some substances in this region (e.g., methane);
- The reduced thickness of the troposphere in this region;


$^{62}$ Such aerosols absorb infrared radiation all the time, and enhanced cloudiness by some aerosols increases infrared absorption in the polar night.
Annex A of Draft LEO-SCS-002 Standard, With Karsell Slate Added (June 17, 2014)

- Any regional amplifications (or feedbacks) in the Arctic that increase or decrease the radiative forcing of the stressor;
- The spatial and seasonal variations in Arctic albedo;
- The differences in stability and precipitation in the Arctic atmosphere, which can affect rates of removal of aerosols from wet deposition;
- All other relevant meteorological and atmospheric circulation conditions of the Arctic;
- Other seasonal effects; and
- Any other considerations relevant in characterization of Arctic radiative forcing, taking into account the goal and scope of the study.

4.2.4.2.3. Arctic Response Coefficients. The Arctic response coefficient (ARC) is a unitless factor that characterizes the Arctic temperature response per W m\(^{-2}\) radiative forcing in the indicated region, relative to the global climate sensitivity.

ARCs are defined for each of the four zonal bands for which the RFPs are provided. ARC values have been established for four latitude bands: the Southern hemisphere extratropics (28°S - 90°S); the tropics (28°S - 28°N); the Northern hemisphere mid-latitudes (28°N - 60°N); and the Arctic (60°N - 90°N).\(^{63,64}\) The ARCs for these latitude bands can be used as a default.

ARCs vary based on substance, season, and elevation of the radiative forcing, as well as other factors relevant in the Arctic.\(^{65,66,67}\) These variations should be taken into account when possible, with ARCs established based on peer-reviewed scientific research.

4.2.4.2.4. Climate Sensitivity Factor. The Climate Sensitivity Factor (CSF) characterizes the climate system’s inertial response, which lags behind the radiative forcing due to the thermal mass of the land and oceans, and snow and ice response. The CSF corresponds to an approximate equilibrium in climate sensitivity of 1.06°C per W m\(^{-2}\), corresponding to an increase of 3.9°C in global mean temperature for the CO\(_2\) concentration (see Shindell 2012).\(^{68}\) It is evaluated using Equation 4.6.

Equation 4.6. The Climate Sensitivity Factor. *

\[
\text{CSF} = \frac{0.631}{8.4} e^{-t/8.4} + \frac{0.429}{409.5} e^{-t/409.5}
\]

Where:
- CSF is the Climate Sensitivity Factor, in units of °C (W m\(^{-2}\))\(^{-1}\)
- \(t\) is expressed in years
- The first term approximates the relatively rapid response of the land and upper ocean


The second term approximates the slower response of the deep ocean

*The two terms of this equation approximate the relatively rapid response of the land and upper ocean, and slower response of the deep ocean as reported for simulations with the Hadley Centre climate model. See Shindell (2012).

4.2.4.3. Time Horizon Used in Characterization. Due to the current state of the Arctic region, where many endpoints have currently been reached and even exceeded to different degrees, the shortest possible timeframe is used in the characterization of indicator results. The time horizon used in ATP calculations is 20 years.

4.2.4.4. Characterization of Change in Biogenic Carbon Storage Levels. When relevant, the Arctic temperature response associated with the net change in the atmospheric burden of CO₂ (and other climate forcers) resulting from the change in biogenic storage levels shall be characterized. This includes any flows classified according to Section 4.2.3.

The method used to characterize ATP is the same as for any other activity that alters the atmospheric burden of a climate forcing substance (i.e., emissions of GHGs). The change in the Arctic near-surface temperature resulting from the activity after 20 years is calculated, then normalized to the change in Arctic near-surface temperature after an emission of one Teragram of CO₂.
4.2.5. **Indicator Equation and Unit of Measure.** The indicator result at Node 5 is calculated using Equation 4.7. The result is expressed in mass of carbon dioxide equivalents (CO$_2$e). The units used should also note that the ATP-20 was used in the calculation, and so can be expressed in units such as kg CO$_2$e (ATP-20). The indicator is called Arctic Surface Temperature Change.

**Equation 4.7. Indicator equation for Arctic Climate Change, calculated at Node 5 (Arctic surface temperature change).**

\[
\text{Arctic Surface Temperature Change} = \sum_n (\text{Emissions}_n \times \text{ATP-20}_n)
\]

Where:
- \( n \) represents all of the climate forcers emitted from a unit process
- Emissions are the emissions of the climate forcer
- ATP-20 is the Arctic Temperature Potential, calculated based on a 20-year time horizon, for the climate forcer

4.2.6. **Additional Reporting Requirements.** Uncertainty analysis is a good technique to understand the relevance to final results of uncertainties in the environmental characterization data used. The results of this uncertainty analysis can be reported along with results as a confidence interval.

Results shall be reported as combined net results. The contribution to positive and negative Arctic temperature changes (warming and cooling) could also be reported in addition to these net results. In cases where the net result for Arctic Climate Change is negligible, results shall still be reported, noting in the LCIA profile that stressors are contributing to both positive and negative radiative forcing, but that net results are negligible.

4.2.7. **Addressing Additional Limitations in Types, Accuracy, and Availability of Environmental Data.** In some cases, there are insufficient data to characterize the ATP for a flow that is classified. In these instances, conservative assumptions should be made regarding the in order to estimate the ATP value. The effect on final results of these assumptions should be assessed using sensitivity analysis. If the effect on final results for Arctic Climate Change is not significant, the conservative assumption can be used in characterization of the ATP. In this case, the description of the assumptions and methods used shall be included in the LCA report.

If the ATP cannot be accurately characterized, and sensitivity analysis determines that is value has a significant effect on final results, care should be taken in how results are reported. A confidence interval could be reported, to represent this uncertainty. If data are available to estimate only a lower or upper confidence bound for results, the upper or lower confidence bound of final results can be reported. In considering how to present results, the goal and scope of the LCA should be taken into account. In these cases, it must be communicated in the LCA report and any EPDs or C-EPDs which are generated, whether the values presented are a confidence interval, or a lower or upper confidence bound of results.

In some cases, even a defensible upper or lower confidence bound for indicator results cannot be assessed with the available data. In these cases, results must be reported as inventory flows.
This will limit the environmental relevance of results; this must be disclosed in the LCA report. For EPDs and C-EPDs, the resulting limitations in comparability must also be described.

4.3. Ocean Acidification

4.3.1. Impact Category. This impact category represents the degree to which CO$_2$ emissions lead to decreases in the pH of the ocean, negatively impacting coral reefs and other marine life by lowering both the aragonite and calcite saturation levels.

Ocean acidification represents an increasing risk of disruption of the global ocean ecosystem. Acting along with other ocean stressors, including ocean warming, increases in eutrophication on a large scale, trash, chemical releases such as mercury, overfishing, and other stressors, ocean acidification is contributing to increasing risk to the ocean biosphere.

4.3.2. Stressor-Effects Network. The stressor-effects network relates to the net absorption of atmospheric CO$_2$ into the world’s oceans as carbonic acid (H$_2$CO$_3$). The network for Ocean Acidification is linked to the stressor-effects network for the impact categories of Global Climate Change and Arctic Climate Change (Table 4.4).

Table 4.4. Stressor Effects Network for Ocean Acidification.

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
</table>
| 1    | Emissions of CO$_2$ and other substances which oxidize to form CO$_2$ (i.e., methane) | High uncertainty. Measurements of emissions are not directly reflective of consequences on endpoints, as they do not consider: fate and transport of emissions; fraction of CO$_2$ absorbed by the oceans; changes in ocean pH; or reductions in Aragonite saturation state. | Low uncertainty. Data required:  
  - Emissions data |
| 2    | Contribution to increase in global concentrations of CO$_2$ in the atmosphere | Moderate uncertainty. Measurements are poorly reflective of consequences on endpoints, as they do not consider: the fraction of CO$_2$ absorbed by the oceans; changes in ocean pH; or reductions in Aragonite saturation state. | Low uncertainty. Data required:  
  - Emissions levels  
  - Atmospheric lifetime of CO$_2$ and methane |
| 3    | A fraction of CO$_2$ is absorbed by the ocean, maintaining equilibrium between atmospheric and oceanic CO$_2$ concentrations, given current oceanic conditions | Low uncertainty. Projections of absorption of atmospheric CO$_2$ is reflective of consequences on endpoints, but does not characterize changes in ocean pH, or represent reductions in aragonite saturation state. | Low uncertainty. Data required:  
  - Emissions levels  
  - Measurements of amount of CO$_2$ absorption into oceans each year. |
| 4 (Midpoint) | Contribution to increasing concentration of carbonic acid in the oceans leading to reduction in ocean pH levels (i.e., increase in ocean acidity) | Low uncertainty. Measurements of ocean pH are reflective of consequences on endpoints, but do not directly reflect endpoints of effects to oceanic organisms, as they do not directly represent reductions in aragonite saturation state | Low uncertainty. Data required: • Emissions levels • Estimates of amount of CO₂ absorption into oceans each year. • Rate of formation of carbonic acid from CO₂ |
| 5 (Midpoint) | Contribution to decrease in the Aragonite and calcite saturation levels from CO₂ because of increases in bicarbonate concentrations | Low uncertainty. Measurements of aragonite saturation state strongly reflect changes in viability of calcifying organisms, the most sensitive of species. | • Data not available to link emissions of CO₂ to decreases of Aragonite saturation state. |
| 6 (Midpoint) | A. The pH of the ocean drops below 8.0 for the first time in 20 million years B. Aragonite saturation state in the surface ocean decreases below 3.0 on a global basis C. Aragonite saturation horizon shoals from 1-2 km depths, to shallow <1km depths not seen in 50 million years | Low uncertainty. Strong linkage. Projections of significant changes to ocean pH and aragonite saturation state are strongly reflective of significant impacts to marine calcifiers and other organisms. | • Data not available to link emissions of CO₂ to decreases of Aragonite saturation state and pH below potential thresholds. |
| 7. (Endpoints) | A. Changes in ocean ecosystems on a global and regional basis, including the local to regional decrease or extinction of selected species populations, and simultaneous increases in populations of other more resilient species B. The most sensitive ocean ecosystems, such as coral reefs, experience significant declines and possible elimination, with no recovery anticipated for hundreds of thousands or millions of years C. Decrease in viability of certain marine calcifying organisms, due to reductions in growth, survival, reproduction rates, as well as other organism impacts | Low uncertainty. Endpoints. | Data not available to link specific emissions of CO₂ to endpoints of ocean acidification. |
4.3.2.1. Selection of the Category Indicator. Proceeding along the environmental mechanism, the environmental relevance of the possible category indicators for ocean acidification is low until Node 4, representing the decrease in ocean pH. Nodes 1-3 are poorly reflective of endpoints as they characterize neither changes in ocean pH, nor the measurement of reductions in Aragonite saturation state, which directly impacts marine calcifying organisms. The node of decreased ocean pH is considered to moderately reflect endpoints, as it is closely linked to the reduction in aragonite saturation, which varies with ocean pH along with other aspects of ocean chemistry and temperature.

The reduction in Aragonite saturation state strongly reflects the endpoints of impacts on marine organisms, particularly calcifiers, and so has high environmental relevance. However, there are no recognized characterization models with which to establish characterization factors at this node. By contrast, a characterization model for the indicator at Node 4, based on increases in carbonic acid concentrations, is well defined, and the data required to characterize it are readily available.

The indicator result shall be characterized at Node 4, the oceanic absorption of carbonic acid, if data is available.

Only one environmental mechanism is relevant for this impact category: Ocean Acidification. Accordingly, only one category indicator is reported.

4.3.2.2. Identifying Core Impact Categories and Category Indicators. All known product systems emit carbon dioxide; for all LCA studies, Ocean Acidification will be a core impact category.

In cases where the net result for Ocean Acidification is negligible, results should still be reported, only noting that the net results are negligible.

4.3.3. Classification. CO₂ and other carbon-containing chemicals (e.g., methane) that are ultimately oxidized into CO₂ in the atmosphere are the only chemicals that contribute to this indicator. All CO₂ emissions are included in this impact category, as well as emissions of methane and other substances that are chemically converted in the atmosphere into CO₂. Other emissions can be classified if they have a relevant effect on ocean acidity.

4.3.3.1. Classification of Effects on Biogenic Systems. The classification of effects from biogenic systems for this impact category shall include all of the same flow(s) classified for Global Climate Change. The same guidance and provisions apply (see Section 4.1.3.2).
4.3.4. Characterization

4.3.4.1. Stressor Characterization Factors (S-CFs). The S-CF characterizes the conversion rate of atmospheric CO$_2$ into carbonic acid in the oceans, on a mass basis. One mole of CO$_2$ dissolved in the ocean converts into one mole of carbonic acid. Other substance emissions that convert into CO$_2$ in the atmosphere include methane; it should be assumed that, over time, these other emissions will be fully converted to CO$_2$. The S-CF for these other emissions accounts for their relative molar mass compared to CO$_2$. The S-CFs for CO$_2$ and methane, the two primary contributors to this indicator, are shown in Table 4.5, in units of kilogram carbonic acid per kilogram of emission.

Table 4.5. S-CFs Used for Ocean Acidification

<table>
<thead>
<tr>
<th>Substance</th>
<th>Stressor Characterization Factor (kg H$_2$CO$_3$ / kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide</td>
<td>1.41</td>
</tr>
<tr>
<td>Methane</td>
<td>3.87</td>
</tr>
</tbody>
</table>

4.3.4.2. Environmental Characterization Factor. Two factors are used to calculate the E-CF: the CO$_2$ Absorption Factor, and the Ocean Acidity Factor.

4.3.4.2.1. CO$_2$ Absorption Factor. This factor accounts for the net fraction of CO$_2$ emissions associated with a unit process that is absorbed by the ocean within the study time horizon. Approximately 25% of each year’s CO$_2$ emissions is absorbed by the oceans.$^{69, 70}$ Accordingly, when considering CO$_2$ emissions over short timeframes, the CO$_2$ Absorption Factor for most unit operations is 0.25. The absorption rate of 25% is measured on an annual basis, and is representative of the fraction of present-day emissions of CO$_2$ that will be absorbed by the oceans on the timescales relevant to most LCA studies.

Over longer time scales, as carbon is transported to the deep ocean layers and sediments through mixing, overturning, and biological and chemical removal, the ocean will absorb a significantly larger fraction of the emitted CO$_2$ than 25%. Since the Industrial Revolution, the equivalent of approximately one-third of CO$_2$ emissions have been absorbed by the oceans.$^{71}$ If the scope of the LCA study considers emissions over long time scales, the CO$_2$ Absorption Factor will need to account for the increased absorption that occurs over longer time periods.

---


4.3.4.2.2. Ocean Acidity Factor. The Ocean Acidity Factor compares the current global mean ocean pH to the pre-Industrial baseline condition. The OAF is calculated as $10^{(pH_0 - pH)}$, where $pH$ is the current global mean ocean pH, and $pH_0$ is the pre-Industrial global mean ocean pH, which preponderance of evidence shows was approximately 8.2. The OAF was equal to 1 during pre-Industrial times.

NOTE. The global ocean pH may have decreased from 8.25 in pre-Industrial times to about 8.14 in 2004.

4.3.4.3. Characterization of Changes in Biogenic Carbon Storage Levels. When relevant, the increased burden of $H_2CO_3$ in the oceans associated with the net change in the atmospheric burden of $CO_2$ resulting from the changes in biogenic carbon storage levels shall be characterized. The method used in this characterization is the same as for any other activity that alters the atmospheric burden of a climate forcing substance (i.e., emissions).

4.3.5. Indicator Equation and Unit of Measure. The indicator result at node 4 is calculated using Equation 4.8. It is reported in mass of carbonic acid ($H_2CO_3$). The indicator is called the carbonic acid formation.

**Equation 4.8. Indicator result for Ocean Acidification for a single unit process, calculated at node 4 (carbonic acid formation).**

\[
\text{Carbonic Acid Formation} = \sum_i (\text{Emissions} \times S-CF \times E-CF)
\]

Where:
- \(S-CF\) represents the kilograms of carbonic acid produced per kilogram of substance emission
- \(E-CF\) represents the $CO_2$ absorption fraction, and the Ocean Acidity Factor
- \(i\) represents the total substances contributing to ocean acidification emitted from a unit process

4.3.6. Reporting Requirements. There are no special reporting requirements for category indicator results for Ocean Acidification.


5. Regional Environmental Impacts from Emissions

5.1 Regional Acidification

5.1.1. Impact Category. This impact category represents the deposition of acids into terrestrial and inland water receiving environments where the buffering capacity threshold of regional soils and water bodies has been exceeded.

5.1.1.1. Definition of Exceedance of Threshold. For Regional Acidification, regions which are in exceedance of threshold are defined as those for which the buffering capacity of soils and/or freshwater water bodies has been exceeded.

5.1.2. Stressor-Effects Network. The stressor-effects network for Regional Acidification is shown in Table 5.1. The fate and transport of acidifying emissions and subsequent deposition into regions in exceedance of threshold for regional acidification (Nodes 2 and 3 in Table 5.1) will vary based upon the region of emission and other considerations. Accordingly, regional characterization is necessary to assess accurate results. The use of representative data can help to guide characterization, but could lead to significant uncertainties which may compromise the ability to achieve the goals of the LCA study.

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Stressors)</td>
<td>Total levels of acidifying emissions (expressed in SO$_2$ equivalents) from a unit process.</td>
<td>Very high uncertainty. Characterization does not consider: dispersion and subsequent deposition of acids, or whether these acids deposit into sensitive regions, or pH changes in soils and waters as a result of acidic deposition from all regional sources.</td>
<td>Low uncertainty. Data requirements: Emissions levels of all acidifying substances. Potential for hydrogen ion release of emitted substances.</td>
</tr>
<tr>
<td>2 (Midpoint)</td>
<td>Contribution to increased atmospheric concentrations of acids resulting from atmospheric dispersion of acidifying emissions, leading to increased deposition of acids.</td>
<td>High uncertainty. Characterization does not consider: deposition of these acids into sensitive regions, or pH changes in soils and waters as a result of acidic deposition from all regional sources.</td>
<td>Low uncertainty. Data requirements: Emissions levels of all acidic substances. Potential for hydrogen ion release of emitted substances. Dispersion modeling, requiring inputs of meteorological, climatological, and other data. Mapping of areas in exceedance of threshold for regional acidification.</td>
</tr>
<tr>
<td>3 (Midpoint)</td>
<td>Contribution to deposition of acids into receiving environments in which buffering capacity has been exceeded.</td>
<td>Moderate uncertainty. Characterization does not consider: pH changes in soils and waters as a result of acidic deposition from all regional sources; and resulting endpoints.</td>
<td>Low uncertainty. Data requirements: Emissions levels of all acidic substances. Potential for hydrogen ion release of emitted substances. Dispersion modeling, requiring inputs of meteorological, climatological, and other data. Mapping of areas in exceedance of threshold for regional acidification.</td>
</tr>
</tbody>
</table>
### 4 (Midpoint)

**Characterization at this node not possible given data limitations.**

| Contribution to accumulated deposition of acids from all sources, leading to changes in pH of water bodies and soils. | Low uncertainty. Strongly reflective of endpoints. | Data is usually unavailable regarding the contribution of specific emission sources to pH changes for specific inland environments and water bodies. |

### 5 (Endpoint)

**Characterization at this node not possible given data limitations.**

| Contribution to various endpoint effects (e.g., changes to vegetative composition, fish kills) | Low uncertainty. Directly reflective of endpoints. | Data is unavailable regarding the contribution of specific emission sources to endpoints of regional acidification. |

#### 5.1.2.1. Selection of Category Indicator.

The indicator for this impact category shall be at Node 3, if data is available, characterizing the fraction of an acidifying emission which deposits into regions of exceedance of threshold for regional acidification. Generally, environmental data is widely available on a global basis which can enable the dispersion modeling of Regional Acidification at Node 3.

NOTE. Dispersion models such as the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model, developed initially through a joint effort by the US National Oceanic and Atmospheric Administration and Australia’s Bureau of Meteorology, are applicable globally. The data required are globally gridded meteorological data for regular time intervals, which are generally widely available.

NOTE. The Harmonized World Soil Database provides over 15,000 different soil mapping units on a global basis. This database combines regional and national updates of soil information worldwide.

In some instances, data will be unavailable to characterize Regional Acidification at Node 3. This will occur in cases where the location of unit process(es) in the product system with acidifying emissions cannot be determined, or for other reasons. In these cases, the effect on final results of the uncertainty which is introduced by the lack of data must be considered. Sensitivity analysis can be used to explore the relevance of using representative data for E-CFs. If data limitations for characterization at Node 3 result in significant inaccuracies which could compromise the ability to achieve the goal of the LCA study, characterization at Node 3 may not be possible.

In these cases, characterization can be at Node 1, representing the level of acidifying emissions which can be linked to the product system, expressed in sulfur dioxide equivalents using the Stressor Characterization Factors for this impact category (see Section 5.1.4.1). Characterization at Node 1 has low environmental relevance. This lack of environmental relevance shall be described in the LCA report. If the results are used in an EPD or C-EPD, a disclaimer must be provided stating clearly that the results should not be used as the basis for comparison.
5.1.2.2. Identifying Core Impact Categories and Category Indicator(s). In practice, Regional Acidification will be a relevant impact category for almost all product systems. This is due to the emissions of acidifying substances from combustion of coal, the main global source of electricity generation. There are many other common sources of acidifying emissions which could also contribute. If the scope of an LCA study includes coal-fired electricity generation, it can be assumed that Regional Acidification will be a relevant impact category.

In practice, it should always first be assumed that Regional Acidification is a relevant impact category.

5.1.3. Classification. All acidifying emissions to air are classified, including, but not limited to: sulfur dioxide, sulfuric acid, nitrogen dioxide, nitric oxide, nitric acid, ammonia, hydrochloric acid, hydrofluoric acid, hydrogen sulfide, and phosphoric acid.

5.1.4. Characterization

5.1.4.1. Stressor Characterization Factors. The S-CFs represent the potential of substances to release hydrogen ions into the receiving environment, compared to the potential for sulfur dioxide to release hydrogen ions into the receiving environment. The S-CFs for several strong acids shown in Table 5.2 can be used.

NOTE. The S-CF therefore characterizes the theoretical maximum acidification of a substance, compared to the theoretical maximum acidification of sulfur dioxide.

Table 5.2. Potential for release of hydrogen ions per kilogram of substance, compared to potential for release of hydrogen ions per kilogram of sulfur dioxide. Source: EDIP97.74

<table>
<thead>
<tr>
<th>Substance</th>
<th>Formula</th>
<th>kg SO$_2$e / kg substance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>NH$_3$</td>
<td>1.88</td>
</tr>
<tr>
<td>Hydrochloric acid</td>
<td>HCl</td>
<td>0.88</td>
</tr>
<tr>
<td>Hydrofluoric acid</td>
<td>HF</td>
<td>1.60</td>
</tr>
<tr>
<td>Hydrogen sulfide</td>
<td>H$_2$S</td>
<td>1.88</td>
</tr>
<tr>
<td>Nitric acid</td>
<td>HNO$_3$</td>
<td>0.51</td>
</tr>
<tr>
<td>Nitric oxide</td>
<td>NO</td>
<td>1.07</td>
</tr>
<tr>
<td>Nitrogen dioxide</td>
<td>NO$_2$</td>
<td>0.70</td>
</tr>
<tr>
<td>Phosphoric acid</td>
<td>H$_3$PO$_4$</td>
<td>0.98</td>
</tr>
<tr>
<td>Sulfur dioxide</td>
<td>SO$_2$</td>
<td>1.00</td>
</tr>
<tr>
<td>Sulfuric acid</td>
<td>H$_2$SO$_4$</td>
<td>0.65</td>
</tr>
</tbody>
</table>

74 Environmental Design of Industrial Products (EDIP), in Danish UMIP. 1996.
5.1.4.2. Environmental Characterization Factors. For a given unit process, the E-CF is the fraction of acidifying emissions which deposit into receiving environments that are in exceedance of threshold for regional acidification. The E-CF is expressed on a scale of 0 to 1, with 1 representing 100 percent deposition in environments where thresholds are exceeded.

Dispersion modeling is required to determine the E-CF. This dispersion modeling should use mathematical and numerical techniques to simulate the physical and chemical processes that affect substances that may disperse and react in the atmosphere, based on inputs of meteorological data and source information. The dispersion model which is selected for use depends upon the goal and scope of the LCA study, but should be derived from peer-reviewed work.

NOTE. Dispersion models which are used can include those used in regulatory applications by air quality management agencies and by other organizations, such as those used in the United States to determine compliance with National Ambient Air Quality Standards.

NOTE. The US Environmental Protection Agency provides guidance and support for the use of numerous air quality models through the Technology Transfer Network at the Support Center for Regulatory Atmospheric Modeling. This guidance is periodically updated and revised to ensure the new model developments or expanded regulatory requirements are incorporated. Access to the descriptions of air dispersion models routinely used in air quality management studies can be found at the website of the US EPA’s Support Center for Regulatory Atmospheric Modeling.

