



Textile  
Exchange

# Life Cycle Assessment for Cotton

## Model comparison

**Title:** Life Cycle Assessment for Cotton Model comparison

**On behalf of:** Textile Exchange

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*Cover photo: Abhishek Khedekar*

# Executive summary

Textile Exchange is currently conducting Life Cycle Assessment (LCA) studies across multiple fiber and material categories and has outlined key principles for responsible data use in its recent position paper *Ensuring Integrity in the Use of Life Cycle Assessment* (Textile Exchange, 2025). Although these principles were developed in the context of Textile Exchange's own work, they are equally relevant in a broader context, since LCA studies are also being undertaken by various other organizations and programs that rely on transparent and methodologically robust data and interpretation. To deepen understanding of how methodological choices and assumptions influence LCA results, Textile Exchange has initiated a complementary assessment comparing several agricultural LCA models, using cotton as a case study. The comparison was carried out through a collaborative process involving the providers of agricultural LCA models that are commonly used in cotton LCA studies. All providers received the same input datasets and applied their standard modeling approaches, after which the outputs were evaluated across several impact categories through a consistent contribution analysis framework.

Climate change results showed moderate to medium ranges, with the minimum and maximum values differing by up to  $-14\%$  and  $+30\%$  from the average of all models. While all models consistently identified the same main hotspots, the observed variation has a substantial effect on the interpretation of results. Additional uncertainty arises when specific aspects are considered, such as land use change or potential emissions related to soil carbon stock changes. Emission factors, characterization factors, and background data were identified as key drivers of the observed variation. Results for other impact categories (acidification, eutrophication, resource depletion, water scarcity, ecotoxicity) showed similar or even much larger variation between model providers than was observed for climate change.

The findings reinforce messages from recent publications on the integrity of LCA results in the fashion, textile, and apparel industry, which highlight that results from different studies or databases should not be compared. The present study shows why this caution is necessary. It illustrates that variation arising solely from the use of different agricultural LCA models can exceed the differences that studies typically aim to evaluate. This also reflects the rationale behind requirements in International Organization for Standardization (ISO) standards such as ISO 14044 and ISO 14067, which specify that comparative assertions are only permissible when it can be ensured that the compared results are based on consistent methodological choices, data sources, and data quality. It should also be noted that in real-world cases, data collection and aggregation introduce additional variance in LCA results, and these sources of variability were not assessed in this study.

The study acknowledges that methodological assumptions differing among models is valid and expected. The purpose of this study is not to evaluate the quality or robustness of the participating models but to show how making such assumptions affects impact results. No single approach can be viewed as universally preferable, and the most suitable option is always case specific. However, the findings show there are several focus areas for further alignment emerging, such as the use of emission factors provided by the Intergovernmental Panel on Climate Change (IPCC) or modeling approaches for eutrophication pathways. Industry-aligned modeling guidelines, such as the cotton LCA methodology developed under the guidance of Cascale in collaboration with industry experts and stakeholders, can help to provide better-aligned and reproducible outcomes.

The study is a positive example of valuable precompetitive collaboration. The joint exercise helped to identify methodological challenges in agricultural LCA, increase transparency, and improve understanding of the use of agricultural LCA data and results.

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# Introduction

## Background

In the fashion, textile, and apparel industry, Life Cycle Assessment (LCA) has become a central tool for quantifying environmental impacts across materials, products, and supply chains. Textile Exchange acknowledges the importance of LCA data for measuring the environmental impact of the raw materials and fibers used by the industry and is currently conducting several studies covering different fiber and material categories. In parallel, the organization has published a position paper *Ensuring Integrity in the Use of Life Cycle Assessment* (Textile Exchange, 2025). In this paper, Textile Exchange emphasizes that reliable use of LCA data requires a clear understanding of the underlying assumptions, methodological choices, and contextual limitations associated with each dataset.

To support this objective, Textile Exchange has initiated a complementary project to compare several agricultural LCA models, using cotton as a case study. Multiple model providers currently support the development of LCA studies, often applying varying assumptions, methodological approaches, and background datasets. These differences can result in inconsistencies in the results generated and create uncertainty about how individual LCA studies relate to each other. This issue has been particularly relevant for cotton, as stakeholders of the Textile Exchange cotton LCA project have expressed a need for greater clarity on how modeling approaches influence outcomes. This model comparison project therefore aims to assess to what extent differences in LCA results across cotton systems are driven by variations in model structure and assumptions, thereby enhancing transparency and interpretability for users across the industry.

## Project scope

The model comparison project was established as a collaborative initiative involving a working group composed of providers of agricultural models that are widely used in cotton LCA studies. The objective of this collaboration was to systematically evaluate how methodological differences between models influence the resulting impact profiles, and to identify opportunities for greater alignment and transparency.

Participating model providers were identified and invited by the project team based on their recognized contribution to textile-relevant agricultural LCA data and models (see Table 1). It should be noted that, in addition to the participating providers, further model providers were invited to contribute to the study but declined the invitation.

Each participating model provider received the same set of input datasets representing cotton production systems. Using this harmonized input data, the providers conducted their own LCA modeling according to their standard methodologies, and the life cycle impact assessment methods to be applied were prescribed in advance. The resulting outputs were analyzed through a predefined contribution analysis framework to ensure consistent evaluation across models.

Differences in results were then examined and explained in relation to the underlying methodological assumptions, modeling structures, and background data. Based on these findings, conclusions were drawn regarding the interpretation of LCA data and the extent to which results can be compared across models. In addition, the exercise aimed to identify areas where methodological alignment would be feasible and beneficial for improving the robustness and interpretability of future cotton LCA studies.

**It is important to emphasize that the objective of this project was not to evaluate the quality or robustness of the participating models. Rather, the focus was on analyzing and**

**explaining differences in the methodologies applied and the resulting outputs, without assigning value judgments to any specific approach.** It should also be noted that this study is not intended to assess or compare real-world cotton production systems, programs or regions. All results are based on a hypothetical but realistic test dataset that was applied uniformly across models for the sole purpose of benchmarking model behavior and identifying methodological drivers of variation. The outcomes should therefore be interpreted exclusively in this context and not be used as indicators of actual environmental performance in any specific setting.

It should also be noted that this evaluation used prescribed and harmonized input data in order to isolate and examine the variation introduced solely by the different agricultural LCA models. In real-world applications, additional sources of uncertainty arise from data collection, aggregation, preprocessing, and calculation steps before data are entered into any model. These stages involve numerous methodological choices and assumptions that can introduce variance equal to or greater than the variation observed in the modeling exercise itself.

