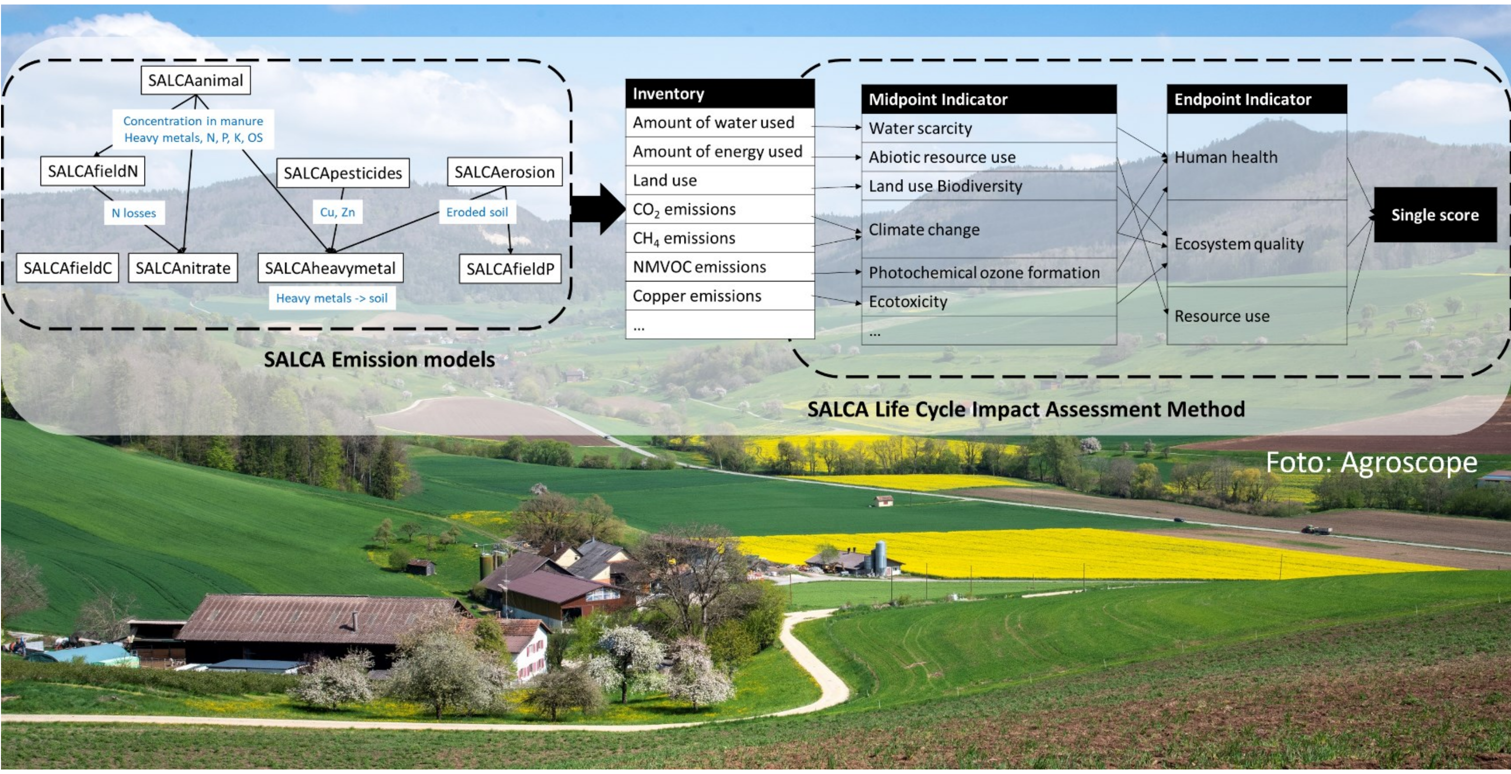
Agroscope Science | No. 183 / 2024



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Recommended impact assessment method within Swiss Agricultural Life Cycle Assessment (SALCA)

v2.01

Authors

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Agroscope

Agroscope good food, healthy environment

Imprint

Publisher	Agroscope Reckenholzstrasse 191 8046 Zürich www.agroscope.ch
Information	melanie.douziech@agroscope.admin.ch
Cover Photo	Gabriela Brändle
Download	www.agroscope.ch/science
Copyright	© Agroscope 2024
ISSN	2296-729X
DOI	https://doi.org/10.34776/as183e

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Summary

Life Cycle Assessment (LCA) is a standardized method for the evaluation of the environmental impacts linked to the life cycle of a product or system. One of the steps in LCA consists in translating the gathered data on resource and material uses, in short the Life Cycle Inventory (LCI), into environmental impacts. For example, expressing the amount of carbon dioxide, methane and nitrous oxide emitted over the life cycle of bread as climate change impact in kg of CO_2-equivalents. This step is called life cycle impact assessment (LCIA). Different impact categories exist besides climate change, such as eutrophication, ecotoxicity, or particulate matter formation. These impact categories can rely on different models depending on the LCIA method used. In fact, scientists are continuously improving existing methods and updating LCIA methods. Carefully reviewing and choosing available LCIA methods is essential to ensure the best estimation of potential environmental impacts estimated with LCA.

The Swiss Agricultural Life Cycle Assessment (SALCA) method was developed specifically for the evaluation of agricultural systems with LCA (Nemecek et al., 2023). It includes guidelines for example for the definition of the system boundaries or functional unit as well as models to estimate emissions linked to agricultural practices. The latest update of the LCIA method in SALCA dates back to 2016 (Roesch et al., 2016). The aim of this report is therefore to present an update of the LCIA method included in SALCA, the SALCA-LCIA v2.01.

One can differentiate different types of indicators in LCIA. Life cycle inventory indicators are directly taken from the quantified resource uses and emissions of the system analysed (=LCI). On the other hand, while midpoint indicators are more directly linked to the LCI than endpoint indicators, which are further down the cause-effect pathway, both use models to estimate the environmental impacts from the LCI. In addition, while a wide range of midpoint impact categories exist, endpoint indicators are typically human health, ecosystem quality, and resource use.

The SALCA LCIA v2.01 regroups 5 life cycle inventory indicators, 12 midpoint indicators sometimes differentiated by environmental compartment, and recommends one method to calculate LCA results at endpoint level in the context of sustainability assessment. The life cycle inventory indicators are renewable and non-renewable energy use, water use, deforestation and land occupation. The midpoint indicators describe soil quality, species loss potential because of land use, climate change impact, eutrophication, ozone depletion, abiotic resource use, water scarcity, acidification, ozone formation, human toxicity, particulate matter and ecotoxicity. The recommended endpoint method is ReCiPe 2016 v1.1 because it allows, next to the quantification of three endpoint impacts (ecosystem quality, human health, resource use), the calculation of a single score using method-specific normalization and weighting sets (Huijbregts et al., 2017). When applying the SALCA-LCIA v2.01 method, all life cycle inventory and midpoint indicators have to be calculated. The goal and scope of the study, the sensitivity of the indicators to changes assessed in the study, the results available in other similar scientific studies all influence which indicators are finally used to derive the main conclusions. The chosen categories need to give a full picture of the environmental impacts of the analysed system. The calculation of impacts at endpoint level can be useful in sustainability assessment studies where a single score for the environmental dimension is compulsory for optimization between the different dimensions of sustainability, but is not part of SALCA for an environmental assessment only.

Further developments in LCIA linked to harmonization efforts or improvements of existing models or for better spatial representativeness will be closely followed and evaluated to potentially update the SALCA-LCIA method presented here.

Zusammenfassung

Ökobilanz (engl. Life Cycle Assessment, LCA) ist eine standardisierte Methode zur Bewertung der Umweltauswirkungen des Lebenszyklus eines Produkts oder Systems. In einem der Schritte einer LCA werden die gesammelten Ressourcen- und Materialverbräuche sowie die Emissionen des analysierten Systems, kurz das Ökoinventar (Life Cycle Inventory, LCI), in Umweltauswirkungen übersetzt. Zum Beispiel werden die Mengen an Kohlendioxid, Methan und Lachgas, die während des Lebenszyklus von Brot emittiert werden, als Auswirkung auf den Klimawandel in kg CO_2-Äquivalenten ausgedrückt. Dieser Schritt wird als Wirkungsabschätzung (Life Cycle Impact Assessment, LCIA) bezeichnet. Um ein breites Spektrum an Umweltwirkungen abzubilden, umfasst die Ökobilanz neben dem Klimawandel noch andere Wirkungskategorien, wie Eutrophierung, Ökotoxizität oder Feinstaubbildung. Je nach verwendeten LCIA-Methoden können diese Wirkungskategorien auf unterschiedlichen Modellen beruhen. Diese Modelle werden nämlich oft auf den neusten Stand der Wissenschaft angepasst. Eine sorgfältige Prüfung und Auswahl der verfügbaren LCIA-Methoden ist deshalb notwendig, um die bestmögliche Schätzung der potenziellen Umweltauswirkungen zu gewährleisten, die mit der Ökobilanz ermittelt werden.