This dispersion modeling must characterize deposition into regions that are beyond exceedance of threshold for Regional Acidification, using maps of exceedance zones. This mapping requires the specification of the soil sensitivity characteristics in order to determine the buffering capacity within the receiving environment(s) affected by unit process(es) in the product system under study. This mapping can include the parameters such as the organic carbon content, pH, water storage capacity, soil depth, cation exchange capacity of the soil and clay fraction, total exchangeable nutrients, lime and gypsum contents, sodium exchange percentage, salinity, textural class, and granulometry. The specific determination of how exceedance zones are defined using available data shall be described in the LCA report.

5.1.5. Indicator Equation and Unit of Measure. The category indicator result (at Node 3) for Regional Acidification is shown in Equation 5.1, for a single unit process. The indicator result is expressed in units of mass of sulfur dioxide equivalent (SO₂e).

Equation 5.1. Indicator equation for a single unit process for Regional Acidification, characterized at Node 3 (deposition of acids into regions in exceedance of threshold for Regional Acidification).

\[
\text{Regional Acidification} = \sum_n (\text{Emissions}_n \times \text{S-CF}_n \times \text{E-CF})
\]

Where:
- \( \text{Emissions}_n \) represent the acidifying substances emitted by the unit process, in units of mass
- \( n \) is the total number of acidifying substances emitted by the unit process
- \( \text{S-CF} \) represents the potential for release of hydrogen ions from the emitted substance, when compared to sulfur dioxide
- \( \text{E-CF} \) represents the fraction of the emission which deposits into regions which are in exceedance of threshold for regional acidification
5.2. Stratospheric Ozone Depletion

5.2.1. Impact Category. This impact category represents the potential depletion of the stratospheric ozone layer caused by specific releases of various ozone depleting substances (ODSs) from unit process(es) in the product system under study.

5.2.2. Stressor-Effects Network. The stressor-effects network involves the release of ODSs into the atmosphere which, when transported to the stratosphere, react with stratospheric ozone, causing a net reduction in stratospheric ozone concentrations. These reduced concentrations lead to increased ultraviolet (UV) radiation reaching the Earth’s surface, which can cause a variety of impacts on human health and the environment (see Table 5.3).

Table 5.3. Stressor Effects Network for Stratospheric Ozone Depletion

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Stressors)</td>
<td>High overall uncertainty. (Low environmental relevance.) Emissions of ozone depleting substances (ODS).</td>
<td>High uncertainty. Characterization does not consider: the fraction of ODSs transporting to the stratosphere and forming free radicals; the current state of the stratospheric ozone layer; formation of seasonal ozone hole; or endpoints resulting from increased UV exposure.</td>
<td>Low uncertainty. Data requirements: Emissions levels of ozone depleting substances.</td>
</tr>
<tr>
<td>2 (Midpoint)</td>
<td>Moderate overall uncertainty. (Moderate environmental relevance.) A fraction of ODSs transport to the stratosphere, and react to form free radical reactive intermediates (chlorine, bromine, iodine free radicals).</td>
<td>Moderate uncertainty. Characterization does not consider: contribution to thinning of the ozone layer; formation of seasonal ozone hole; or endpoints resulting from increased UV exposure.</td>
<td>Low uncertainty. Data requirements: Emissions levels of ozone depleting substances. Environmental data linking ODSs to the amount of stratospheric ozone destruction, by type of ODS.</td>
</tr>
<tr>
<td>3 (Midpoint)</td>
<td>Characterization at this node not possible given data limitations. Contribution to reduction of stratospheric ozone concentrations and the global thinning of the stratospheric ozone layer.</td>
<td>Moderate uncertainty. Characterization does not consider: formation of seasonal ozone hole; or endpoints resulting from increased UV exposure.</td>
<td>Data is not available to characterize contribution of a specific emission to reduction in concentrations of ozone in the stratosphere.</td>
</tr>
<tr>
<td>4 (Midpoint)</td>
<td>Characterization at this node not possible given data limitations. Contribution to formation of the seasonal Ozone Hole over Antarctica, and significant regional thinning of ozone layer in the Arctic.</td>
<td>Low uncertainty. Strongly reflective of endpoints.</td>
<td>Data is not available to characterize contribution of a specific emission to formation of seasonal Ozone Hole.</td>
</tr>
</tbody>
</table>
5 (Endpoint) Characterization at this node not possible given data limitations.

Contribution to endpoints affecting the environment and human health. Exposures to increased UV radiation can result in increased risks of cancer and cataracts as the Antarctic Ozone Hole oscillates and spreads out over populated areas.

Low uncertainty. Directly reflective of endpoints.

Data is not available to characterize the contribution of a specific emission to endpoints resulting from increased UV exposure.

5.2.2.1. Selection of Category Indicator. The indicator for this impact category is at Node 2. Environmental data is readily available to characterize results, which shall not be at a lower node.

5.2.2.2. Identification of Core Impact Categories and Category Indicator(s). In practice, since the signing of the Montreal Protocol, emissions of ODSs have been reduced significantly globally. For almost all applications, ODSs have been almost entirely phased out in favor of non-ozone depleting substances. Unless emissions of ODSs from specific unit process(es) in the product system are observed, this impact category will not be relevant. In practice, it can usually be assumed that Stratospheric Ozone Depletion is not a relevant impact category.

Care should be taken in interpreting outputs from LCI models when using secondary inventory data from commercially available databases (e.g., Ecoinvent). These models include the use of representative data for unit process(es) far “upstream”, which may include outdated datasets which include emissions of ODSs. Results in the LCI analysis of ODSs may be reported, but are in fact an artifact of the databases and model outputs. This impact category should only be considered relevant if specific ODS emission sources are identified. These specific emissions sources must be described in the LCA report.

Sensitivity analysis can be used to help determine if ODS emissions can be linked to the product system under study. If emissions of ODSs are reported in the LCI analysis, the significance of the emission should be determined by increasing the scale of the functional unit significantly. If, using the scaled up functional unit, the total emissions of ODSs are negligible, and would not be detectable given typical measurement uncertainty at the scale considered, this impact category can be excluded as relevant.

FOR EXAMPLE. In a study of a fabricated steel product made in North America, the functional unit is assessed for ton of product. At this scale of functional unit, the total ODS emissions (measured using Ozone Depletion Potentials) is roughly one microgram (10^-9 kilograms) of CFC-11 equivalent. To determine if Stratospheric Ozone Depletion is relevant, the results were scaled to the total annual production of the steel product in North America, roughly 1,000,000 tons per year. At this scale of functional unit, the emissions levels of ODSs from the product system are roughly 10 kilograms.
Considering that at the national scale, the confidence interval regarding emissions of ODSs is on the order of ±1,000 or ±10,000 tons of CFC-11, an indicator result for national steel production showing result of 10 kilograms CFC-11 equivalent is far below current measurement thresholds. This impact category was not relevant.

5.2.3. Classification. All substances on a list of ozone depleting substances established by the 1987 Montreal Protocol are classified as ODSs.

5.2.4. Characterization

5.2.4.1. Stressor Characterization Factors. The Stressor Characterization Factor for an ODS is the Ozone Depletion Potential (ODP) established under the Montreal Protocol.

5.2.4.2. Environmental Characterization Factors. The category indicator is at Node 2, characterized using S-CFs based upon the Ozone Depletion Potential. There is no E-CF.

5.2.5. Indicator Equation and Unit of Measure. The equation for calculating results for Stratospheric Ozone Depletion is shown in Equation 5.2. The result is reported in units of mass of CFC-11 equivalent, using ODPs.

Equation 5.1. Indicator equation for assessing results for a single unit process for stratospheric ozone depletion, at Node 2.

\[
\text{Stratospheric Ozone Depletion} = \sum_n (\text{Emissions} \times \text{ODP})
\]

Where:
- \( n \) represents the total number of ODSs emitted by the unit process
- ODP represents the Ozone Depletion Potential of the ODS
- Emissions are in units of mass

5.3. Hazardous Environmental Contaminant Exposure Risks

5.3.1. Impact Category. This impact category considers releases of hazardous environmental contaminants (HECs) from unit process(es) in the product system, which can lead to risks of exposure to flora and fauna. These HECs are emitted into air, soil or water, and can affect many types of ecosystems, including freshwater, marine, and terrestrial. However, through fate and transport, usually freshwater ecosystems are affected.

The emissions which are relevant to this impact category are usually chemicals which have long residence times in the environment. HECs can result in chronic exposures to flora and fauna, which may occur after fate and transport through multiple media, and may occur years after an emission occurs. However, in some instances, significant continuous emission sources of chemicals with relatively short residence times can lead to steady-state concentrations of HECs in the receiving environment, leading to a risk of exposure to flora and fauna.

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The severity, spatial scale, and reversibility, of risks to flora and fauna associated with emissions of different HECs from different unit processes will vary broadly, depending on factors such as the HEC emitted, scale of emission, timing of emission, duration of emission, medium of emission, and regional setting. The midpoints and endpoints associated with this impact category vary for all of these reasons. Accordingly, site-specific assessment of HEC Exposure Risks is required. Secondary data shall not be used in the assessment of this impact category.

5.3.1.1. Definition of Hazardous Environmental Contaminant. In general, HECs are those substances with proven linkages between emissions, exposure to flora/fauna, and onset of chronic or acute toxic effects in sensitive species. These chemicals are considered hazardous and are included for consideration in this impact category, subject to the requirements of Section 5.3.2.2.

At the outset of the study, the set of HECs considered should be clearly defined. For a given LCA study, the set of HECs will be screened to identify those emission sources which have emissions which are relevant for HEC Exposure Risks (see Section 5.3.2.2).

To establish a set of HECs, published lists of chemicals which have been observed in the environment at concentrations above defined thresholds (regulatory thresholds, or otherwise) should be investigated. Lists of chemicals which are targeted for regulation or remediation should be consulted first, as this is a strong indication that exposure has occurred in flora and fauna.

Such a list has been established by the US National Oceanic and Atmospheric Administration (NOAA), for use in the Sediment Quality Guidelines. The chemicals defined in the Sediment Quality Guidelines are shown in Table 5. 4. This list can be used as the basis for a list of HECs.
Table 5.4. The list of substances covered by NOAA’s Sediment Quality Guidelines.

<table>
<thead>
<tr>
<th>Heavy Metals</th>
<th>PCH (continued)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>Low-molecular weight PAH</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Benz(a)anthracene</td>
</tr>
<tr>
<td>Chromium</td>
<td>Benzo(a)pyrene</td>
</tr>
<tr>
<td>Copper</td>
<td>Crysene</td>
</tr>
<tr>
<td>Lead</td>
<td>Dibenzo(a,h)anthracene</td>
</tr>
<tr>
<td>Mercury</td>
<td>Fluoranthene</td>
</tr>
<tr>
<td>Nickel</td>
<td>Pyrene</td>
</tr>
<tr>
<td>Silver</td>
<td>High molecular weight PAH</td>
</tr>
<tr>
<td>Zinc</td>
<td><strong>Polychlorinated biphenyls (PCB)</strong></td>
</tr>
<tr>
<td>Polycyclic Aromatic Hydrocarbons (PCH)</td>
<td>Chlordane</td>
</tr>
<tr>
<td>Acenaphthene</td>
<td>Dieldrin</td>
</tr>
<tr>
<td>Acenaphthylene</td>
<td>DDD</td>
</tr>
<tr>
<td>Anthracene</td>
<td>DDE</td>
</tr>
<tr>
<td>Fluorene</td>
<td>DDT</td>
</tr>
<tr>
<td>2-Methyl naphthalene</td>
<td>Endrin</td>
</tr>
</tbody>
</table>

For a given unit process, other hazardous chemicals may be relevant in this impact category than are included in Table 5.4.

5.3.1.2. Definition of Threshold Exceedance for HEC Exposure Risks. For a given HEC, the threshold is a concentration in a specific medium, usually water. If emissions are found to be relevant in this impact category (based on the requirements of Section 5.3.2.2), the threshold used, and basis of the threshold, shall be described in the LCA report. For HEC Exposure Risks, regions in exceedance of threshold are defined as those receiving environments where concentrations of a HEC are above these defined critical thresholds.

The threshold used must be defined by HEC, and must be based upon a quantitative, measurable value representing the concentration level resulting in onset of the critical toxic effect in sensitive flora or fauna, taking into account as many species and as many taxonomic groups as possible. The definition of the threshold should rely on the tenth percentile value of concentrations which have been observed to result in the critical toxic effect in flora and fauna (rather than the mean value). The concentration used to define the exceedance of threshold for a given HEC shall be clearly described and justified in the report, along with data sources.

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NOTE. The Effects Range-Low (ERL) values, published by the National Oceanic and Atmospheric Administration (NOAA), can be used to determine the threshold concentration for a given HEC. ERL values are established for heavy metals and several persistent organic substances, and have been used in the Sediment Quality Guidelines used by NOAA.79

5.3.2. Stressor-Effects Network. The stressor effects network, shown in Table 5.5, provides a general framework; however, for each separate indicator included for HEC Exposure Risks within the study scope, a separate stressor-effects network should be modeled. This model should describe the site-specific circumstances of stressors, midpoints, and endpoints, in the cause-effect relationship resulting from the classified emission source. This will greatly aid in the characterization of results.

The midpoint of the contamination of the receiving environment over thresholds (Node 3 in Table 5.5) is directly linked to the risk of exposures of flora/fauna. For receiving environments which are contaminated, the contaminants, spatial scale, persistence, and level of contamination, should be understood. Contaminated receiving environments may be linked to emissions occurring at unit process(es) considered in the product system under study, but may also be linked with unit processes outside of the scope of the LCA. Accordingly, it is important to understand other emissions sources which are contributing to this midpoint.

Table 5.5. Stressor effects network for Hazardous Chemical Exposure Risks (ecotoxicity).

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Stressors)</td>
<td>Emissions of HECs into air, water, and soils.</td>
<td><em>High uncertainty.</em> Characterization does not consider: fate and transport; measurement of contribution to contamination receiving environment; risks of exposure to flora/fauna; exposures over thresholds which could result in toxic effects in sensitive species of flora/fauna.</td>
<td><em>Low uncertainty.</em> Data requirements: Emissions levels of HECs.</td>
</tr>
<tr>
<td>2 (Midpoint)</td>
<td>Dispersion of HECs into the receiving environment, leads to contribution to increases in background concentrations in the atmosphere, sediments, silage, water supplies, or bioaccumulation in organisms.</td>
<td><em>High uncertainty.</em> Characterization does not consider: measurement of contribution to contamination receiving environment above known thresholds; risks of exposure to flora/fauna; levels of exposures over thresholds which could result in toxic effects in flora/fauna which may occur.</td>
<td><em>Moderate uncertainty.</em> Data requirements: Emissions levels. Modeling of fate and transport of specific HECs, and contribution to contaminated receiving environments.</td>
</tr>
</tbody>
</table>

### 3 (Midpoints)

**Moderate overall uncertainty.** (Moderate environmental relevance.)

<table>
<thead>
<tr>
<th>Contribution to</th>
<th>Moderate uncertainty. Characterization does not consider levels of exposures over thresholds which could result in toxic effects in flora/fauna.</th>
</tr>
</thead>
<tbody>
<tr>
<td>increases in background concentrations of HECs over thresholds, leading to risks of exposure to flora/fauna.</td>
<td></td>
</tr>
</tbody>
</table>

### 4 (Midpoints)

**Characterization at this node not possible given data limitations.**

<table>
<thead>
<tr>
<th>Contribution to exposures over thresholds to flora/fauna occur as a result of contaminated receiving environment</th>
<th>Low uncertainty. Strongly reflective of toxic effects resulting from exposures in flora/fauna.</th>
</tr>
</thead>
</table>

### 5 (Endpoints)

**Characterization at this node not possible given data limitations.**

<table>
<thead>
<tr>
<th>Contribution to toxic endpoints in flora/fauna. If contamination is significant in scale, large-scale ecosystem endpoints can result.</th>
<th>Low uncertainty. This is a direct measurement of endpoints for this impact category.</th>
</tr>
</thead>
</table>

The emissions which are relevant to this impact category may also be linked to stressor effects networks for Hazardous Food/Water Exposure Risks, since the midpoints at Node 2 and 3 (contamination of the receiving environment) are similar.

#### 5.3.2.1. Selection of Category Indicator(s)

After identifying all emissions of HECs which are relevant in this impact category (see Section 5.3.2.2), distinct category indicators are defined.

To define these distinct category indicators, the stressor-effects network for each species of HEC found to be relevant should first be considered separately. Separate category indicators shall be reported for each HEC emitted under the following conditions:

- Midpoints in the stressor-effects network linked to the emission are distinct in spatial extent, duration, severity of contamination, and species which could be exposed.

- Where multiple types of ecosystems are affected, representing distinct environmental mechanisms, multiple indicators should be established (i.e., for freshwater, marine, and terrestrial ecosystems).
The species affected and toxic endpoints associated with exposure to each chemical are distinct in their character, temporal duration, severity, persistence, reversibility, or other considerations.

The characterization model used to assess category indicator results (dependent upon data availability) is distinct.

Aggregation of emissions of different HECs into a single category indicator must be done with care; even emissions which occur at similar levels, at the same place and time, can lead to cause-effects chains which are distinct. Aggregation is only possible if there are consistent measures of ecotoxicity available for use. If there is no scientific basis for aggregation of multiple HECs using S-CFs (see Section 5.3.4), separate category indicators must be reported.

The node selected to characterize HEC Exposure Risks, is preferentially at Node 3, representing the fraction of an emission contributing to the contamination of a receiving environment in exceedance of threshold.

In practice, there is rarely sufficient data available to characterize results at Node 3. Characterization at Node 2 should be used if possible. This characterizes the fraction of an emission contributing to contamination of the receiving environment, irrespective of whether contamination occurs above thresholds.

However, in many instances, characterization data will not be available for characterization above Node 1, which characterizes emissions levels. Characterization at Node 1 has low environmental relevance. This lack of environmental relevance shall be described in the LCA report. If indicator results are used in EPDs or C-EPDs, a disclaimer must be provided stating clearly that the results should not be used as the basis for comparison.

The stressor-effects network shall be described in the LCA report. The specific midpoint of contaminated receiving environment into which an emission transports must be described in the LCA report and EPDs or C-EPDs; if multiple midpoints are occurring as a result of an emission, all must be described.

Due to the close linkage between the stressor effects network for the initial nodes of HEC Exposure Risks and HFWC Exposure Risks, in many cases, category indicators will be similar in these two impact categories, and characterization models will be the same. If the initial nodes in the stressor effects network are the same, and if characterization models are the same, then one category indicator must be reported for both of these impact categories, to avoid double counting. However, in the LCA report and EPDs or C-EPDs, the midpoints and endpoints relevant to both impact categories shall be described.
5.3.2.2. Identifying Core Impact Categories and Category Indicator(s). Due to the extensive data collection and analysis required to characterize category indicators for HEC Exposure Risks, it is essential to carefully screen the product system under study to identify unit process(es) which are contributing to risks of exposure of flora/fauna to HECs over defined thresholds. This screening is intended to minimize the amount of data collection required.

NOTE. Although for a given study, characterization may be at Node 1, the determination of this impact category as relevant is based on a screening of linkages to the midpoint at Node 3, representing the risk of exposure to flora/fauna to HECs at concentrations over defined thresholds.

This impact category should be considered relevant for a given HEC emitted from a single unit process, if the emission satisfies two conditions:

- The given HEC has been detected as a contaminant in the local receiving environment. The concentration of the HEC should occur over the defined threshold level defined for the HEC according to Section 5.3.1.2.

- The emission must be shown to contribute to the local instance of contamination.

As part of the iterative process, those unit process(es) in the product system which result in significant emissions of HECs should be identified; it can then be determined if these emissions are occurring in regions where the HEC in question occurs in the local receiving environment at concentrations over the defined threshold. Monitoring data of contaminant concentrations is often readily available from governmental monitoring programs or in published literature.

This screening should consider the gross scale of emissions levels occurring in a product system conservatively, based on total annual emissions from specific unit process(es) of concern. If emissions levels of a specific HEC are negligible even using conservative assumptions, the emission will not be relevant in this impact category. An efficient screening will require expert judgment to guide the iterative process.

When conducting this screening, it is important to identify types of unit process(es) which have been known in the other cases to have emissions which contribute measurably to risks of exposure to flora/fauna to HECs at concentrations over defined thresholds. This can include consideration of: unit processes by type, when similar unit processes are known to emit HECs which cause contamination of receiving environments; the HEC and region of emission, if the HEC is a widespread contaminant in the receiving environment where the unit process is located; or the regulatory setting in which a unit process is located, if emissions controls in the region where it is located are lax.

Unit process(es) located in regions where contamination of local receiving environment(s) is an issue of concern to regional government agencies and or other stakeholders, should also be identified.

In many cases, the most significant emissions contributing to HEC Exposure Risks will occur far “upstream” in the product system under study. These significant emission sources often occur in small unit operations in overseas regions, subject to lax emissions controls. A thorough screening of the available literature can help to determine if such unit processes exist in the product system under study.
The persistence of the HEC which is emitted by a unit process should be considered, to help identify emissions which could present a risk of exposure to flora/fauna in the long term. Measures of the persistence of an HEC should consider its chemical half-life or elimination time in different media (e.g., soil, sediments, water).

The level of emission of an HEC should also be understood in the context of the local receiving environment. In some cases, emissions of HECs with relatively short environmental lifetimes can still lead to increased steady-state concentrations of the receiving environment, if the emissions are maintained continuously at high levels.

**FOR EXAMPLE.** In the United States, atrazine is a widely used herbicide which has a relatively short half-life in most receiving environments, due its tendency to chemically decompose in sunlight. However, due to substantial volumes of application of atrazine for agricultural purposes in the Midwestern US, atrazine occurs at elevated concentrations in surface water across much of the region.\(^\text{80}\)

Care should be taken to ensure that this impact category is not mistakenly identified as relevant. HEC Exposure Risks can be ruled out as a relevant impact category if there are no unit process(es) in the product system which contribute measurably to the risk of exposure to flora/fauna to HECs at concentrations over defined thresholds. The justification for the inclusion or exclusion of this impact category shall be provided in the LCA report.

When screening to determine if HEC Exposure Risks is a core impact category, the scale of the functional unit used shall be large enough to include observed instances of midpoints of contaminated receiving environments in exceedance of threshold; the functional unit must not be set arbitrarily low, which could rule out this impact category even in cases where risks of exposure to flora/fauna are occurring and can be linked to emissions from a unit process in the product system. This screening will take care, and may require sensitivity analysis.

An initial screening for the relevance of this impact category may determine that the scale of the functional unit may need to be revised, or that goal and/or scope may need to be revised in other ways. The exclusion of this a core impact category should be a key subject of the critical review phase.

**NOTE.** Although results from LCI models may indicate that the number of HECs emitted from a product system is significant, in practice, very few emissions will be of a nature and scale that risks of exposure to flora/fauna will result.

\(^{80}\) See United States Geological Survey: Watershed Regressions for Pesticides (WARP) Atrazine Model.
5.3.3. Classification. All emissions of HECs which are relevant for this impact category according to the requirements of Section 5.3.2.2 are classified. Multiple category indicators may be reported according to the requirements of Section 5.3.2.1.

5.3.4. Characterization

5.3.4.1. Stressor Characterization Factors. The S-CF is determined by HEC, and is separately defined for each category indicator included in the study scope according to the requirements of Section 5.3.2.1.

In cases where multiple HECs are considered in a single category indicator, the S-CF characterizes the ecotoxicity of each HEC to the ecotoxicity of a reference contaminant. For each category indicator, the same reference contaminant, and consistent measures of ecotoxicity, must be used.

NOTE. For category indicators which include emissions of a single HEC, the HEC is its own reference contaminant, and results are expressed in mass of the emission.

The S-CF for this impact category is shown in Equation 5.3.

**Equation 5.3. Stressor characterization factor for HEC Exposure Risks.**

\[
S - CF_i = \frac{\text{eco toxicity}_i}{\text{eco toxicity}_{reference}}
\]

Where:

- **S-CF is the Stressor Characterization Factor for a given HEC, denoted i**
- **Eco toxicity is the measure of the eco toxicity for the given HEC (denoted i), and the reference contaminant.**

NOTE. Results of emissions levels multiplied with the S-CF shall give results in units of equivalent mass of the reference contaminant. The S-CF equation will thus depend upon the units of the measures of ecotoxicity which are used.

The relative ecotoxicity of a HEC should be based upon a quantitative, measurable value representing the concentration level resulting in onset of the critical toxic effect in sensitive flora or fauna, taking into account as many species and as many taxonomic groups as possible. The definition of the threshold should rely on the tenth percentile value of concentrations which have been observed to result in the critical toxic effect in flora and fauna (rather than the mean value). The concentration used as the basis of determining the relative ecotoxicity of a chemical should be the same as used to define the exceedance of threshold for a given HEC. The basis of values of the relative ecotoxicity of different HECs shall be clearly described and justified in the report, along with data sources.