Table 1 lists the participating model providers and highlights some of their contributions to LCA work in the textile, cotton, and/or LCA sector (see also section 6. Acknowledgements).

**Table 1: Model providers working group**

Organization	Relevant contribution to Textile/cotton LCA data	Key reference / link
Mérieux NutriSciences   Blonk	<ul style="list-style-type: none"> <li>Agri-footprint database supplies agricultural life cycle inventories (LCIs) widely used in crop-level LCA, including cotton</li> <li>Provides data for the EF 3.1 database</li> </ul>	<a href="#">Agri-footprint Database</a>
Cascale and Worldly	<ul style="list-style-type: none"> <li>Developed the Higg Materials Sustainability Index (MSI) Cotton LCA methodology</li> <li>Leads a cotton LCA working group with participation from major cotton programs, enabling submission of consistent data to the Higg MSI, with implementation managed concurrently by Worldly</li> </ul>	<a href="#">Higg Product Tools Cotton LCA Methodology - Cascale</a>
EarthShift Global	<ul style="list-style-type: none"> <li>Authored position paper <i>From Data to Impact – How to Get Cotton LCAs Right</i></li> <li>Provides LCA consultancy and guidance</li> </ul>	<a href="#">EarthShift Global – Cotton LCA Position Paper</a>
Field to Market	<ul style="list-style-type: none"> <li>Fieldprint Platform delivers field-level sustainability metrics for US cotton, supporting farm data integration and benchmarking in LCA</li> </ul>	<a href="#">Fieldprint Platform</a>
Quantis	<ul style="list-style-type: none"> <li>World Apparel and Footwear LCA Database (WALDB) provides textile and apparel LCI datasets including cotton</li> </ul>	<a href="#">World Apparel &amp; Footwear LCA Database (WALDB)</a>
Sphera	<ul style="list-style-type: none"> <li>Maintains the Managed LCA Content (MLC) database, including data for cotton cultivation and processing</li> <li>Leads Textile Exchange’s cotton LCA</li> </ul>	<a href="#">Sphera Managed LCA Content</a>
Cool Farm Tool*	<ul style="list-style-type: none"> <li>Widely applied farm-level carbon and environmental footprint calculator</li> </ul>	<a href="#">Cool Farm Tool</a>

\*Cool Farm Tool does not conduct studies on their own; results were provided by Quantis.

# Approach

This section outlines how the model comparison was designed and implemented, including the preparation of the inventory test dataset and results template, the selection of impact assessment categories and contribution analysis approach, and the procedures applied for reviewing and evaluating the results.

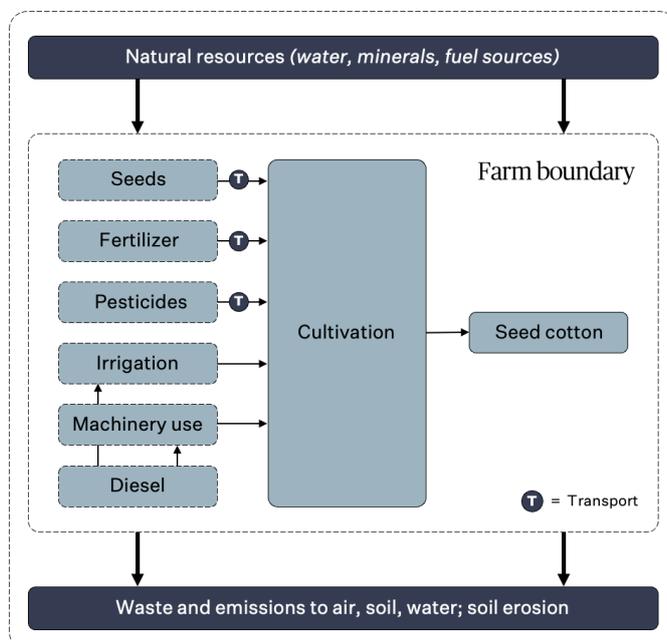
## Inventory test dataset

For the model comparison exercise, a standardized inventory dataset was prepared to serve as a common input across all participating models. The dataset represented a hypothetical but realistic cotton production system with parameter values approximating conditions in Texas, United States (US).<sup>1</sup> The intention was to provide a simplified yet credible representation of cotton cultivation that would allow for direct comparison of modeling approaches while minimizing complexity in data entry.

Two production scenarios were defined to capture contrasting nutrient management conditions:

- **Scenario 1:** Conventional production with mineral fertilizer application and a positive nitrogen balance (N surplus).
- **Scenario 2:** Cultivation system with organic fertilizer input, lower yield and with a negative nitrogen balance (N deficit).

To limit the number of varying parameters, irrigation water use and fuel consumption were kept constant on a per-hectare basis across both scenarios. The system boundary was defined at the field border, excluding ginning and post-harvest processes, see Figure 1.



**Figure 1: System boundaries**

<sup>1</sup> The test dataset was developed based on modified and simplified data compiled for the Textile Exchange cotton LCA and reviewed for plausibility from members of the working group.

Results were expressed using kilogram of seed cotton at field border as the functional unit. Table 2 summarizes the test inventory data used in this study. Additional information, including the calculated nitrogen balance per hectare, the classification, Chemical Abstracts Service (CAS) numbers, and US Environmental Protection Agency (EPA) pesticide chemical (PC) codes of the applied pesticides, as well as conversions to US customary units, are provided in the supplemental material (see Annex A1).