Die Swiss Agricultural Life Cycle Assessment (SALCA)-Methode wurde speziell für die Bewertung von landwirtschaftlichen Systemen mit LCA entwickelt (Nemecek et al., 2023). Sie enthält Richtlinien für die Definition der Systemgrenzen oder der funktionellen Einheit sowie Modelle zur Abschätzung der mit der landwirtschaftlichen Produktion verbundenen Emissionen. Die letzte Aktualisierung der LCIA-Methode in SALCA stammt aus dem Jahr 2016. Ziel dieses Berichts ist es daher, eine Aktualisierung der in SALCA enthaltenen LCIA-Methode, die SALCA-LCIA v2.01, vorzustellen.

Bei LCIA unterscheidet man drei Arten von Indikatoren, nämlich Lebenszyklusinventar-Indikatoren, Midpoint- und Endpoint-Wirkungsindikatoren. Lebenszyklusinventar-Indikatoren werden direkt aus den quantifizierten Ressourcenverbräuchen und Emissionen des analysierten Systems abgeleitet (=Ökoinventar). Midpoint Wirkungsindikatoren sind zwar direkter mit dem Ökoinventar verbunden als Endpoint Indikatoren, die weiter im Ursache-Wirkungs-Pfad liegen, aber beide Indikatoren basieren auf Modellen zur Schätzung der Umweltauswirkungen. Während dem es eine Vielzahl an Midpoint Indikatoren gibt, beziehen sich die Endpoint Indikatoren in der Regel auf die menschliche Gesundheit, die Qualität des Ökosystems und die Ressourcennutzung.

Die SALCA LCIA v2.01 umfasst 5 Lebenszyklusinventar-Indikatoren und 12 Midpoint-Indikatoren, die manchmal nach Umweltkompartiment unterschieden werden, und empfiehlt eine Methode zur Berechnung der LCA-Ergebnisse auf Endpoint Ebene. Die Lebenszyklusinventar-Indikatoren sind erneuerbare und nicht-erneuerbare Energienutzung, Wassernutzung, Abholzung und Landnutzung. Zu den Midpoint-Indikatoren gehören die abiotische Ressourcennutzung, Wasserknappheit, Bodenqualität, Versauerung, der potenzielle Artenverlust durch die Landnutzung, die Auswirkungen des Klimawandels, die Eutrophierung, der Ozonabbau, die Ozonbildung, die Humantoxizität, die Bildung von Feinpartikeln und die Ökotoxizität. Die empfohlene Endpoint-Methode ist ReCiPe 2016 v1.1, da sie neben der Quantifizierung von drei Endpunktauswirkungen (menschliche Gesundheit, Qualität des Ökosystems, Ressourcennutzung) auch die Berechnung eines Gesamtindikators (single score) unter Verwendung methodenspezifischer Normalisierungs- und Gewichtungsfaktoren ermöglicht (Huijbregts et al., 2017). Bei Anwendung der SALCA-LCIA v2.01-Methode müssen alle Lebenszyklusinventar- und Midpoint-Indikatoren berechnet werden. Welche Indikatoren letztendlich zur Ableitung der wichtigsten Schlussfolgerungen verwendet werden bestimmt sich durch das Ziel und den Umfang der Studie, die Sensitivität der Indikatoren gegenüber den in der Studie bewerteten Veränderungen und die in anderen ähnlichen wissenschaftlichen Studien verfügbaren Ergebnisse. Die gewählten Indikatoren müssen ein möglichst vollständiges Bild der Umweltauswirkungen des untersuchten Systems vermitteln. Die Berechnung der Auswirkungen auf Endpoint Ebene kann in Studien nützlich sein, in denen eine Optimierung zwischen verschiedenen Dimensionen erforderlich ist, ist aber nicht für alle Anwendungen von SALCA-LCIA v2.01 vorgesehen.

Weitere Entwicklungen im Bereich der LCIA in Verbindung mit Harmonisierung oder Verbesserungen bestehender Modelle, z. B. für eine bessere räumliche Repräsentativität, werden aufmerksam verfolgt und bewertet, um die hier vorgestellte SALCA-LCIA-Methode bei Bedarf zu aktualisieren.

Résumé

L'analyse du cycle de vie (ACV) est une méthode normalisée d'évaluation des impacts environnementaux liés au cycle de vie d'un produit ou d'un système. L'une des étapes de l'ACV consiste à traduire les données recueillies sur l'utilisation des ressources et des matériaux, en bref l'inventaire du cycle de vie (ICV), en impacts environnementaux. Par exemple, exprimer les quantités de dioxyde de carbone, de méthane et de protoxyde d'azote émises au cours du cycle de vie d'un pain en tant qu'impact sur le changement climatique en kg d'équivalents CO_2. Cette étape est appelée évaluation de l'impact du cycle de vie (Life Cycle Impact Assessment, LCIA en anglais). Outre le changement climatique, il existe d'autres catégories d'impact, telles que l'eutrophisation, l'écotoxicité ou la formation de particules. Ces catégories d'impact peuvent s'appuyer sur différents modèles en fonction de la méthode d'évaluation de l'impact du cycle de vie utilisée. En effet, les scientifiques améliorent constamment les modèles existants et mettent à jour les méthodes LCIA. Il est donc essentiel d'examiner et de choisir avec soin les méthodes d'analyse du cycle de vie disponibles pour garantir la meilleure estimation possible des impacts environnementaux potentiels estimés par ACV.

La méthode suisse d'analyse du cycle de vie agricole (SALCA) a été développée spécifiquement pour l'évaluation des systèmes agricoles à l'aide de l'ACV (Nemecek et al., 2023). Elle comprend des lignes directrices, par exemple pour la définition des limites du système ou de l'unité fonctionnelle, ainsi que des modèles pour estimer les émissions liées aux pratiques agricoles. La dernière mise à jour de la méthode LCIA dans SALCA date de 2016. L'objectif de ce rapport est donc de présenter une mise à jour de la méthode LCIA incluse dans SALCA, la SALCA-LCIA v2.01.

On peut distinguer différents types d'indicateurs dans la méthode LCIA. Les indicateurs de l'inventaire du cycle de vie sont directement déduits des utilisations de ressources et des émissions quantifiées du système analysé (=ICV). Par ailleurs, si les indicateurs de type midpoint sont plus directement liés à l'ICV que les indicateurs de type endpoint, qui se situent plus loin dans la chaîne de causalité, tous deux utilisent des modèles pour estimer les impacts environnementaux de l'ICV. En outre, alors qu'il existe un large éventail de catégories d'impacts midpoints, les indicateurs endpoint sont généralement la santé humaine, la qualité des écosystèmes et l'utilisation des ressources.

Le SALCA LCIA v2.01 regroupe 5 indicateurs d'ICV, 12 indicateurs midpoints parfois différenciés par compartiment environnemental, et recommande une méthode pour calculer les résultats de l'ACV au niveau de l'impact endpoint. Les indicateurs d'inventaire du cycle de vie sont la consommation d'énergie renouvelable et non renouvelable, la consommation d'eau, la déforestation et l'occupation des sols. Les indicateurs midpoint décrivent la qualité des sols, le potentiel de perte d'espèces en raison de l'utilisation des sols, l'impact sur le changement climatique, l'eutrophisation, l'appauvrissement de la couche d'ozone, l'utilisation des ressources abiotiques, l'épuisement des ressources en eau, l'acidification, la formation d'ozone, la toxicité humaine, les particules fines et l'écotoxicité. La méthode d'évaluation recommandée est ReCiPe 2016 v1.1 car elle permet, outre la quantification de trois impacts (santé humaine, qualité des écosystèmes, utilisation des ressources), le calcul d'un score unique en utilisant des ensembles de normalisation et de pondération spécifiques à la méthode (Huijbregts et al., 2017). Lors de l'application de la méthode SALCA-LCIA v2.01, tous les indicateurs de l'inventaire du cycle de vie et midpoint doivent être calculés. L'objectif et l'étendue de l'étude, la sensibilité des indicateurs aux changements évalués dans l'étude, les résultats disponibles dans d'autres études scientifiques similaires sont autant d'éléments qui influencent le choix des indicateurs finalement utilisés pour tirer les principales conclusions. Les catégories choisies doivent donner une image complète des impacts environnementaux du système analysé. Le calcul des impacts au niveau des indicateurs endpoint peut être utile dans les études où l'optimisation entre différentes dimensions est nécessaire, mais n'est pas prévu pour toutes les applications de SALCA-LCIA v2.01.

Les développements ultérieurs des méthodes de LCIA liés aux efforts d'harmonisation ou aux améliorations des modèles existants, pour une meilleure représentativité spatiale, par exemple, seront suivis de près et évalués afin de mettre à jour la méthode SALCA-LCIA présentée ici.