NOTE. The Effects Range-Low (ERL) values, published by the National Oceanic and Atmospheric Administration (NOAA), can be used to determine the relative ecotoxicity for some HECs. ERL values are...
established for heavy metals and several persistent organic substances, and have been used in the 

For some HECs, ERL values may not be available. In these cases, extreme care must be taken in 
how the ecotoxicity of different HECs is established, in order to provide a defensible basis of 
aggregation for multiple HECs included in a single category indicator. If there is no scientifically 
defensible basis for assessing S-CFs for multiple HECs based on consistent measures of 
ecotoxicity, there is no way to aggregate emissions into a single category indicator. In these 
cases, separate category indicators must be reported for each emission.

When deriving S-CFs, the uncertainty in the measures of ecotoxicity which are used must be 
considered in the context of the goal and scope of the study. The resulting data quality of the S- 
CF, and effect on the data quality of the final result for HEC Exposure Risks, must be described 
in the LCA report.

If the uncertainty in the S-CFs which are calculated are very high, it may not be possible to 
achieve the goal(s) of the study. In these cases, the goal and scope may need to be revised. 
Alternatively, final results can be expressed using a confidence interval.

5.3.4.2. Environmental Characterization Factors. For category indicators in this impact 
category, three levels of reporting at three different nodes are possible, based upon the data 
availability.

For a given category indicator, the same characterization must be applied to all relevant 
emissions of HECs. Comparison between results calculated using different characterization 
models is not possible. In LCA report, the characterization model used to derive results must be 
described clearly wherever results are reported.

The three possible nodes which can be used for characterization are:

- Node 3, characterizing the fraction of an emission which contributes to the contamination of 
a receiving environment where an HEC is present at concentrations exceeding the defined 
threshold.

- Node 2, characterizing the fraction of an emission which contributes to the contamination of 
the receiving environment (irrespective of whether it is in exceedance of threshold).

- Node 1, characterizing the emissions level of the HEC.

The characterization models used for assessment at each node are described in the sections 
below.

5.3.4.2.1. Characterization of Contribution to Contamination of Receiving Environments 
in Exceedance of Threshold. The E-CF assesses the fraction of an HEC emission which
contributes to contamination of a receiving environment which is in exceedance of threshold. At
Node 3, the characterization model used at is the most environmentally relevant measure which
is possible given current techniques. However, the characterization must integrate modeling of
the fate, transport, and accumulation of each HEC which is emitted, and may require significant
modeling resources to complete.

The uncertainty inherent in the modeling of fate and transport of HECs throughout the
receiving environment shall be considered when characterizing results for this indicator.
Uncertainty levels should be described in the LCA report and EPDs or C-EPDs, preferably as a
confidence interval. The modeling uncertainty may be significant enough that the goal of the
LCA study cannot be achieved. In these cases, the goal and scope may need to be revised, or the
colorization of results must be at a lower node which has less associated uncertainty.

The severity, spatial scale, reversibility, and persistence, of receiving environment contamination associated
with different emissions from different unit processes will vary broadly, depending on factors
such as the HEC emitted, scale of emission, timing of emission, duration of emission, medium of
emission, and regional setting. Associated midpoints and endpoints associated vary for all of
these reasons. Accordingly, site-specific assessment at this node is required. Secondary data
shall not be used in the characterization.

5.3.4.2.2. Characterization of Contribution to Contamination of Receiving Environments.
The E-CF assesses the fraction of an HEC emission which contributes to contamination of the
receiving environment, irrespective of whether the receiving environment is in exceedance of
threshold. The characterization must integrate modeling of the fate, transport, and
accumulation of each HEC which is emitted.

The uncertainty inherent in the modeling of fate and transport of HECs throughout the
receiving environment shall be considered when characterizing results for this indicator.
Uncertainty levels should be reported in the LCA report and any EPDs or C-EPDs, preferably as
a confidence interval. The modeling uncertainty may be significant enough that the goal of the
LCA study cannot be achieved. In these cases, the goal and scope may need to be revised, or the
colorization of results must be at Node 1, which has less associated uncertainty.

The severity, spatial scale, reversibility, and persistence, of receiving environment contamination associated with different emissions from different unit processes will vary broadly, depending on factors such as the HEC emitted, scale of emission, timing of emission, duration of emission, medium of emission, and regional setting. Associated midpoints and endpoints associated vary for all of these reasons. Accordingly, site-specific assessment at this node is required. Secondary data shall not be used in the characterization.

5.3.4.2.3. Characterization of Emissions Levels. At Node 1, indicator results assessed at this
node have no E-CF. Emissions contributing to a category indicator are assessed strictly as
emissions levels, and do not integrate fate and transport. Results at this node have low
environmental relevance, and should not be used as the basis for comparisons.

5.3.5. Indicator Equation and Unit of Measure. For results reported at Node 3, the indicator
equation is shown in Equation 5.4; for results at Node 2, the indicator equation is shown in
Equation 5.5; for results reported at Node 1, the indicator equation is shown in Equation 5.6.
Regardless of the node of characterization, results are reported in units of mass equivalents of
the reference substance.

Equation 5.4. Indicator equation for a single unit process for HEC Exposure Risks, with results reported
at Node 3 (contribution to contamination of receiving environments in exceedance of threshold).

\[
\text{HEC Exposure Risks} = \sum_i (\text{Emissions}_i \times \text{S-CF}_i \times \text{E-CF}_i)
\]

Where:
- Emissions are the emissions levels of a given HEC, reported in units of mass.
- S-CF is the Stressor Characterization Factor for each HEC, representing its ecotoxicity relative
to the reference contaminant.
- E-CF is the Environmental Characterization Factor, which characterizes the fraction of the
emission which contributes to the contamination of receiving environment(s) in exceedance of
threshold.

Equation 5.5. Indicator equation for a single unit process for HEC Contamination, with results reported
at Node 2 (contribution to contamination of the receiving environment).

\[
\text{HEC Contamination} = \sum_i (\text{Emissions}_i \times \text{S-CF}_i \times \text{E-CF}_i)
\]

Where:
- Emissions are the emissions levels of a given HEC, reported in units of mass.
- S-CF is the Stressor Characterization Factor for each HEC, representing its ecotoxicity relative
to the reference contaminant.
- E-CF is the Environmental Characterization Factor, which characterizes the fraction of the
emission which contributes to the contamination of the receiving environment.

Equation 5.6. Indicator equation for a single unit process for HEC Emissions, with results reported at
Node 1 (emissions levels).

\[
\text{HEC Emissions} = \sum_i (\text{Emissions}_i \times \text{S-CF}_i)
\]

Where:
- Emissions are the emissions levels of a given HEC, reported in units of mass.
- S-CF is the Stressor Characterization Factor for each HEC, representing its ecotoxicity relative
to the reference contaminant.

5.3.6. Additional Reporting Requirements. In the LCA report and any EPDs or C-EPDs, the
midpoint of contaminated receiving environment in exceedance of threshold associated with a
category indicator shall be described.
The name of the category indicator used to assess results shall be clearly stated in the LCIA profile. The name used shall clearly describe the modeling used, and not overstate the environmental relevance of results.

5.3.7. Addressing Additional Limitations in the Types, Accuracy and Availability of Environmental Data. The first step in characterization of results in this impact category is the screening for determination of relevance of emissions, according to the requirements and guidance provided in Section 5.3.2. In some product systems, where unit process(es) in the product system are distributed in extensive global supply chains, lax regulations and poor monitoring in certain regions might make it impossible to determine the relevance of specific emissions sources to this impact category. If the screening cannot be conducted, then determination of the relevance of this impact category is not possible; this could affect the ability to achieve the goals of the LCA study. If the relevance of this impact category cannot be determined, the goal and scope of the LCA study may need to be revised.

In certain cases, although the scale of emission from a unit process may be unknown, the nature and region of an emission occurring in the product system under study will be understood, and there will be observational data which clearly shows that the emission contributes to the active midpoint of contamination of a receiving environment in exceedance of threshold. In these cases, the category indicator name shall be reported, with the midpoints and endpoints described, although results cannot be assessed at any node.

5.4. Eutrophication

5.4.1. Impact Category. This impact category addresses both terrestrial and aquatic eutrophication impacts. While terrestrial eutrophication midpoints and endpoints are rare and very difficult to specifically identify, aquatic eutrophication midpoints constitute major impacts to freshwater, as well as affecting major marine bodies of water such as the Gulf of Mexico, with well-defined midpoints and endpoints. As such, this impact category is focused on accounting for aquatic eutrophication impacts; if specific terrestrial midpoints are identified, a characterization model must be established, with results reported as a separate category indicator.

Aquatic eutrophication usually occurs when nutrients (biologically available nitrogen and phosphorus) are added beyond a receiving water body’s ability to process them. This leads to increases in primary productivity of algae, which in turn leads to multiple and complex changes to aquatic ecosystems, including blooms of microscopic and macroscopic algae, and increased turbidity in the water column. Eutrophication typically occurs as a result of indirect runoff from emissions to soil, or from direct emissions to water of eutrophying compounds. These effects are often called the “primary symptoms” of eutrophication, and are herein referred as such.

Increased decay as a result of increased algae formation will eventually deplete levels of dissolved oxygen, leading to hypoxia and anoxia; this depletion in oxygen levels leads to major disruptions to local ecosystems as organisms that require oxygen cannot survive. These effects are sometimes called the “secondary symptoms” of eutrophication, and are herein referred as such.
In rare cases, a second mechanism is also possible to deplete dissolved oxygen, whereby organic compounds in the water remove oxygen directly through enhanced aerobic microbial activity.

### 5.4.1.1. Definition of Threshold Exceedance for Eutrophication.

For Eutrophication, regions which are in exceedance of threshold are defined separately for primary and secondary symptoms.

For the primary symptoms of eutrophication, regions in exceedance of threshold include those in which algae concentrations are above levels that the receiving water body can accept. Water bodies experiencing this exceedance are already experiencing negative effects to local ecosystems, including reduction in benthic vegetation, and increased turbidity.

For a specific receiving water body, the exceedance of threshold for primary symptoms of eutrophication is determined quantitatively, based usually upon measures of primary productivity, including but not limited to: mean productivity, chlorophyll-a concentrations, or algal biomass. Exceedance can also be based on concentrations of total phosphorus or nitrogen.

For a given receiving environment, specific conditions of these measurements must be defined, which depend upon the affected receiving water body. These specific conditions will vary based upon the characteristics of the local climate, hydrology, ecosystem, and other considerations. The definition of the specific measures used to determine if a region is in exceedance of threshold for primary symptoms can be based upon local regulations. The basis of determination of whether a receiving water body is in exceedance of threshold for primary symptoms of eutrophication shall be described and justified in the LCA report.

For secondary symptoms of eutrophication, regions in exceedance of threshold include those in which there are levels of dissolved oxygen below certain thresholds for hypoxia. Aerobic organisms in water bodies experiencing this exceedance are already seriously impacted, which can lead to disruptions to local ecosystems.

For a specific receiving water body, the conditions used to define the threshold for secondary symptoms should reflect the characteristics of the local receiving water body. The exceedance of threshold values in Table 5. 6 can be used as a reference. Most regulatory frameworks, including the US Environmental Protection Agency, recognize the threshold identified in Table 5. 6, set at 5 mg/L of dissolved oxygen content. The basis of determination of whether a receiving water body is in exceedance of threshold for secondary symptoms of eutrophication shall be described and justified in the LCA report.

### Table 5. 6. Threshold characterization and exceedance of threshold values, based upon the concentration of dissolved oxygen

*Source: National Oceanic and Atmospheric Administration, Effects of Nutrient Enrichment on the Nation’s Estuaries. 2007.*

<table>
<thead>
<tr>
<th>State</th>
<th>Dissolved Oxygen Content, mg/L</th>
<th>Threshold Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anoxia</td>
<td>0</td>
<td>Exceedance of Threshold</td>
</tr>
<tr>
<td>Hypoxia</td>
<td>0-2</td>
<td>Exceedance of Threshold</td>
</tr>
<tr>
<td>Biological Stress</td>
<td>2-5</td>
<td>Exceedance of Threshold</td>
</tr>
<tr>
<td></td>
<td>&gt;5</td>
<td>Below Threshold</td>
</tr>
</tbody>
</table>
When determining the exceedance of threshold for primary or secondary symptoms in a specific water body, the temporal nature of eutrophication should be considered. Depending upon local conditions, exceedance of threshold could be episodic (i.e., occurring at infrequent intervals), periodic (i.e., occurring at frequent and predictable intervals, usually during the growing season), or persistent (i.e., occurring on a continuous basis). Understanding the temporal nature of the midpoint of exceedance of threshold can aid in characterization.

### 5.4.2. Stressor-Effects Network

The stressor-effects network for this impact category depends upon the size, nature, location, timing, and duration, of an emission, as well as other considerations. The resulting scale, severity, timing, and duration of midpoints in the stressor effects network will vary for many reasons.

The stressor effects network for this impact category, shown in Table 5.7, provides a general framework; however, for each receiving water body experiencing the symptoms of eutrophication affected by eutrophying emissions within the study scope (based upon the requirements of Section 5.4.2.1 and 5.4.2.2), a separate stressor-effects network shall be modeled, describing the site-specific circumstances of stressors, midpoints, and endpoints, in the cause-effect relationship. This will greatly aid in the characterization of results, and will ensure that only relevant impacts are included.

Table 5.7. Stressor effects network for Eutrophication.

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Stressors)</td>
<td>Emissions of eutrophying substances associated with activities at a unit process.</td>
<td>High uncertainty. Characterization does not consider: the transport of eutrophying emissions in the receiving environment; subsequent increase in algae concentrations; subsequent decrease in depletion of oxygen concentrations; or endpoints resulting from primary and/or secondary symptoms of eutrophication.</td>
<td>Low uncertainty. Data requirements: Emissions levels of eutrophying substances. Potential for increased algae formation from emissions.</td>
</tr>
<tr>
<td>2 (Midpoint)</td>
<td>Contribution to increases in nutrient and algae concentrations in the receiving environment as eutrophying emissions from a unit process transport in the receiving environment.</td>
<td>High uncertainty. Characterization does not consider: increase in algae concentrations in regions in exceedance of threshold; subsequent decrease in depletion of oxygen concentrations; or endpoints resulting from primary and/or secondary symptoms of eutrophication.</td>
<td>Low uncertainty. Data requirements: Emissions levels of eutrophying substances. Potential for increased algae formation from emissions. Transport modeling data for eutrophying substances.</td>
</tr>
<tr>
<td>Node</td>
<td>Description</td>
<td>Uncertainty</td>
<td>Data Requirements</td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td>-------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>3 (Midpoint)</td>
<td>Contribution to primary symptoms of eutrophication, when a fraction of eutrophying emissions transport to regions in exceedance of threshold for primary symptoms of eutrophication. These symptoms occur in an episodic, periodic, or persistent basis.</td>
<td>Moderate uncertainty. This indicator has moderate linkage to endpoints, as it takes into account the transport of emissions into regions in exceedance of threshold for the primary symptoms of eutrophication.</td>
<td>Emissions levels of eutrophying substances. Potential for increased algae formation from emissions. Transport modeling data for eutrophying substances. Data on conditions in the receiving environment regarding primary symptoms of eutrophication (i.e., chlorophyll concentrations, total P, or total N).</td>
</tr>
<tr>
<td>4 (Midpoint)</td>
<td>Contribution to secondary symptoms of eutrophication, as increased algae growth occurs in regions in exceedance of threshold for secondary symptoms of eutrophication. Increased algae growth leads to increased decay of organic matter, and subsequent depletion of dissolved oxygen. These symptoms occur in an episodic, periodic, or persistent basis.</td>
<td>Low uncertainty. This indicator has linkage to endpoints, as it takes into account the transport of emissions into regions in exceedance of threshold for the secondary symptoms of eutrophication, which are typically the most significantly impacted regions.</td>
<td>Moderate uncertainty. Data requirements: Emissions levels of eutrophying substances. Potential for increased algae formation from emissions. Transport modeling data for eutrophying substances. Data on conditions in the receiving environment regarding secondary symptoms of eutrophication (i.e., dissolved oxygen concentrations).</td>
</tr>
<tr>
<td>5 (Endpoint)</td>
<td>Endpoints occur as a result of both primary and secondary symptoms, including effects to aerobic organisms such as fish, elimination of aquatic bottom vegetation, harmful and toxic algal blooms, and further ecosystem disruptions.</td>
<td>Low uncertainty. Directly reflective of endpoints.</td>
<td>Data is not available to characterize contribution of an emission to endpoint of eutrophication.</td>
</tr>
</tbody>
</table>

The stressor effects network in Table 5. 7 includes both primary and secondary symptoms of eutrophication. However, in some cases, primary symptoms can occur and lead to endpoints, without the occurrence of secondary symptoms. In these cases, this stressor effects network will not apply, as the midpoint at Node 4 does not occur, and endpoints will be distinct. This
illustrates the need to develop the stressor effects network for eutrophication separately each
affected receiving water body included in the study scope.

5.4.2.1. Selection of Category Indicator(s). For each receiving water body affected by
emissions of eutrophying substances which can be linked to unit process(es) in the product
system under study, a distinct category indicator should be reported, provided a distinct
characterization model is established. A description and justification for the category indicators
which are reported shall be provided in the LCA report.

NOTE. This disaggregation is based upon the distinct nature of the stressor effects network of
eutrophication in distinct water bodies. The distinct nature of eutrophication in different locations is
affected by differences in the spatial extent and/or location of the receiving water body, type of receiving
water system (e.g., freshwater or marine system), severity of threshold exceedances, type of threshold
exceedances (i.e., primary or secondary), and other considerations.

The characterization model which is used depends on the state of threshold exceedance in the
affected receiving water body. If the receiving water is in exceedance of threshold for secondary
symptoms, characterization shall be at Node 4, characterizing the fraction of an emission
transporting to areas in exceedance of threshold. If the receiving water is in exceedance of
threshold only for primary symptoms, characterization shall be at Node 3.

In some cases, characterization may be not be possible at these nodes, as a result of lack of
environmental data, or lack of data regarding the locations of unit process(es) in the product
system. In these cases, characterization can be at Node 1, representing emissions levels of
eutrophying substances, provided that Eutrophication is determined to be a core impact
category according to the requirements of Section 5.4.2.2.

Characterization at Node 1 has low environmental relevance. This lack of environmental
relevance shall be described in the LCA report. If indicator results are used in EPDs or C-EPDs, a
disclaimer must be provided stating clearly that the results should not be used as the basis for
comparison.

In rare cases, emissions of both nutrients and organic chemicals directly contributing to oxygen
depletion may be affecting the same receiving water body in exceedance of threshold for
secondary eutrophication. In these cases, equivalencies can be established to aggregate
nutrients and oxygen depleting chemicals into a single category indicator, using S-CFs. The basis
of such equivalencies must be described in the LCA report. If no equivalencies can be
established using credible research, then aggregation is not possible.

5.4.2.2. Identifying Core Impact Categories and Category Indicator(s). Due to the extensive
data collection and analysis required to characterize category indicators for this impact
category, it is essential to carefully screen the product system under study to identify unit
process(es) which are contributing to eutrophication in areas in exceedance of threshold (Node
3 or 4 in the stressor-effects network). This screening should be intended to minimize the
amount of data collection required, by focusing the scope of the study on emission(s) associated
with a product system which are linked to eutrophication in regions in exceedance of threshold.
For a specific unit process, eutrophication should be included as a relevant core impact category, if the following conditions are satisfied:

- Eutrophying emissions can be linked to activities at the unit process.
- The eutrophying substances resulting from these emissions transport to a receiving water body in exceedance of threshold for eutrophication (either primary or secondary symptoms).

In the first iteration, the potential for eutrophication should be assessed at Node 1, using S-CFs. The unit process(es) which are the main contributors to the potential for eutrophication should be identified, and their region determined. The nature of these unit process(es) should be considered, to understand similar unit processes that have been known in the other cases to have emissions which contribute measurably to eutrophication in local receiving water bodies. For these unit process(es), the local regulatory setting and regional conditions should be understood.

The most significant type of unit process contributing to eutrophication is agriculture, especially in certain regions, such as the Midwestern region of the United States. If agriculture in such a region is found to be a significant contributor to final results for the potential for eutrophication, then the specific emissions linked to activities at this unit process should be understood, and the contribution to eutrophication in regions of exceedance of threshold determined.

Care should be taken when interpreting the outputs of LCI models, when using secondary inventory databases (e.g., Ecoinvent). Emissions of eutrophying substances can vary broadly based upon the type of unit process, regional practices, emission types, season of emission, and other considerations; this means that secondary inventory data may have significant additional uncertainty.

This impact category should only be considered relevant if specific emission sources of eutrophying substances are identified and linked to unit process(es) in the product system under study. These emissions sources must be described in the LCA report.

Sensitivity analysis can be used to help determine if eutrophying emissions can be linked to unit process(es) in the product system under study. If emissions of eutrophying substances are reported in the LCI analysis, the significance of the emission should be determined by increasing the scale of the functional unit. If, using the scaled up functional unit, the total emissions of eutrophying substances across the entire product system are negligible, this impact category can be excluded as relevant.

### 5.4.3. Classification

Classification depends upon whether the affected receiving water body is in exceedance of threshold for the primary or secondary symptoms of eutrophication, based on the definitions in Section 5.4.2.

For category indicators characterizing contribution to eutrophication in a receiving water body in exceedance of threshold for primary symptoms (Node 3 in Table 5.7), emissions of all substances contributing to the primary symptoms of eutrophication should be classified. This includes emissions of biologically-available nitrogen and phosphorus compounds.
NOTE. Air emissions of biologically-available nitrogen and phosphorous compounds can eventually deposit in regions of exceedance of threshold, but are not expected to be a major contributor to eutrophication. Before including specific air emissions in the indicator result, a screening should be conducted to determine if the air emissions from a unit process are resulting in contributions to the indicator result.

For category indicators characterizing contribution to eutrophication in a receiving water body in exceedance of threshold for secondary symptoms (Node 4 in Table 5. 7), emissions of all substances contributing to secondary symptoms of eutrophication should be classified. This includes emissions of biologically-available nitrogen and phosphorus compounds, as well as organic chemicals contributing directly to chemical and biological oxygen demand.

In classification for category indicators at either node, the controlling nutrient must also be identified for a given receiving water body. Nitrogen and phosphorus are the main nutrients controlling algae growth, and initially, compounds of both nitrogen and phosphorus should be considered. Only the controlling nutrient should be classified.

NOTE. The relative importance of nitrogen and phosphorus varies in between different water bodies, and can even vary in the same water body over time. In most fresh water bodies, phosphorus is the limiting nutrient; in marine systems, nitrogen is typically the limiting nutrient. The limiting nutrient can be determined with N/P calculations.

5.4.4. Characterization.

5.4.4.1. Stressor Characterization Factors. S-CFs are separately defined for characterization of emissions of nutrients and oxygen depleting chemicals, based on the distinct nature of these stressors and the midpoints they effect (see Table 5. 7). For nutrients, the S-CF characterizes the potential contribution to algae formation, compared to the potential contribution to algae formation from the limiting nutrient (either nitrogen or phosphorus). For oxygen depleting chemicals, the S-CF characterizes the potential contribution to depletion of oxygen.

In rare cases, emissions of both nutrients and oxygen depleting chemicals may be affecting the same receiving water body in exceedance of threshold for secondary eutrophication. In these cases, equivalencies must be established to aggregate nutrients and oxygen depleting chemicals using S-CFs. The basis of such equivalencies must be described in the LCA report. If no equivalencies can be established using credible research, then aggregation is not possible, and separate indicators must be reported (see Section 5.4.2.1).
5.4.4.1.1. Characterization of Potential Contribution to Algae Formation. For nutrients, the S-CF represents the potential contribution to algae formation of an emission, using the Redfield ratio. S-CFs can be derived from peer-reviewed sources. S-CFs based upon the Redfield ratio are shown in Table 5.8 for receiving environments with different limiting nutrients.

Table 5.8. S-CF values, characterizing the Redfield ratio in environments with different limiting nutrients. Source: Table 6.1, Danish Guidelines.83, 84

<table>
<thead>
<tr>
<th>Substance</th>
<th>Formula</th>
<th>S-CF (Nitrogen-Limited Environment)</th>
<th>S-CF (Phosphorus Limited Environment)</th>
<th>S-CF (Limiting Nutrient not determined)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>kg N. eq. / kg substance</td>
<td>kg P eq. / kg substance</td>
<td>kg NO₃⁻ eq. / kg substance</td>
</tr>
<tr>
<td>Nitrogen Compounds</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ammonia</td>
<td>NH₃</td>
<td>0.82</td>
<td>0</td>
<td>3.64</td>
</tr>
<tr>
<td>Nitrate</td>
<td>NO₃⁻</td>
<td>0.23</td>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>Nitrite</td>
<td>NO₂⁻</td>
<td>0.30</td>
<td>0</td>
<td>1.35</td>
</tr>
<tr>
<td>Cyanide</td>
<td>CN</td>
<td>0.54</td>
<td>0</td>
<td>2.38</td>
</tr>
<tr>
<td>Total Nitrogen</td>
<td>N</td>
<td>1.00</td>
<td>0</td>
<td>4.43</td>
</tr>
<tr>
<td>Phosphorus Compounds</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phosphate</td>
<td>PO₄³⁻</td>
<td>0</td>
<td>0.33</td>
<td>10.45</td>
</tr>
<tr>
<td>Pyrophosphate</td>
<td>P₂O₇⁻²</td>
<td>0</td>
<td>0.35</td>
<td>11.41</td>
</tr>
<tr>
<td>Total Phosphorus</td>
<td>P</td>
<td>0</td>
<td>1.00</td>
<td>32.03</td>
</tr>
</tbody>
</table>

5.4.4.1.2. Characterization of Potential Contribution to Depletion of Oxygen. For oxygen depleting chemicals, the S-CF represents the potential contribution to depletion of oxygen resulting from an emission. The S-CF should be based on chemical oxygen demand (COD) or biological oxygen demand (BOD) tests.