**Table 2: Inventory test dataset**

Parameter	Scenario 1	Scenario 2	Unit
Yield (seed cotton)	2,800	1,000	kg/ha
<b>Fertilizer</b>			
Urea ammonium nitrate (UAN)	88.8	0	kg/ha
Urea	57.9	0	kg/ha
Diammonium phosphate (DAP)	147.9	0	kg/ha
Muriate of potash (MOP)/Potassium chloride (KCl)	95.0	0	kg/ha
Unspecific fertilizer as nitrogen (N)	26.6	0	kg/ha
Unspecific fertilizer as phosphorus pentoxide (P <sub>2</sub> O <sub>5</sub> )	18.3	0	kg/ha
Organic fertilizer—livestock manure (1% N, 0.5% P <sub>2</sub> O <sub>5</sub> )	0	1,500	kg/ha
Organic fertilizer—compost (2.5% N, 1% P <sub>2</sub> O <sub>5</sub> )	0	250	kg/ha
<b>Pesticides</b>			
Glyphosate	3.9	0	kg a.i./ha
Acetochlor	1.1	0	kg a.i./ha
s-Metolachlor	1.1	0	kg a.i./ha
Acephate	0.6	0	kg a.i./ha
Oxamyl	0.4	0	kg a.i./ha
Diclotophos	0.34	0	kg a.i./ha
Tribufos	0.69	0	kg a.i./ha
Sodium chlorate	0.7	0	kg a.i./ha
Thidiazuron	0.1	0	kg a.i./ha
Azoxystrobin	0.1	0	kg a.i./ha
Pyraclostrobin	0.2	0	kg a.i./ha
Tetraconazole	0.2	0	kg a.i./ha
<b>Irrigation</b>			

Parameter	Scenario 1	Scenario 2	Unit
Amount of irrigation water applied	2,537		m <sup>3</sup> /ha
Electricity use for irrigation	445		MJ/ha
Diesel use for irrigation	28.4		l/ha
<b>Machinery</b>			
Diesel	60		l/ha
<b>Seeds</b>			
Seeds	12		kg/ha
<b>Additional considerations</b>			
Crop residues (cotton stalks) left on the field			

Where requested by the model providers, the following distribution of tillage regimes was specified: 50% no tillage, 25% conservation or reduced tillage, and 25% conventional or full tillage.

## Results template, impact assessment categories and contribution analysis

To ensure consistency and comparability across models, a standardized results template was developed and provided to all participating model providers. The template specified the impact assessment methods, units, and contribution analysis to report the results. Each model provider reported impact results per kilogram of seed cotton at field border for the predefined impact categories listed in Table 3.

**Table 3: Impact assessment methods considered in the comparison**

Impact category	Method
Climate change (global warming potential)	EF 3.1 (IPCC AR6 GWP100, excluding biogenic CO <sub>2</sub> )
Eutrophication	CML 2016
Abiotic resource depletion (fossil)	CML 2016
Water resources depletion	EF 3.1 (water use, based on AWARE factors)
Ecotoxicity	EF 3.1 (ecotoxicity)
Acidification potential	EF 3.1

The selected impact categories and methods were based on those used in the Higg MSI within the context of Cascale's *Cotton Methodology* (Cascale, 2024) and reflect the main impact methods assessed in Textile Exchange's current cotton LCA study. Applying CML 2016 for eutrophication has the advantage of integrating different nutrient pathways into a single indicator, which facilitates direct comparison between models (in contrast to the EF 3.1 eutrophication methods

that consist of several indicators). Acidification potential was added to the set of Higg MSI impact categories due to its relevance for scenarios involving organic fertilizer application.<sup>2</sup>

To enable a detailed understanding of where potential differences in results originate, a predefined contribution analysis framework was provided to all model providers, as specified in Table 4.

**Table 4: Contribution analysis considered in the comparison**

Contribution	Definition
Crop protection	Emissions related to production and application of crop protection agents.
Field emissions	Emissions from agricultural soil related to fertilizer application, crop residues and soil erosion.
Irrigation	Impacts including water consumption for irrigation, energy consumption from pumps, impacts of provision of energy and related combustion emissions (in case of diesel pumps).
Land use change	Carbon emissions related to the conversion of forest (or other land use type) to agricultural land, if applicable (model providers were invited to use their own tools or estimates if available).
Machinery	Emissions from tractor use and provision of fuel.
Fertilizer production	Emissions related to fertilizer production.
Transport	Emissions related to transport of inputs to farm.

In addition to reporting the results, model providers were asked to submit a summary document describing the methodology and model used. The information requested is listed below. An overview of the information provided by each model provider is available as supplementary material (see Annex A2).

- Model name and version, along with software used
- Availability of model documentation (publicly accessible, with link if applicable)
- Level of validation or third-party certification of the model
- Source of background datasets (fertilizers, pesticides, fuel, electricity; including database name, year, and version number)
- Consideration of biogenic carbon uptake in the product (optional, included, excluded, or accounting for delayed emissions)
- Emission modeling method: N<sub>2</sub>O
- Emission modeling method: NH<sub>3</sub>

<sup>2</sup> The choice of impact assessment methods is not discussed further in this study. However, it should be noted that additional variability in results can also arise from the selection and application of life cycle impact assessment methods. While it is generally understood that only results calculated using the same impact assessment method and characterization factors are directly comparable, confusion can occur in practice due to differences in method versions or updates to characterization factors. Typical examples include the use of different global warming characterization factor sets (for example, different IPCC assessment report versions) or the misinterpretation of indicators as being comparable when they are based on modified methods or use different units (for example, USEtox versus EF 3.1 freshwater ecotoxicity).

- Emission modeling method: NO<sub>3</sub>
- Emission modeling method: phosphorus emissions
- Additional comments or notes

## Results generation and review

Each participating model provider independently generated initial results based on the standardized input dataset and the defined impact assessment framework. The submitted results underwent individual review, including benchmarking and plausibility checks, to verify that the input data had been entered correctly and that central assumptions made by the model providers were consistent with the objectives and scope of the project.