Riassunto

L'analisi del ciclo di vita (in inglese Life Cycle Assessment, LCA) è un metodo standardizzato per valutare l'impatto sull'ambiente del ciclo di vita di un prodotto o di un sistema. Una delle fasi di un LCA consiste nel tradurre i dati raccolti sull'utilizzo delle risorse e dei materiali e sulle emissioni prodotte (input e output), in breve l'inventario del ciclo di vita (Life Cycle Inventory, LCI), in impatti ambientali. Ad esempio, le quantità di biossido di carbonio, metano e protossido d'azoto emessi durante il ciclo di vita del pane sono espresse come impatto sul cambiamento climatico in kg di CO_2 equivalenti. Questa fase è chiamata valutazione dell'impatto del ciclo di vita (Life Cycle Impact Assessment, LCIA). Oltre al cambiamento climatico esistono altre categorie d'impatto, tra cui leutrofizzazione, l'ecotossicità o la formazione di polveri fini. Queste categorie d'impatto possono basarsi su diversi modelli a seconda del metodo LCIA utilizzato. Infatti, gli scienziati migliorano continuamente i modelli esistenti e aggiornano i metodi LCIA. È dunque importante esaminare e scegliere accuratamente i metodi LCIA disponibili per garantire la migliore stima possibile dei potenziali impatti ambientali che vengono determinati con l'LCA.

Il metodo svizzero di analisi del ciclo di vita delle attività agricole (Swiss Agricultural Life Cycle Assessment, SALCA) è stato appositamente sviluppato per valutare i sistemi agricoli con l'LCA (Nemecek et al., 2023). Comprende linee guida, ad esempio per definire i limiti del sistema o l'unità funzionale nonché modelli per stimare le emissioni collegate alle attività agricole. L'ultimo aggiornamento del metodo LCIA in SALCA risale al 2016 (Roesch et al., 2016). L'obiettivo di questo rapporto è dunque quello di presentare un aggiornamento del metodo LCIA contenuto in SALCA, il SALCA-LCIA v2.01.

Nell'LCIA si distinguono tre tipi di indicatori: gli indicatori dell'inventario del ciclo di vita, gli indicatori d'impatto midpoint ed endpoint. Gli indicatori dell'inventario del ciclo di vita derivano direttamente dalle risorse utilizzate e dalle emissioni quantificate per il sistema analizzato (LCI). Gli indicatori midpoint sono più direttamente correlati all'LCI rispetto agli indicatori endpoint, che si situano alla fine della catena causa-effetto, ma entrambi si basano su modelli per stimare gli impatti ambientali derivanti dall'LCI. Inoltre, se esiste un'ampia gamma di categorie d'impatto midpoint, gli indicatori endpoint sono generalmente la salute umana, la qualità dell'ecosistema e l'utilizzo di risorse.

Il SALCA LCIA v2.01 raggruppa 5 indicatori LCI e 12 indicatori midpoint, talora distinti per comparto ambientale, e raccomanda un metodo per calcolare i risultati dell'LCA a livello di impatto endpoint. Gli indicatori dell'inventario del ciclo di vita sono il consumo di energie rinnovabili e non rinnovabili, il consumo idrico, la deforestazione e l'utilizzo del suolo. Gli indicatori midpoint descrivono la qualità dei suoli, la potenziale perdita di biodiversità dovuta all'utilizzo del suolo, l'impatto sul cambiamento climatico, l'eutrofizzazione, l'assottigliamento dello strato di ozono, l'utilizzo delle risorse abiotiche, la scarsità di acqua, l'acidificazione, la formazione di ozono, la tossicità umana, le polveri fini e l'ecotossicità. Il metodo endpoint raccomandato è ReCiPe 2016 v1.1 poiché consente, oltre che di quantificare tre impatti endpoint (qualità degli ecosistemi, salute umana, utilizzo delle risorse), anche di calcolare un singolo indicatore (single score) che utilizza fattori di normalizzazione e di ponderazione specifici al metodo (Huijbregts et al., 2017). Quando si applica il metodo SALCA-LCIA v2.01 devono essere calcolati tutti gli indicatori dell'inventario del ciclo di vita e midpoint. L'obiettivo e la portata dello studio, la sensibilità degli indicatori ai cambiamenti valutati nello studio, i risultati disponibili in altri studi scientifici simili influenzano la scelta degli indicatori utilizzati per trarre le principali conclusioni. Gli indicatori scelti devono dare un quadro completo degli impatti ambientali del sistema analizzato. Il calcolo degli impatti a livello degli indicatori endpoint può essere utile negli studi in cui è necessario ottimizzare le diverse dimensioni della sostenibilità, ma non è previsto per tutte le applicazioni di SALCA-LCIA v2.01.

Gli ulteriori sviluppi dei metodi dell'LCIA legati agli sforzi di armonizzare o migliorare i modelli esistenti, ad esempio per ottenere una migliore rappresentatività spaziale, saranno seguiti con attenzione e valutati per apportare i necessari aggiornamenti al metodo SALCA-LCIA qui presentato.

1 Introduction

Life Cycle Assessment (LCA) is a standardized method for the evaluation of the environmental impacts linked to the life cycle of a product or system (International Standard Organisation (ISO), 2006a, 2006b). LCA is conducted following four distinct steps (1) goal and scope definition, (2) inventory analysis, (3) life cycle impact assessment (LCIA), and (4) interpretation. The process is not linear, iterations between the different steps are possible.

In the goal and scope definition, methodological choices are made, the system boundaries are set, allocation methods chosen and the functional unit of the analysis is defined. The functional unit describes the unit in which the environmental impacts are expressed, for example 1kg of product or 1kWh of electricity. The inventory analysis is the most time-consuming step as data on the resource and material use for all processes found in the life cycle has to be collected. The impact assessment step then translates the emissions and resource uses gathered in the inventory analysis into environmental impacts. For example, at the inventory level, the emissions of methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) related to the life cycle of a product are quantified. In the impact assessment step, these emissions are translated into the climate change impact expressed in kg of CO_2 equivalents per kg of product. Finally, in the interpretation step, the results are interpreted and the entire LCA study is reflected upon. The consequences of the methodological choices are also evaluated.

Despite its standardization, its detailed implementation is not prescribed, and a lot of research is ongoing for each step of LCA. Initiatives exist to develop standards for the application of LCA to specific products and so ensure the comparability of their results (European Commission, 2018). Emission models are also continuously developed and improved. Research is also ongoing in the field of impact assessment modelling where new impact categories are continuously developed (Woods et al., 2021) and existing ones improved. The Joint Research Center published a comprehensive overview of available methods in 2011 (EC-JRC-IES, 2011). Since then, several methods have been updated and new recommendations and global approaches have been proposed (Life Cycle Initiative, 2022; Verones et al., 2020).

The Swiss Agricultural Life Cycle Assessment (SALCA) method was developed specifically for the evaluation with LCA of agricultural systems (Nemecek et al., 2023). It includes guidelines for the definition of the system boundaries, functional unit, allocation methods, models to estimate emissions linked to agricultural practices, calculation tools, impact assessment methods and concepts for analysis, interpretation and communication. The emission models for nutrients, pesticides and more as well as impact assessment methods for biodiversity and soil quality are presented by Nemecek et al. (2023). The latest update of the impact assessment methods used in SALCA dates back to 2016 (Roesch et al., 2016). The aim of this report is therefore to present the updated impact categories to be included in the latest SALCA method as presented in Nemecek et al. (2023).

Spatially differentiating impact categories to account for regional differences can, in some cases, greatly influence the conclusions drawn from an LCA study. An example would be the water stress which is geographically variable and thus implies that growing tomatoes in summer in Spain will likely imply more water stress than growing the same tomatoes in summer in Switzerland. This report does however not investigate nor discuss the regionalization of impact categories. Interested readers are directed to the (Roesch et al., 2024).

This report first explains the terminology in life cycle impact assessment. Second, the updated SALCA LCIA method is presented starting with an explanation on how the method was updated. Third, the single impact categories and indicators of the method are presented. Fourth, some guidance is provided about how the SALCA LCIA results should be communicated. Finally, we discuss the possible future updates of the SALCA LCIA method.