The COD test considers the amount of organic compounds in water, and is expressed in terms of the mass of oxygen consumed per liter of solution (in units of mg/L). The BOD test measures the amount of oxygen required for microorganisms to decompose organic matter, and is measured in units of oxygen consumed per liter of solution (mg/L). Either basis is acceptable for the S-CF used in this indicator result.

Indicator results are reported in mass of oxygen demand, and so the S-CF for this indicator is computed as the mass of oxygen demand per mass of chemical emission. Either the COD or BOD test can be used to evaluate this equivalency for specific chemicals.

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82 At this time, a method for computing S-CFs for this indicator that is more accurate than use of the Redfield ratio has not been identified.


84 In situations where the limiting nutrient cannot be determined, the final column can be used.
5.4.4.2. Environmental Characterization Factors. The E-CF represents the emissions transporting into waters above exceedance of threshold, and so depends upon whether the characterization is at Node 3 or 4 (representing contribution to symptoms of primary or secondary eutrophication, respectively). The E-CF represents the fraction of emission of an eutrophying substance that is transported into receiving waters above the appropriate exceedance of threshold value for the indicator result.

The E-CF is expressed on a scale of 0 to 1, with 1 representing 100 percent transport or deposition in environments where thresholds are exceeded. It is expressed on a scale of 0 to 1, with 1 representing 100 percent transport in environments where thresholds are exceeded. In situations where emissions to soil, water, and air are all occurring, E-CF values should be determined separately for each compartment, to reflect differences in fate and transport.

FOR EXAMPLE. The E-CF for emissions to soil must account for the percent that runs off into waterways and subsequently transports to the affected receiving water body.

Site-specific modeling techniques of fate and transport are required to assess the E-CF for Eutrophication. When assessing E-CFs, published literature should be surveyed. Particularly in regions subject to the regulation of emissions of eutrophying substances, government agencies or other organizations may have established fate and transport models which can be used as the basis of E-CFs. Whenever possible, this type of publicly available data should be retrieved and used. The basis and data sources used to calculate E-CFs shall be described in the LCA report.

FOR EXAMPLE. In the United States, the US Geological Survey has established the SPARROW Surface Water-Quality Modeling tool, a publicly available modeling tool for the regional interpretation of water-quality monitoring data. The SPARROW tool empirically estimates the origin and fate of contaminants in river networks, including eutrophying substances, and quantifies uncertainties in model predictions. SPARROW has been used to estimate the amount of phosphorus and nitrogen from emissions into the Mississippi/Atchafalaya River Basins which transport to the eutrophied regions in the Gulf of Mexico. For emissions of eutrophying substances into the Mississippi or Atchafalaya River watersheds, results from SPARROW can be used to establish E-CFs for Eutrophication in the Gulf of Mexico.
5.4.5. **Indicator Equation and Unit of Measure.** If the category indicator is at Node 3 or 4, results are calculated using Equation 5.7. For emissions of nutrients, the results are reported in units of mass of nitrogen or phosphorus equivalent, depending on the limiting nutrient.

If the category indicator is at Node 4, and emissions are organic chemicals which directly contribute to oxygen depletion, the results are reported in units of mass of chemical or biological oxygen demand.

**Equation 5.7.** Indicator equation for a single unit process for Eutrophication, characterized at Node 3 or 4.

\[
\text{Eutrophication} = \sum_n \sum_j \text{Emissions}_{n,j} \times S-CF_{n,j} \times E-CF_{n,j}
\]

*Where:*

- \( n \) is the total number of eutrophying emissions linked to the unit process
- \( j \) represents soil, water, and air emissions, which may have different E-CF values for a specific eutrophying emission
- Emissions represent the eutrophying emissions linked to the unit process, in units of mass
- S-CF represents the Redfield ratio of the emitted substance, when compared to nitrogen or phosphorus (depending on the limiting nutrient), or the potential contribution to oxygen depletion
- E-CF represents the fraction of the emission which transports into regions which are in exceedance of threshold for eutrophication.

5.4.6. **Additional Reporting Requirements.** In the LCA report and EPDs or C-EPDs, any receiving water bodies considered in category indicators for Eutrophication (meeting the requirements of Sections 5.4.2.1 and 5.4.2.2) shall described. In this description, the location of the water body, type of symptom experienced, and severity of eutrophication in exceedance of threshold shall be included. The category indicator name should also describe the receiving water body which is affected.

5.4.7. **Addressing Additional Limitations in Types, Accuracy, and Availability of Environmental Data.** The most important environmental data regards the fate and transport of eutrophying substances. In some cases, there may not be data available to establish E-CFs for a category indicator, even in cases where specific emissions sources of eutrophying substances have been identified in the product system under study, and linked to the contribution to exceedances of threshold of eutrophication in specific receiving water bodies, according to the requirements of Section 5.4.2.1 and 5.4.2.2. In these cases, results can be reported at Node 1 for unit process(es) which are known to contribute to eutrophication.

If data is not available to characterize Eutrophication, or to determine if it is a relevant impact category, it may not be possible to achieve the goals of the LCA study. In these cases, the goal and scope may need to be revised.
6. Human Health Impacts from Emissions

The impact categories in this group address endpoints to human health. There are five impact categories in this group:

- Ground Level Ozone (GLO) Exposure Risks.
- PM2.5 Exposure Risks.
- Hazardous Chemical Exposure Risks in ambient air.
- Hazardous Substance Exposure Risks in indoor air.
- Hazardous Chemical Exposure Risks by ingestion.

These impact categories characterize toxic chemical releases that present health risks to humans from exposure, and include chemicals that are cancer-causing, and those that can lead to acute and non-cancerous chronic health effects, if humans are exposed.

Each of these impact categories represents a distinct environmental mechanism, based on the route and extent of exposure of humans of various hazardous substances. Aggregation of these emissions into just one or two category indicators is not allowed. Each environmental mechanism for which a distinct characterization model is available is modeled as separate category indicator.

The first two impact categories (GLO Exposure Risks, and PM2.5 Exposure Risks), will be relevant to almost all product systems. These impact categories address ozone and particulate matter exposures, which are the two most harmful components of urban smog. Urban smog is prevalent in almost all industrialized regions in the world.

The latter three impact categories address emissions of hazardous substances. For the purposes of this Standard, to be defined as “hazardous”, a substance must satisfy two conditions: (1) there must be a documented route of exposure to humans, which leads to a measurable risk of exposure; and (2) exposures have been observed to result in toxic effects in humans. Although a chemical may be inherently toxic if a human is exposed, if there is no route of exposure, no toxic endpoints can result. For the purposes of this Standard, chemicals are only considered hazardous if there is a potential route of exposure and inherent toxicity has been documented.

These last three impact categories in this section address the three most common routes of exposure to humans resulting from emissions of hazardous substances. As each route is different, those chemicals which are considered hazardous within each impact category are different.

6.1. Ground Level Ozone (GLO) Exposure Risks

6.1.1. Impact Category. The impact category for ground level ozone (GLO) exposure risks considers human health impacts which could result from risks of exposure to ground level ozone. Impacts to vegetation are not separately addressed.

It is important to recognize that industrial sources of GLO only emit precursors and do not actually emit GLO directly. The major types of precursors are nitrogen oxides (NOx) and non-

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85 Hazardous chemicals may include those listed under: the US EPA, under the provisions of SARA Title III Section 313, Toxic Release Inventory (TRI), Clean Air Act (CAA) Section 112(r) substances; the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA); the International Agency for Research on Cancer (IARC) Monographs on the Evaluation of Carcinogenic Risks to Humans; and chemicals of concern in other countries where studies are conducted. These are listed, for instance, in US EPA, Office of Solid waste and Emergency Response’s “List of Lists: Consolidated List of Chemicals Subject to the Emergency Planning and Community Right-To-Know Act (EPCRA) and Section 112(r) of the Clean Air Act ,” EPA 550-B-01-003, October 2001.
methane volatile organic compounds (NMVOCs), which react to form GLO only occur under certain atmospheric conditions, usually only in certain times of the year.

Millions of people live in regions with elevated concentrations of GLO, and exposures can lead to a wide variety of illnesses and lifelong disabilities. Human health impacts from GLO exposure are widely recognized to occur above critical background concentrations; as a result, in many countries, emissions are tightly controlled in “non-attainment areas”, where these health thresholds are exceeded regularly.

**For example.** The US Environmental Protection Agency has set National Ambient Air Quality Standards (NAAQS) to protect human health for several air pollutants, including ozone. The current NAAQS standard for ozone is 75 parts per billion (ppb), determined over a rolling average of an 8-hour period. Under the NAAQS, areas in non-attainment are those in which the 3-year average of the fourth highest 8-hour average maximum ozone concentrations is over 75 ppb. These NAAQS threshold levels are used to assess air quality with respect to human health and to seek mitigation and controls from major sources of various precursors in a given region.

The preponderance of evidence shows that the 75 ppb threshold used in the NAAQS does not address the chronic effects from GLO in sensitive human populations, which occurs at lower concentrations. The World Health Organization (WHO) has defined an average concentration of 60 ppb of ozone over an 8-hour period as a health threshold relevant to sensitive populations.

NOTE. Although the health threshold used in the United States is 75 ppb, 60 ppb health threshold is the regulatory guideline imposed in the European Union.

Based on the health threshold defined by the WHO, this impact category accounts for emissions of ozone precursors that contribute to ozone which transports into regions in which concentrations of GLO exceed the 60 ppb 8-hour health threshold at any point during the year.

NOTE. GLO is also a source of tropospheric ozone, a climate forcing substance, representing a serial impact mechanism accounted for under a separate group of impact categories (see Section 4 of Annex A).

### 6.1.1.1. Definition of Threshold Exceedance for GLO Exposure Risks

The World Health Organization (WHO) has defined an average concentration of 60 ppb of ozone over an 8-hour period as a health threshold relevant to sensitive populations. The indicator used in this Standard is based upon risks of chronic exposure to the most sensitive subpopulations.

For GLO Exposure Risks, the exceedance of threshold is defined based upon the 60 ppb 8-hour health threshold defined by the World Health Organization. Regions where the 8-hr average ozone concentration exceeds 60 ppb at any hour of the year are considered to be in exceedance of the threshold.

### 6.1.2. Stressor-Effects Network

The stressor effects network for GLO Exposure Risks is shown in Table 6.1. The spatial extent, severity, and level of threshold exceedance, of the midpoints in the stressor-effects network will vary significantly based upon the region of emission, season of emission, emission type, and other considerations. Site-specific assessment of category indicators in this impact category are required, in order to reflect this regional variability. The
use of representative data in characterization can help to guide characterization during the iterative process, but could lead to significant uncertainties which may compromise the ability to achieve the goals of the LCA study.

Table 6.1. Stressor Effects Network for GLO Exposure Risks.

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Stressors)</td>
<td>Emissions of ozone precursors (NOx, VOCs) from a unit process.</td>
<td>Very high uncertainty. Characterization does not consider: dispersion of ozone precursors and resulting ozone formation; contribution to increases in regional GLO concentrations, on episodic and persistent basis; contribution to risks of exposure to regional populations over health thresholds; resulting exposure of humans; toxic endpoints to humans which can be caused by chronic exposure to ozone.</td>
<td>Low uncertainty. Data requirements: Emissions levels of ozone precursors.</td>
</tr>
<tr>
<td>2 (Midpoint)</td>
<td>Atmospheric dispersion of precursors leads to photochemical ozone formation in NOx or VOC limited airsheds, occurring primarily during the ozone season.</td>
<td>High uncertainty. Characterization does not consider: contribution to increases in regional GLO concentrations, on episodic and persistent basis; contribution to risks of exposure to regional populations over health thresholds; resulting exposure of humans; toxic endpoints to humans which can be caused by chronic exposure to ozone.</td>
<td>Low uncertainty. Data requirements: Emissions level of ozone precursors. Dispersion modeling, assessing atmospheric conversion of ozone precursors, and reflecting dispersion based on regional and local conditions.</td>
</tr>
<tr>
<td>3 (Midpoint)</td>
<td>Contribution to increases in regional GLO concentrations, which can lead to acute risks of exposure to populations in the region when ozone concentrations (on an irregular basis) exceed thresholds.</td>
<td>Moderate uncertainty. Characterization does not consider: contribution to increases in regional GLO concentrations, on a persistent basis; contribution to risks of exposure to regional populations over health thresholds; resulting exposure of humans; toxic endpoints to humans which can be caused by chronic exposure to ozone.</td>
<td>Low uncertainty. Data requirements: Emissions level of ozone precursors. Dispersion modeling, assessing atmospheric conversion of ozone precursors, and reflecting dispersion based on regional and local conditions. Hourly data on ambient ozone concentrations. Regional population density.</td>
</tr>
<tr>
<td>4 (Midpoint)</td>
<td>Contribution to persistent increases in regional GLO concentrations over the course of a year in regions where health thresholds are exceeded, leading to chronic risks of exposure to populations in the region over threshold.</td>
<td>Low uncertainty. Characterization of risks of exposure on a chronic basis if strongly reflective of endpoints.</td>
<td>Low uncertainty. Data requirements: Emissions level of ozone precursors. Dispersion modeling, assessing atmospheric conversion of ozone precursors, and reflecting dispersion based on regional and local conditions. Hourly data on ambient ozone concentrations. Regional population density.</td>
</tr>
</tbody>
</table>
### 6.1.2.1. Selection of Category Indicator

For this impact category, one category indicator is assessed, for GLO Exposure Risks. The category indicator shall be at Node 4 if data is available, representing the contribution to increases in regional GLO concentrations in regions where health thresholds are exceeded, leading to chronic risks of exposure to humans over threshold. A detailed description of the characterization model is provided in Section 6.1.4.2.1.

In some cases, data may be unavailable to assess results at Node 4. This may be due to a lack of data on ambient background concentrations of ozone, which makes it impossible to assess the AOT60 air quality metric or Cumulative Risk Factors (see Section 6.1.4). In these cases, results can be assessed at Node 3, characterizing the contribution to increases in regional GLO concentrations where people are exposed, irrespective of the 60 ppb 8-hour health threshold. A detailed description of the characterization model is provided in Section 6.1.4.2.2. Results characterized at this node have lower environmental relevance than results characterized at Node 4.

In some cases, data may be unavailable to assess results at Nodes 3 or 4. This may be due to a lack of data regarding the locations of unit process(es) in the product system, lack of data for dispersion modeling, or lack of population density maps. Due to the high variability in the stressor-effects network for this impact category, results at Node 1 have very low environmental relevance, and could be misleading. If results cannot be assessed at either Node 3 or 4, results for GLO Exposure Risks should be reported as “No data.”

**NOTE.** Results at Node 1 account only for potential photochemical ozone formation, omitting differences in total exposed regional populations, and exposure to different levels of GLO concentrations over threshold. Once the differences in the severity and population densities are included in the category indicator calculation, differences in indicator results for similar emissions levels can be significant. For GLO Exposure Risks, comparisons based upon Node 1 results would be misleading.

### 6.1.2.2. Identifying Core Impact Categories and Category Indicator(s)

Based on the WHO health threshold, GLO Exposure Risks will be relevant for any unit process(es) in the product system which emit ozone precursors that contribute to the elevation of ozone concentrations in regions in which concentrations of GLO exceed the 60 ppb 8-hour health threshold at any point during the year. GLO Exposure Risks is only relevant for emission precursors leading to ozone formation which disperses into regions in exceedance of the health threshold.

To determine for which unit process(es) GLO Exposure Risks is relevant, the region(s) included in the scope of the LCA study must first be mapped, identifying areas in exceedance of the 60 ppb 8-hour health threshold. This mapping is based on rolling 8-hour average ozone concentrations, using ambient monitored ozone data that is interpolated and processed. Areas
in exceedance of the threshold should be identified; the only unit process(es) included are those which result in GLO which transports to these regions in exceedance.

When considering the product system as a whole, GLO Exposure Risks will be a relevant impact category in almost all cases, and this impact category can initially be assumed to relevant for a given LCA study. This is due to the nearly ubiquitous emissions of ozone precursors from combustion, arising from energy generation and from other sources, and the elevated concentrations of ozone in most regions where extensive industrial activity occurs. Product systems almost always will include unit process(es) which emit ozone precursors into regions in exceedance of threshold.

Only if a product system has a scope limited to unit processes in remote regions, away from industrial activities, could GLO Exposure Risks not be relevant.

6.1.3. Classification. Air emissions leading to the formation of ground level ozone are classified. This depends upon whether the receiving environment into which ozone precursors transport is NO\textsubscript{X}-limited, or VOC-limited.

Whenever the concentration (measured in parts per million, or ppm) of VOCs is more than approximately 8 times that of NO\textsubscript{X}, the reaction that creates ozone is limited by the amount of NO\textsubscript{X} in the air (NO\textsubscript{X}-limited). Similarly, when the concentration of VOCs is less than approximately 8 times that of NO\textsubscript{X}, the reaction is said to be VOC-limited. Only the limiting precursor shall be classified.

NOTE. Most receiving environments are NO\textsubscript{X}-limited. Only in rare cases is a receiving environment VOC-limited, which case, NMVOC emissions shall be classified.

The basis of determination for whether receiving environment(s) considered in the study scope are NO\textsubscript{X}-limited, or VOC-limited, should be described in the LCA report.

6.1.4. Characterization. If data is available, the category indicator is at Node 4, characterizing the chronic risk of exposure to humans in regions in exceedance of threshold. The category indicator can be at Node 3, characterizing risk of exposure to humans of ozone, irrespective of health thresholds.

The Stressor Characterization Factor characterizes the mass of ozone formed by the emission of an ozone precursor.

For results calculated at either Node 3 or 4, the Environmental Characterization Factor is calculated independently for emissions from each unit process for which GLO Exposure Risks is relevant (according to Section 6.1.2.2). As this can require extensive data collection and dispersion modeling, characterization must be accomplished in an iterative fashion, in order to minimize data collection requirements and streamline the process. The following steps are intended to provide useful guidance:

- In the first iteration, the potential for GLO formation should be assessed (Node 1 in the stressor effects network), considering only whether the receiving environment(s) included in the study scope are NO\textsubscript{X}-limited or VOC-limited (to ensure S-CFs are appropriately applied; see Section 6.1.4.1). The “key” unit processes for the potential for GLO formation should be identified (i.e., those unit processes which are main contributors to results).
• The location of all “key” unit processes should then be determined. Any “key” unit process(es) in non-attainment areas (for countries with stringent air quality regulations, e.g., the United States or EU) should be identified, and their location determined. Any “key” unit process(es) in overseas regions without stringent air quality regulations, where elevated GLO concentrations are common (e.g., urban areas in China or India), should also be identified, and their location determined.

• Based on their location, readily available E-CFs (e.g. those derived from previous studies, or E-CFs at a node for which environmental data is readily available) should then be applied to assess results for each of the “key” unit processes. Representative E-CFs should be applied to assess results for the “key” unit process(es) for which there are no readily available E-CFs, and for the “non-key” unit processes (i.e., those which are not major contributors to results). These representative E-CFs can be based on E-CFs for nearby unit processes, or on regional averages.

• The second iteration of results should be assessed by combining results from all unit processes; this characterizes results at Node 4 (or Node 3). A new set of “key” unit processes should be identified, based upon these results.

• The data quality of results for GLO Exposure Risks in the second iteration should be carefully considered, taking into account the uncertainty introduced by the use of representative E-CFs applied to “key” unit process(es) and “non-key” unit processes. The effect on results should be considered in the context of the goal and scope of the LCA study.

• If the data quality achieved in the second iteration is not sufficient to achieve the goals of the LCA study, dispersion modeling must be used to derive site-specific E-CFs for those unit process(es) where representative E-CFs were used to assess results in the second iteration. Representative E-CFs should not be used for “key” unit process(es) located in non-attainment regions or in overseas regions with elevated GLO concentrations, as the E-CFs for these regions can be significantly higher than E-CFs in other regions.

• Representative E-CFs should be replaced with site-specific E-CFs, and results assessed for the third iteration.

In practice, there may be cases where site-specific E-CFs cannot be determined for unit process(es) in the study scope, and the use of representative E-CFs results in a significant effect on data quality of results which makes it impossible to achieve the goals of the LCA study. In these cases, the goal and scope may need to be revised.

6.1.4.1. Stressor Characterization Factors. The S-CF for this indicator represents the chemical transformation of the ozone precursor emissions to ground level ozone. The conversion rates are dependent upon meteorological conditions and the background concentrations of both VOCs and NOx.

For NOx-limited receiving environments, the ratios of conversion from NOx to ozone can range significantly — for instance, from 0.2 to 1.3 kilograms ozone per kilogram of NOx released,
depending upon the regional background concentrations of VOCs and how limited the NO\textsubscript{x} concentrations are within that region\textsuperscript{86}. If data is unavailable regarding site-specific conversion rates, a default S-CF value of 1 for NO\textsubscript{X} can be used, which is the equivalent of one kilogram of ozone formation per kilogram of NO\textsubscript{X} emitted.

For VOC-limited receiving environments, the S-CF for relevant VOCs should be based upon measures such as the Maximum Incremental Reactivity.

6.1.4.2. Environmental Characterization Factors. For GLO Exposure Risks, the E-CF is established separately for each unit process in the study scope in a different location. The E-CF is established with a distinct characterization model, depending on whether the category indicator assessed is at Node 3 or 4. Category indicator results at different nodes cannot be compared or aggregated into a single result.

6.1.4.2.1. Characterization of Contribution to Risk of Ozone Exposures in Regions over Threshold (Node 4). For assessment at Node 4, the first step is determining the dispersion domain for GLO of the unit process. The dispersion domain is the area into which ozone formed by emissions at the unit process transports, and is determined using dispersion modeling.

NOTE. Dispersion models which can be used include the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model, developed initially through a joint effort by the US National Oceanic and Atmospheric Administration and Australia's Bureau of Meteorology.

NOTE. The US Environmental Protection Agency provides guidance and support for the use of numerous air quality models through the Technology Transfer Network at the Support Center for Regulatory Atmospheric Modeling. This guidance is periodically updated and revised to ensure the new model developments or expanded regulatory requirements are incorporated. Access to the descriptions of air dispersion models routinely used in air quality management studies can be found at the website of the US EPA's Support Center for Regulatory Atmospheric Modeling.

The E-CF for a unit process for GLO (assessed at Node 4) then requires establishment of three factors for each region in the dispersion domain: the Population Exposure Coefficient (PEC), the AOT60 air quality metric, and Cumulative Risk Factor for GLO (CRF). In practice, these factors are determined for each grid cell in the dispersion domain.

The PEC for a grid cell is the population in the grid cell, assessed using population density maps. The PEC has units of persons.

For a given grid cell, the AOT60 value expresses the hourly ozone concentration above 60 parts per billion (ppb), integrated over the course of an ozone season, with results in units of ppb O\textsubscript{3} * hours.

\textsuperscript{86} LCIA Practitioner’s Manual, Scientific Certification Systems, the Swedish Environmental Research Institute (IVL) and Soil and Water, 1997.
The CRF is a unitless factor which characterizes the severity of risks of human exposure over the threshold for GLO Exposure Risks. The CRF for a grid cell is the ratio of the AOT60 value in that grid cell and 480 ppb-hrs.

NOTE. 480 ppb-hrs is equivalent to one day of exceedance of the 60 ppb 8-hour health threshold.

To establish the E-CF for a unit process, the PEC, AOT60, and CRF, for each grid cell are multiplied and integrated across the regions in the dispersion domain in exceedance of the threshold for GLO Exposure Risks, according to Equation 6.1. The E-CF is calculated per ton of ozone precursors emitted from the unit process over the course of one year (usually NOx).


\[
E\text{-CF for a unit process} = \sum_n \text{PEC}_n \times \text{AOT60}_n \times \text{CRF}_n / \text{ton NOx eq.}
\]

Where:
- E-CF is in units of persons * hours * ppm O\textsubscript{3} / tons NO\textsubscript{x} eq.
- \(n\) represents all grid cells in the dispersion domain in exceedance of threshold for GLO Exposure Risks.
- PEC is the population exposure coefficient, representing the population in the grid cell.
- AOT60 is the AOT60 air quality metric in each grid cell.
- CRF is the Cumulative Risk Factor for each grid cell.