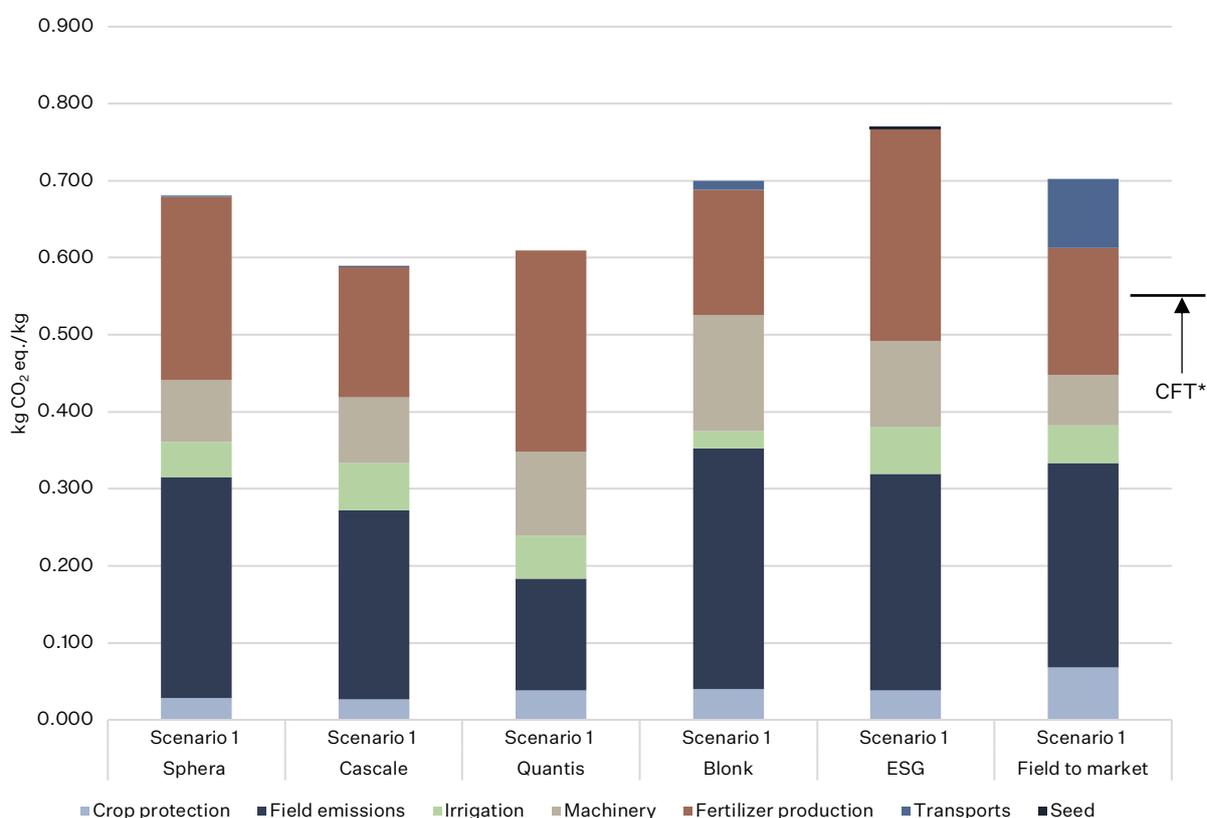
Following the individual review phase, a joint review was conducted with all model providers. During the joint review phase, all model providers had the opportunity to examine their results in comparison with those of the other participants and to provide comments or explanations where differences were observed. This collaborative process allowed for methodological assumptions to be clarified and reasons for variation between models to be documented transparently.

# Results

This section presents the results of the model comparison exercise. It begins with a detailed comparison of climate change impact assessment results generated by the participating model providers. Climate change was selected as the illustrative example because it represents the most widely applied and comparable indicator across agricultural LCA studies, and it was the only impact category for which all model providers reported complete results. This is followed by a summary of the observed ranges across all impact categories. In addition, a brief overview of selected supplementary scenarios provided by individual model providers is presented. All numerical results, including the complete set of impact categories and detailed model outputs, are available in the supplementary material (see Annex A3). All results are presented per kilogram of seed cotton at field border, excluding ginning and post-harvest processes.

## Detailed comparison of impacts on climate change results

Figure 2 shows the comparison of impacts on climate change for scenario 1.



**Figure 2: Comparison of impacts on climate change—scenario 1**

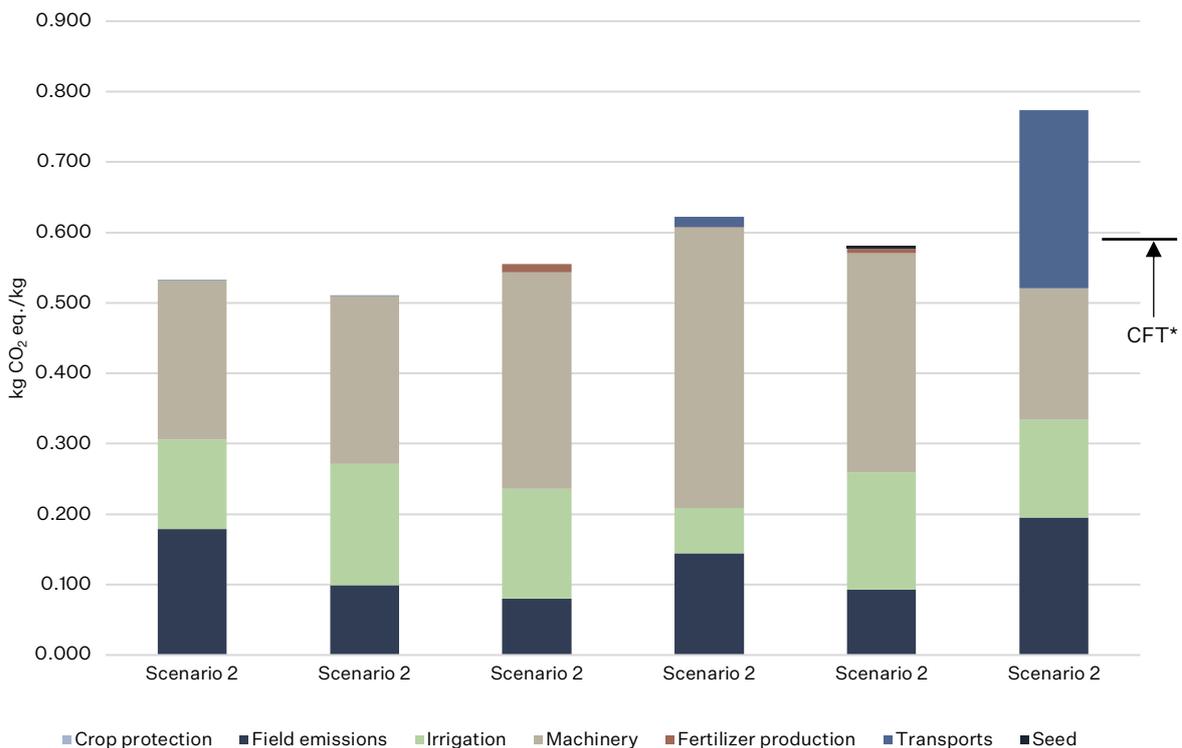
\* The predefined contribution analysis was not available for the Cool Farm Tool (CFT); only total impact results are shown.