2 Life cycle impact assessment

As mentioned in the introduction, life cycle impact assessment (LCIA) is the third phase of life cycle assessment (LCA) and focuses on translating emissions and resource use into environmental impacts. The ISO norm foresees three mandatory steps for LCIA, namely selection, classification and characterization (International Standard Organisation (ISO), 2006a, 2006b). The selection step implies that impact categories, indicators and models are chosen that are most suited to the purpose of the study. In the classification step, the inventory emissions are assigned to each of the chosen impact categories. Characterization of emissions and translation into specific impacts is finally done in the characterization step. LCIA differentiates between two types of impact assessment levels: midpoint and endpoint levels. Midpoint indicators are more directly linked to the inventory and describe the impact in-between the emission and resource use and the final damage, while endpoint indicators are further down the cause-effect chain and aim to describe the final damage caused. Climate change – expressed by the global warming potential – is, for example, a midpoint indicator whereas the potential effect of increased water temperature due to climate change on freshwater species would be characterized in the endpoint indicator “ecosystem quality”. In both cases, characterization models are used to translate the inventory to the characterized impact. All characterization models propose so-called characterization factors (CFs) which allow to translate the amount of resources used or the emissions into the actual impact indicators. For the climate change impact category, for example, CFs are used to translate emissions of specific greenhouse gases like CH_4 or N_2O into CO_2-equivalents based on assumptions related to their radiative forcing or temperature change potential (IPCC, 2021).

While a large variety of midpoint indicators exist, the most common endpoint indicators are human health, ecosystem quality and resource use. Human health is typically expressed in “Disability Adjusted Life Years” (DALYs), ecosystem quality in “Potentially Disappeared Fraction of species” (PDF) and resource use in the additional amount of energy or money needed to extract an additional unit of the resource.

Next to the three mandatory steps of impact assessment, the ISO standard foresees four optional steps, namely normalization, weighting, grouping, and data quality analysis. Grouping (Nemecek et al., 2011) and data quality analysis such as uncertainty and sensitivity analysis will not be explained here. Normalization and weighting are the two other optional steps in impact assessment applied to summarize life cycle impact assessment results in a single score. Normalization implies to put LCIA results into perspective of another system by dividing the indicators results by the ones of a reference system. This reference system can either be a geographical entity (e.g. a country) or an alternative system. Once normalized, the LCIA results can be assigned priorities using weights and a weighted single score can then be calculated. The basis for normalization and weighting are therefore subjective choices and not characterization models. Midpoint and endpoint characterization models are defined within so-called impact assessment methods, together with normalization and weighting sets if available. ReCiPe 2016 (Huijbregts et al., 2017), the Product Environmental Footprint (PEF) (European Commission, 2018), or LC-Impact (Verones et al., 2020) are examples of such impact assessment methods (Roesch et al., 2024).

Figure 1 illustrates the different stages from the inventory analysis over the midpoint and endpoint indicator modelling until the optional calculation of a single score. Figure 1 also describes which steps are typically included in an impact assessment method. Midpoint indicators are found in all impact assessment methods. Some impact assessment methods include indicators from the life cycle inventory stage, e.g. if an appropriate impact assessment model is lacking, or endpoint indicators, and some also propose normalization and weighting sets to get to a single score.

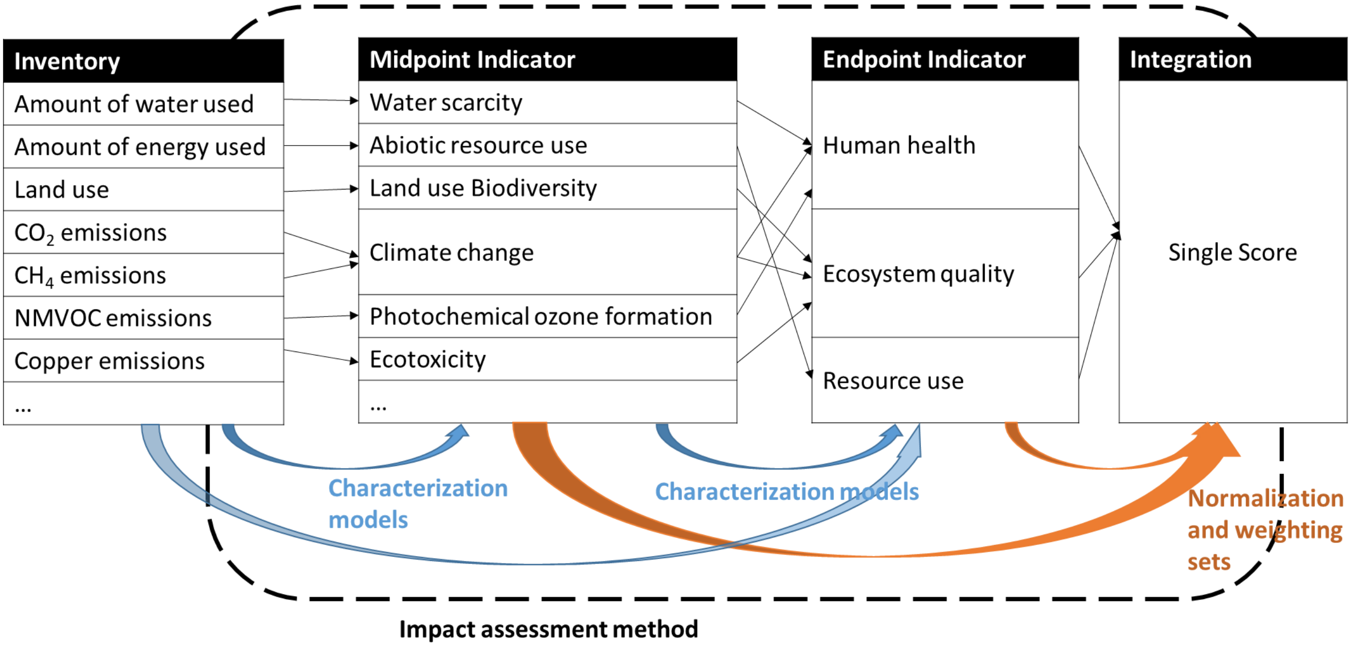

Figure 1: Illustration of the different stages from the life cycle inventory to midpoint, endpoint and single score characterization in life cycle assessment. All elements are defined in an impact assessment method. The characterisation at the midpoint level is mandatory according to ISO-norms, while, inventory- and endpoint indicators as well as the integration in a single score are optional parts. Going directly from the inventory to the endpoint characterization is less common, as shown by the lighter colour of the arrow.

The updated SALCA impact assessment method presented here includes indicators at the inventory, midpoint and endpoint level. The focus is laid on the indicators at inventory and midpoint level. The endpoint indicators are proposed to allow the computation of a single score, useful in projects aiming at optimizing the environmental impact in the broader context of sustainability assessment where the use of a single value is compulsory. Since normalisation and weighting are based on subjective choices and not on characterisation processes derived from environmental sciences, a single score is not part of SALCA for an environmental assessment only. The criteria for including specific methods are explained in Chapter 0.

3 SALCA impact assessment method

3.1 Overview

Table 1 lists the SALCA impact assessment method, referred to as SALCA-LCIA v2.01. Details on the approach to define the SALCA LCIA method and the individual models per impact category are provided in the next chapters. A translation of the impact category names to French and German are provided in the Appendix.

Table 1: List of all impact categories included in the SALCA impact assessment method. The application level describes for which region the indicators can be applied. The differentiation between LCI, midpoint and endpoint refers to the theory of Life Cycle Assessment (see Chapter 2). The column "Adaptations to the method" gives an indication whether the method listed in the column "Method used" was implemented directly or if adaptations were necessary. These adaptations are detailed in Chapter 3.4. For the toxicity categories, all available factors are included (recommended+interim) to ensure a broad coverage of potentially toxic chemicals. The two methods at the bottom of the table in italics are recommended for sensitivity analysis.

Area of Protection	Impact category	Application level	LCI / Midpoint/ Endpoint	Method used	Adaptations to the method
Resource use	Abiotic resource use	Global	Midpoint	CML-IA (baseline), abiotic depletion (elements, ultimate reserve) (CML, 2016)	No
Resource use	Renewable resource use	Global	LCI	Cumulative Energy Demand "Renewable resources" (Frischknecht et al., 2007)	No
Resource use	Non-renewable resource use	Global	LCI	Cumulative Energy Demand "Non-renewable resources" (Frischknecht et al., 2007)	No
Resource use	Water use	Global	LCI	Selected LCI results, additional (SimaPro v1.05)	No
Resource use	Land transformation - Deforestation	Global	LCI	ReCiPe Midpoint (H) v 2008, only natural land transformation (Goedkoop et al., 2009)	Yes
Resource use	Land occupation - Total	Global	LCI	ReCiPe Midpoint (H) v 2008, only Agricultural land occupation, urban land occupation (Goedkoop et al., 2009)	Yes
Resource use	Land occupation - Agricultural	Global	LCI	ReCiPe Midpoint (H) v 2008, only Agricultural land occupation, urban land occupation (Goedkoop et al., 2009)	Yes
Resource use	Land occupation - Non-Agricultural	Global	LCI	ReCiPe Midpoint (H) v 2008, only Agricultural land occupation, urban land occupation (Goedkoop et al., 2009)	Yes
Resource use	Land occupation - Agricultural food	Global	LCI	ReCiPe Midpoint (H) v 2008, only Agricultural land occupation, urban land occupation (Goedkoop et al., 2009)	Yes
Resource use	Land occupation - Agricultural non-food	Global	LCI	ReCiPe Midpoint (H) v 2008, only Agricultural land occupation, urban land occupation (Goedkoop et al., 2009)	Yes
Resource use	Soil quality - LANCA	CH	Midpoint	Environmental Footprint 3.1 (Bassi et al., 2023)	No
Resource use	Soil quality - SALCA	Global	Midpoint	*Implemented in a separate workflow* (Oberholzer et al., 2012)	