6.1.4.2.2. Characterization of Contribution to Risk of Ozone Exposure (Irrespective of Health Threshold). For assessment at Node 3, the first step is determining the dispersion domain for GLO of the unit process. The dispersion domain is the area into which ozone formed by emissions at the unit process transports. At Node 3, the dispersion domain can be assessed using dispersion modeling. For results at this node, the dispersion domain can also be approximated by assuming the dispersion domain exists within a fixed radius from the emission source, typically 300-km, depending on local meteorological conditions and source characteristics. Assumption of this dispersion domain will result in higher uncertainty than a dispersion domain assessed using dispersion models; this is a limitation which should be considered in the context of the goal and scope of the LCA study.

For results at Node 3, the E-CF is the accumulated human exposure to ozone within the dispersion domain, over the course of the ozone season. The E-CF is calculated per ton of ozone precursors emitted from the unit process over the course of one year (usually NOx). The E-CF is measured in units of population exposure per mass of NOx (e.g., persons * hours / ton NOx).

6.1.5. Indicator Equation and Unit of Measure. The category indicator result (at Node 4) for GLO Exposure Risks is shown in Equation 6.2, for a single unit process. The indicator result is expressed in units of persons * ppb O\textsubscript{3} * hours.

Equation 6.2. Indicator equation for a single unit process for GLO Exposure Risks, characterized at Node 4 (contribution to risks of GLO exposure in regions in exceedance of threshold).

\[
\text{GLO Exposure Risks} = \sum_n (\text{Precursor emissions}_n \times \text{S-CF}_n \times \text{E-CF})
\]

Where:
6.2. Particulate Matter (PM2.5) Exposure Risks

6.2.1. Impact Category. The impact category for PM2.5 Exposure Risks considers human health impacts which could result from risks of exposure particulates under 2.5 micrometers in diameter. These risks of exposure are linked to emission of particulates as well as secondary aerosol particle precursor releases (sulfate and nitrate aerosols formed from SO\textsubscript{x} and NO\textsubscript{x} emissions, respectively).

6.2.1.1. Definition of Threshold Exceedance for PM2.5 Exposure Risks. Although for GLO Exposure Risks, clear thresholds have been identified for concentrations of GLO above which sensitive populations can experience health effects, the preponderance of evidence shows that there is little to suggest a threshold of particulate concentrations below which no adverse health effects would be anticipated. According to the World Health Organization, adverse health effects resulting from PM2.5 exposures have been demonstrated at concentrations not greatly above the background concentration, which is roughly 3 μg PM2.5/m\textsuperscript{3} in the United States and Western Europe.\textsuperscript{87} Accordingly, there is no relevant health threshold for PM2.5 Exposure Risks. However, in practice, it may be useful to use an operational threshold of 1 μg PM2.5/m\textsuperscript{3} for PM2.5. By including in the scope only those areas with elevated PM2.5 concentrations, this will simplify computations greatly, although results will not be significantly affected.

6.2.2. Stressor-Effects Network. The stressor effects network for PM2.5 Exposure Risks is shown in Table 6.2. The spatial extent, severity, and duration, of the midpoints in the stressor-effects network will vary significantly based upon the region of emission, season of emission, emission type, and other considerations. Site-specific assessment of category indicators in this impact category is required, in order to reflect this regional variability. The use of representative data in characterization can help to guide characterization during the iterative process, but could lead to significant uncertainties which may compromise the ability to achieve the goals of the LCA study.

### Table 6.2 Stressor Effects Network for PM2.5 Exposure Risks

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Stressors)</td>
<td>Emissions of primary particulates and precursors (SO$_x$ and NO$_x$) from a unit process.</td>
<td>Very high uncertainty. Characterization does not consider: dispersion of particulates and precursors; contribution to increases in regional PM2.5 concentrations; contribution to risks of exposure to regional populations; resulting exposures; toxic endpoints to humans which can be caused by chronic exposure to fine particulates.</td>
<td>Low uncertainty. Data requirements: Emissions levels of particulates and particulate precursors.</td>
</tr>
<tr>
<td>2 (Midpoint)</td>
<td>Atmospheric dispersion of primary particulates, and conversion of a fraction of SO$_x$ and NO$_x$ to form secondary particulates, which could expose regional populations.</td>
<td>Moderate uncertainty. Characterization does not consider: contribution to increases in regional PM2.5 concentrations; contribution to risks of exposure to regional populations due to severity of exposures; resulting exposures; toxic endpoints to humans which can be caused by chronic exposure to fine particulates.</td>
<td>Low uncertainty. Data requirements: Emissions levels of particulates and particulate precursors. Dispersion modeling, assessing dispersion of primary particulates and atmospheric conversion of precursors, and reflecting dispersion based on regional conditions.</td>
</tr>
<tr>
<td>3 (Midpoint)</td>
<td>Contribution to persistent increase in regional PM2.5 concentrations, leading to acute and chronic risks of exposure to populations in the region as a result of severity of increased concentrations.</td>
<td>Low uncertainty. Characterization of risks of exposure on a chronic basis has strong linkage endpoints.</td>
<td>Low uncertainty. Data requirements: Emissions levels of particulates and particulate precursors. Dispersion modeling, assessing dispersion of primary particulates and atmospheric conversion of precursors, and reflecting dispersion based on regional conditions. Data regarding ambient PM2.5 concentrations. Regional population density.</td>
</tr>
<tr>
<td>4 (Midpoint)</td>
<td>Contribution to acute and chronic exposures to PM2.5 of populations in the region.</td>
<td>Low uncertainty. Exposure to PM2.5 is directly linked to resulting endpoints.</td>
<td>Data is not available to link specific emissions of particulates and precursors to resulting human exposures.</td>
</tr>
<tr>
<td>5 (Endpoints)</td>
<td>Contribution to human health effects including asthma, lung cancer, cardiovascular issues, birth defects, and premature death</td>
<td>Low uncertainty. Directly linked to endpoints.</td>
<td>Data is not available to link specific emissions of particulates and precursors to resulting human health endpoints in regional populations.</td>
</tr>
</tbody>
</table>
6.2.2.1. Selection of Category Indicator. For this impact category, one category indicator is assessed, for PM2.5 Exposure Risks. The category indicator shall be at Node 3 if data is available, characterizing the contribution to the severity of risks of exposure to regional populations from PM2.5. A detailed description of the characterization model is provided in Section 6.2.4.

In some cases, data may be unavailable to assess results at Node 3. This may be due to a lack of data on ambient background concentrations of PM2.5, which makes it impossible to assess the Accumulated Exposure Coefficient or Cumulative Risk Factors (see Section 6.2.4). In these cases, results can be assessed at Node 2, characterizing the contribution to risks of human exposures to PM2.5 (irrespective of the severity of the risk). A detailed description of the characterization model is provided in Section 6.2.4.2. Results characterized at this node have lower environmental relevance than results characterized at Node 3, but environmental data is more readily available.

In some cases, data may be unavailable to assess results at Nodes 3 or 2. This may be due to a lack of data regarding the locations of unit process(es) in the product system, lack of data for dispersion modeling, or lack of population density maps. Due to the high variability in the stressor-effects network for this impact category, results at Node 1 have very low environmental relevance, and could be misleading. If results cannot be assessed at either Node 3 or 2, results for PM2.5 Exposure Risks should be reported as “No data.”

6.2.2.2. Identifying Core Impact Categories and Category Indicators. As there is no relevant health threshold, PM2.5 Exposure Risks is relevant for any unit process(es) in the product system which emit primary particulates or secondary particulate precursors that contribute to the elevation of PM2.5 concentrations and subsequent risks of exposure to regional populations.

When considering the product system as a whole, PM2.5 Exposure Risks will be a relevant impact category in almost all cases, and this impact category can initially be assumed to be relevant for a given LCA study. Product systems almost always will include unit process(es) which emit particulates or precursors into regions which can affect regional populations.

6.2.3. Classification. All primary particulate matter and secondary particulate matter precursors are classified in this indicator.

6.2.4. Characterization. The category indicator should be at Node 3, characterizing the contribution to severity of chronic risks of exposure to regional populations from PM2.5. The category indicator can be at Node 2, characterizing risk of exposure to humans of PM2.5, irrespective of the severity of risks.

The Stressor Characterization Factor characterizes the mass of PM2.5 emitted, or resulting from formation of secondary particulates.

For results calculated at either Node 3 or 2, E-CFs are calculated independently for emissions from each unit process for which PM2.5 Exposure Risks is relevant (according to Section 6.2.2.2). As this can require extensive data collection and dispersion modeling, characterization of Node 3 must be accomplished in an iterative fashion, in order to minimize data collection requirements and streamline the process. The following steps are intended to provide useful guidance:
• In the first iteration, the emissions of PM2.5 should be assessed at Node 1 in the stressor effects network, considering both direct emissions and emissions of precursors which form PM2.5. The “key” unit processes for PM2.5 emissions should be identified (i.e., those unit processes which are main contributors to results).

• The location of all “key” unit processes should then be determined. Any “key” unit process(es) in non-attainment areas for PM2.5 (for countries with stringent air quality regulations, e.g., the United States or EU) should be identified, and their location determined. Any “key” unit process(es) in overseas regions without stringent air quality regulations, where elevated PM2.5 concentrations are common (e.g., urban areas in China or India), should also be identified, and their location determined.

• Based on their location, readily available E-CFs (e.g., those derived from previous studies, or E-CFs at a node for which environmental data is readily available) should then be applied to assess results for each of the “key” unit processes.

• Representative E-CFs should be applied to assess results for the “key” unit process(es) for which there are no readily available E-CFs, and for the “non-key” unit processes (i.e., those which are not major contributors to results). These representative E-CFs can be based on E-CFs for nearby unit processes, or on regional averages.

• The second iteration of results should be assessed by adding results from all unit processes. A new set of “key” unit processes should be identified, based upon these results.

• The data quality of results for PM2.5 Exposure Risks in the second iteration should be carefully considered, taking into account the uncertainty introduced by the use of representative E-CFs applied to “key” unit process(es) and “non-key” unit processes. The effect on results should be considered in the context of the goal and scope of the LCA study.

• If the data quality achieved in the second iteration is not sufficient to achieve the goals of the LCA study, dispersion modeling may be necessary to derive site-specific E-CFs for those unit process(es) where representative E-CFs were used to assess results in the second iteration. Representative E-CFs should not be used for “key” unit process(es) located in non-attainment regions or in overseas regions with elevated PM2.5 concentrations, as the E-CFs for these regions can be an order of magnitude higher than E-CFs in other regions.

• Representative E-CFs should be replaced with site-specific E-CFs, and results assessed for the third iteration.

In practice, there may be cases where site-specific E-CFs cannot be determined for unit process(es) in the study scope, and the use of representative E-CFs results in a significant effect on data quality of results which makes it impossible to achieve the goals of the LCA study. In these cases, the goal and scope may need to be revised.
6.2.4.1. Stressor Characterization Factors. The S-CF for PM2.5 Exposure Risks characterizes
the mass of PM2.5 transported in the atmosphere as the result of an emission. For emissions of
primary particulates, the S-CF characterizes the fraction of PM2.5. For emissions of secondary
particulate precursors (SO_x and NO_x), the S-CF characterizes the chemical transformation of the
precursor emissions into PM2.5.

The conversion rates of precursors depend on atmospheric and meteorological conditions; the
fraction of particulates that are PM2.5 (i.e., less than 2.5 microns in diameter) can also depend
upon the fuel type used in combustion. The basis of S-CFs used shall be described and justified
in the LCA report.

6.2.4.2. Environmental Characterization Factors. For PM2.5 Exposure Risks, the E-CF is
established separately for each unit process in the study scope in a different location. The E-CF
is established with a distinct characterization model, depending on whether the category
indicator assessed is at Node 3 or 2. Category indicator results at different nodes cannot be
compared or aggregated into a single result.

6.2.4.2.1. Characterization of Contribution to Severity of Chronic Exposure Risks to PM2.5
(Node 3). For assessment at Node 3, the first step is assessing the dispersion domain for PM2.5
of the unit process. The dispersion domain is the area into which PM2.5 resulting from
emissions occurring at the unit process transports, and is determined using dispersion
modeling.

The E-CF for a unit process for PM2.5 Exposure Risks (assessed at Node 3) then requires
establishment of three factors for each region, by grid cell, in the dispersion domain: the
Population Exposure Coefficient (PEC), the Accumulated Exposure Coefficient for PM2.5 (AEC),
and the Cumulative Risk Factor for PM2.5 (CRF).

The PEC for a grid cell is the population in each grid cell, assessed using population density
maps. The PEC has units of persons.

The AEC for a given grid cell, is the hourly concentration of PM2.5, integrated over the course of
the year. This factor is units of µg PM2.5 / m^3 * hours.

The CRF is a unitless factor which characterizes the severity of risks of human exposure to
PM2.5, when compared to exposures to background concentrations of PM2.5. The CRF is
calculated for a grid cell, by first assessing the annual average PM2.5 concentration in that grid
cell (measured in units of µg PM2.5 per m^3). This annual average concentration is integrated
over one hour, then divided by the accumulated hourly background PM2.5 concentration,
integrated over the course of one year. This characterizes the severity of risk exposure to
PM2.5, which results in health risks at essentially any concentration.

The preponderance of evidence suggests that in the absence of anthropogenic sources of
particulates, the annual average background concentration of PM2.5 is roughly 3 µg PM2.5 / m^3;
the accumulated hourly background concentration over the course of one year is therefore
26,280 hours * µg PM2.5 / m^3. The annual average PM2.5 concentration in the grid cell is
therefore divided by 26,280 hours * µg PM2.5 / m^3 (see Equation 6.3).

NOTE. The ambient background concentration for PM2.5 is the concentration which would persist in the
absence of all anthropogenic emissions. The preponderance of evidence shows that this background
concentration varies between 1 and 5 \( \mu g \) PM2.5 / m\(^3\) on an annual average basis;\(^{88,89,90}\) moister regions likely tend towards the lower end of this range, while drier regions towards the higher end. For the purposes of this Standard, 3 \( \mu g \) PM2.5 / m\(^3\) is used, as the rough midpoint of this range of concentrations.

Equation 6.3. Cumulative risk factor for PM2.5 Exposure Risks.

\[
\text{Cumulative Risk Factor (PM2.5)} = \frac{(\mu g \text{ PM2.5} / m^3)_{avg} \times 1 \text{ hour}}{26,280 \mu g \text{ PM2.5} / m^3 \times \text{hours}}
\]

Where:

- \((\mu g \text{ PM2.5} / m^3)_{avg}\) is the annual average concentration of PM2.5 in the grid cell.
- 26,280 \( \mu g \) PM2.5 / m\(^3\) \( \times \) hours is the accumulated ambient background concentration of PM2.5.

To establish the E-CF for a unit process, the PEC, AEC, and CRF, for each grid cell are multiplied and integrated across the regions in the dispersion domain for PM2.5 Exposure Risks, according to Equation 6.4. For the purposes of calculation, regions in the dispersion domain with annual average background concentrations under 1 \( \mu g \) PM2.5 / m\(^3\) can be excluded from the calculation; these will be minor contributors to final results, and this exclusion can streamline the required computations. The E-CF is normalized to the total emissions of PM2.5 from the unit process over the course of one year.

Equation 6.4. Calculating the Environmental Characterization Factor for a single unit process for PM2.5 Exposure Risks.

\[
\text{E-CF for a unit process} = \sum_n PEC_n \times \text{AEC}_n \times \text{CRF}_n / \text{ton PM2.5}
\]

Where:

- E-CF is in units of persons \( \times \) hours \( \times \mu g \text{ PM2.5} / m^3 \) / ton PM2.5 eq.
- \( n \) represents all grid cells in the dispersion domain.
- PEC is the population exposure coefficient, representing the population in the grid cell.
- AEC is the accumulated concentration of PM2.5 over the course of one year in the grid cell.
- CRF is the Cumulative Risk Factor for each grid cell.

6.2.4.2.2. Characterization of Contribution to Risks of Exposure to PM2.5 (Node 2). For assessment at Node 2, the first step is determining the dispersion domain for PM2.5 of the unit process. The dispersion domain is the area into which PM2.5 emitted at the unit process transports. At Node 2, the dispersion domain can be assessed using dispersion modeling.

For results at this node, the dispersion domain can also be approximated by assuming the dispersion domain exists within a fixed radius from the emission source, typically 300-km, depending on local meteorological conditions and source characteristics. Assumption of this dispersion domain will result in higher uncertainty than a dispersion domain assessed using dispersion models; this is a limitation which should be considered in the context of the goal and scope of the LCA study.

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\(^{90}\) McKendry, I. G. \textit{Background concentrations of PM2.5 and Ozone in British Columbia, Canada.} Reported prepared for British Columbia Ministry of Environment, March 2006.
For results at Node 2, the E-CF is the accumulated human exposure to PM2.5 within the dispersion domain, over the course of one year. The E-CF is calculated per ton of PM2.5 emissions from the unit process over the course of one year. The E-CF is measured in units of population exposure per mass of PM2.5 (e.g., persons * hours / ton PM2.5).

6.2.5. Indicator Equation and Unit of Measure. The category indicator result (at Node 3) for PM2.5 Exposure Risks is shown in Equation 6.5, for a single unit process. The indicator result is expressed in units of persons * µg PM2.5 eq. / m³ * hours.

Equation 6.5. Indicator equation for a single unit process for PM2.5 Exposure Risks, characterized at Node 3 (contribution to risks of PM2.5 exposure).

\[ \text{PM2.5 Exposure Risks} = \sum_n (\text{Emissions}_n \times S-CF_n \times E-CF) \]

Where:
- \( n \) represents the total number of particulates and aerosol particle precursors emitted by a unit process
- Emissions are particulates and aerosol particle precursors emitted by a unit process
- \( S-CF \) is the amount of PM2.5 which transports throughout the dispersion domain as the result of the emission
- \( E-CF \) represents exposed population, as well as the severity of the exposure

6.3. Hazardous Ambient Air Contaminant Exposure Risks

6.3.1. Impact Category. This impact category considers emissions to air of hazardous ambient air contaminants (HAACs) from unit process(es) in the product system, which can result in risks of human exposure through inhalation in ambient air.

Depending on the type of unit process considered, there are many types of emissions that could be relevant, including organic chemicals, heavy metals, and other substances. Most commonly, exposure occurs on a chronic basis, as human populations are exposed to concentrations of HAACs exceeding health thresholds over long periods of time.

The scale, severity, and duration of risks of human exposure through inhalation due to the increased concentrations of HAACs will vary broadly, depending on factors such as the chemical species emitted, local population density, unit process type, scale of emission, timing of emission, regional topography, climate, weather patterns, and other characteristics of the region in which an emission occurs. The midpoints and endpoints associated with this impact category vary for all of these reasons. Accordingly, site-specific assessment of HAAC Exposure Risks is required. Secondary data shall not be used in the assessment of this impact category.

6.3.1.1. Definition of Hazardous Ambient Air Contaminant. For this impact category, HAACs are those contaminants which have the potential to expose humans via inhalation in ambient air, and which have been observed to cause adverse effects if humans are exposed to air concentrations over health thresholds.

At the outset of the study, the set of HAACs considered should be clearly defined. HAACs should include those substances which have exposed humans in the past in ambient air over health
thresholds. The set of HAACs considered can be based upon lists of regulated emissions developed by government agencies.

*For example.* To define a set of HAACs, the hazardous air pollutants defined by the United States Environmental Protection Agency could be used.

For a given LCA study, the set of HAACs will be screened to identify those emission sources which have emissions which are relevant for HAAC Exposure Risks (see Section 6.3.2.2).

**6.3.1.2. Definition of Threshold Exceedance for HAAC Exposure Risks.** For a given HAAC, the health threshold is a concentration in ambient air, usually expressed in units of µg/m³ or ppb. If emissions are found to be relevant in this impact category (based on the requirements of Section 6.3.2.2), the threshold used, and basis of the threshold, shall be described in the LCA report.

The health threshold for a given HAAC is the maximum safe ambient air concentration of the HAAC at which a continuous inhalation exposure to the human population is likely to be without an appreciable risk of deleterious effects during a lifetime.

Whenever possible, the health threshold for an HAAC should be based upon published estimates of the maximum safe ambient air concentration. The health threshold can be based upon the Reference Concentration for Chronic Inhalation Exposure (RfC); RfCs are provided for many HAACs in the US EPA Integrated Risk Information System database.¹

If published estimates of the maximum safe ambient air concentration do not exist for an HAAC, the health threshold must be estimated. The health threshold shall be derived from a NOAEL (no-observed-adverse-effects level), LOAEL (lowest-observed-adverse-effects-level), or benchmark concentration, with uncertainty factors applied to reflect limitations of the data used.

*NOTE.* If NOAELs, LOAELs, or benchmark concentrations, are used directly to estimate the health threshold for a given HAAC, the appropriate statistical interpretation of these measures must be taken into account. NOAELs and LOAELs are not direct estimates of a threshold level for adverse effects in humans resulting from exposure. For example, a NOAEL from a specific study could in fact result in significant, yet undetected incidence of adverse effects in the exposed population; or alternatively, the NOAEL could be significantly lower than the actual threshold level.² Conservative assumptions shall be made to account for uncertainty in NOAEL and LOAELs, using uncertainty and extrapolation factors, based on the approach used by the US EPA to define RfCs in non-cancer assessments.

For some HAACs, the onset of adverse effects after exposure may occur at levels which are so low they cannot be defined (e.g., for known carcinogens). This means that there is no measurable ambient air concentration which is safe. In these cases, the health threshold can

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¹ Based on definition from US EPA Risk Assessment Glossary.
be defined operationally as the lowest air concentration at which the HAAC can be detected on a routine basis.

6.3.2. Stressor-Effects Network. The stressor-effects network for this impact category is shown in Table 6.4. The specific spatial scale, number of people exposed, and severity of risks of human exposures over threshold can vary greatly based on type and the region of emission.

Analysis of the risks of human exposures to concentrations of HAACs over health thresholds (Node 3 in Table 6.4) is necessary to determine if exposure risks to humans are linked to emissions from a given unit process. If human exposure to HAACs can be documented as a relevant impact category (according to requirements of Section 6.3.2.2), the unit processes and HAACs resulting in exposure, along with the human health endpoints that can result from an exposure, should be understood and described in the LCA report, and in EPDs and C-EPDs which are generated.

Table 6.4. Stressor-Effects network for HAAC Exposure Risks.

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Stressors)</td>
<td>Emissions of HAACs to air.</td>
<td><em>High uncertainty.</em> Characterization does not consider: resultant concentrations of pollutants in ambient settings; population exposed to concentrations exceeding health thresholds; the dose-response relationship of toxic effects resulting from exposures.</td>
<td>Low uncertainty. Data requirements: Emissions levels, by HAAC.</td>
</tr>
<tr>
<td>2 (Midpoint)</td>
<td>Contribution to increases in concentrations of specific contaminants in ambient air exceeding known health thresholds.</td>
<td><em>High uncertainty.</em> Characterization does not consider: population exposed to concentrations exceeding health thresholds; the dose-response relationship of toxic effects resulting from exposures.</td>
<td>Low uncertainty. Data requirements: Modeling of fate and transport, by HAAC, considering: the scale of an emission; the type of contaminant; and regional setting, which determines the characteristics of regional dispersion.</td>
</tr>
<tr>
<td>3 (Midpoints)</td>
<td>Contributions to elevated concentrations of HAACs at levels exceeding health thresholds, occurring on a chronic basis, leading to risks of exposure by inhalation.</td>
<td><em>Moderate uncertainty.</em> Characterization does not consider the extent of exposures occurring, or the dose-response relationship of toxic effects resulting from exposures.</td>
<td>Low uncertainty. Data requirements: Modeling of fate and transport, by HAAC, considering: the scale of an emission; the type of contaminant emitted; and regional setting, which determines the characteristics of regional dispersion. NOAELs/LOAELs, by HAAC. Regional population density within the dispersion domain of each HAAC that is emitted.</td>
</tr>
</tbody>
</table>
For emissions of certain persistent chemicals, emissions to ambient air can result eventually in risks of exposure by ingestion, if the substance considered transfers to water and/or soils where it could eventually be ingested through contamination of food and/or water. If midpoints and endpoints in the stressor-effects network, and characterization models used, are distinct for the routes of both inhalation (ambient air) and ingestion, then category indicators in this impact category, and for the impact category of Hazardous Chemical Exposure Risks (ingestion), will be relevant and should be reported separately.

6.3.2.1. Selection of Category Indicator(s). After identifying all emissions of HAACs which are relevant in this impact category (see Section 6.3.2.2), distinct category indicators are defined.

To define these distinct category indicators, the stressor-effects network for each species of HAAC found to be relevant should first be considered separately. Separate category indicators shall be reported for each HAAC emitted under the following conditions:

- Human health endpoints associated with inhalation of each HAAC are distinct in character, temporal duration, severity, persistence, reversibility, or other aspects.
- Midpoints or endpoints in the stressor-effects network are significantly different in spatial scale, temporal scale, severity of exposures, or other considerations.
- The characterization model used to assess category indicator results is distinct.