For scenario 1, which is based on mineral fertilizer application, field emissions and fertilizer production emerge as clear hotspots, although their relative contributions vary among model providers. In the case of field emissions, nitrous oxide (N<sub>2</sub>O) modeling choices are the primary source of variation, largely driven by the selection of emission factors. Most model providers base their calculations on the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories, which offer several emission factor options, including

aggregated values as well as disaggregated factors for wet and dry climates.<sup>3</sup> The aggregated emission factor typically produces mid-range estimates, while the disaggregated dry-climate factor (which can be applicable due to the climate classification of Texas) yields lower results. Importantly, the classification into wet or dry conditions affects not only direct N<sub>2</sub>O emissions but also the emission factor used for nitrate leaching (and therefore also strongly influences eutrophication results, see section 3.2). Under the aggregated and wet scenarios, a fixed value of 24% of applied nitrogen is assumed to leach as nitrate. In contrast, the dry scenario assumes an emission factor of 0% for nitrate leaching.

Fertilizer production datasets also exert a clear influence, depending on the background database and degree of regionalization applied. Differences are observed not only when different background databases were used, such as ecoinvent and Sphera MLC, but also when model providers were using the same background database. This is likely because model providers use different datasets or dataset proxies to account for the respective fertilizer types. Use of different versions of databases is also likely to contribute to differences (for example, for model providers that use ecoinvent databases, the reported use version ranges from 3.8 to 3.11).

Irrigation energy use and machinery-related impacts vary to some extent across models. Since energy consumption and fuel use values were provided to all model providers, any observed differences in results can be attributed to variations in the combustion emission profiles or differences in the underlying background databases, although these categories relate to areas where background datasets are expected to be well aligned.



**Figure 3: Comparison of impacts on climate change—scenario 2**

\* The predefined contribution analysis was not available for the Cool Farm Tool (CFT); only total impact results are shown.

<sup>3</sup> Please refer to the documentation provided in the supplementary material (Annex A2) for an overview of the emission factors used per model provider.

Figure 3 presents the comparison of climate change impacts for scenario 2, which is based on organic fertilizer application. Due to the dataset structure (see Table 2), where energy and fuel use per hectare are similar to those in scenario 1 but yields are lower, the resulting emission profile is scaled accordingly, leading to higher impacts from these contributors per kilogram of harvested product. All model providers appear to apply a consistent approach in treating organic fertilizer inputs as burden-free,<sup>4</sup> resulting in very low or negligible associated impacts from fertilizer provision, with transport as a single exception in one case.<sup>5</sup> At the same time, because a lower amount of nitrogen is applied in the system (both on a per hectare basis and per kilogram of harvested product), the contribution of field emissions is reduced. This effect is specific to climate change impacts and may differ for other impact categories (see Table 5 and the detailed results in Annex A3).

## Summary across impact categories

For each impact category and scenario, the average result across all models was calculated. The minimum and maximum deviations from this average were then assessed and classified as follows:

- **Moderate:** up to +/- 15% divergence
- **Medium:** between +/- 15% and +/-30% divergence
- **Large:** between +/- 30% and +/-50% divergence
- **Very large:** larger than +/- 50% divergence

There are no universally established thresholds for defining what constitutes a small, moderate, or large difference in LCA results. A robust assessment would require statistical testing based on the variability of the input data, which is often not available in LCA studies and was beyond the scope of this study that relies on illustrative data. The indicative ranges applied here are based on expert judgment and prior experience from comparing datasets across different LCI databases. They should not be considered definitive or normative but rather serve to support consistent interpretation of relative differences within this study. Table 5 shows a summary of the observed ranges across all impact categories included in this study.

**Table 5: Summary of the observed ranges across impact categories**

Impact category	Scenario	Mean result (unit)	$\Delta$ min %	$\Delta$ max %	Spread class
Climate change	1	0.68 kg CO <sub>2</sub> -eq/kg	-13%	+14%	Moderate
	2	0.60 kg CO <sub>2</sub> -eq/kg	-14%	+30%	Medium

<sup>4</sup> There is ongoing debate regarding whether organic fertilizer should be classified as a waste product without associated environmental burdens from animal husbandry, or as a valuable co-product of milk and meat production, thereby carrying an environmental burden. The LEAP guidelines published by the Food and Agriculture Organization (FAO, 2016) provide allocation guidance for manure exported off farm, distinguishing between "co-product," "waste," and "residual" classifications. Most LCA studies and models currently treat organic fertilizers as "residual," meaning they enter plant production systems without any upstream environmental burdens from animal production but still account for emissions related to their field application. This approach is also currently used in Cascale's *Cotton Methodology* (Cascale, 2024).

<sup>5</sup> Different assumptions can apply regarding means of transport, transport distance of organic fertilizer to the field, and the consideration of return trips.

Impact category	Scenario	Mean result (unit)	$\Delta$ min %	$\Delta$ max %	Spread class
<b>(IPCC AR6 GWP100, excluding biogenic CO<sub>2</sub>)</b>					
<b>Acidification (EF 3.1)</b>	1	0.0165 mol H <sup>+</sup> -eq/kg	-36%	+25 %	Large
	2	0.0183 mol H <sup>+</sup> -eq/kg	-31%	+49%	Large
<b>Eutrophication (CML 2016)</b>	1	0.015 kg PO <sub>4</sub> <sup>3-</sup> -eq/kg	-93%	+225%	Very large
	2	0.0096 kg PO <sub>4</sub> <sup>3-</sup> -eq/kg	-74%	+82%	Very large
<b>Abiotic resource depletion, fossil (CML 2016)</b>	1	5.84 MJ/kg	-8 %	+10%	Moderate
	2	5.62 MJ/kg	-20%	+13%	Medium
<b>Water resources depletion (Water Use, EF 3.1)</b>	1	27.1 m <sup>3</sup> -eq/kg	-28%	+15%	Medium
	2	64.6 m <sup>3</sup> -eq/kg	-53%	+36%	Very large
<b>Ecotoxicity, freshwater (EF 3.1)</b>	1	94.0 CTUe/kg	-28%	+24%	Medium
	2	3.98 CTUe/kg	-35%	+61%	Very large

The contribution profiles for climate change have been discussed in detail in section 3.1. Overall, results for climate change impacts show moderate variation in scenario 1 and medium variation in scenario 2. Additional context to explain variation in the other impact categories is provided below.