Ecosystem quality	Climate change impact GWP100	Global	Midpoint	IPCC GWP100 fossil & LULUC including carbon cycle response (previously referred to as climate carbon feedback), without biogenic carbon dioxide emissions (IPCC, 2021)	Yes
Ecosystem quality	Water scarcity	Global	Midpoint	AWARE (Boulay et al., 2018)	No
Ecosystem quality	Land use - Biodiversity SALCA	CH	Endpoint	*Implemented in a separate workflow* (Jeanneret et al., 2008)	
Ecosystem quality	Land use - Biodiversity - regional species loss potential	Global	Endpoint	Land use biodiversity using only the "PSLreg Occupation" and "PSLreg Transformation" (Chaudhary & Brooks, 2018)	No
Ecosystem quality	Land use - Biodiversity - global species loss potential	Global	Endpoint	Land use biodiversity using only the "PSLglo Occupation" and "PSLglo Transformation" (Chaudhary & Brooks, 2018)	No
Ecosystem quality	Terrestrial acidification	Global	Midpoint	ReCiPe 2016 Midpoint (H) (Huijbregts et al., 2017)	No
Ecosystem quality	Marine eutrophication	Global	Midpoint	ReCiPe 2016 Midpoint (H) (Huijbregts et al., 2017)	No
Ecosystem quality	Freshwater eutrophication	Global	Midpoint	ReCiPe 2016 Midpoint (H) (Huijbregts et al., 2017)	No
Ecosystem quality	Terrestrial eutrophication	Global	Midpoint	Environmental Footprint 3.1 (Bassi et al., 2023)	No
Ecosystem quality	Ozone depletion	Global	Midpoint	ReCiPe 2016 Midpoint (H) (Huijbregts et al., 2017)	No
Ecosystem quality	Freshwater ecotoxicity	Global	Midpoint	USEtox 2 (recommended + interim) v2.12 (USEtox, 2019)	Yes
Ecosystem quality	Terrestrial ecotoxicity	Global	Midpoint	LC-Impact - Terrestrial (PAF m3 day) average pref. | all imp. | 100y (Verones et al., 2020)	Yes
Ecosystem quality and human health	Photochemical Ozone formation	Global	Midpoint	ReCiPe 2016 Midpoint (H) (Huijbregts et al., 2017)	No
Human health	Human toxicity - cancer	Global	Midpoint	USEtox 2 (recommended + interim) v2.12 (USEtox, 2019)	No
Human health	Human toxicity - non-cancer	Global	Midpoint	USEtox 2 (recommended + interim) v2.12 (USEtox, 2019)	Yes
Human health	Particulate matter	Global	Midpoint	Environmental Footprint 3.1 (Bassi et al., 2023)	No
Resource use	*All resource use*	*Global*	*Midpoint*	CEENE v3.0 "all midpoint impacts" (Dewulf et al., 2007)	No
Ecosystem quality	*Climate change impact GTP100*	*Global*	*Midpoint*	IPCC GTP100 fossil and LULUC without biogenic carbon dioxide emission (IPCC, 2021)	Yes

3.2 Approach to this update of the SALCA impact assessment method

The update of the SALCA-LCIA v2.01 relies primarily on literature reviews, on experiences from numerous previous studies on LCA in the agri-food sector and on new impact assessment method developments within the Agroscope Life Cycle Assessment research group.

The first step consisted in choosing the impact categories to include in the SALCA-LCIA v2.01. Starting point was the work of (Roesch et al., 2016), who listed relevant impact categories for the environmental impact assessment of farms. Compared to their work, some methods were added to ensure a broad coverage of environmental aspects relevant when considering agricultural product value chains beyond the scope of the farm. Photochemical ozone formation, ozone depletion, particulate matter formation, and human toxicity were therefore added since they are each driven by different emissions. Photochemical ozone formation is mostly linked to methane emissions and nitrogen oxides, ozone depletion to nitrous oxide, particulate matter (PM) formation to primary PM below 2.5µm, and human toxicity to carcinogenic and non-carcinogenic effects of chemicals on humans. We further limit the number of life cycle inventory (LCI) indicators, meaning direct listing of resources or emission flows related to a specific inventory, to water use, renewable and non-renewable resource use, land transformation and land occupation. Such LCI indicators were used as proxies for missing or immature impact categories, but recent developments in LCIA reduce their need. Including some LCI indicators is still necessary to ensure the comparability of future studies with previous work using alternative impact assessment models, while keeping the number of impact categories limited. An overview of the included LCI-indicators is provided in Chapter 3.3.

The second step consisted in choosing the model to be used for each impact category. We here reviewed recommendations from the International Life Cycle Data system (ILCD) and the Global Life Cycle Impact Assessment Method (GLAM), as well as the impact assessment methods ReCiPe 2016 v1.1, LC-IMPACT, and Environmental Footprint (EF) v3.1 to get a complete picture of available models (Bassi et al., 2023; Huijbregts et al., 2017; Verones et al., 2020). In some cases, specific Google Scholar searches were additionally conducted whenever information on some impact categories was missing from those reports or to check whether more recent methodological developments were available. Only impact assessment models at least partly implemented in LCA software tools such as SimaPro (PRé Sustainability, 2023), were finally retained. In some cases, the models chosen per impact category were adapted to reflect some recent advances in the field. A detailed explanation of the impact assessment models used and potential adaptations thereof are given in Chapter 3.4.

In a third step, we chose the appropriate endpoint impact assessment method to be included in the SALCA-LCIA v2.01. Combining models from different impact assessment methods to estimate endpoint indicators bears the risk of incompatible assumptions and modelling pathways. Our aim was therefore to choose a single endpoint impact assessment method that would (1) ensure a transparent and consistent impact assessment at endpoint level, (2) rely as much as possible on the most recent impact assessment models, (3) be recognized and tested by the scientific community, and (4) allow the calculation of a single score based on the endpoint indicators. We reviewed ReCiPe 2016 v1.1, LC-Impact, Ecological Scarcity 2021, IMPACT World+, Stepwise 2006, EPS2015, and LIME3 (Bulle et al., 2019; FOEN, 2021; Huijbregts et al., 2017; Inaba & Itsubo, 2018; Steen, 2015; Verones et al., 2020; Weidema, 2014). The results of this evaluation are presented in Chapter 3.5.

Finally, we defined a default set of midpoint impact categories that has to be calculated and reported in every project and proposed criteria to help choosing which impact categories to further investigate or discuss in a specific project (Chapter 0). According to the goal of a project, individual impact categories can be selected as “target impacts”. The other impacts still have to be presented as an analysis of trade-offs and synergies.

3.3 Life cycle inventory indicators

The life cycle inventory (LCI) indicators included in the SALCA-LCIA v2.01 are listed in Table 1. The following subchapters describe briefly the models used for each LCI indicator. Including these inventory indicators was important, first, to allow for comparisons with older studies and, second, because they are relatively easy to interpret.

3.3.1 Renewable and non-renewable energy resource use

This impact category describes the amount of renewable and non-renewable energy resources used expressed according to their higher heating value. These two impact categories, expressed in megajoule (MJ), were defined based on the model proposed by (Frischknecht et al., 2007) and describe the total amount of energy embodied in the evaluated system differentiated between renewable and non-renewable. The renewable resource use impact category sums all energy flows from renewable energy resources, namely biomass (including feedstock), hydropower (including potential energy in reservoir), hydrogen, wood, geothermal, wind energy, solar and water from barrage. The non-renewable resource use impact category sums all energy flows from non-renewable resources such as coal, peat, oil, or uranium.

3.3.2 Water use

The “water use” impact category, expressed in m^3, describes the amount of blue water used over the life cycle of the studied system. Blue water describes the water extracted from lakes, rivers, groundwater, ice or snow. This impact category is basically the sum of all water uses in an inventory (Frischknecht et al., 2007). The conversion from a mass flow into volume is based on a 1000 kg/m^3 density.

3.3.3 Land transformation - Deforestation

The “deforestation” indicator, expressed in m^2, included in the SALCA-LCIA v2.01 sums the amount of land transformed from forest into any other type of land use (e.g., crop or urban). The impact category of land transformation from the ReCiPe Midpoint Hierarchist v2008 method was used as starting point for this impact category on deforestation (Goedkoop et al., 2009). Transformation back to forest areas reduce the total of this impact category. All transformation flows were assigned a value of 1 (“transformation from”), respectively -1 (“transformation to”), except for the flow “transformation to/from unspecified” which was assigned a value of (-0.4) according to the assumptions in ReCiPe 2008 (Goedkoop et al., 2009). A list of all transformation flows included in this indicator, based on SimaPro nomenclature, is given in Table 2 in the Appendix.