Aggregation of emissions of different HAACs into a single category indicator is only possible if there are consistent measures of inhalation toxicity available for use as the basis for S-CFs. If there is no scientific basis for aggregating multiple HAACs using S-CFs (see Section 6.3.4.1), multiple category indicators must be reported.

Ideally, the midpoint selected for the category indicator would be Node 3, representing contribution to risk of exposure to HAACs at levels exceeding health thresholds. However,
at the present time, a characterization model has not been established for characterization
at Node 2 or higher nodes. Therefore, characterization is currently confined to Node 1 – i.e.,
measuring levels of emissions into ambient air.

NOTE. This does not preclude the establishment of characterization models at Node 2 or
higher in specific LCA studies. If results are characterized at Node 2 or higher, the basis
of data sources and modeling must be described in the LCA report. The uncertainty in
any data sources and models must be considered. As characterization models become
established and more broadly available, these may be incorporated into future versions
of this Standard.

Characterization at Node 1 has low environmental relevance. This low environmental
relevance shall be described in the LCA report. In any EPDs or C-EPDs, a disclaimer must be
provided stating clearly that the results at this node should not be used as the basis for
comparison.

6.3.2.2. Identifying Core Impact Categories and Category Indicator(s). Due to the
extensive data collection and analysis required to characterize category indicators for HAAC
Exposure Risks, it is essential to carefully screen the product system under study to identify
the unit processes contributing to risks of human exposures to considered HAACs (see
Section 6.3.1.1) at concentrations exceeding defined health thresholds (see Section 6.3.1.2).
This screening minimizes the amount of data collection required.

NOTE. Although characterization takes place at Node 1, the determination of this
impact category as relevant is based on a screening of the linkage of emissions to the
midpoint at Node 3, representing the risks of exposure to humans from inhalation of
HAACs at levels exceeding health thresholds.

HAAC Exposure Risks shall only be considered relevant for a given HAAC emitted from a
given unit process, if the emission satisfies two conditions:

- The given HAAC has been detected in ambient air at concentrations over the defined
  health threshold in the region of emission. (The health threshold is defined by
  HAAC, according to the requirements of Section 6.3.2.)
- The emission of the HAAC at the given unit process contributes to increased
  concentrations in ambient air in the region of emission.

As part of the iterative process, those unit processes which result in significant emissions of
HAACs to air should be identified; it can then be determined if these emissions are
occurring in regions in which the HAAC occurs at levels which exceed the defined health
threshold. This type of ambient monitoring data is often readily available from
governmental monitoring programs or in published literature. Dispersion modeling may be
required to determine if emissions contribute to specific instances of polluted ambient air.

If a unit process has been determined to exist in a region where air concentrations of the
HAAC are over the defined health threshold, and the unit process has associated emissions
of the HAAC, the emission still must be linked to the increased concentration of that HAAC.
The expected transport distance and residence time of the HAAC in question, as well as the
proximity of the emission source to potentially exposed populations, must be considered.
Whether this impact category is included as relevant depends on the goal and scope of the LCA study. When screening to determine if HAAC Exposure Risks is a core impact category, the scale of the functional unit used shall be large enough to include observed instances of midpoints of ambient air with HAAC concentrations over threshold. The functional unit should be scaled based upon the gross scale of emission levels in the product system. The functional unit must not be set arbitrarily low, which could rule out this impact category even in cases where HAAC Exposure Risks are occurring and can be linked to emissions from the product system. This screening may require sensitivity analysis.

NOTE. If specific data is unavailable for gross emissions, gross emissions can be estimated using conservative assumptions. This impact category is not relevant if emission levels of HAACs are negligible, even when considering the gross scale of emissions estimated using conservative assumptions.

The justification for the inclusion or exclusion of this impact category shall be provided in the LCA report.

The initial screening for relevance of HAAC Exposure Risks may determine that the scale of the functional unit needs revision, or that the goal and/or scope needs revision in other ways. The exclusion of this impact category should be a key subject of the critical review phase.

NOTE. Although the number of HAACs emitted from a product system is usually significant, in practice, very few emissions will be of a nature and scale that human exposure from inhalation in ambient air will result. Very few contaminants with inherent toxic properties are emitted in sufficient volume to warrant inclusion as relevant. Furthermore, in most regions, very few HAACs are present above health thresholds. The screening for this impact category should be able to quickly determine if this impact category is relevant to unit processes in the product system. An efficient screening will require expert judgment and sensitivity analysis to guide the iterative process.

6.3.3. Classification. HAACs presenting a risk of exposure through inhalation of ambient air are classified. This includes all emissions of HAACs meeting the requirements of Section 6.3.2.2.

6.3.4. Characterization.

6.3.4.1. Stressor Characterization Factors. The S-CF is specific to a given HAAC, and is separately defined for each category indicator included in the study scope.

In cases where multiple types of HAACs are considered in a single category indicator, the S-CF characterizes the inhalation toxicity of each contaminant compared to the inhalation toxicity of a reference contaminant with similar human health endpoints. For each category indicator, the same reference contaminant, and consistent measures of inhalation toxicity, must be used.

NOTE. For category indicators that only include emissions of a single HAAC, the HAAC is its own reference contaminant.
The S-CF for this impact category is shown in Equation 6.6.

**Equation 6.6. Stressor characterization factor for HAAC Exposure Risks.**

\[
S - CF_i = \frac{\text{inhalation toxicity}_i}{\text{inhalation toxicity}_{\text{reference}}}
\]

*Where:*
- \(S - CF_i\) is the Stressor Characterization Factor for a given HAAC, denoted \(i\)
- Inhalation toxicity is the measure of the inhalation toxicity for the given contaminant (denoted \(i\)), and the reference contaminant.

**NOTE.** Emissions levels multiplied by the S-CF gives results in units of equivalent mass of the reference contaminant. The S-CF equation will depend upon the units of the measures of inhalation toxicity that are used.

For HAACs which have a clear dose threshold for onset of toxic health effects, the inhalation toxicity can be characterized using the lowest inhalation exposure threshold linked to onset of the critical toxic effect. This is typically measured in milligrams / cubic meter for daily inhalation exposure.

**NOTE.** The Reference Concentration for Chronic Inhalation Exposure (RfC) for an HFWC, from the US Environmental Protection Agency’s Integrated Risk Information System database, can be used to characterize the S-CF for HFWCs which have toxic effects that have a dose threshold for onset.

However, for many HAACS, there is no clear dose threshold for onset. In these cases, extreme care must be taken in defining the inhalation toxicity of different HAACs and the reference contaminant, in order to provide a defensible basis of aggregation for multiple HAACs into a single category indicator.

**FOR EXAMPLE.** Carcinogenicity is a toxic effect that does not exhibit a clear threshold for onset. S-CFs for carcinogenicity must be represented by measures such as Inhalation Unit Risk.

If there is no scientifically defensible basis for assessing S-CFs for multiple HAACs based on consistent measures of inhalation toxicity, there is no way to aggregate emissions into a single category indicator. In these cases, separate category indicators must be reported for each emission.

**NOTE.** The lack of a consistent basis for aggregation may indicate that the toxic endpoints of HAACs are different, and/or that the stressor-effects networks are distinct.

In all cases, the uncertainty and/or confidence level inherent in the measures of inhalation toxicity used as the basis for calculating S-CFs must be considered.
For HAACs exhibiting toxic effects with a clear dose threshold for inhalation, measures based on the onset of the critical toxic effect are the most widely used, as these measures usually contain the least inherent uncertainty. However, even these measures can contain inherent uncertainties of one order of magnitude or more. When deriving S-CFs, the uncertainty in the measure of inhalation toxicity should be considered in the context of the goal and scope of the study. If the uncertainty in the S-CFs are very high, it may not be possible to achieve the goals of the study. In these cases, the goal and scope may need to be revised.

The measures of inhalation toxicity used must be based upon empirical measurements from peer-reviewed studies. Generic extrapolation between measures, such as the lowest onset threshold for the critical toxic effect and the median effective dose (ED50) value for a given HAAC, shall not be used.

### 6.3.4.2. Environmental Characterization Factors.
For category indicators in this impact category, characterization models for nodes higher than Node 1 have not been established (see Section 6.3.2). There is no E-CF for characterization at Node 1.

#### 6.3.5. Indicator Equation and Unit of Measure.
Results (at Node 1) are calculated using Equation 6.7. Results are reported in units of mass equivalents of the reference contaminant.

**Equation 6.7. Indicator equation for a single unit process for HAAC Exposure Risks, with results reported at Node 1 (emissions levels).**

\[
\text{HAAC Emissions} = \sum_i (\text{Emissions}_i \times S\text{-CF}_i)
\]

*Where:*
- *Emissions* are the emissions levels of a given HAAC, reported in units of mass.
- *S-CF* is the Stressor Characterization Factor for each HAAC, representing its inhalation toxicity relative to the reference contaminant.

#### 6.3.6. Additional Reporting Requirements.
The terminology used to describe category indicator results shall be descriptive of the characterization model which is used. Terminology which overstates the environmental relevance of the result shall not be used.

#### 6.3.7. Addressing Additional Limitations in Types, Accuracy, and Availability of Environmental Data.
The first step in characterization of results in this impact category is the screening for determination of relevance of emissions, according to the requirements and guidance provided in Section 6.3.2. In some product systems, where unit process(es) are distributed in extensive global supply chains, lax regulations and poor monitoring in certain regions might make it impossible to determine the relevance of specific emissions sources to this impact category. If the screening cannot be conducted, then determination of the relevance of this impact category may not be possible; this could affect the ability to achieve the goals of the LCA study. If the relevance of this impact category cannot be determined, the goal and scope of the LCA study may need to be revised.

### 6.4. Hazardous Indoor Air Contaminant Exposure Risks
6.4.1. Impact Category. This impact category considers emissions to air of hazardous indoor air contaminants (HIACs) from unit process(es) that transport into indoor environments and can result in risks of human exposure through inhalation.

Depending on the type of unit process considered, many types of emissions can be relevant, including volatile organic chemicals (VOCs), semi-volatile organic chemicals (SVOCs), dust, and emissions of other contaminants. In some cases, ambient pollutants from outdoor emissions can enter indoor environments as well.

Most commonly, exposure occurs on a chronic basis, as occupants of indoor settings are exposed to concentrations of HIACs over long periods of time.

**NOTE.** In rare instances, acute exposures to high concentrations of HIACs can occur, usually as a result of accidents or spills in certain types of industrial facilities. However, in the majority of cases, individuals are exposed daily to substances in confined indoor spaces, often for extended periods of time, resulting in chronic risks of exposure; this indicator focuses on these chronic risks.

The scale, severity, timing, and duration of risks of human exposure through inhalation in indoor settings will vary broadly, depending on factors such as the HIAC which is emitted, unit process type, scale of emission, timing of emission, ventilation rates, and other characteristics of the indoor setting. The midpoints and endpoints associated with this impact category vary for all of these reasons. Accordingly, site-specific assessment of HIAC Exposure Risks associated with a unit process is required. Secondary data shall not be used in the assessment of this impact category.

6.4.1.1. Definition of Hazardous Indoor Air Contaminant. For this impact category, HIACs are those contaminants which have the potential to expose humans via inhalation in indoor air, and which have been observed to cause adverse effects if humans are exposed to air concentrations over health thresholds.

At the outset of the study, the set of HIACs considered should be clearly defined. HIACs should include those substances which have exposed humans in the past in indoor air over health thresholds. Depending on the product system under study, a wide variety of hazardous substances can be emitted into indoor environments and considered relevant, including volatile organic chemicals (VOCs), semi-volatile organic chemicals (SVOCs), dust, and emissions of other contaminants. The set of HIACs considered can be based upon lists of target emissions covered in voluntary standards or regulations regarding indoor air.

**For example.** The set of HIACs considered can be based upon target VOCs can be from *The Standard Method for the Testing and Evaluation of Volatile Organic Chemical Emissions from Indoor Sources Using Environmental Chambers*, the emission testing method for the California Specification 01350.

**Note.** Many SVOCs do not constitute major sources of indoor air exposures but may re-absorb onto surfaces, only to be re-admitted over an extended time period.

For a given LCA study, the set of HIACs will be screened to identify those emission sources which have emissions which are relevant for HIAC Exposure Risks (see Section 6.4.2.2).
6.4.1.2. Definition of Threshold Exceedance for HIAC Exposure Risks. For a given HIAC, the health threshold is a concentration in indoor air, usually expressed in units of µg/m³ or ppb. If emissions are found to be relevant in this impact category (based on the requirements of Section 6.4.2.2), the threshold used, and basis of the threshold, shall be described in the LCA report.

The health threshold for a given HIAC is the maximum safe indoor air concentration of the HIAC at which a continuous inhalation exposure to the human population is likely to be without an appreciable risk of deleterious effects during a lifetime.

Whenever possible, the health threshold for an HIAC should be based upon published estimates of the maximum safe indoor air concentration. The health threshold can be based upon the Chronic Reference Exposure Level (CREL). CRELs are provided for many HIACs by the State of California Office of Environmental Health Hazard Assessment (OEHHA). If a CREL is not available for a given HIAC, the RfC can be used (see Section 6.3.1.2).

If published estimates of the maximum safe indoor air concentration do not exist for an HIAC, the health threshold must be estimated. The health threshold shall be derived from a NOAEL (no-observed-adverse-effects level), LOAEL (lowest-observed-adverse-effects-level), or benchmark concentration, with uncertainty factors applied to reflect limitations of the data used.

NOTE. If NOAELs, LOAELs, or benchmark concentrations, are used directly to estimate the health threshold for a given HIAC, the appropriate statistical interpretation of these measures must be taken into account. NOAELs and LOAELs are not direct estimates of a threshold level for adverse effects in humans resulting from exposure. For example, a NOAEL from a specific study could in fact result in significant, yet undetected incidence of adverse effects in the exposed population; or alternatively, the NOAEL could be significantly lower than the actual threshold level. Conservative assumptions shall be made to account for uncertainty in NOAEL and LOAELs, using uncertainty and extrapolation factors, based on the approach used by the OEHHA to define CRELs.

For some HIACs, the onset of adverse effects after exposure may occur at levels which are so low they cannot be defined (e.g., for known carcinogens). In these cases, the health threshold can be defined operationally as the lowest air concentration at which the HIAC can be detected on a routine basis.

6.4.2. Stressor-Effects Network. The stressor-effects network for this impact category depends upon the size, location, timing, duration, and indoor setting of an emission; the resulting scale, severity, timing, and duration of midpoints of concentrations of HIACs will vary for many reasons. The stressor-effects network for this impact category, shown in Table 6.5, provides a general framework; however, for each separate indicator included, a separate

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stressor-effects network shall be modeled. This model should consider the site-specific circumstances of stressors, midpoints, and endpoints, in the cause-effect relationship resulting from the emission source. This will greatly aid in the characterization of results, and ensure that relevant impacts are identified.

**NOTE.** This stressor-effects network is nearly always linked to emissions of HIACs directly into indoor settings; however, ambient pollutants can in some cases transport into indoor settings, and outdoor emissions in some instances must therefore be considered.

The midpoint at Node 3, risks of human exposures to concentrations of HIACs exceeding health thresholds (Table 6.5), is important to understand. For a given unit process, the contaminants, level of contamination, timing of increased concentrations, and use of protective equipment affect the risks of exposure at this node, and must be understood to determine if this is a relevant impact category (per Section 6.4.2.2).

If human exposure to HIACs can be documented as a relevant impact category, the location of exposures, unit process resulting in exposure, and human health endpoints which can result from an exposure should also be understood and described in the LCA report, and in EPDs and C-EPDs which are generated.

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Stressors)</td>
<td>Emissions of HIACs into indoor air.</td>
<td>High uncertainty. Characterization does not consider: resultant concentrations of HIACs in indoor settings; duration and timing of exposure to these pollutants; number of individuals exposed to concentrations over health thresholds; the use of protective equipment that would reduce exposures; the dose-response relationship of toxic effects resulting from exposures.</td>
<td>Low uncertainty. Data requirements: Emissions levels, by HIAC.</td>
</tr>
<tr>
<td>(High overall uncertainty. (Low environmental relevance.))</td>
<td>(Rare cases) Emissions of HIACs into outdoor air.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 (Midpoint)</td>
<td>Contribution to increase in concentrations of HIACs.</td>
<td>High uncertainty. Characterization does not consider: duration and timing of exposure to HIACs; number of individuals exposed to concentrations over health thresholds; the use of protective equipment that would reduce exposures; the dose-response relationship of toxic effects resulting from exposures.</td>
<td>Moderate uncertainty. Data requirements: Modeling of fate and transport, by HIAC, considering: the scale of an emission; the volume of interior space into which an emission occurs; the ventilation rate in the indoor setting; and type of HIAC emitted.</td>
</tr>
</tbody>
</table>

Table 6.5. Stressor-Effects Network for HIAC Exposure Risks.
### 3. Midpoints

**Moderate to high overall uncertainty.**

(Low to moderate environmental relevance.)

Contributions to elevated concentrations of HIACs associated with exceedance of chronic health thresholds, leading to risks of exposure by inhalation.

**Moderate to high uncertainty.**

Characterization does not consider the use of protective equipment, or the dose-response relationship of toxic effects resulting from exposures.

### 4. Midpoints

**Characterization at this node not possible given data limitations.**

Contributions to continuous inhalation exposures to HIACs over health thresholds.

**Low uncertainty.**

Strongly reflective of health effects resulting from human exposures.

Data linking emissions to observed exposures in specific populations (rarely available).

### 5. Endpoints

**Characterization at this node not possible given data limitations.**

Contribution to specific toxic effects such as: effects to the immune system, alterations to genetic and enzyme systems, damages to the nervous system and increased risk of cancer.

**Low uncertainty.**

This is a direct measurement of endpoints for this impact category.

Data linking emissions to exposures in specific populations and their corresponding health effects (rarely available).

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Emissions of certain HIACs can also result indirectly in risks of exposure by ingestion, if the HIACs transfer to solid surfaces and skin. If midpoints and endpoints in the stressor-effects network, and characterization model used, are distinct for the routes of both indoor inhalation and ingestion, then category indicators in this impact category, and for the impact category of Hazardous Food or Water Contaminant Exposure Risks, will be relevant and should be reported separately.

In rare instances, emissions contributing to ambient pollutant concentrations (i.e., ground level ozone and/or particulate matter) will also contribute to concentrations of indoor pollutants, as outdoor pollutants invade indoor spaces. In these cases, separate indicators should be reported for relevant indicators representing ambient exposure risks (e.g., Ground Level Ozone Exposure Risks, PM2.5 Exposure Risks) as well as for indicators in this impact category.

### 6.4.2.1. Selection of Category Indicator(s)

After identifying all emissions of HIACs which are relevant in this impact category (see Section 6.4.2.2), distinct category indicators are defined.

To define these distinct category indicators, the stressor-effects network for each HIAC found to be relevant should first be considered separately. Separate category indicators shall be reported for each HIAC emitted under the following conditions:
• Midpoints in the stressor-effects network are distinct in the location of human exposure, duration of exposures, severity of exposures over health thresholds, and number of humans exposed.

• Human health endpoints associated with inhalation of each HIAC are distinct in their character, temporal duration, severity, persistence, reversibility, or other considerations.

• The characterization model used to assess category indicator results is distinct.

Aggregation of emissions of different HIACs into a single category indicator is only possible if there are consistent measures of inhalation toxicity available for use as the basis for S-CFs. If there is no scientific basis for aggregating multiple HIACs using S-CFs (see Section 6.4.4.1), multiple category indicators must be reported.

Ideally, the midpoint selected for the category indicator would be Node 3, representing the contribution to the risk of exposure to concentrations of HIACs exceeding human health thresholds in indoor environments. However, at the present time, a characterization model has not been established for characterization at Node 2 or higher nodes. Therefore, characterization is at Node 1 – i.e., measuring emissions levels into indoor settings.

**NOTE.** This does not preclude the establishment of characterization models at Node 2 or higher in specific LCA studies. If results are characterized at Node 2 or higher, the basis of data sources and modeling must be described in the LCA report. The uncertainty in any data sources and models must be considered. As characterization models become established and more broadly available, these may be incorporated into future versions of this Standard.

Characterization at Node 1 has low environmental relevance. This low environmental relevance shall be described in the LCA report. In any EPDs or C-EPDs, a disclaimer must be provided stating clearly that the results at this node should not be used as the basis for comparison.

In practice, there will be many cases where no data are available to characterize results at any node, even when the contribution to human exposures to HIACs over health thresholds is observed and documented at unit process(es) in the product system. In these cases, the reporting requirements described in Section 6.4.6 apply.

**6.4.2.2. Identifying Core Impact Categories and Category Indicator(s).** Due to the extensive data collection and analysis required to characterize category indicators for HIAC Exposure Risks, it is essential to carefully screen the product system under study to identify the unit processes contributing to risks of human exposures to HIACs (see Section 6.4.1.1) at concentrations exceeding defined health thresholds (see Section 6.4.1.2). This screening minimizes the amount of data collection required.

**NOTE.** Although characterization takes place at Node 1, the determination of this impact category as relevant is based on a screening of linkages to the midpoint at Node 3, representing the risks of exposure to humans from inhalation in indoor settings.
This core impact category should be considered relevant for a given HIAC emitted from a given unit process, if the emission satisfies three conditions:

- In indoor environments at the given unit process, the HIAC has been detected in air at concentrations over known health thresholds.
- In cases where these elevated concentrations are detected, protective equipment is not used, or is not used sufficiently, to prevent exposures to humans by inhalation.
- Emissions of the HIAC are shown to contribute to contamination of indoor air at this unit process.

These emissions can occur from many possible unit process(es) in the product system. However, indoor air emissions are not usually included in inventory datasets. Accordingly, during the initial screening, it is important to identify types of unit processes that have been known in other cases to have emissions that contribute measurably to human inhalation exposure to HIACs. These unit processes may include, for instance, various stages of manufacturing, and the use of specific product types.

**FOR EXAMPLE.** Carpets, flooring, furniture, and other products used indoors may emit VOCs during their use, leading to risk of exposure to building occupants.

**FOR EXAMPLE.** In factories, emissions may occur as a result of the handling of intermediate chemicals, which can volatilize and result in emissions to indoor air, leading to elevated concentrations of HIACs. However, in many factory settings, protective equipment is used (e.g., face masks) preventing or strictly limiting potential human exposures. The regulatory setting and factory policies must be carefully considered when assessing indoor exposure risks in factory settings.

*Note.* Just because a similar unit process has resulted in human exposures does not mean that exposures are occurring in the product system under study. Careful research must determine whether these emissions are occurring, based on primary data sources.

In some cases, data may be unavailable to determine whether emissions at a given unit process are contributing to the risk of exposures, even when secondary data or unverified anecdotal information strongly indicate that such exposures are occurring. Only direct observations can be used as a concrete basis for determination of the relevance of this impact category. If it cannot be determined if an emission source leads to relevant impacts, the ability to achieve the goals of the study may be affected, and the goal and/or scope may need revision.

Whether this impact category is included as relevant depends on the goal and scope of the LCA study. When screening to determine if HIAC Exposure Risks is a core impact category, the scale of the functional unit used shall be large enough to include observed instances of midpoints of contaminated indoor air over known health thresholds. The functional unit must not be set arbitrarily low, which could rule out this impact category even in cases where HIAC Exposure Risks are occurring and can be linked to emissions from the product system. This screening may require sensitivity analysis.
The initial screening for the relevance of this impact category may determine that the scale of the functional unit needs revision, or that the goal and/or scope needs revision in other ways.

The justification for the inclusion or exclusion of this impact category shall be provided in the LCA report.

6.4.2.2.1. **Using Emissions Testing Data.** For products that may emit HIACs during the use phase (e.g., furniture or flooring products used in indoor environments), emissions testing can be used to help determine if this impact category is relevant. Emissions testing results for a given product can be used as the basis for determining if HIAC Exposure Risks is a relevant impact category. A description of the emission testing protocol used shall be included in the LCA report.

*FOR EXAMPLE.* The *Standard Method for the Testing and Evaluation of Volatile Organic Chemical Emissions from Indoor Sources Using Environmental Chambers*, the emission testing method for the California Specification 01350, can be used as the basis of such emissions testing.

In determining the relevance of the impact category, the emissions of specific HIACs must be considered in the context of the indoor environment as a whole. A product may satisfy requirements for an emissions testing protocol, and still contribute measurably to instances of elevated concentrations of HIACs over health thresholds. In these cases, the tested product emits an HIAC into an indoor environment in which concentrations of the HIAC are over health thresholds. In these cases, the tested product contributes to these elevated concentrations, and emissions of the HIAC will be relevant to this impact category.

6.4.2.2.2. **Using Concentration Testing Data.** For some unit processes, local regulations mandate the testing of concentrations of certain substances in indoor settings over certain time periods, and at certain intervals of time.