Results for acidification are mainly driven by field emissions. Therefore, the choice of emission modeling method has a strong influence, similar to what is observed for climate change (see previous section, it should also be noted that some model providers use a Tier 2 approach according to the IPCC classification with even more granular emission factors). Differences also occur in the treatment of organic fertilizer emissions, which are typically associated with higher ammonia emission factors and consequently greater acidification impacts. The relative comparison between scenario 1 (mineral fertilizer-based) and scenario 2 (organic fertilizer-based) varies substantially among model providers. Although the results are of the same order of magnitude and show general consistency in terms of hotspots and contribution patterns, the overall range of results must be classified as large.

Benchmarking eutrophication results is particularly challenging due to the multiple emission pathways involved, including nitrate leaching, phosphorus losses, soil erosion, and surface runoff. The estimation of these pathways requires numerous assumptions to be made, and most available methods provide only approximate representations, which introduces substantial uncertainty and potential for divergence. As noted above, the IPCC disaggregated “dry” approach assumes no nitrate leaching, leading to notably lower eutrophication results than the “wet” or “aggregated” approach. Consequently, large variation among models and approaches was anticipated and is clearly reflected in the outcomes. The overall range of results for eutrophication must therefore be classified as very large. There is also no consistent pattern across model providers regarding whether scenario 1 (mineral fertilizer-based, N surplus) or scenario 2 (organic fertilizer-based, N deficit) yields higher eutrophication impacts.

Abiotic depletion potential (ADP) refers to the potential environmental impact associated with the extraction of non-renewable natural resources, such as minerals and fossil fuels. Consequently, ADP results are exclusively driven by background processes, such as fertilizer production and energy provision. Despite the differences observed in climate change impacts across background databases, results for ADP show a good degree of consistency among model providers. The overall spread is moderate for scenario 1 and medium for scenario 2.

The water use impact category in the EF 3.1 impact assessment methods corresponds to water resources depletion, which is calculated by multiplying reported irrigation water consumption by a characterization factor (available water remaining (AWARE)). Since identical irrigation volumes were provided to all model providers, any differences in results should only stem from the selection of characterization factors. Although not explicitly assessed in the documentation request, potential sources of variation include the use of unspecified versus agriculture-specific factors, the choice between US average and Texas subnational factors, and differences in the AWARE version applied. Overall, results show medium variation in scenario 1 and very large variation in scenario 2 (the broader range observed in scenario 2 reflects the higher irrigation water consumption per kg harvested product in this scenario, which amplifies the effect of differing characterization factors).

To assess ecotoxicity impacts, all model providers used the same list of active ingredients for pesticide application. Differences between models can therefore arise from missing active ingredients that require the use of proxies or generic pesticide datasets, as well as from differences in emission modeling, regarding the partitioning of emissions to water, air, or soil. The EF 3.1 characterization factors for freshwater ecotoxicity span several orders of magnitude, meaning that the use of a single proxy substance can substantially influence results. Consequently, scenario 1 shows a medium range of variation across models. It should be noted that these results are based on a relatively small list of active ingredients and therefore represent an optimistic estimate. In many real-world LCA applications, more active ingredients are present, along with their associated data gaps, which typically increases the potential for variability across datasets. In scenario 2, no pesticide application is included, resulting in very low absolute impact values, which are primarily influenced by background processes and fuel combustion. The relative range of results is therefore very large, but the absolute differences remain small in magnitude.

## Additional scenarios provided by the model providers

### **Inclusion of land use change (LUC)**

Land use change (LUC) in LCA studies refers to greenhouse gas emissions associated with the conversion of land from one use to another. This includes direct changes, such as the conversion of forest to cropland, and indirect effects caused by market-driven land expansion. LCA studies usually focus on direct LUC.<sup>6</sup> In this comparison exercise, model providers were invited to calculate direct LUC emissions using their default methodologies and underlying data sources.<sup>7</sup> Most providers reported no land use change impacts for cotton cultivation in the US, reflecting the assumption of stable or already converted agricultural land. Two providers reported land use change emissions, including contributions from peat oxidation, which indicates that their underlying datasets or modeling assumptions include region-specific carbon stock changes, as shown in Table 6.

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<sup>6</sup> A detailed discussion about LUC definitions, different accounting approaches and the consideration of LUC in different standards and guidelines is provided in Textile Exchange's *Biogenic Carbon Guideline* (Textile Exchange, 2024).

<sup>7</sup> A small contribution from land use change emissions is embedded in all background datasets. Most data providers did not report these emissions under land use change as a separate category because of its minor relevance and instead included these contributions within the respective provisioning impacts. Therefore, they considered the land use change category as referring to land use change in the foreground system, that is, on farm.

**Table 6: Climate change impacts including LUC and peat oxidation**

Contribution	Quantis including LUC		Blonk including LUC	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
	kg CO <sub>2</sub> -eq/kg			
Baseline emissions	0.610	0.555	0.700	0.622
Land use change	0.133	0.372	0.000	0.000
Peat oxidation	0.000	0.000	0.022	0.064
<b>Total</b>	<b>0.742</b>	<b>0.927</b>	<b>0.723</b>	<b>0.687</b>
Increase due to consideration of LUC and peat oxidation	22%	67%	3%	10%

Reported increases ranged from approximately 3% to approximately 67%,<sup>8</sup> depending on whether peat emissions and LUC datasets were included. It should be noted that these results reflect a relatively low LUC risk context, such as the US. In production regions where LUC or peat-related emissions constitute larger hotspots, the magnitude of these differences would likely be higher.

### Additional scenarios

Field to Market usually accounts for soil carbon sequestration or emissions in their carbon footprint assessments. These assessments are usually done at farm level, and their standard application involves the use of a full ecosystem model to quantify soil carbon stock changes based on detailed, field-specific input data (Tier 3 model according to the IPCC classification). For the purpose of this comparison exercise, however, they estimated soil carbon stock changes using the generic information provided in the test dataset. The resulting values should therefore be regarded as indicative only, representing a potential or exemplary change in soil carbon stocks rather than a specific result. It should also be noted that the results were not reviewed in detail under the scope of this comparison. The results provided by Field to Market indicated an additional emission of 0.5 kg CO<sub>2</sub> eq./kg harvested product for scenario 1 and 1.3 kg CO<sub>2</sub> eq./kg for scenario 2. These values correspond to an increase in impact on climate change of about 67% and 171%, respectively, relative to the baseline that excludes soil carbon stock changes.

Important considerations related to uncertainty in modeling soil carbon stock changes and how this is addressed across different guidelines and standards are discussed in depth in Textile Exchange's *Biogenic Carbon Guideline* (Textile Exchange, 2024) and Textile Exchange's *Regenerative Agriculture Landscape Analysis* (Textile Exchange, 2022). These aspects are therefore not elaborated on further in this section.