3.3.4 Land occupation

The land occupation impact category, expressed in m^2 occupied in a year, sums the areas of land occupied for different uses over a one-year period. It is based on the ReCiPe Midpoint Hierarchist v2008 method (Goedkoop et al., 2009). We differentiated between agricultural, non-agricultural, agricultural food and agricultural non-food land occupied through the life cycle of the considered system. Agricultural land occupation includes inventory flows with one of the following keywords, following SimaPro nomenclature: agriculture/agricultural, annual crop, permanent crop, cropland, grassland and pasture. Among the agricultural land occupation, we further differentiated between land occupation suitable for (direct) food production (agricultural peatland, agroforestry, annual crop, permanent crop, and cropland) and land occupation of surfaces that are not suitable for food production (grassland and pasture). Land occupation categories with a general label such as “heterogeneous, agricultural” or “agriculture” were not assigned to food nor non-food land occupation categories.

3.4 Midpoint indicators

The aim of Chapter 3.4 is not to give an overview of all available impact assessment models, but rather to briefly present the model chosen for the SALCA impact assessment method and a justification for it. The midpoint indicators included in the SALCA-LCIA v2.01 are listed in Table 1.

3.4.1 Abiotic resource use

The Abiotic Depletion Potential indicator from the CML impact assessment is used to quantify the amount of mineral resources such as metals, phosphorus or potassium potentially depleted for the life cycle of the studied system (CML, 2016). This method relies on the depletion concept, meaning the reduction of a resource’s stock, and expresses the depletion potential as the ratio of the extraction rate to the size of the natural stock. The size of the natural stock is approximated by the ultimate reserve, meaning the crustal content (Life Cycle Initiative, 2022). Including this impact category allows for a full picture on the use of limited resources linked to the life cycle of a product. It is expressed in kg Antimony (Sb)-equivalent.

3.4.2 Soil Quality – SALCA

This impact category describes the soil quality impact assessment model developed by (Oberholzer et al., 2012) and assesses the influence of agricultural practices on the soil quality of a field. The model computes a single score in a five-step scale ranging from -2 to +2 corresponding to the following five classes: highly unfavorable, unfavorable, neutral, favorable and highly favorable. The model estimates on-farm soil quality with nine measurable soil indicators, three each in the areas of soil physics (plant rooting depth, macropore volume, aggregate stability), soil chemistry (organic carbon content, heavy metal content, organic pollutants) and soil biology (earthworm biomass, microbial biomass, activity of soil microorganisms). SALCA Soil Quality estimates relative changes due to soil and crop management practices, using empirical modelling based on expert knowledge and supported by available literature. SALCA Soil Quality requires data on site characteristics, fertilisation, pesticide applications, soil tillage, crop rotation, crop residues, machinery usage and grazing animals.

This impact category is currently designed for an application to the Swiss context and similar pedo-climatic conditions (Central/Western Europe) so that a systematic application to all LCA studies is not always adequate.

3.4.3 Soil Quality – LANCA

The LANCA model was developed to quantify soil quality impacts caused by different land use types (Bos et al., 2016). It accounts for five different soil functions covering several ecosystem services: erosion resistance, mechanical filtration, physicochemical filtration, groundwater regeneration and biotic production. De Laurentiis et al. (2019) derived a single score soil quality index from the LANCA soil indicators. The model considers the soil quality in more general terms and can therefore be applied to any geographical context as well as to soil-quality impacts of non-agricultural activities (e.g., through resource extraction or construction work), but is not sensitive to agricultural practices and should therefore complement the aspects not covered by the SALCA Soil Quality model. The unit of the LANCA indicator, called Soil Quality Index (SQI), is in points. This indicator is included in the Environmental Footprint v3.0 impact assessment method (Bassi et al., 2023), whose characterisation factors are used in the SALCA-LCIA v2.01. Smaller values of this indicator mean that the land use activity is expected to cause a smaller difference in the ecosystem quality compared to a situation where it would not take place.

3.4.4 Climate change impact

The impact of greenhouses gas (GHG) emissions is quantified by the climate change impact category and expressed in kg of CO_2-equivalents. Carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) are relevant GHG in the context of agriculture. Different modelling approaches are proposed by the Intergovernmental Panel on Climate Change (IPCC), namely either looking at the Global Warming Potential (GWP) or the Global Temperature Change Potential (GTP) of the GHG emissions, both with different time horizons. The SALCA-LCIA v2.01 includes the GWP100 as default characterization model, which describes the radiative forcing accumulated over a 100 year time horizon resulting from pulse emissions of the different GHG compared to CO_2 (FAO, 2023). For sensitivity analysis, SALCA-LCIA v2.01 uses the GTP100, which describes the temperature increase resulting from a pulse emission of the GHGs compared to the one resulting from a pulse-emission of CO_2 100 years after the emission (FAO, 2023). This is in line with the recommendations of GLAM (UNEP, 2016), except that SALCA-LCIA v2.01 does not foresee the inclusion of GWP20 in the sensitivity analysis to not complicate the interpretation of the outcomes. Depending on the goal and scope of the study, including further models for climate change impact modelling might be necessary. In fact, the FAO proposes a guidance to choose the most appropriate GHG accounting metric depending on the question to be addressed and the time-frame, which is of particular importance for the short-lived GHG methane (FAO, 2023). While GWP can be useful when the aim is to reduce overall potential damage, GTP can provide more information when the question relates to impacts occurring during a specific year.

The CFs available in IPCC 2021 were implemented in the SALCA-LCIA v2.01 accounting for land use and land use change (LULUC) and carbon cycle response, previously referred to as climate carbon feedback but without considering biogenic carbon emissions (IPCC, 2021). The CF for CO_2 emissions in the stratosphere and troposphere were set to 1.7 to account for the fact that CO_2 emissions occurring in the higher levels of the atmosphere have more impact (Allen et al., 2018; Lee et al., 2021).

3.4.5 Water scarcity

The water scarcity indicator describes the potential of water deprivation in an area caused by water use because of the existing water needs for humans and ecosystems in the same area. The SALCA-LCIA v2.01 estimates water scarcity impacts based on the AWARE model (Available WAter REmaining) (Boulay et al., 2018). The impacts are expressed in m^3 and the CF compares the average water remaining in the world to the water remaining in a specific area. The remaining water has to cover human and environmental water consumption. World and country-specific averages are used, based on the weighting described in Boulay et al. (2018) without differentiating any use.

3.4.6 Land use – Biodiversity – SALCA

The SALCA biodiversity method (Jeanneret et al., 2014; Nemecek et al., 2023) was developed as an expert system for including biodiversity in agricultural LCA. The method describes the effect of agriculture on 11 indicator species groups on agricultural land, and sums up the evaluation for all groups to a single score. The impact is primarily influenced by the type of agricultural land use (e.g., different crops, intensive and extensive grassland, semi-natural habitats) and agricultural management. For each habitat, the impact of agricultural management activities, such as soil tillage or spraying pesticides, can be accounted for as well and heightens or lowers the final score. The method covers only agricultural land use and excludes other sectors (e.g., through mineral extraction or construction work). This impact category is designed for an application to the Swiss context and is also applicable to Central and Western Europe. For other regions, adaptations would be needed.

3.4.7 Land use– Biodiversity – species loss potential

The SALCA-LCIA v2.01 quantifies land use and land use change impacts on biodiversity using the method of (Chaudhary & Brooks, 2018) which uses species-area relationships to estimate the potentially disappeared fraction (PDF) of species due to a specific land use or land use change. It distinguishes between five land use types (forest, plantation, cropland, grassland, and urban) and three intensity levels of each land use type. The effect on five indicator species groups is taken into account. The method can be applied to all life cycle stages (upstream and downstream of agriculture), but cannot take into account the effect of agricultural management practices or distinguish between different crops and is therefore meant to be used in complement to SALCA biodiversity for the aspects not covered by this model. It can be applied worldwide. The method provides regional and global characterization factors. Regional factors describe the potential of land use or land use change to eliminate species in the ecoregion where the land use occurs, while the global factors describe the potential to eliminate species globally and thus emphasize the damage caused by products from regions with a high number of threatened or endemic species (Chaudhary & Brooks, 2018). This method was recommended by the second GLAM phase (Life Cycle Initiative, 2022).