*FOR EXAMPLE.* In the United States, this can include regulations enforced by agencies such as the Occupational Safety and Health Administration.

If data are available based on results of regulatory testing protocols, they can be used to determine relevance of the impact category. In such cases, the timing of the most recent testing and past history of infractions must be taken into account, and the local regulation, and timing and characteristics of the tests conducted must be described in the LCA report.

6.4.3. **Classification.** All emissions of HIACs which are relevant to this impact category per the requirements of Section 6.4.2.2 are classified.

For some product systems, it may not be possible to classify all HIACs contributing to this impact category, as a result of data limitations. Based on the significance of the omission, the goal and scope of the LCA study may need to be revised.
6.4.4. Characterization

6.4.4.1. Stressor Characterization Factors. The S-CF is determined separately by HIAC, and is separately defined for each category indicator included in the study scope (see Section 6.4.2.1).

In cases where multiple types of HIACs are considered in a single category indicator, the S-CF characterizes the inhalation toxicity of each HIAC to the inhalation toxicity of a reference contaminant with similar human health endpoints. For each category indicator, the same reference contaminant, and consistent measures of inhalation toxicity, must be used.

**NOTE.** For category indicators based on emissions of a single HIAC, the HIAC is its own reference contaminant.

The S-CF for this impact category is determined as shown in Equation 6.8.

**Equation 6.8. Stressor characterization factor for HIAC Exposure Risks.**

\[
S - CF_i = \frac{\text{inhalation toxicity}_i}{\text{inhalation toxicity}_{\text{reference}}}
\]

*Where:*
- \(S - CF_i\) is the Stressor Characterization Factor for a given HIAC, denoted \(i\)
- Inhalation toxicity is the measure of the inhalation toxicity for the given HIAC (denoted \(i\)), and the reference contaminant.

**NOTE.** Emissions levels multiplied by the S-CF produces results in units of equivalent mass of the reference contaminant. The S-CF equation will depend upon the units of the measures of inhalation toxicity.

For HIACs with toxic effects in humans which have a clear dose threshold for onset, the inhalation toxicity can be characterized using the lowest inhalation exposure threshold resulting in onset of the critical toxic effect. This is typically measured in milligrams / cubic meter for daily inhalation exposure.

**NOTE.** Values of the chronic Reference Exposure Level (CREL) for chemicals, which are reported by the State of California Office of Environmental Health Hazard Assessment, can be used to characterize the S-CF for HIACs and toxic effects that have a dose threshold for onset.

**NOTE.** If a CREL is not available for an HIAC, the inhalation Reference Concentration (RfC) can be used, which are reported in the US Environmental Protection Agency’s Integrated Risk Information System database.

However, for many HIACs, there is no clear dose threshold for onset of toxic effects. In these cases, extreme care must be taken in defining the inhalation toxicity of different HIACs and
the reference contaminant, in order to provide a defensible basis for aggregation for multiple HIACs under a single category indicator.

FOR EXAMPLE. Carcinogenicity is a toxic effect that does not exhibit a clear threshold for onset. S-CFs for carcinogenicity must be represented by measures such as the Inhalation Unit Risk.

If there is no scientifically defensible basis for assessing S-CFs for multiple HIACs based on consistent measures of inhalation toxicity, there is no way to aggregate emissions into a single category indicator. In these cases, separate category indicators must be reported for each HIAC which is emitted.

NOTE. The lack of a consistent basis for aggregation often indicates that the toxic endpoints of HIACs are different, and that the stressor-effects networks are distinct.

In all cases, the uncertainty and/or confidence level inherent in the measures of inhalation toxicity used as the basis for calculating S-CFs must be considered.

When deriving S-CFs, the uncertainty in the measure of inhalation toxicity should be considered in the context of the goal and scope of the study.

NOTE. For HIACs exhibiting toxic effects with a clear dose threshold based upon inhalation, measures based on the onset of the critical toxic effect are the most widely used, as these measures usually contain the least inherent uncertainty. However, even these measures can contain inherent uncertainties of one order of magnitude or more.

If the uncertainty in the S-CFs is very high, it may not be possible to achieve the goals of the LCA study. In these cases, the goal and scope may need to be revised.

The measures of inhalation toxicity used must be based upon empirical measurements from peer-reviewed studies. Generic extrapolation between measures, such as the lowest onset threshold for the critical toxic effect and the median effective dose (ED50) value for a given HIAC, shall not be used.

6.4.4.2. Environmental Characterization Factors. For category indicators in this impact category, characterization models for nodes higher than Node 1 have not been established (see Section 6.4.2). There is no E-CF for characterization at Node 1.
6.4.5. Indicator Equation and Unit of Measure. Results (at Node 1) are calculated using Equation 6.9. Results are reported in units of mass equivalents of the reference contaminant.

**Equation 6.9. Indicator equation for a single unit process for HIAC Exposure Risks. Results calculated using this equation are at Node 1, characterizing emissions of HIACs.**

\[
\text{HIAC Emissions} = \sum_i (\text{Emissions}_i \times S-CF_i)
\]

*Where:*
- \(\text{Emissions}_i\) are the emissions levels of a given HIAC, reported in units of mass.
- \(S-CF_i\) is the Stressor Characterization Factor for each HIAC, representing its inhalation toxicity relative to the reference contaminant.

6.4.6. Additional Reporting Requirements. In some instances, data on emission levels will be unavailable for a given unit process, even though specific emissions of HIACs are known to contribute to impacts in this impact category. Under such circumstances, characterization of indicator results is not possible. In these cases, the relevant category indicator shall be noted as relevant, and the location of emissions, type of emissions, and HIACs contributing to elevated concentrations in indoor air over health thresholds, shall be described in the LCA report, and any EPDs and C-EPDs which are generated.

The stressor-effects network should be described in the LCA report. The specific midpoint of contaminated indoor air to which an emission can be linked must be described in the LCA report, and EPDs and C-EPDs which are generated. Endpoints of human health effects resulting from exposures to the relevant HIACs should also be included in the description.

6.5. Hazardous Food or Water Contaminant Exposure Risks

6.5.1. Impact Category. This impact category considers releases of hazardous food or water contaminants (HFWCs) from unit process(es) in the product system that can result in risks of human exposure through ingestion. The potential routes of human exposure by ingestion usually include the contamination of drinking water or food supply (e.g., agricultural products, ocean going fish).

The emissions most relevant to this impact category are contaminants with long residence times in the environment, which can bioaccumulate in organisms and the human body, and/or are chemically mobile. These chemicals can result in chronic human exposures, which will usually only occur after transport through multiple media, and may occur years after an emission occurs.

**NOTE.** In some instances, emissions may occur which result in acute human exposures in the short term. In practice, such acute exposures occur in rare instances.

The severity, spatial scale, and reversibility of risks of human exposure through ingestion will vary broadly, depending on factors such as the HFWC emitted, scale of emission, timing of emission, duration of emission, medium of emission, and regional setting. The midpoints and
endpoints associated with this impact category vary for all of these reasons. Accordingly, site-specific assessment of HFWC Exposure Risks associated with a unit process is required. Secondary data shall not be used in the assessment of this impact category.

6.5.1.1. Definition of Hazardous Food or Water Contaminants. For this impact category, HFWCs are those contaminants which have the potential to expose humans via ingestion of food or water, and which have been observed to cause adverse effects if humans are exposed to oral doses over health thresholds.

At the outset of the study, the set of HFWCs considered should be clearly defined. The set of HFWCs should include those which have exposed humans in the past from ingestion of food or water at concentrations over health thresholds. This includes contaminants which have been detected in ground or surface water supplies, or in food sources such as leafy crops, root crops, meat, dairy products, fish or seafood.

In practice, the set of HFWCs will be limited to a small number of persistent and/or bioaccumulative chemicals, which are also mobile.

NOTE. Due to its persistence and mobility, mercury contamination is an issue at regional and global levels. Mercury should be included in the initial set of HFWCs.

For a given LCA study, the set of HFWCs will be screened to identify those emission sources which are relevant for HFWC Exposure Risks (see Section 6.5.2.2).

6.5.1.2. Definition of Threshold Exceedance for HFWC Exposure Risks. For a given HFWC, the health threshold is a concentration, defined separately in food and water, usually expressed in units such as mg/kg, µg/kg, or ppb. If emissions of an HFWC are found to be relevant in this impact category (based on the requirements of Section 6.5.2.2), the health threshold used, and basis of the threshold, shall be described in the LCA report.

The health threshold for a given HFWC is the maximum safe concentration of the HFWC in drinking water or food supplies, below which there is no known or expected risk to health, with oral ingestion on a daily basis over a lifetime.

Whenever possible, the health threshold for an HFWC should be based upon published estimates of the maximum safe concentration in food or water. For contamination of drinking water supplies, Maximum Contaminant Level Goals (MCLGs) are provided for many HFWCs by the US EPA; MCLGs are estimates of the level of a contaminant in drinking water below which there is no known or expected risk to health. If available, the MCLG can be used to define the health threshold for a given HFWC if it is a water contaminant. For contamination of food supplies, maximum allowed levels in food defined by government agencies can be used as the basis of defining the health threshold for an HFWC.

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For example. The European Commission has defined maximum levels in food for children of several heavy metals and organic substances, which could be used as the basis of the health threshold for these HFWCs.

For example. The US EPA has established tolerances (also known as residue limits) for pesticides in foods. These residue limits can be used as the basis of a health threshold for pesticides.

If published estimates of the maximum safe concentration do not exist for an HFWC, the health threshold must be estimated. To establish the health threshold for given HFWC in food or water, the dose of the HFWC must be considered to which a person can be exposed to on a daily basis over an extended period of time (usually a lifetime) without suffering adverse effects. For an HFWC, this dose can be established based upon the Reference Dose for Chronic Oral Exposure (RfD), established by the US EPA, or similar measures, such as the Acceptable Daily Intake (ADI). The health threshold used is based upon the safe daily dose and expected consumption of the HFWC.

Note. RfDs and ADIs are based upon the NOAEL, LOAEL, or benchmark dose for a given HFWC. If an RfD or ADI is not available for a given HFWC, the health threshold must be based upon a NOAEL, LOAEL, or benchmark dose. The uncertainty in these measures related to human exposures should be considered. Conservative assumptions shall be made to account for uncertainty in NOAEL, LOAELs, and benchmark concentrations.

For some HFWCs, the onset of adverse effects after exposure may occur at levels which are so low they cannot be defined. In these cases, the health threshold can be defined operationally as the lowest concentration in food or water at which the HFWC can be detected on a routine basis.

6.5.2. Stressor-Effects Network. The stressor-effects network for this impact category depends upon the size, location, timing, duration, and nature, of an emission; the resulting scale, severity, and reversibility of midpoints of contaminated food/water supplies will vary for many reasons.

The stressor-effects network for this impact category, shown in Table 6.6, provides a general framework. However, for each separate indicator included within the study scope, a separate stressor-effects network should be modeled. This model should describe the site-specific stressors, midpoints, and endpoints in the cause-effect relationship linked to each classified emission source which is considered. This will greatly aid in the characterization of results.

The midpoint of contaminated food and water supplies (Node 4) is directly linked to the risk of human exposure. For contaminated food and water supplies, the contaminants, spatial scale, persistence, and level of contamination should be understood. Contaminated food and water supplies may be linked to emissions occurring at one or more unit processes considered in the product system under study, but may also be linked with unit processes outside of the scope of the LCA. Accordingly, it is important to understand other emissions sources that are contributing to these midpoints.
If HFWC Exposure Risks can be documented as a relevant impact category (Section 6.5.2.2), the human health endpoints that can result from an exposure should be understood and described in the LCA report, and in any EPD and C-EPD which is generated.

Table 6.6. Stressor-Effects network for HFWC Exposure Risks.

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Stressors)</td>
<td>Emissions of HFWCs into air, water, and soils</td>
<td>High uncertainty. Characterization does not consider: fate and transport; contribution to contamination of food/water supplies; risks of exposure resulting from contamination of food/water supplies; levels of exposures exceeding health thresholds which could result in toxic effects in humans.</td>
<td>Low uncertainty. Data requirements: Emissions levels of HFWCs.</td>
</tr>
<tr>
<td>2 (Midpoint)</td>
<td>Dispersion of HFWCs into the receiving environment</td>
<td>High uncertainty. Characterization does not consider: contribution to contamination of food/water supplies; risks of exposure resulting from contamination of food/water supplies; levels of exposures exceeding health thresholds which could result in toxic effects in humans.</td>
<td>Moderate uncertainty. Data requirements: Modeling of fate and transport of specific HFWCs, based on emissions levels.</td>
</tr>
<tr>
<td>3 (Midpoints)</td>
<td>Contribution to persistent contamination of the receiving environment (increases in background concentrations of HFWCs in the atmosphere, sediments, silage, water supplies, or bioaccumulation in organisms).</td>
<td>High uncertainty. Characterization does not consider: risks of exposure resulting from contamination of food/water supplies; levels of exposures exceeding health thresholds which could result in toxic effects in humans.</td>
<td>Moderate uncertainty. Data requirements: Modeling of fate and transport of specific HFWCs, and contribution to contaminated receiving environments.</td>
</tr>
<tr>
<td>4 (Midpoints)</td>
<td>Contribution to contamination of food and water supplies, presenting a risk of human exposures by ingestion.</td>
<td>Moderate uncertainty. Characterization does not consider the severity of exposures over health thresholds are not considered.</td>
<td>Moderate uncertainty. Data requirements: Modeling of fate and transport of specific HFWCs, and contribution to contaminated food/water supplies. Monitored concentrations of HFWCs. Measurements of exposure thresholds in humans, by contaminant.</td>
</tr>
</tbody>
</table>
The emissions which are relevant to this impact category may also be linked to stressor-effects networks for ecotoxicity, since the midpoint at Node 3 (persistent contamination of the receiving environment) is similar.

6.5.2.1. Selection of Category Indicator(s). After identifying all emissions of HFWCs which are relevant in this impact category (see Section 6.5.2.2), distinct category indicators are defined.

To define these distinct category indicators, the stressor-effects network for each species of HFWC found to be relevant should first be considered separately. Separate category indicators shall be reported for each HFWC emitted under the following conditions:

- Midpoints in the stressor-effects network linked to the emission are distinct in spatial extent, duration, severity of contamination, and number of humans that could be exposed.
- The route of exposure to humans in the stressor-effects network (Node 5) is distinct.
- Human health endpoints associated with ingestion of each HFWC are distinct in character, temporal duration, severity, persistence, reversibility, or other aspects.
- The characterization model used to assess category indicator results is distinct.

Aggregation of emissions of different HFWCs into a single category indicator must be done with care; even emissions that occur at similar levels, at the same place and time, may lead to distinct cause-effects chains.

FOR EXAMPLE. Heavy metals, such as mercury, have significantly different chemical half-lives, mobility in the environment, and toxic effects compared to organic chemicals. Even if mercury and an organic chemical are co-emitted, the distinct nature of the persistence, mobility, and risk of human exposures means that it may not be possible to aggregate emissions of mercury and organic chemicals into a single category indicator.

Aggregation of HFWCs into the same category indicator is only possible if there are consistent measures of oral toxicity available for use. If there is no scientific basis for
aggregation of multiple HFWCS using S-CFs (see Section 6.5.4.1), multiple category indicators must be reported.

Ideally, the midpoint selected to characterize HFWC Exposure Risks would be Node 4, representing the fraction of an emission contributing to the contamination of a food/water supply.

In practice, there is rarely sufficient data available to characterize results at Node 4. Therefore, characterization at Node 3 should be used if possible – i.e., the fraction of an emission contributing to persistent contamination of the receiving environment, irrespective of whether food/water supplies are contaminated.

However, in many instances, data will not be available for characterization above Node 1, which characterizes emissions levels. Characterization at Node 1 has low environmental relevance. This low environmental relevance shall be described in the LCA report. In any EPDs or C-EPDs, a disclaimer must be provided stating clearly that the results at this node should not be used as the basis for comparison.

The stressor-effects network should be described in the LCA report. The midpoint(s) of contaminated food/water supply to which an emission can be linked must be described in the LCA report, and in EPDs and C-EPDs which are generated. Endpoints of human health effects resulting from exposures to the relevant chemicals should also be included.

6.5.2.2. Identifying Core Impact Categories and Category Indicator(s). Due to the extensive data collection and analysis required to characterize category indicators for this impact category, it is essential to carefully screen the product system under study to identify the unit processes that are contributing to risks of human exposure to HFWCs over defined health thresholds. This screening should minimize the amount of data collection required.

**NOTE.** Although for a given study, characterization may be at Node 1, the determination of this impact category as relevant is based on a screening of linkages to the midpoint at Node 4, representing the risk of exposure to humans from ingestion of food/water where HFWCs are present over defined health thresholds.

HFWC Exposure Risks should be considered relevant for a given HFWC emitted from a given unit process, if the emission satisfies two conditions:

- The given HFWC has been detected as a contaminant in a specific water supply used for drinking (ground or surface water), or in a specific source of food for humans (e.g., leafy crops, root crops, meat, dairy products, fish, or seafood from oceans and lakes). The concentration of the HFWC should occur at levels exceeding the defined health threshold for the medium that is contaminated. (The health threshold is defined by HFWC, according to the requirements of Section 6.5.2.)
- The emission must be shown to contribute to contamination of the specific water supply or food source.

As part of the iterative process, those unit process(es) in the product system that result in significant emissions of HFWCs should be identified; it can then be determined if these
emissions are occurring in regions where the HFWC in question occurs in food/water supplies at concentrations over the defined health threshold. This type of monitoring data is often readily available from governmental monitoring programs or in published literature.

An alternative approach is to identify regions considered in the study where a HFWC occurs in food/water supplies at concentrations over the defined health threshold, and determine if any emission sources in the study scope could contribute.

If a unit process has been determined to exist in a region where concentrations of the HFWC are over the defined health threshold in food or water supplies, and the unit process has associated emissions of the HFWC, the emission still must be linked to the increased concentration of that HFWC. In establishing the linkage, the persistence and bioaccumulative properties of the HFWC emitted by a unit process should be considered. Measures of the persistence of a chemical species should consider its chemical half-life or elimination time in different media (e.g., soil, sediments, water); and measures of its bioaccumulative properties, such as the bioconcentration or bioaccumulation factor.

**NOTE.** An HFWC can be considered to be persistent if one of the following conditions exists: its water solubility is > 3 ppm (mg/L), its soil adsorption coefficient (KOC) is \(< 1,900 \text{ cm}^3/\text{g}\), its hydrolysis half-life is \(> 14\) days, its aerobic soil metabolism half-life is \(> 610\) days, or its anaerobic soil metabolism half-life is \(> 9\) days.

**NOTE.** An HFWC can be considered to be bioaccumulative if: its bioconcentration factor or bioaccumulation factor has been shown to be \(> 500\) in the tissues of humans, fish, wildlife, or plants, in any environmental media, in any research; or if log $K_{ow}$ of a substance is \(\geq 4\).

When conducting this screening, it is important to identify types of unit processes that have been known in the other cases to have emissions that contribute measurably to risks of exposure to humans via ingestion. This can include consideration of: unit processes by type, when similar unit processes are known to emit substances that cause contamination of food or water supplies; the chemical species and region of emission, if the species is a widespread contaminant in food or water supplies where the unit process is located; or the regulatory setting in which a unit process is located, if emissions controls in the region where it is located are lax.

**FOR EXAMPLE.** Coal-fired power plants emit trace amounts of mercury, though the level of mercury emitted depends on the assay of coal used and emission controls in place. Electricity generation derived from coal-fired sources should be investigated, to determine if resulting mercury emissions are contributing to contamination of food or water supplies in the region.

Unit process(es) located in regions where contamination of food or water supplies is an issue of concern to regional government agencies and or other stakeholders should also be identified.

**FOR EXAMPLE.** Contamination of sediments in the Great Lakes region of North America has been addressed by legislation in both the United States and Canada. The US EPA has a program devoted to assessment and remediation of contaminated sediments.
Contamination of food and water supplies in this region are an issue, particularly resulting from methylmercury contamination of fish. Emissions contributing to regional instances of contamination in the Great Lakes region should be considered for relevance in this impact category.

In some cases, the most significant emissions of HFWCs will occur far “upstream” in the product system under study. These significant emission sources often occur in small unit operations in regions subject to less stringent emission controls. A thorough screening of the available literature can help to determine if such unit processes exist in the product system under study. Contamination of food and water supplies is often well-researched even in countries with lax emission controls, and data will usually be available to link a unit process to these active midpoints.

Care should be taken to ensure that this impact category is not mistakenly identified as relevant. HFWC Exposure Risks can be ruled out as a relevant impact category if there are no unit process(es) in the product system that contribute measurably to the risk of exposure to humans to HFWCs by ingestion of food or water where concentration of HFWCs are over defined health thresholds. For a given HFWC emitted from a given unit process, the following guidance can be used to exclude this impact category as relevant:

- If there are no contaminated food or water supplies in which the HFWC occurs over the defined health threshold, in regions to which the HFWC could transport (considering its persistence in the environment);
- If the HFWC has very low transport potential, and even if present in the environment, cannot pose a risk to human exposures through ingestion;
- If the HFWC has a very short elimination time in the environment into which it is emitted, and has no possibility of transporting to cause contamination of food or water supplies before it is removed from the environment through chemical decomposition or other processes.

The justification for the inclusion or exclusion of this impact category shall be provided in the LCA report.

Whether this impact category is included as relevant to a product system depends on the goal and scope of the LCA study. When screening to determine if HFWC Exposure Risks is a core impact category, the scale of the functional unit used shall be large enough to include observed instances of midpoints of contaminated food or water supplies. The functional unit should be scaled based upon the gross scale of emission levels in the product system. The functional unit must not be set arbitrarily low, which could rule out this impact category even in cases where HFWC exposure risks are occurring and can be linked to emissions from a unit process in the product system. This screening may require sensitivity analysis.

NOTE. If specific data is unavailable for gross emissions, gross emissions can be estimated using conservative assumptions. This impact category is not relevant if emission levels of HFWCs are negligible, even when considering the gross scale of emissions estimated using conservative assumptions.
An initial screening for the relevance of this impact category may determine that the scale of
the functional unit, or the goal and scope, needs revision. The exclusion of this as a core
impact category should be a key subject of the critical review phase.

**NOTE.** While the number of HFWCs emitted from all unit processes in a product system can be
large, in practice, very few emissions will be of a nature and scale that risks of human exposure
from ingestion will result. In addition, in most regions, very few HFWCs are present above
known health thresholds in food or water supplies. The screening for HFWC Exposure Risks
should be able to quickly determine if this impact category is relevant to unit processes in the
product system. An efficient screening will require expert judgment and sensitivity analysis to
guide the iterative process.

### 6.5.1.2.1. Relevance of Product Material Composition.

In some cases, a product in use may include, as part of its physical composition, an HFWC. In such cases, there must
be a route of exposure of ingestion to humans during the use phase to warrant inclusion
of this impact category as relevant. In many cases, such products will in fact pose no risk
to humans, as there is no possible route of exposure.

**FOR EXAMPLE.** An office chair is known to contain lead, a HFWC, as part of its
material composition. However, this lead is present as a trace material in the chair's
aluminum components; it is chemically inert and bonded in the aluminum's crystal
structure. There is no possible mechanism by which this lead could expose humans
by ingestion. The presence of lead in the office chair does not warrant inclusion of
HFWC Exposure Risks as relevant for this product system.

Conversely, a product may contain only inert chemicals as part of its physical
composition, and yet contribute to active midpoints of food or water supply
contamination during its production. This highlights the need for a thorough screening
of the product system to identify contributors to HFWC Exposure Risks, irrespective of
the product's material composition.

**FOR EXAMPLE.** Finished polyurethane foam is itself a chemically inert product that
does not contain materials that are significantly toxic. However, polyurethane foam
is sometimes produced using a precursor chemical called toluene diisocyanate
(TDI); effects of TDI exposure can include primary irritation, sensitization (e.g.,
"isocyanate asthma"), and progressive impairment of lung function as a result of
long-term exposures.\(^{96}\) Although TDI is not present in finished polyurethane foam,
in some industries, TDI use has been poorly regulated, and there have been
documented instances of worker exposure and resulting toxic effects through
inadvertent TDI ingestion.\(^{97}\) Although in this case, the finished product has no
hazardous material constituents, HFWC Exposure Risks could be a relevant impact
category if TDI is used in its production.

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\(^{96}\) US Environmental Protection Agency, Integrated Risk Information System. 2,4-\(\sim\)/2,6-\(\sim\) Toluene diisocyanate mixture (TDI)
(CASRN 26471-62-5)

In practice, there is very little correlation between HFWCs present in a product and resulting exposure to humans.

6.5.3. Classification. All emissions of HFWCs which meet the requirements of a relevant impact category described in Section 6.5.2.2 shall be classified. Different HFWCs may be classified into separate category indicators.