Sphera provided an additional scenario that derives leaching emissions from the nitrogen balance of the cultivation system, calculated as total nitrogen inputs minus nitrogen outputs, as suggested in the Product Environmental Footprint (PEF) method (European Commission, 2021). In this approach, any negative nitrogen balance is compensated through the addition of fertilizer inputs

<sup>8</sup> The large difference between scenarios 1 and 2 in this case can be explained by the fact that land use change emissions are calculated on a per hectare basis and are therefore identical for scenario 1 and scenario 2 when expressed per unit area. When results are converted to a per kilogram functional unit, the lower yield in scenario 2 amplifies the contribution of the area-based land use change emissions, resulting in a proportionally higher climate change intensity per kilogram of harvested product.

to close the balance. This modeling option is described in detail in a scenario assessment in Textile Exchange's cotton LCA and is therefore not further elaborated in this report.

# Discussion

## Data entry and review

All model providers updated their results after an initial individual results review and outlier screening. This process helped clarify assumptions and resolve issues in data entry, which led to improved alignment across models. The purpose of this step was to avoid misunderstandings or unintended errors without prescribing methodological choices. More directive interventions, such as mandating specific emission factors or background datasets, would likely have produced even closer agreement but would not have been consistent with the objective of the exercise, which was to allow each model provider to process the dataset using their default settings (see also limitations). The outcomes further suggest that detailed benchmarking at the contribution analysis level can be a valuable component of quality assurance and critical review in LCA studies. It should also be noted that in real-world cases, data collection and aggregation introduce additional variance in LCA results, and these sources of variability were not assessed in this study.

## Variation in results

Climate change results showed moderate to medium ranges, while all models identified the same main hotspots. Nevertheless, the observed variation has a substantial effect on interpretation. Even under optimistic assumptions, many farming interventions discussed in the literature that aim to reduce greenhouse gas emissions are generally expected to achieve reductions by approximately 30% (without accounting for carbon removals).<sup>9</sup> This implies that emission reductions can only be assessed and reported reliably within the same assessment system.

**Comparisons across different models or studies are not meaningful because the variation introduced by the use of different models can be larger than the magnitude of the claimed difference.**

Additional uncertainty is introduced when specific aspects such as land use change emissions or potential emissions from soil carbon stock changes are included, as illustrated in the supplementary scenarios. These contributions can be highly relevant, and the assumptions applied in these areas can have a large influence on total results and the corresponding hotspot analysis.

The results for eutrophication give rise to major concerns regarding the robustness of this impact category. The sources of variation are understandable, since the category includes multiple emission pathways that are difficult to quantify and that require very generic assumptions. However, the fact that variation is so large and that no consistent pattern emerges despite the distinct profiles of fertilizer types, yield differences, and nitrogen balances across the test scenarios indicates that this impact category provides a limited basis for drawing meaningful conclusions, at least as applied in the context of this study. Considering that eutrophication is commonly used in agricultural LCA studies and is included in the Higg MSI set of impact categories, this clearly calls for stronger methodological alignment.

Overall, the considerations around variation in climate change impacts are even more pertinent for the other impact categories. In most cases, the variation between models is so large that meaningful comparison of alternative scenarios is only possible when the same model and the same underlying assumptions are applied. It should also be noted that these results only cover the

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<sup>9</sup> Recent examples include intervention-based emission reduction results reported by CottonConnect (CottonConnect, 2025) and BASF (BASF, 2024).

cradle-to-field-gate system boundary and that each downstream processing step will introduce additional variation.

## Limitations

Some limitations of the study should also be acknowledged. The exercise followed a pragmatic and collaborative approach and included only a limited set of models. No statistical analysis was conducted, and the reported ranges are interpreted qualitatively. Therefore, they may be influenced by subjective judgment. Not all underlying methods and modeling assumptions were reviewed in detail, so some black box elements remain in the interpretation of the results. In addition, as noted above, there is uncertainty regarding the degree of intervention and alignment applied during the process. Although the intention was that model providers run their models as they are, some guidance was introduced to reduce misunderstandings and correct evident inconsistencies. This introduces uncertainty about the extent to which the results fully reflect independent application of each model.

# Conclusions

This study represents a rare precompetitive collaboration in which multiple model and database providers contributed to a shared benchmarking exercise. The collective effort enabled a transparent comparison of outcomes based on identical inventory data and provides an improved understanding of how and why the use of different LCA models can lead to variation in results. In particular, the choice of emission factors, characterization factors, and background data was identified as an important contributor to the observed variation.

There are valid reasons why model providers apply different methodological assumptions in their modeling, for example the use of aggregated versus disaggregated IPCC emission factors. The aim of this study is not to judge the quality or robustness of these approaches, but to illustrate how such methodological choices influence the resulting impact indicators and to provide readers with additional context to support the interpretation of agricultural LCA results. Since there is no universally accepted methodological consensus, none of the approaches can be considered superior and the most appropriate choice is likely case specific.

The exercise indicates that detailed inventory review and benchmarking, including reproducibility checks as part of the quality assurance and/or critical review process, can help avoid distortions that stem from misinterpreting input data or from simple data entry mistakes.

The findings reinforce messages from recent publications on the integrity of LCA results in the fashion, textile, and apparel industry, for example Textile Exchange's position paper *Ensuring Integrity in the Use of Life Cycle Assessment* (Textile Exchange, 2025), Better Cotton Initiative's *From data to impact: How to get cotton LCAs right* (EarthShift Global, 2025), and Cascale's *Cotton Methodology* (Cascale, 2024). These publications highlight that results from different studies or databases should not be compared. The present study illustrates why this caution is necessary. Even with identical inventory data, the minimum and maximum values differed by up to -14% and +30% from the average of all models (for scenario 2). Such variation makes cross-study or cross-database comparisons highly unreliable. This also reflects the rationale behind the requirements in ISO standards such as ISO 14040 and ISO 14067, which specify that comparative assertions are only permissible when it can be ensured that the compared results are based on consistent methodological choices, data sources, and data quality.

Industry-aligned modeling guidelines can support improved consistency of LCA results. The study demonstrates that approaches such as the cotton LCA methodology developed under the guidance of Cascale in collaboration with industry experts and stakeholders (Cascale, 2024) can help to provide better-aligned and more reproducible outcomes. This methodology generates cotton datasets by running inventory data through a single harmonized calculation framework rather than sourcing life cycle impact assessment (LCIA) results from different models or databases, as was the case for earlier cotton datasets in the Higg MSI.