3.4.8 Terrestrial acidification

This impact category quantifies the effect of acidifying substances emitted to the air on vulnerable terrestrial ecosystems. For agricultural systems, the impacts are dominated by emissions of ammonia, sulphur dioxide and nitrogen oxides. Changes in acidity levels are potentially harmful for ecosystems. The terrestrial acidification model proposed in ReCiPe 2016 v1.1 (Hierarchist) was implemented in SALCA-LCIA v2.01 to evaluate the impact in kg of SO_2-equivalents of the emission of acidifying substances on ecosystems. The latest global recommendations available (Life Cycle Initiative, 2022) are the use of a specific fate model with a different aggregation scheme than the one implemented in ReCiPe 2016 v1.1 and LC-Impact (Verones et al., 2020) to derive weighted averages for the CFs at the world and country level. Such an aggregation is necessary since the CFs are calculated at a grid-cell level, corresponding to the resolution of the atmospheric model used to describe emissions of acidifying substances. Given the little differences between the aggregation method implemented in GLAM (Life Cycle Initiative, 2022) and in ReCiPe 2016 v1.1 (Huijbregts et al., 2017)and the lack of examples using the GLAM-based aggregation method, SALCA-LCIA v2.01 implements the approach of ReCiPe 2016 v1.1 (Hierarchist).

3.4.9 Eutrophication

Eutrophication describes the increase of nutrient levels, such as phosphorus and nitrogen, in the environment. Freshwater eutrophication is for example responsible for algae bloom and in turn the disappearance of other freshwater species. Marine, freshwater, and terrestrial eutrophication are included in SALCA-LCIA v2.01. Marine eutrophication is mainly driven by nitrogen emissions, and freshwater eutrophication by phosphorus emissions, so that they are sometimes referred to as N- and P-eutrophication. They are expressed in kg N-equivalent and kg P-equivalent. SALCA-LCIA v2.01 uses the models proposed in ReCiPe 2016 v1.1 (Hierarchist) for marine and freshwater eutrophication, and so follows the fate model recommendations of GLAM (Life Cycle Initiative, 2022).

GLAM does not recommend any terrestrial eutrophication method, probably because it was found to correlate to terrestrial acidification. Since terrestrial eutrophication is an additional indicator of ammonia-driven eutrophication and ammonia is an important emission in the agricultural context, terrestrial eutrophication was included in SALCA-LCIA v2.01. The model implemented in the EF v3.1 was used in this case to express the potential of acidification of substances emitted to soil in kg N-equivalent (Bassi et al., 2023). Correlations between these impact categories can be used to streamline the communication as described in Chapter 4.

3.4.10 Ozone depletion

This impact category describes the depletion of stratospheric ozone due to the emission of ozone depleting substances and is expressed in kg CFC11-equivalent. We choose the modelling approach of ReCiPe 2016 v1.1 (Hierarchist) because it relies on most up to date and global models. Including ozone depletion when considering agricultural systems is important, since N_2O is expected to remain the largest ozone-depleting emission throughout the 21st century (Ravishankara et al., 2009). N_2O emissions are mostly associated with N-fertilizers and manure applied to soils (Campbell et al., 2017).

3.4.11 Ecotoxicity

Ecotoxicity describes the impact of chemical emissions into the environment. In agriculture, pesticides and heavy metals are the main sources of ecotoxicological impacts. One differentiates the impact on freshwater, marine, and terrestrial ecosystems. The USEtox consensus model recommended in GLAM provides estimates of the ecotoxicological impact of chemical emissions on freshwater ecosystems and is also the approach used in SALCA-LCIA v2.01 (USEtox, 2019).The units are in potentially affected fraction of species (PAF) within a day (d) and a given volume of freshwater (1m^3) (=PAF*m^3*d).

For now, USEtox does not provide any CFs for the terrestrial and marine ecosystems. The marine ecotoxicity is not of primary concern in the LCA of Swiss agricultural systems, so that no alternative solution was looked for to include this impact category in SALCA-LCIA v2.01. On the contrary, terrestrial ecotoxicity is relevant for several agricultural systems so that the CFs included in the LC-Impact method (Verones et al., 2020) were included in SALCA-LCIA v2.1. This required to convert the CFs from “Potentially Disappeared Fraction (PDF) of species per day per m^3” to “PAF per day per m^3” by multiplying the factor by 2 (PAF = 2*PDF) (Verones et al., 2020).

In addition, SALCA-LCIA v2.1 foresees an extended set of CFs for the terrestrial and freshwater ecotoxicity of pesticides, whenever no CFs were available in the methods for terrestrial and freshwater ecotoxicity. These additional CFs were included assuming that all pesticides potentially have an ecotoxicological impact and that no characterization means not considering their potential impacts in LCA. This extended set relies on proxies generated based on the mode of actions of pesticides, describing the most fundamental property of a pesticide’s active ingredient, or the group classification (e.g., herbicide, insecticide, etc.). First, the geometric means of the CFs of terrestrial and freshwater ecotoxicity were calculated for each mode of action and for each group classification individually using a specific mapping file based on the CF available in the methods (USEtox and LC-Impact). Second, for each pesticide used in SALCAfuture (Nemecek et al., 2023) it was checked whether a CF for that substance was already provided by the methods for terrestrial and freshwater ecotoxicity. If not, the mode of action or the group was assigned to the substance in a third step. Fourth, the calculated geometric mean for the corresponding mode of action or group classification was assigned as proxy CF of the substance. Finally, if the mode of action or the group classification was not available, a generic proxy corresponding to the geometric mean over all existing CFs of terrestrial and freshwater ecotoxicity was assigned to the chemical. This method was also used in Furrer et al. (2023). For a selection of substances, no proxies were calculated although the substances were specified in SALCAfuture because toxicity effects are assumed to be very small and an approximation with proxies based on the values of all other chemical substances would lead to an overestimation of the impacts (Table 3 in the Appendix). A summary of the number of proxies generated for each toxicity method is given in Table 4 in the Appendix.

3.4.12 Photochemical ozone formation

This impact category describes the formation of tropospheric ozone as a result of reactions between NO_x and Non Methane Volatile Organic Compounds (NMVOCs). We chose the modelling approach of ReCiPe 2016 v1.1 (Hierarchist), which expresses this impact category in kg NO_x-equivalents (Huijbregts et al., 2017). This modelling approach relies on the most up to date and global fate models.

3.4.13 Human toxicity

SALCA-LCIA v2.01 differentiates the carcinogenic and non-carcinogenic impacts on human health, expressed in cancer and non-cancer cases, respectively, based on the USEtox model CFs (Fantke et al., 2015). As for ecotoxicity, USEtox is the consensus model widely accepted in LCA and recommended by GLAM to model human toxicity impacts.

For the non-carcinogenic effects, the same approach as for ecotoxicity was adopted to estimate CF proxies for pesticides assuming again that all pesticides potentially have a non-carcinogenic toxic effect. On the contrary, since not all pesticides have a carcinogenic effect, the proxy approach was not applied to them in this case.

3.4.14 Particulate matter

Particulate matter (PM) is fine solid matter dispersed and spread by air movement (Huijbregts et al., 2017). The impact assessment model of EF v3.1 (EU, 2021) was implemented in SALCA-LCIA v2.01 to describe the impact on human health of PM with a diameter of 2.5 micrometers or less (PM2.5). The impact is expressed in disease incidents. This method corresponds to the GLAM recommendations (Life Cycle Initiative, 2022). Including PM in LCA allows to account for the impacts on human health of dust emissions or emissions resulting from the burning of fossil fuels.

3.4.15 All resource use: Cumulative Exergy Extraction from the Natural Environment (CEENE)

The SALCA-LCIA v2.01 includes different impact categories to account for resource use: abiotic resource use, renewable resource use and non-renewable resource use. These impact categories are not expressed in the same unit so that a direct comparison is difficult. The CEENE model makes it possible to express all resource uses in the same unit, namely in MJ of exergy (Dewulf et al., 2007). GLAM recommends this model whenever the goal is to quantify the relative changing opportunities of future generations to use mineral resources due to a current mineral resource use (Life Cycle Initiative, 2022). Given its relative complexity in interpretation compared to the other models, it is included in SALCA-LCIA v2.01 for sensitivity purposes only.

3.5 Endpoint indicators

The focus of the SALCA-LCIA v2.01 is on the midpoint impacts. In some cases, however, summarizing the environmental impacts in fewer impact categories can be useful. In those cases, endpoint impact indicators can be very useful, since they do not imply any subjective choices (as would be necessary for normalization and weighting, which would also result in a single score) but only additional modelling steps.

Among the reviewed impact assessment methods providing endpoint indicators, ReCiPe 2016 v1.1, LC-Impact, Ecological Scarcity 2021, IMPACT World+, Stepwise 2006, EPS2015, and LIME3, we found that ReCiPe 2016 v1.1, LC-Impact and IMPACT World+ satisfied LCA modelling requirements, showed an extensive documentation, were implemented in recent LCA software and relied on the most up to date models. As such they all satisfied the first two criteria defined in Chapter 3.2. ReCiPe 2016 v1.1 is the most established and tested endpoint impact assessment method and the only one allowing a single score calculation based on all three endpoint indicators, ecosystem quality, resource use and human health. The SALCA-LCIA v2.01 therefore foresees the use of ReCiPe 2016 v1.1 whenever single score impact assessment is required in a specific study or project.