6.5.4. Characterization

6.5.4.1. Stressor Characterization Factors. The S-CF is determined by HFWC, and is separately defined for each category indicator included in the study scope, according to the requirements of Section 6.5.2.1. In cases where multiple HFWCs are considered in a single category indicator, the S-CF characterizes the oral toxicity of each HFWC compared to the oral toxicity of a reference contaminant with similar human health endpoints. For each category indicator, the same reference contaminant, and consistent measures of oral toxicity, must be used.

NOTE. For category indicators that include emissions of a single HFWC, the HFWC is its own reference contaminant.

The S-CF for this impact category is shown in Equation 6.10.

Equation 6.10. Stressor characterization factor for HFWC Exposure Risks.

\[
S - CF_i = \frac{\text{oral toxicity}_i}{\text{oral toxicity}_{\text{reference}}}
\]

Where:
- S-CF is the Stressor Characterization Factor for a given HFWC, denoted i
- Oral toxicity is the measure of the oral toxicity for the given HFWC (denoted i), and the reference contaminant.

NOTE. Results of emissions levels multiplied by the S-CF shall give results in units of equivalent mass of the reference contaminant. The S-CF equation will thus depend upon the units of the measures of oral toxicity that are used.

For HFWCs with toxic effects in humans which have a clear dose threshold for onset, the oral toxicity of the HFWC can be characterized using the lowest oral exposure threshold resulting in onset of the critical toxic effect, typically measured in mg dose / kg body-day.

NOTE. The Reference Dose for Chronic Oral Exposure (RfD) for an HFWC, from the US EPA’s Integrated Risk Information System database, can be used to characterize the S-CF for HFWCs which have toxic effects with a clear dose threshold for onset.

However, for many HFWCs, there is no clear dose threshold for onset. In these cases, extreme care must be taken in defining the oral toxicity of different HFWCs and the reference contaminant, in order to provide a defensible basis of aggregation for multiple HFWCs included in a single category indicator.
FOR EXAMPLE. Carcinogenicity is a toxic effect that does not exhibit a clear dose threshold for onset. S-CFs for carcinogenicity must be represented by measures such as the Oral Slope Factor.

FOR EXAMPLE. Although inorganic lead is a substance which can induce toxic effects which are similar to those induced by other heavy metals, there is no dose threshold for the toxic effects of lead. Current observations indicate that any exposure to lead can lead to toxic effects; certain effects can result from such low levels of lead concentrations in the bloodstream that there is essentially no threshold. This means it is not possible to establish oral toxicity based on a dose threshold for inorganic lead, since no such dose threshold exists.

If there is no scientifically defensible basis for assessing S-CFs for multiple HFWCs based on consistent measures of oral toxicity, there is no way to aggregate emissions into a single category indicator. In these cases, separate category indicators must be reported for each emission.

NOTE. The lack of a consistent basis for aggregation often indicates that the toxic endpoints of HFWCs are different, and that the stressor-effects networks are distinct.

In all cases, the uncertainty and/or confidence level inherent in the oral toxicity measures used as the basis for calculating S-CFs must be considered.

For HFWCs exhibiting toxic effects with a clear dose threshold, measures based on the onset of the critical toxic effect are the most widely used, as these measures usually contain the least inherent uncertainty. However, even these measures can contain inherent uncertainties of one order of magnitude or more. When deriving S-CFs, the uncertainty in the measure of oral toxicity should be considered in the context of the goal and scope of the study. If the uncertainty levels in the S-CFs which are calculated are very high, it may not be possible to achieve the goal(s) of the study. In such cases, the goal and scope may need to be revised.

The oral toxicity measures used must be based upon empirical measurements from peer-reviewed studies. Generic extrapolation between measures such as the lowest onset threshold for the critical toxic effect and the median effective dose (ED50) value for a given chemical species shall not be used.

6.5.4.2. Environmental Characterization Factors. For category indicators in this impact category, three levels of reporting at three different nodes are possible, based upon data availability (see Section 6.5.2. and Table 6.6):

- Node 4, Characterizing the fraction of a HFWC emission that contributes to the contamination of a food or water supply where concentrations of the HFWC are over the defined health threshold.

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• Node 3, Characterizing the fraction of a HFWC emission that contributes to the persistent contamination of the receiving environment (not considering contamination of any food/water supplies, or the defined health threshold).

• Node 1, Characterizing the emission level of relevant HFWCs.

For a single category indicator, the same characterization model must be applied to all emissions of all HFWCs from all relevant unit processes. Comparison between results calculated using different characterization models is not possible. In LCA reports and any, the category indicator selected and characterization model used to derive results must be described.

The characterization models used for assessment at each node are described in the sections below.

6.5.4.2.1. Characterization of Contribution to Food or Water Supply Contamination. The E-CF assesses the fraction of a HFWC emission that contributes to contamination of a food or water supply in the receiving environment, in which concentrations of the HFWC exceed the defined health threshold. At Node 4, the characterization model used is the most environmentally relevant measure that is possible. However, the characterization must integrate modeling of the fate, transport, and accumulation of each HFWC emitted, and will typically require significant modeling resources to complete.

The uncertainty inherent in the modeling of fate and transport of HFWCs throughout the receiving environment shall be considered when characterizing results for this indicator. Uncertainty levels should be included where results are reported, preferably as a confidence interval. The model uncertainty may be significant enough that the goal of the LCA study cannot be achieved. In these cases, the goal and scope may need to be revised, or the characterization of results must be at a lower node which has less associated uncertainty.

NOTE. For the emissions of certain HFWCs, the risk of human exposure occurs after extensive transport, long after the emission occurs. In these cases, modeling of fate and transport may not be possible due to the very high uncertainties associated with this modeling.

The severity, spatial scale, and reversibility of food and water supply contamination associated with different emissions from different unit processes will vary broadly, depending on factors such as the HFWC emitted, scale of emission, timing of emission, duration of emission, medium of emission, and regional setting. Associated midpoints and endpoints vary for all of these reasons. Accordingly, site-specific assessment at this node is required. Secondary data shall not be used in the characterization.
6.5.4.1.2. Characterization of Contribution to Receiving Environment Contamination. The E-CF assesses the fraction of a HFWC emission that contributes to persistent contamination of the receiving environment, irrespective of contamination of food or water supplies, or whether contamination is at levels exceeding the defined health threshold. The characterization must integrate modeling of the fate, transport, and accumulation of each HFWC that is emitted. It must consider the persistence of the HFWC in the receiving environment into which it is emitted.

The uncertainty inherent in the modeling of fate and transport of chemicals throughout the receiving environment shall be considered when characterizing results for this indicator. Uncertainty levels should be included where results are reported, preferably as a confidence interval. The modeling uncertainty may be significant enough that the goal of the LCA study cannot be achieved. In these cases, the goal and scope may need to be revised, or the characterization of results must be at Node 1, which has less associated uncertainty.

The severity, spatial scale, and reversibility of persistent receiving environment contamination associated with different emissions from different unit processes will vary broadly, depending on factors such as the HFWC emitted, scale of emission, timing of emission, duration of emission, medium of emission, and regional setting. Associated midpoints and endpoints vary for all of these reasons. Accordingly, site-specific assessment at this node is required. Secondary data shall not be used in the characterization.

6.5.4.1.3. Characterization of Emissions Levels. At Node 1, indicator results assessed have no E-CF. Emissions contributing to a category indicator are assessed strictly as emissions levels, and do not integrate fate and transport.

6.5.5. Indicator Equation and Unit of Measure. For results reported at Node 4, the indicator equation is shown in Equation 6.11; for results at Node 3, the indicator equation is shown in Equation 6.12; for results reported at Node 1, the indicator equation is shown Equations 6.13. Regardless of the node of characterization, results are reported in units of mass equivalents of the reference contaminant.
Equation 6.11. Indicator equation for a single unit process for HFWC Exposure Risks, with results reported at Node 4 (contribution to contamination of food or water supplies).

\[ \text{HFWC Exposure Risks} = \sum_i (\text{Emissions}_i \times \text{S-CF}_i \times \text{E-CF}) \]

Where:
- Emissions are the emission levels of a given HFWC, reported in units of mass.
- S-CF is the Stressor Characterization Factor for each HFWC, representing its oral toxicity relative to the reference contaminant.
- E-CF is the Environmental Characterization Factor, which characterizes the fraction of the emission that contributes to the contamination of a specific food/water supply where concentrations of a HFWC exceed the defined health threshold.

Equation 6.12. Indicator equation for a single unit process for HFWC Persistent Contamination, with results reported at Node 3 (contribution to persistent contamination of the receiving environment).

\[ \text{HFWC Persistent Contamination} = \sum_i (\text{Emissions}_i \times \text{S-CF}_i \times \text{E-CF}) \]

Where:
- Emissions are the emission levels of a given HFWC, reported in units of mass.
- S-CF is the Stressor Characterization Factor for each HFWC, representing its oral toxicity relative to the reference contaminant.
- E-CF is the Environmental Characterization Factor, which characterizes the fraction of the emission that contributes to the persistent contamination of the receiving environment.

Equation 6.13. Indicator equation for a single unit process for HFWC Emissions, with results reported at Node 1 (emissions levels).

\[ \text{HFWC Emissions} = \sum_i (\text{Emissions}_i \times \text{S-CF}_i) \]

Where:
- Emissions are the emission levels of a given HFWC, reported in units of mass.
- S-CF is the Stressor Characterization Factor for each HFWC, representing its oral toxicity relative to the reference contaminant.

6.5.6. Additional Reporting Requirements. In the LCA report, and EPDs and C-EPDs which are generated, the midpoint of contaminated food or water supplies associated with a category indicator shall be described, along with the toxic endpoints that can result from human intake of the relevant HFWC.

The name of the characterization model used to describe the category indicator. The category indicator name which is used shall clearly describe the modeling used, and not overstate the environmental relevance of results.
6.5.7. Addressing Additional Limitations in Types, Accuracy, and Availability of Environmental Data. The first step in characterization of results in this impact category is the screening for determination of relevance of emissions of HFWCs, according to the requirements and guidance provided in Section 6.5.2. In some product systems, where unit processes in the product system are distributed in extensive global supply chains, lax regulations and poor monitoring might make it impossible to determine the relevance of specific emission sources to this impact category. If the screening cannot be conducted, then determination of the relevance of this impact category is not possible; this could affect the ability to achieve the goals of the LCA study. If the relevance of this impact category cannot be determined, the goal and scope of the LCA study may need to be revised.

In certain cases, although the scale of emission from a unit process may be unknown, the nature and region of an emission occurring in the product system under study will be understood, and there will be observational data clearly showing that the emission contributes to the active midpoint of contamination of a food or water supply. In these cases, the HFWC emitted and region of emission shall be reported as a separate indicator, with the midpoints and endpoints described, although results cannot be assessed.

*FOR EXAMPLE.* The mining of certain materials, including mercury and arsenic, in countries such as China, has been observed to contribute to regional instances of contamination of food and/or water supplies from heavy metals. However, inventory data will typically be unavailable to characterize emissions of these heavy metals resulting from mining in these regions, which often occurs in unit processes that are very far upstream. Although inventory data may be unavailable, it must be reported in the LCA report, and in EPDs and C-EPDs, that emissions of HFWCs are occurring from mining in this region.

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7. Risks from Untreated Hazardous and Radioactive Wastes

These impact categories account for the disposal of untreated hazardous and radioactive wastes that may result in unanticipated consequences to human health and the environment.

The classification of wastes as “hazardous” or “radioactive” is based upon regulations such as those established under the Resource Conservation and Recovery Act (RCRA), set by the Nuclear Regulatory Commission, or defined by the Basel Convention. This group of impact categories addresses the current state of treatment, storage, and disposal of specific waste streams.

7.1. Risks from Radioactive Wastes

7.1.1. Impact Category. This impact category considers the risks of impacts to the environment and human health that would occur in the event that untreated radioactive wastes escape from containment.

While this impact category considers the radioactivity inherent in radioactive wastes in general (including both low-level and high-level wastes, and the production of mill tailings from uranium mining), in practice, the disposal of spent nuclear fuel is the main source of risk. High-level waste generated from spent fuel reprocessing may also be a significant contributor to risks, in regions where reprocessing occurs.

7.1.2. Stressor-Effects Network. The stressor-effects network involves the generation of untreated radioactive wastes, the near-term storage of these wastes, the transfer to long-term storage, and the potential human health and environmental impacts that could occur in the event of breach of containment and migration into the receiving environment (see Table 7.1). The waste stream that typically makes the most significant contributions to risks from radioactive wastes is spent nuclear fuel from nuclear-powered electricity generation. In countries where spent nuclear fuel is reprocessed, the production of high-level radioactive waste from nuclear fuel reprocessing may also be a significant contributor to these risks.

Table 7.1. Stressor-effects network for risks from radioactive wastes.

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Stressors)</td>
<td>High overall uncertainty. (Low environmental relevance.)</td>
<td>High uncertainty. Characterization does not consider differences in the radioactivity of different waste streams and low probability that waste that is stored will transport into the receiving environment.</td>
<td>Low uncertainty. Data requirements: Amount of untreated radioactive waste generated.</td>
</tr>
</tbody>
</table>
2 (Midpoint)
High overall uncertainty.
(Low environmental relevance.)

| Inherent radioactivity of untreated radioactive wastes in short-term and long-term holding facilities. | High uncertainty. Characterization does not consider the probability that waste that is stored will transport to the receiving environment. | Low uncertainty. Data requirements: Amount of untreated radioactive waste generated, and inherent radioactivity of the waste stream over time as different isotopes decay. |

3 (Midpoint)
Characterization at this node not possible given data limitations.

| Contribution to emissions resulting from breach of containment. | Low uncertainty. Strong linkage to resulting endpoints, due to the radioactivity and persistence of the emitted substances. | No environmental data are available to assess the contribution to emissions linked to a specific source of untreated radioactive waste, due to the low probability of breach of containment. |

4 (Multiple Endpoints)
Characterization at this node not possible given data limitations.

| Contribution to multiple impacts to human health and the environment from dispersion of radioactive substances and contamination of the receiving environment in the long term. | Low uncertainty. Directly reflective of endpoints. | No environmental data are available linking a specific source of untreated radioactive waste to endpoints resulting from breaches of containment. |

7.1.1.1 Selection of Category Indicator(s). For this impact category, breach of containment which leads to endpoints occurs only in rare circumstances. Characterization of emissions resulting from breach of containment is not possible unless such breach occurs.

As a result, the category indicator is Node 2, characterizing the risks arising from the inherent radioactivity of untreated radioactive wastes in storage, without taking the probability of breach of containment into account.

7.1.1.1.1. Category Indicators for Short-Term and Long-Term Storage of Untreated Radioactive Wastes. Almost all of the risk from untreated radioactive wastes arises from radioactivity associated with spent nuclear fuel in storage. High-level radioactive waste from fuel reprocessing can also be a significant contributor to these risks in regions where fuel reprocessing occurs.

After untreated radioactive wastes are generated, they are transported to short-term (also known as interim) storage facilities, usually in dry casks or cooling ponds; in these locations, the radioactive waste is intended to be stored from 30 to 120 years. The category indicator must be reported at Node 2, which characterizes the risks from the inherent radioactivity of untreated radioactive wastes in short-term storage.

In most regions, long-term storage repositories for untreated radioactive wastes do not exist, and the end disposition after interim storage is not known. Although the

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103 In many countries (including the United States and Canada), there are no sites in the planning stage for the long-term disposition of nuclear waste.
potential endpoints from breaches of containment in short-term storage are known from past accidents at nuclear power plants, there is no precedent for determining the possible endpoints that could arise from long-term nuclear storage.

A second category indicator can be reported, which characterizes the risks from inherent radioactivity of untreated radioactive wastes in long-term storage.

7.1.1.2. Identifying Core Impact Categories and Category Indicator(s). If nuclear electricity generation or spent fuel reprocessing occurs in the product system under study, risks from radioactive wastes will be a relevant impact category.

The following unit processes could also contribute to results in this impact category:

- Uranium mining;
- Uranium milling and tailings waste handling;
- Fuel enrichment;
- Fuel bundle production; and
- Waste management for spent nuclear fuel.

7.1.3. Classification. All untreated radioactive waste moved into storage without being reprocessed shall be classified.

The risks considered in this impact category are nearly always dominated by the generation of spent nuclear fuel from nuclear power generation. In regions where fuel reprocessing occurs, high level radioactive waste from fuel re-processing may also be a significant contributor to risks. In practice, the contribution to risks from radioactive wastes from other waste streams will be negligible in comparison to these two waste streams, and can be neglected without having a significant effect on results.

7.1.4. Characterization

7.1.4.1. Stressor Characterization Factors. The S-CF for this category indicator assesses the accumulated decay heat generated per mass of untreated radioactive waste, over the time horizon used in indicator calculations (i.e., considering short-term or long-term storage; see Section 7.1.2.1). The S-CF therefore has units of energy per mass of waste (e.g., Gigajoules per ton of spent nuclear fuel).

NOTE. Measures of the decay heat of untreated radioactive wastes have the strongest linkage to risks of breach of containment.

The S-CF must account for the material composition of the untreated radioactive waste, and any characteristics that lead to differences in its generated decay heat over time.

7.1.4.2. Environmental Characterization Factors. Modeling of the fate and transport of untreated radioactive wastes is highly uncertain, and only exceptional circumstances lead to breaches in containment. The characterization of such breaches of containment are highly uncertain, and results are reported at Node 2, representing the risks from radioactivity inherent in untreated radioactive waste.
Based on the Node 2 analysis, no environmental characterization is performed, and no E-CFs are applied.

7.1.5. **Indicator Equation and Unit of Measure.** The indicator equation is shown in Equation 7.1. The reported units characterize the amount of waste heat generated, in units of energy.

_Equation 7.1. Indicator equation for risks from radioactive wastes for a given unit process_

\[
\text{Waste Heat Generated} = \sum_n (\text{Waste Generated}_n \times \text{S-CF}_n)
\]

Where:
- \(\text{Waste generated}_n\) represents the mass of a specific type of untreated radioactive waste that is generated
- \(\text{S-CF}_n\) represents the decay heat per unit mass of the specific type of waste
- \(n\) represents all types of radioactive waste generated by a unit process

7.2. **Risks from Untreated Hazardous Wastes**

7.2.1. **Impact Category.** This impact category considers the risks of impacts to the environment and human health that would occur in the event that untreated hazardous wastes escape from containment.

7.2.2. **Stressor-Effects Network.** The stressor-effects network involves the generation and storage of untreated hazardous wastes, and the potential human health and ecological impacts that could occur in the event of breach of containment and migration into the receiving environment.

The risks inherent in untreated hazardous wastes differ by unit process and by the types of hazardous waste generated. Differences in the storage facilities used, volatility and/or combustibility of the waste, length of storage, and other factors can also lead to differing levels of risks. The stressor-effects network shown in Table 7.2 provides a general framework, but it can be useful to separately model the stressor-effects network for each separate mechanism of untreated hazardous waste which occurs in the scope of the study. This can aid in the characterization of results.
Table 7.2. Stressor Effects Network for Risks from Untreated Hazardous Wastes

<table>
<thead>
<tr>
<th>Node</th>
<th>Characterization of the Node</th>
<th>Uncertainty Arising from Weakness in Linkage to Endpoints</th>
<th>Uncertainty in Characterization, and Data Required to Characterize this Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Stressors)</td>
<td>Inherent hazards from untreated hazardous wastes which are generated.</td>
<td>High uncertainty. Characterization does not consider differences in the relative hazard of different waste streams and low probability that stored waste will transport into the receiving environment.</td>
<td>Low uncertainty. Data requirements: Amount of untreated hazardous waste generated.</td>
</tr>
<tr>
<td>High overall uncertainty. (Low environmental relevance.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 (Midpoint)</td>
<td>Inherent hazards from storage of untreated hazardous wastes.</td>
<td>High uncertainty. Characterization does not consider the probability that stored waste will transport to the receiving environment.</td>
<td>Low uncertainty. Data requirements: Amount of untreated hazardous waste generated, and measures of the inherent hazardous characteristics of the waste stream over time.</td>
</tr>
<tr>
<td>High overall uncertainty. (Low environmental relevance.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 (Midpoint)</td>
<td>Contribution to emissions resulting from breach of containment.</td>
<td>Low uncertainty. The amount of emissions transporting to the receiving environment has a strong linkage to resulting endpoints.</td>
<td>No environmental data are available to assess the contribution to emissions linked to a specific source of untreated hazardous waste, due to the low probability of breach of containment.</td>
</tr>
<tr>
<td>Characterization at this node not possible given data limitations.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 (Multiple Endpoints)</td>
<td>Contribution to multiple impacts to human health and the environment from dispersion of hazardous substances and contamination of the receiving environment.</td>
<td>Low uncertainty. Directly reflective of endpoints.</td>
<td>No environmental data are available linking a specific source of untreated hazardous waste to endpoints resulting from breaches of containment.</td>
</tr>
<tr>
<td>Characterization at this node not possible given data limitations.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7.2.2.1. Selection of Category Indicator(s). The US Environmental Protection Agency (EPA) and the 1989 Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal104 define a waste as hazardous if:

- It exhibits certain hazardous characteristics.
- It originates from specific waste streams (e.g., substances arising from specific industrial processes).
- It contains constituents that are themselves considered hazardous.

Hazardous characteristics include, but are not limited to, ignitability, corrosivity, reactivity, and toxicity. US regulation Title 40 CFR 261.21 and Annex III of the Basel Convention contain detailed guidelines defining hazardous characteristics. The Basel Convention

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The 1989 Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal
includes a longer list of hazardous characteristics. In addition, Title 40 CFR 261.21 has quantitative guidelines that can aid in the classification of hazardous substances.

Each chemical that meets any of the above criteria in specified lists should be included in a distinct indicator. Multiple indicators are reported to account for waste streams with different hazardous characteristics (e.g., ignitable versus corrosive hazardous wastes).

The characterization should be at Node 2, which characterizes the hazardous characteristics of the untreated hazardous waste stream (see Section 7.2.4.1).

In some cases, data will be insufficient to characterize the hazardous characteristics of the untreated hazardous waste stream. In these cases, results shall be reported at Node 1, characterizing the amount of untreated hazardous waste generated, measured in units of mass or volume.

**7.2.2.2. Identifying Core Impact Categories and Category Indicator(s).** This is a relevant impact category only if hazardous wastes are generated and stored without treatment. Care should be taken not to report hazardous waste streams which are subsequently treated, when there will be no risk of the breach of containment.

In most developed countries, the production of untreated hazardous waste will occur only rarely, as environmental regulations exist which mandate the treatment of hazardous wastes. However, certain industry sectors in these countries have legal exemptions, which means that untreated hazardous wastes are produced and disposed legally. Depending on the scope of the study, the product system should be screened for unit process(es) of types which have obtained such exemptions.

**FOR EXAMPLE.** To classify a waste as hazardous under the Resource Conservation and Recovery Act (RCRA), the Toxicity Characteristic Leaching Procedure (TCLP) is used. Wood treated with the treatment chemical, chromated copper arsenate (CCA), fails the TCLP for arsenic, and therefore meets the definition of a hazardous waste according to the US EPA. However, the US EPA has provided an exemption for CCA wood for certain applications, such as for utility poles, to avoid classification as a hazardous waste. As CCA-treated wood fails the TCLP test, it is classified as an untreated hazardous waste if it is disposed without treatment. Therefore, untreated hazardous waste is a relevant impact category for product systems involving disposal of untreated CCA-treated wood.

In some instances, breaches of containment of untreated hazardous waste are observed, and can be linked to a unit process in the product system under study. In such cases, impacts from these emissions will separately be reported in other separate impact categories, such as Ecotoxicity, and Hazardous Chemical Exposure Risks, provided distinct environmental mechanisms and characterization models are defined.

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7.2.3. **Classification.** All flows of untreated hazardous waste meeting the US EPA or Basel Convention definitions (see Section 7.2.2.1) shall be classified. Flows of hazardous waste that are treated after generation shall not be classified.

7.2.4. **Characterization.**

7.2.4.1. **Stressor Characterization Factors.** For characterization at Node 2, the S-CF shall be determined separately for the hazardous characteristic of distinct types of untreated hazardous waste. For each waste with distinct hazardous characteristics, quantitative data shall be used to determine S-CFs as appropriate.

If characterization is at Node 1, there is no applicable S-CF, and results are reported based on the mass of untreated hazardous waste generated, measured in units of mass or volume.

7.2.4.2. **Environmental Characterization Factors.** The uncertainty is too great to model the transport of untreated hazardous waste emitted during breaches of containment. Therefore environmental characterization is not conducted, and no E-CFs are used.

7.2.5. **Indicator Equation and Unit of Measure.** Due to the diverse nature of the environmental mechanisms for risks from untreated hazardous wastes, different units of measure and indicator equations will be applicable in different contexts. The indicator equation and unit of measure used should be reported and described in the LCA report. The reported units depend upon the hazardous characteristics of the stream of untreated hazardous wastes.

If characterization is at Node 1, the results are assessed based upon the amount of untreated hazardous waste which is generated (assessed using mass or volume).

7.2.6. **Additional Reporting Requirements.** In all cases, the hazardous characteristics of the untreated hazardous waste streams shall be described in the LCA report, and in EPDs and C-EPDs which are generated.