Based on the findings, several focus areas for further alignment emerge. As an example, a better alignment on the use of IPCC emission factors could be discussed among model and data providers. Different emission factor sets may be appropriate for different study scopes, although the aggregated average factors are likely preferable when comparability and consistency are priorities. As a second example, the eutrophication impact category requires more attention. The large variation and low reproducibility observed in this study indicate that methodological alignment is essential if the category is to be used for any meaningful interpretation. Some relevant analysis and recommendations are available in recently published recommendations to update the PEF method (Wolf, Thylmann, De Weert, Salim, & Bosco, 2025) and can serve as a starting point for further work in this regard.

As mentioned above, data collection, aggregation, and preprocessing introduce additional variability in LCA results that was not assessed in this study. This omission reflects the fact that input data quality is already a central focus of most LCA studies and was not the primary objective of the present assessment, which focused on methodological variation at the modeling stage. Nevertheless, alignment, transparency, and reproducibility of data collection and aggregation procedures are equally critical for ensuring robust and interpretable results.

Therefore, future studies should investigate whether systematic variation introduced upstream of the modeling process can be explicitly addressed. A useful follow-up assessment could extend the scope of the present approach by providing only data sources, or raw primary data from data collection, rather than finalized life cycle inventory inputs. Such an approach would allow investigation into how differences in data interpretation, aggregation, and preprocessing across practitioners or model providers influence LCA outcomes, and would further support efforts toward increased transparency and reproducibility in agricultural LCA.

To close, it is worth reiterating the value of the precompetitive collaboration. Exercises such as this provide a structured environment to identify methodological challenges in the generation of agricultural LCA results and to explore where further alignment would be most beneficial for improving the robustness and reproducibility of results. Ultimately, these exercises help to increase transparency and contribute to a better understanding of the use of LCA data and results.

# Acknowledgements

The following individuals contributed to the working group and supported the coordination, technical review, and implementation of this model comparison exercise through their expertise and active participation:

Textile Exchange: Francesca Sartor, Eleni Thrasyvoulou, Felicity Clarke

Blonk: Elena Koukouna

Cascale: Melissa O de León, Joel Mertens, Quinten Geleijnse

Cotton Incorporated: Jesse Daystar

EarthShift Global: Juanita Barrera, Lise Laurin

Field to Market: Eric Coronel

Worldly: Paula Bernstein, Sarah Mahmassani

Quantis: Tereza Levova, Josephine Pratiwi

Sphera: Angelica Mendoza Beltran, Verena Margraf, Raveen Johnson

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## Annex A: Supplementary material

- **Annex A1:** Inventory Test Dataset [[Link](#)]
- **Annex A2:** Model Documentation [[Link](#)]
- **Annex A3:** Detailed Results [[Link](#)]

# Annex B: Glossary

## **Abiotic depletion potential**

Abiotic depletion potential (ADP) is a measure for the use of non-renewable energy carriers, comparable to the cumulative energy demand (CED) of fossil fuels.

## **Acidification potential**

A measure of emissions that cause acidifying effects to the environment. The acidification potential (AP) is a measure of a molecule's capacity to increase the hydrogen ion (H<sup>+</sup>) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline, and the deterioration of building materials.

## **Aggregated vs disaggregated emission factors**

An alternative emission factor sets where aggregated factors represent broader averages, while disaggregated factors represent more specific conditions (for example, climate-specific factors)

## **Allocation**

Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems (ISO 14040:2006, section 3.17)

## **Background data (background system)**

Upstream processes represented by secondary LCI datasets, for example, production of fertilizers, fuels, and electricity from background databases.

## **Characterization factor**

A factor used in LCIA to convert an elementary flow (for example, CH<sub>4</sub> to air) into an impact indicator result (for example, kg CO<sub>2</sub> eq.).

## **Climate change (global warming potential)**

A measure of greenhouse gas emissions, such as CO<sub>2</sub> and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare.

## **Comparative assertion**

An environmental claim of superiority or equivalence versus another product system that performs the same function, subject to stricter ISO requirements when disclosed publicly.

## **Contribution analysis**

A structured breakdown of total impacts into contributing life cycle stages or process groups (for example, field emissions, fertilizer production, irrigation).

## **Ecotoxicity**

A measure of toxic emissions that are directly harmful to the health of the environment.

**Emission factor**

A coefficient used to estimate emissions from an activity level (for example, kg N<sub>2</sub>O emitted per kg N applied), often drawn from IPCC or other guidance.

**Eutrophication**

Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems, increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.

**Foreground system**

The processes modeled with primary focus and explicit activity data, here mainly on farm operations and direct field emission modeling.

**Functional unit**

Quantified performance of a product system for use as a reference unit (ISO 14040:2006, section 3.20).

**Impact assessment (life cycle impact assessment, LCIA)**

Phase of Life Cycle Assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product (ISO 14040:2006, section 3.4).

**Inventory data (life cycle inventory, LCI)**

Phase of Life Cycle Assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle (ISO 14040:2006, section 3.3).

**Intergovernmental Panel on Climate Change (IPCC) tiers (Tier 1, 2, 3)**

Levels of methodological complexity and data specificity for emission estimation, with Tier 1 as the most generic and Tier 3 typically the most data intensive and model based.

**Life cycle**

A view of a product system as “consecutive and interlinked stages ... from raw material acquisition or generation from natural resources to final disposal” (ISO 14040:2006, section 3.1). This includes all material and energy inputs as well as emissions to air, land, and water.

**Life Cycle Assessment (LCA)**

Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO 14040:2006, section 3.2). A standardized method to compile and evaluate inputs, outputs, and potential environmental impacts of a product system across its life cycle.

**Model provider**

An organization that develops, maintains, and applies an agricultural LCA model or calculation framework, and that generated results for this study by running the prescribed inventory dataset using its own standard methodologies, assumptions, and background data.

### **Water resources depletion**

An assessment of the potential to deprive other users of water, calculated as blue water consumption multiplied with regional characterization factors (available water remaining (AWARE)). It accounts for the net intake and release of freshwater across the product system, while considering differences in water availability between regions. It should be noted that AWARE is not a direct scarcity metric, but a measure of potential user deprivation.