4 Communication keys

By default, all midpoint impact indicators listed in Table 1 are calculated when using SALCA-LCIA v2.01. The results of all LCI and midpoint indicators, except CEENE and GTP 100, should be reported in the supplementary information of the document being written. The results of the CEENE and GTP 100 methods should be discussed in the main text only if they provide additional insights or are of particular interest for the project or the audience.

For deriving the main conclusions, not all impact indicators listed in Table 1 necessarily need to be discussed. The choice depends on the goal and scope of the study, so that it is not possible to define a universal set of indicators that needs to be reported in every study. Instead, the following criteria should be considered to motivate the choice of the indicators to be discussed in the main text.

- What is the goal of the project?
  - The impact categories included in the main text should be sensitive to changes/measures evaluated in the project. For example, one should include water use as impact category if one evaluates measures to reduce the water consumption of a specific installation.
  - The geographical scope of the project can also motive the indicators choice. Projects with a global focus without a Swiss reference will likely not benefit from the inclusion of impact categories with a CH-application level so that they do not need to be discussed in the main text.
  - Depending on the targeted audience, different indicators can be listed. If the target audience are scientists, all impact categories listed in Table 1 can be reported and discussed in the main text. For other audiences, discussions might help to identify which impact categories are particularly important to them and should in any case be discussed in the main text. These discussions alone can however not define which impact categories to include and the other criteria should in any case be considered.
- Which environmental impacts are typically relevant for the system under study?
  - Based on literature, previous experience and the goal and scope of the study, one should generate a list of impact categories necessary to give a full picture of the environmental impacts of the analysed system. These impact categories should be discussed in the main text. For comparative studies, one should pay special attention to the impacts which are different between the systems to be able to show trade-offs and synergies.
- Which impacts are typically reported in similar studies? Which environmental impacts show large and relevant differences between the systems in a comparative study?
  - Literature on similar topics ideally with corresponding temporal, geographical and methodological assumptions should be screened to identify the impact categories that are affected by the studied system. Ideally, the results of the impact categories corresponding to the values found in literature should be compared and discussed in the main report.
- Correlations/redundancy between impact indicators
  - Some indicators are often highly correlated (Roesch et al., 2021). This can be because the same emission dominates the impact (such as terrestrial acidification and terrestrial eutrophication dominated by ammonia emissions), or because they have the same drivers (such as cumulative energy demand (CED) and photochemical ozone creation potential (POCP) dominated by fossil fuel consumption). Reporting several such indicators would not alter the conclusions or recommendations. In order to avoid too many repetitions, one of the correlated impact categories is discussed in the main text, the other(s) listed in the supplementary material.

5 Outlook

Life Cycle Impact Assessment is a rapidly evolving field with new or updated impact assessment methods being released more or less regularly depending on the impact assessment method.

The summary and implementation of LCIA methods for SALCA-LCIA v2.01 described in this report represent current best practice. Also comparing the conclusions of this report and the work of (Roesch et al., 2024) on regionalized impact assessment methods, it appears that most of well-developed impact assessment methods included in the updated SALCA LCIA method rely on up to date, spatially explicit models which allow regionalized impact assessments.

With upcoming method updates and further practical experience, the harmonization exercise is likely to involve future updates in the CFs of some impact categories. In this respect, a special focus should be laid on the recommendations of the working group by the Global Life Cycle Impact Assessment (GLAM) Initiative of the United Nations Environmental Program.

Another example is given by Scherer et al. (2023): They recently updated the current impact assessment models for biodiversity impact related to land use by including land use fragmentation. Once the method is implemented in LCA software, we will investigate if and how the CFs should be updated in the SALCA-LCIA v2.01. Similarly, the updates of the USEtox model or the IPCC working group will be followed and implemented in new versions of SALCA-LCIA whenever necessary and available.

Further, developments related to the regionalization of impact categories (Roesch et al., 2024) are likely to lead to updates in the impact assessment methods. Such updates will be monitored by the LCA research group of Agroscope and new versions of the SALCA-LCIA method will be released when appropriate.

6 Appendix

6.1 French and German translation of the impact category names

Table 2: French and German translation of the impact category names

Impact category	Indicateur d'impact	Umweltwirkung
Abiotic resource use	Utilisation des ressources abiotiques	Ressourcennutzung - abiotisch
Renewable resource use	Utilisation des ressources renouvelables	Ressourcennutzung - erneuerbar
Non-renewable resource use	Utilisation des ressources non-renouvelables	Ressourcennutzung - nicht erneuerbar
Water use	Utilisation de l'eau	Wasserverbrauch
Land transformation - Deforestation	Transformation des sols - Déforestation	Flächenumwandlung - Abholzung
Land occupation - Total	Occupation des sols	Flächenbelegung
Land occupation - Agricultural	Occupation agricole des sols	Flächenbelegung Landwirtschaft
Land occupation - Non-Agricultural	Occupation non-agricole des sols	Flächenbelegung Nicht-Landwirtschaft
Land occupation - Agricultural food	Occupation agricole des sols Alimentation	Flächenbelegung Landwirtschaft Nahrungsmittel
Land occupation - Agricultural non-food	Occupation agricole des sols Non-Alimentation	Flächenbelegung Landwirtschaft Nicht-Nahrungsmittel
Soil quality - SALCA	Qualité du sol SALCA	Bodenqualität SALCA
Soil quality - LANCA	Qualité du sol LANCA	Bodenqualität LANCA
Climate change impact GWP100	Changement climatique GWP100	Klimawandel GWP100
Water scarcity	Epuisement des ressources en eau	Wasserknappheit
Land use - Biodiversity SALCA	Utilisation des sols - Biodiversité SALCA	Landnutzung - Biodiversität SALCA
Land use - Biodiversity - regional species loss potential	Utilisation des sols - Biodiversité - potentiel régional de disparition des espèces	Landnutzung - Biodiversität - regionales Artenverlustpotential
Land use - Biodiversity - global species loss potential	Utilisation des sols - Biodiversité - potentiel global de disparition des espèces	Landnutzung - Biodiversität - globales Artenverlustpotential
Terrestrial acidification	Acidification terrestre	Terrestrische Versauerung
Marine eutrophication	Eutrophisation marine	Marine Eutrophierung
Freshwater eutrophication	Eutrophisation eaux douces	Süsswasser-Eutrophierung
Terrestrial eutrophication	Eutrophisation terrestre	Terrestrische Eutrophierung
Ozone depletion	Appauvrissement de la couche d'ozone	Ozonabbau
Freshwater ecotoxicity	Ecotoxicité eau douce	Süsswasser-Ökotoxizität
Terrestrial ecotoxicity	Ecotoxicité terrestre	Terrestrische Ökotoxizität
Photochemical Ozone formation	Formation photochimique d'ozone	Photochemische Ozonbildung
Human toxicity - cancer	Toxicité humaine, substances cancérogènes	Humantoxizität, krebserregend
Human toxicity - non-cancer	Toxicité humaine, substances non-cancérogènes	Humantoxizität, nicht krebserregend
Particulate matter	Particules fines	Feinstaub
All resource use	Utilisation des ressources	Ressourcennutzung
Climate change impact GTP100	Changement climatique GTP100	Klimawandel GTP100

6.2 Details of the proxy generation

Table 3: List of chemical substances for which no proxies were calculated.

Substance	Factor	Unit
Carbon dioxide, fossil	0	PAF m^3 day
Biological control agent	0	PAF m^3 day
Oils, biogenic	0	PAF m^3 day
Oleic acid	0	PAF m^3 day
Fatty acids	0	PAF m^3 day
Mineral oil	0	PAF m^3 day
Petroleum oil	0	PAF m^3 day
Sucrose	0	PAF m^3 day
Maltodextrin	0	PAF m^3 day
Pheromon, unspecified	0	PAF m^3 day
Kaolin	0	PAF m^3 day
Ascorbic acid	0	PAF m^3 day

Table 4: Summary of the number of chemicals for which proxies were calculated. The line “Ratio factors proxy:raw” gives the percentage of proxies calculated in comparison to the number of chemicals for which the chosen impact assessment method provided CFs.

	Ecotoxicity terrestrial		Ecotoxicity freshwater		Human toxicity cancer		Human toxicity non-cancer	
	Organic	*Inorganic*	*Organic*	*Inorganic*	*Organic*	*Inorganic*	*Organic*	*Inorganic*
Number of raw factors	20545	334	24960	408	10230	220	4260	228
MoA[1]	712	8	900	10	0	0	1870	10
Pest. type[2]	848	144	1110	190	0	0	1850	200
Generic	152	40	190	50	0	0	290	60
Number of proxies	1712	192	2200	250	0	0	4010	270
Ratio factors proxy:raw	8%	57%	9%	61%	0%	0%	94%	118%

[1] Mode of action; [2] Pesticide type (e.g., herbicide or insecticide)

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